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VOLUME II - REACTIVE FLYING MACHINES

A. A. Blagonravov, Editor in Chief

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Editor of this volume: Engineer B. N. Vorob'yev
Scientific editor of this volume:
Dr. Phys.-Math. Sci. A. A. Kosmodem'yanskiy

*

Managing editor: L. M. Bekasova
Technical editor: T. A. Zemlyakova
Proofreaders: Ye. A. Vasil'yeva and V. T. Makarov

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Chief Editor: Academician A. A. Blagonravov

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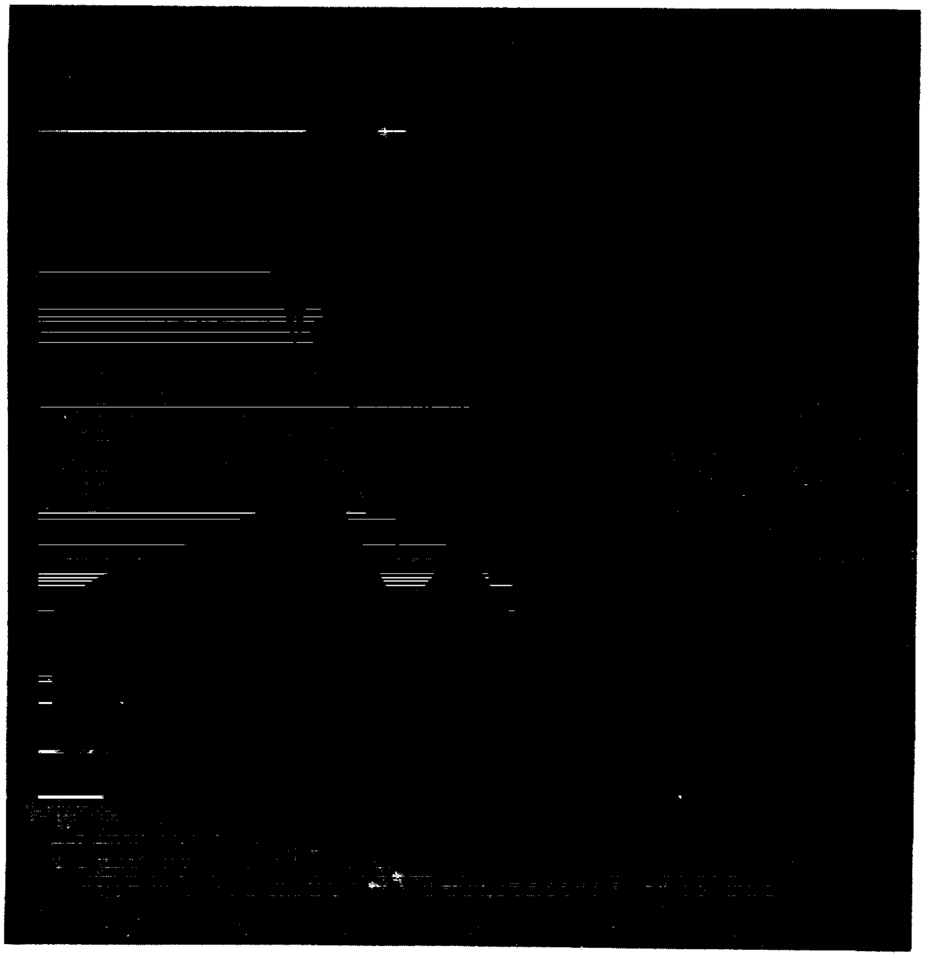
вечно на земле, но, въ
погоне за светом и
пространством, сначала
робко проникнетъ за
пределы атмосферы,
а затем завоюетъ
себе все около-солнечное
пространство.

К. Циолковский

Mankind will not remain forever confined to the Earth. In pursuit of light and space, it will, timidly at first, probe the limits of the atmosphere and later extend its control to the entire solar system.

K. Tsiolkovskiy

(From a letter written by K. E. Tsiolkovskiy
to B. N. Vorob'yev, 12 August 1911)



K. E. Tsiolkovskiy

1910

K. E. Tsiolkovskiy -- the Founder of Modern Rocket Dynamics

Rocket engineering is one of the most important fields of twentieth-century scientific and technical progress.

During World War II the development of reaction propulsion systems was given particular impetus. Rocket batteries, long-range missiles, air-breathing torpedos, and jet aircraft all appeared on the battlefield.

Since the war jet fighters have almost completely displaced propeller-driven fighter planes. As a rule, new high-speed aircraft are all designed with jet engines. Rockets are used to investigate the composition, temperature, and motions of the upper layers of the atmosphere, as well as the propagation of radio waves and solar emission spectra at high altitudes. In fact, scientific and technical journals are now seriously debating the problem of developing a rocket that could launch an artificial earth satellite.

To solve the problems of rocket engineering, we have mobilized resources of science and industry undreamed of in previous eras of technological development. The study of the laws of motion of reaction-propelled bodies is becoming an urgent problem of modern mechanics.

The chief founder of the theory of reaction propulsion, the creator of the principles on which the development of this new field of science is based, was the renowned scientist, inventor and thinker Konstantin Eduardovich Tsiolkovskiy.

The motion of reaction-propelled bodies is more complicated than the motion of propeller aircraft and artillery projectiles. The most important of the complicating factors is the considerable change in the mass of the body during flight.*

The change in the mass of reaction-propelled bodies during flight makes it impossible to employ the formulas of classical mechanics, the theoretical basis for calculating the motion of bodies of constant mass.

It is also known that in engineering problems dealing with the motion of bodies of variable mass (e.g., aircraft with heavy loads of fuel), in order to simplify the analysis, the trajectory is divided

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*It is sufficient to mention that the mass of the German V-2 long-range rocket decreases by two-thirds during the first 60-65 seconds of flight.

into sections, and over each of which the mass of the moving body is assumed to be constant.

The study of the motion of rockets, regarded as bodies of variable mass, was first placed on a solid scientific foundation by K. E. Tsiolkovskiy, who made a major contribution to the development of a new discipline of theoretical mechanics -- the mechanics of bodies of variable mass.

Konstantin Eduardovich Tsiolkovskiy was born on 17 September 1857 in the village of Izhevskoye, Spassk District, Ryazan' Government, the son of a forester. His childhood was clouded by a grave illness -- at nine he caught scarlet fever and almost lost his hearing. Deafness prevented the boy from continuing to attend school, and, from the age of 14, Konstantin Eduardovich began to educate himself, profiting from the books in his father's library. It was then that his passion for invention was aroused: on his own initiative he made balloons out of thin cigarette paper, built a miniature lathe, and designed a wind-driven caleche. Tsiolkovskiy was 16 when his father sent him to Moscow to acquaint himself with industry and continue his independent education.

During these years Tsiolkovskiy conceived the idea of conquering outer space. At one time it seemed to him that space could be explored by utilizing the properties of centrifugal force. As Konstantin Eduardovich wrote later, "I was so excited, so shaken, that I could not sleep all night. I wandered through Moscow, thinking all the time about the great consequences of my discovery. But by dawn I had already realized the error in my reasoning. I felt the disappointment just as keenly as the elation. That night left its impression on my entire life; now, 30 years later, I still sometimes dream of rising to the stars on my machine and experience the same elation as on that unforgettable night."*

In 1879 K. E. passed an examination for teachers and in 1880 was appointed teacher of arithmetic and geometry at the Borovskoye District School in the Kaluga Government.

While teaching at that school, K. E. started his first scientific investigations. It should be noted that Tsiolkovskiy's principal scientific work is related to three major and complex technical problems on which he concentrated all his inventive genius: the all-metal dirigible, the airplane and the long-range rocket.

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*N. A. Rynin. K. E. Tsiolkovskiy -- yego zhizn', raboty i rakety. (K. E. Tsiolkovskiy. His Life, Work and Rockets). Leningrad, p. 10, 1931.

Tsiolkovskiy did most of his work on the all-metal dirigible between 1885 and 1892. His description of an airplane -- with a good streamlined shape and lightweight engine -- and the corresponding calculations were published in 1894. From 1896 on, Tsiolkovskiy worked consistently on the theory of the motion of rockets and proposed a series of designs for long-range rockets and space ships. In the final years of his life, between 1929 and 1935, Tsiolkovskiy labored long and fruitfully to develop the theory of jet flight.

His work on the theory of reaction-propelled bodies is the most valuable and forward-looking part of his entire extensive scientific legacy. All the greatness and depth of his talent, his creative originality and vigor, manifested themselves precisely in these investigations of the flight of rockets and reaction-propelled craft. Tsiolkovskiy pushed back the frontiers of human knowledge, and his idea of using the rocket for the exploration of space is only now, in our own time, beginning to be fully appreciated. He was the father of the theory of modern long-range liquid-fueled rockets and the founder of a rigorously scientific theory of interplanetary travel.

In 1881, when he was 24, Konstantin Eduardovich independently developed the kinetic theory of gases. He sent a report on this to the Petersburg Physico-Chemical Society. The report gained the approval of eminent members of the society, including the great chemist D. I. Mendeleyev himself. For another contribution, entitled "Mekhanika zhivotnogo organizma" (Mechanics of the Animal Organism),* Tsiolkovskiy was unanimously elected a member of the Physico-Chemical Society.

Beginning in 1885, K. E. Tsiolkovskiy started to apply himself zealously to aeronautical problems. He set himself the goal of developing a steerable metal aerostat. Tsiolkovskiy took note of the considerable disadvantages of dirigibles with envelopes of rubberized material: these envelopes wore out rapidly, were a fire hazard, and had very little strength, and the gas with which they were filled was rapidly lost because of the permeability of the fabric. So Tsiolkovskiy wrote a long paper entitled "Teoriya i opyt aerostata" (Theoretical and Practical Aspects of the Aerostat). This gave the scientific justification for the design of a dirigible with a thin metal envelope (of steel or copper); to clarify his explanation, he added appendices containing many original diagrams and figures.

This work, concerned with a totally new problem and accomplished without reference to scientific journals, without communication with

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*Unpublished (Editor's note).

other scientists, required an incredible exertion of creative force and colossal energy. Tsiolkovskiy wrote: "I worked almost continually for two years. I loved teaching, and I would go home very tired, having left behind much of my energy. It was only toward evening that I was able to attend to my calculations and experiments. What was to be done? I had not much time, and not much strength either, so I decided to rise early, at dawn, put in a few hours of creative work, and then go to school and teach. After two years of this kind of life I was plagued by headaches for a full twelve months."*

To Tsiolkovskiy belongs the notable idea of building an aircraft with a metal fuselage. His 1894 article "Aeroplan ili ptitsepodobnaya (aviatsionnaya) letatel'naya mashina" (The Airplane or the Bird-Like (Aerial) Flying Machine) includes a description and sketches of a monoplane, the appearance and aerodynamic design of which are superior to those of aircraft built 15 years later.

In Tsiolkovskiy's airplane the wings have a thick profile with a rounded leading edge, and the fuselage is satisfactorily streamlined.

It is highly interesting that in this particular article Tsiolkovskiy, for the first time in the history of aircraft design, placed special emphasis on the need to streamline the shape of aircraft in order to attain high speeds. The sketches of Tsiolkovskiy's airplane are incomparably superior to subsequent designs by the Wright Brothers, Santos Dumont, Voisin and other inventors. To justify his calculations, Tsiolkovskiy wrote: "In arriving at these figures I proceeded from the most favorable, ideal conditions of drag on the body and wings; in my airplane there are no projecting parts other than the wings; everything is enclosed within a single, smooth shell -- even the passengers."**

Tsiolkovskiy clearly foresaw the importance of gasoline-burning internal combustion engines to aviation. Here is a quotation demonstrating his perfect understanding of the trends of technical progress: "Thus I have theoretical reasons for believing in the possibility of building an extraordinarily light, yet strong gasoline or petrol engine that will be fully equal to the task of flying."*** Konstantin Eduardovich predicted that with time the small airplane would successfully compete with the automobile. But this idea, too, failed to gain

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*N. A. Rynin. K. E. Tsiolkovskiy -- yego zhizn', raboty i rakety. p. 11, 1931.

**K. E. Tsiolkovskiy. Zashchita aeronavta (Protection of the Aeronaut). 1911.

***K. E. Tsiolkovskiy. Sobraniye sochineniy (Collected Works), Vol. I, Moscow. AS USSR Press, p. 70, 1951.

the recognition of Russian scientific officialdom. Neither financial nor even moral support were available for further research on the airplane. At about this period of his life the scientist wrote with bitterness: "In my experiments I arrived at many new conclusions, but my new conclusions are greeted with disbelief by other scientists. These conclusions could be confirmed by repeating my experiments, but [no one knows] when that will happen. It is hard to work alone for many years under unfavorable conditions and receive neither understanding nor support from anyone."*

The problems of interplanetary travel interested Tsiolkovskiy from the very beginning of his creative scientific work. This volume devoted to his work on rocket dynamics includes for the first time his scientific diary "Svobodnoye prostranstvo" (Free Space), which is concerned with the simplest phenomena of mechanical motion in a space free of the effects of gravity and aerodynamic drag. Examining the ways of imparting motion in free space, Tsiolkovskiy arrives at the conclusion that the simplest way of setting a stationary body in motion (or modifying existing motion) is to reduce its mass, i.e., through the reaction of particles expelled from the body. The following extracts are from the manuscript of "Free Space."

"...28 March 1883. Morning.

"...In general, uniform motion along a curve or rectilinear nonuniform motion, in free space, is associated with a continuous loss of mass...

"...Let us assume that a barrel is filled with a highly compressed gas. If one of the spigots is turned on, gas will gush out of the barrel in a continuous jet, and the gas pressure, which expels the gas particles into space, will at the same time cause the barrel to recoil continuously backward.

"The result will be a continuous change in the motion of the barrel."**

Thus, the principle of reaction propulsion was grasped by Tsiolkovskiy at the very beginning of his independent scientific activity. "Free Space" does not contain quantitative results; its conclusions are qualitative and based on the laws of conservation of momentum for closed mechanical systems, but the advantages of utilizing the reaction of an escaping jet for propulsion through free space are

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*N. A. Rynin. K. E. Tsiolkovskiy -- yego zhizn', raboty i rakety, pp. 13-14, 1931.

**Svobodnoye prostranstvo. This volume, page /52.

formulated clearly and explicitly. In our opinion, there is a definite connection between this early work of Tsiolkovskiy's and his fundamental article "Issledovaniye mirovykh prostranstv reaktivnymi priborami" (Exploration of the Universe with Reaction Machines), published 20 years later, in 1903.

II

Let us consider more closely the principal results that Tsiolkovskiy obtained in the theory of rocket flight. Without going into a detailed mathematical exposition, which can in any case be found in the original articles collected in this volume, let us single out the most important accomplishments of the scientist in this field.

In investigating the laws of motion of rockets Tsiolkovskiy proceeded along a rigorously scientific path, introducing one by one the principal forces on which rocket motion depends. First, he tried to explain the potential inherent in the reaction principle of creating mechanical motion and formulated the simplest problem based on the assumption of the absence of gravity and drag. This problem is now called Tsiolkovskiy's first problem. The qualitative aspects of the problem were examined by Tsiolkovskiy as early as in 1883. The motion of the rocket in this simplest case is conditioned solely by the process of expulsion (efflux) of particles of matter from the chamber of the reaction engine. In his mathematical calculations Tsiolkovskiy assumed the constancy of the relative rate of expulsion of the particles, an assumption which is employed to this very day by every basic researcher in rocket dynamics. This assumption is termed Tsiolkovskiy's hypothesis.

Here is how Konstantin Eduardovich justified his hypothesis in his book "Issledovaniye mirovykh prostranstv reaktivnymi priborami": "In order to endow the projectile with maximum velocity, every particle of the combustion products or other form of wake must have maximum relative velocity. This velocity is constant for the particular substances expelled. There is no saving of energy involved, as this is neither possible nor expedient. In other words, a constant relative velocity of the particles expelled must be taken as the foundation of rocket theory."*

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*Issledovaniye mirovykh prostranstv reaktivnymi priborami, Part 1. This volume, page /197.

Through very simple reasoning, Tsiolkovskiy arrives at the basic equation of motion of a rocket in a medium free of external forces. It is known from classical mechanics that closed mechanical systems are subject to the law of conservation of momentum. If, at the initial instant $t = 0$, the velocities of points in the system are zero, the momentum will remain zero throughout the period of motion. Suppose that at moment $t = 0$ the mass of the rocket is M and its velocity $v = 0$; suppose further that the rocket engine expels a mass dM at the rate V_r over an interval of dt, so that the rocket acquires a velocity dv.

From the law of conservation of momentum we obtain

$$dMV_r + Mdv = 0,$$

or

$$dv = - V_r \frac{dM}{M} \qquad (1)$$

Having accepted Tsiolkovskiy's hypothesis, we can integrate (1). We shall have

$$v = - V_r \ln M + C.$$

Since the velocity $v = 0$ when $M = M_0$, $C = V_r$ lin M_0 and, therefore,

$$v = V_r \ln \frac{M_0}{M}. \qquad (2)$$

The rocket will reach its maximum velocity on expending the whole of its stock of fuel. Denoting by M_s the mass of the empty rocket, we obtain from (2)

$$v_{max} = V_r \ln \frac{M_0}{M}. \qquad (3)$$

Equation (3) is known in modern rocket dynamics as Tsiolkovskiy's formula.

Considering that the fuel will have a mass $m = (M_0 - M_s)$, it is convenient to rewrite Tsiolkovskiy's formula (3) as follows:

$$v_{max} = V_r \ln \frac{M_s + m}{M_s} = V_r \ln (1 + z), \qquad (4)$$

where $z = \frac{m}{M_s}$ (ratio of weight of fuel to weight of empty rocket) is termed the Tsiolkovskiy ratio.

In modern terminology, we may call the part of the trajectory corresponding to powered flight (while the engine is burning) the active flight path. The part of the trajectory corresponding to the period when the mass of the rocket is constant may be called the passive flight path.

It follows from equation (4) that:

a) The velocity at burnout (end of active flight path) will be directly proportional to the relative velocity of the expelled particles; if the relative exit velocity doubles, the velocity of the rocket also doubles.

b) The velocity of the rocket at burnout increases with the ratio of the initial weight to the weight at burnout. This relation, however, is more complex, and Tsiolkovskiy expresses in the following theorem:

"If the mass of the rocket plus the mass of the explosives in the reaction propulsion system increases in a geometric progression, the velocity of the rocket will increase in an arithmetic progression."* This law may be illustrated by two series of numbers:

Relative mass of rocket	2	$4=2^2$	$8=2^3$	$16=2^4$	$32=2^5$	$64=2^6$	$128=2^7$
Relative velocity of rocket	1	2	3	4	5	6	7

Tsiolkovskiy writes: "Suppose, for example, that the mass of the rocket plus the explosives is 8 units. I expel 4 units of explosives and obtain a velocity which I will take as unity. Then I expel 2 units of explosives and obtain another unit of velocity; finally I expel the last unit of explosives and obtain yet another unit of velocity; altogether, 3 units of velocity." From the above theorem and Tsiolkovskiy's explanation it is evident that "the velocity of the rocket is far from proportional to the mass of the explosives; it increases extremely slowly but without limit."**

Tsiolkovskiy's formula implies an extremely important practical conclusion: in order to attain the maximum possible burnout velocity, it is much more advantageous to proceed by increasing the relative velocity of the expelled particles than by increasing the relative fuel supply.

Thus, for example, if the object is to double the burnout velocity for a rocket with a ratio of initial weight to empty (fuelless) weight of ~3, we can proceed either by doubling the relative nozzle exit velocity, or increasing the fuel supply to a point at which the ratio of initial weight to empty weight is $3^2 = 9$.

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*Issledovaniya mirovykh prostranstv reaktivnymi priborami. Dopolneniye 1914 g. (1914 Supplement). This volume, page /142.

**Ibid.

It is worth noting that increasing the relative exit velocity requires improvements in the rocket engine and an intelligent choice of fuel constituents, while the second alternative, increasing the relative fuel supply, requires a considerable reduction in the weight of the rocket structure and, unfortunately, in the payload as well.

Tsiolkovskiy's theories on the exploration of outer space with reaction machines, like all progressive scientific ideas, established rational paths for subsequent practical development.

III

Having explained in detail how cosmic velocities may be achieved by means of reaction engines, Tsiolkovskiy carefully investigated the effect of gravitational forces on rocket flight. It is worth noting that Konstantin Eduardovich considered gravity, as it were, a chain fettering man to his home planet. He used the expression "the iron shell of gravitation" when speaking of the radius of action of gravitational forces. Extraordinary interest attaches to Tsiolkovskiy's calculations of the fuel supplies required to break out of this shell. First of all, we should note that gravity decreases with altitude. A man weighing 80 kilograms at the earth's surface will weigh only 20 kilograms at an altitude equal to one earth radius (about 6,400 km). The question is: how much work must be done in order for man to overcome the effect of gravitation completely? Tsiolkovskiy's calculations gave the following answer: "Suppose gravity does not decrease with increasing distance between the body and the planet. Then if the body rises to a height equal to the radius of the planet, it will do an amount of work equal to that required to overcome the planet's gravity completely."

Proof of Tsiolkovskiy's theorem may be obtained by means of the following simple argument. The work done in a potential field of force in moving from point B_1 to some point B_2 is equal to the potential difference, i.e.,

$$A = U_{B_2} - U_{B_1}.$$

The potential function U for a Newtonian field of gravitational attraction is

$$U = \frac{k}{r}.$$

The value of k can be found from the condition that at the earth's surface, when r = R, where R is radius of the earth, the force of gravity is equal to the weight of the body ($-mg_0$). Thus

$$\left(\frac{dU}{dr}\right)_{r=R} = - mg_0,$$

whence

$$k = mg_0R^2.$$

Let us suppose that a body of weight mg_0 moves from the earth's surface to infinity. Then the work done by gravity will be

$$A = U(R) - U(\infty) = - mg_0R,$$

i.e., the weight of the body multiplied by the earth's radius.

Motion along a vertical path in the field of terrestrial gravity requires the selection of an optimal propulsion regime, since, clearly, a forced regime will involve excessive stresses due to the thrust and excessive drag in the denser layers of the atmosphere, while slow combustion may cause the rocket not to ascend at all, since the thrust may then be less than the rocket's own weight. This idea of Tsiolkovskiy's has inspired various Soviet scientists to investigate the optimization of rocket trajectories within the gravitational field.

Tsiolkovskiy paid much attention to investigating drag. He was the first in the history of rocketry to estimate the fuel supply required for a rocket to travel beyond the earth's atmosphere. Since drag impedes attempts to increase the velocity of rockets, Tsiolkovskiy termed the region of action of drag forces "the iron shell of the atmosphere."

The twin shells of gravity and the atmosphere restrict the rocket to the vicinity of the earth's surface. Pierce them and you will be a denizen of outer space, able to direct your rocket toward any planet or asteroid!

Tsiolkovskiy was the first to calculate the optimal angle of ascent of a reaction-propelled vehicle traveling through layers of air of variable density; he also investigated the conditions for rocket take-offs from different planets and asteroids and solved the question of the amount of fuel required for a rocket to return to Earth.

In his work on rocket dynamics, for the first time in the history of science, Tsiolkovskiy determined the efficiency of a rocket and pointed out the advantages of reaction engines at high speeds. Even in his early work he noted a case in which the rocket efficiency would be 100%. This occurs when the relative exhaust velocity is equal to the velocity of the rocket; it is easy to see that in this case the "absolute" velocity of the expelled particles relative to the earth will be zero. Since the exhaust velocities of modern rocket engines range from 1,800 to 2,200 m/sec, it is clear at which rocket velocities they are most efficient.

K. E. Tsiolkovskiy's work on reaction propulsion was not limited to theoretical calculations; it also contains practical advice on the design and construction of individual rocket parts, the selection of fuels, and the shape of nozzles; the problem of ensuring stable flight in an airless space is also considered.

Tsiolkovskiy's rocket is an oblong metal chamber similar in shape to a dirigible or barrage balloon. The nose contains a passenger compartment equipped with control instruments, electric light, CO_2 absorbers, and oxygen tanks. The remainder of the rocket is filled with fuel components which, when mixed, form an explosive mass. The explosive mass is ignited at a certain point, near the center of the rocket, and the combustion products, exhaust gases, flow out of an expanding pipe at a tremendous velocity.

Having derived the initial working formulas of rocket motion, K. E. Tsiolkovskiy outlined a broad program for successive advances in reaction machine technology. The principal aspects of this grandiose development program are as follows: 1. Experiments in situ (meaning laboratories where static tests are performed). 2. Plane motion of a reaction machine (on an airfield). 3. Ascents to a low altitude and gliding descents. 4. Penetration to the more rarefied layers of the atmosphere, i.e. the stratosphere. 5. Flights beyond the confines of the atmosphere and gliding descents. Establishment of independent space stations outside the atmosphere (rockets as artificial earth satellites). 7. Utilization by astronauts of solar energy for respiration, nutrition, and certain other physiological purposes. 8. Utilization of solar energy for travel throughout the solar system and for industry. 9. Visits to the smallest bodies of the solar system (asteroids and planetoids) lying nearer to and farther from the Sun than our own planet. 10. Propagation of mankind throughout the solar system.

IV

Konstantin Eduardovich Tsiolkovskiy devoted much attention to investigating fuels suitable for reaction engines. He formulated the principal requirements which these fuels must meet, requirements which are still used as a guide by scientists and engineers. Here are the results of his studies:*

"The constituents of explosives for reaction-propelled travel must have the following properties:

"1. They must do the maximum amount of work per unit mass during combustion.

"2. On combining they must yield gases or volatile liquids that evaporate on being heated.

"3. During combustion they should develop the lowest possible temperature, so as not to burn or melt the combustion chamber itself.

"4. They should occupy a minimum of space, i.e., be as dense as possible.

"They should be liquid and mix easily. The use of fuels in powder form introduces complications.

"They may also be gaseous, but then they should have a high

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*Dostizheniye stratosfery. Toplivo dlya rakety (The Attainment of the Stratosphere. Fuel for the Rocket). This volume, p. /374.

critical temperature and a low critical pressure, so as to make it convenient to store them in liquefied form. Liquefied gases in general are unfavorable in view of their low temperature, since they absorb heat for their own heating. Moreover, using them involves losses due to evaporation as well as the risk of explosion. Expensive and chemically unstable products and products difficult to obtain are also unsuitable."

Detailed investigations of the rectilinear motion of rockets and the exhaust velocities of different fuels convinced Tsiolkovskiy that the attainment of high cosmic velocities was an extremely difficult technical problem. In order to attain cosmic velocities with the fuels known in his time, in 1919 Tsiolkovskiy proposed a new, original solution. He suggested multistage rockets or rocket trains and gave their detailed mathematical theory.* As he wrote: "By a rocket train I mean a combination of several identical reaction machines moving first along a track, then through the air, then in the void outside the atmosphere, and finally somewhere between the planets and suns. But only part of the train will reach celestial space; the other parts, lacking sufficient velocity, will return to Earth. A single rocket, if it is to attain cosmic velocity, must be provided with a large supply of fuel. Thus, to attain the first cosmic velocity, i.e., 8 km/sec, the weight of the fuel must be at least four times the weight of the rocket with all its other contents. This complicates the design of reaction machines. A rocket train, on the other hand, makes it possible either to attain high cosmic velocities or to limit the store of explosive fuel to comparatively small proportions."

Taking as unity the relative velocity of the particles expelled from the reaction engine nozzle, according to Tsiolkovskiy's calculations, if the relative fuel supply in each chamber equals one-third, we get the following table.

If the relative exhaust velocity is raised to 3 km/sec, a train of 7-8 rockets is sufficient to attain cosmic velocities, and the last stage may turn into an earth satellite.

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*Kosmicheskiye raketnyye poyezda (Space Rocket Trains). This volume, p. /298.

Number of stages	1	2	3	4	5	6	7	8	9	10
Relative velocity of last stage in terms of relative exhaust velocity	1.386	1.856	2.118	2.325	2.491	1.622	1.735	1.835	2.924	3.005

V

In the last years of his life K. E. Tsiolkovskiy worked hard to develop the theory of jet aircraft. His article "Reaktivnyy aeroplan" (The Reactive Aeroplane) describes in great detail the advantages and disadvantages of jet-propelled as compared with propeller-driven aircraft. Pointing to the high rate of fuel consumption in jet engines, Tsiolkovskiy writes: "...our reactive aeroplane consumes five times as much fuel as a conventional plane. But it will fly twice as fast in a layer of the atmosphere where the density is four times less; there, its operating cost will be only 2.5 times higher. Higher still, where the air is 25 times more rarefied, it will fly 5 times faster and utilize energy as efficiently as a propeller-driven aircraft. At an altitude where the air is 100 times more rarefied, the velocity of the jet aircraft will be 10 times higher and it will consume half as much energy as a conventional aircraft." Tsiolkovskiy ends this article with a remarkable sentence reflecting his profound insight into the laws of development of aviation engineering: "The era of propeller-driven aircraft should be followed by an era of jet aircraft, or stratospheric aircraft."

It is worth noting that these lines were written 10 years before the world's first jet plane, built in the USSR, rose into the air.

In his articles "Voskhodyashcheye uskorennoye dvizheniye raketoplana" (The Accelerated Climb of the Rocket Plane) and "Stratoplan polureaktivnyy" (The Semi-Reactive Aeroplane), Tsiolkovskiy provided a theory of the motion of aircraft with fluid jet engines and developed, for the first time in the technical literature, the idea of the turboprop aircraft.

Tsiolkovskiy wrote: "The rocket plane resembles conventional aircraft but, compared with the latter, its wings are small and it has no propeller at all. The rocket plane has a very powerful engine which expels combustion products backward through special conical tubes in the tail. The result is a recoil, a reaction, a repulsion, the force of which enables the rocket plane to achieve its accelerated climb."

The superiority of the rocket plane over the ordinary rocket consists in that the oxidizer is taken directly from the air, thereby resulting in a considerable increase in power.

Tsiolkovskiy's first works on rocket dynamics, written in pre-Revolutionary Russia, failed to win the support of the Government and the scientific establishment. His outstanding ideas about long-range rockets were regarded as empty fantasies and dilettantism.

Tsiolkovskiy met the same fate as many other scientists and inventors in Tsarist Russia. In 1913 there appeared in France the work of the French engineer Esnault-Pelterie "Reflections on the

Results of a Limitless Reduction in the Weight of Engines," which expounded certain formulas of rocket dynamics. This article did not even mention Tsiolkovskiy's name. In 1919 Professor Goddard in America wrote a work on the theory of rectilinear rocket motion, in which Tsiolkovskiy's formula was again derived and the problem of the optimization of vertical rocket flight formulated. Not a line did Goddard devote to Tsiolkovskiy's results, although by that time several works by Konstantin Eduardovich had been published in the form of brochures and periodical articles.

In 1923 Oberth in Germany widely popularized the idea of the space rocket and also failed to consider it necessary to cite Tsiolkovskiy's calculations and projects, although in many cases Oberth's results merely repeat work that Tsiolkovskiy had published 20 years earlier. Only owing to the persistence of numerous Russian engineers and scientists and a large number of articles in the Soviet press was Oberth compelled, in private communications to Tsiolkovskiy, to admit the latter's priority in the development of rockets for space flight. This belittling of the labors of the eminent Russian scientist, the founder of the new scientific discipline of rocket dynamics, continues down to our day. Goddard, Oberth, von Braun and others are called the founders of the theory of long-range rockets, while the name of Tsiolkovskiy is deliberately ignored, although the latter derived the principal working formulas and stated a number of the chief design requirements for rockets of this kind half a century ago.

Tsiolkovskiy's priority in developing the foundations of the dynamics of rocket flight is demonstrated very simply by comparing the corresponding published works. As we pointed out previously, Pelterie's work on the theory of rocket motion was published abroad as late as in 1913, i.e., ten years after Tsiolkovskiy's first work had appeared.

Tsiolkovskiy's works abound in ideas, methods, and factual material.

They reflect a genuine innovator, a blazer of new trails, a bold and original creator of a progressive trend in science.

Although the books currently published in Great Britain and the United States present Tsiolkovskiy's formulas without any reference to the work of their true author, no foreign scientist has yet refuted or can refute Tsiolkovskiy's priority in the theory of reaction propulsion.

It was precisely Tsiolkovskiy who endowed rocket dynamics with that broad, revolutionary sweep and depth that are characteristics of the immortal creations of the human mind. This is an indisputable contribution of Russian science to the common treasury of human culture.

VI

After the Great October Socialist Revolution, the conditions of life and work changed completely for Konstantin Eduardovich. In 1919 he was elected member of the Socialist Academy,* and granted a private pension. The Commission for Providing Scientists With Better Amenities undertook to help Tsiolkovskiy, assuring normal living conditions for him during the difficult and tense period of the Civil War.

The governmental and public organizations of our country began to assist Tsiolkovskiy to publish his works. During 1917-1935 the number of Tsiolkovskiy's articles, brochures and books published was four times greater than during the entire preceding period of his life. In the seven years between 1925 and 1932, approximately 60 works by Tsiolkovskiy concerned with physics, astronomy, mechanics, and philosophy were published. The unflagging attention paid by the Party and Soviet Government to the scientific research work of Konstantin Eduardovich contributed to the widespread popularization and recognition of his works. Essentially, the colossal progress in rocket engineering (especially in the field of aircraft construction), which we are all witnessing, was initiated at the end of the nineteenth century by K. E. Tsiolkosvkiy and to a large degree prepared by the investigations of Konstantin Eduardovich himself and his many successors in the 1930's and 1940's.

Groups for the study of reaction propulsion (GIRD) were organized in Moscow and Leningrad. The GIRD engineers worked closely with Tsiolkovskiy and often it was he who prepared their first plans for scientific and technical research in rocketry. Teams of scientists, inventors and engineers, working under the ideological guidance of Tsiolkovskiy, accomplished results of primary scientific and technical significance. Tsiolkovskiy ceased to feel alone.

The Great October Socialist Revolution was that mighty force which inspired the 60-year-old Tsiolkovskiy with new creative daring. His talent manifested itself in all its formidable splendor. He arose before his contemporaries as the initiator of a new field of human knowledge, a new science, a new technology.

Rocket flight had been observed by many, even before Tsiolkovskiy.

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*The Socialist Academy was organized in June 1918. In 1923 it was renamed the Communist Academy. In 1936 the principal institutes of the Communist Academy were transferred to the Academy of Sciences USSR.

History tells us that the first rockets were built in China more than a thousand years ago. Nevertheless, none of the rocket builders, none of the millions of people who had witnessed fireworks and pyrotechnic displays, created a new science of the theory of rocket flight. Furthermore, gunpowder rockets had attracted the attention of large numbers of highly competent military specialists in the mid-nineteenth century, but in spite of this, prior to Tsiolkovskiy, there was no theory of reaction propulsion.

All the greatness of Tsiolkovskiy's talent, all his creative independence and originality, manifested itself most brilliantly precisely in the investigation of rocket motion, where many others failed to see anything meriting attention.

The ability to reveal the full significance of investigations of the flight of rockets regarded as bodies of variable mass under the conditions of economic and scientific development prevailing in Russia in the early twentieth century seems to us a very remarkable phenomenon. Only a man of exceptional talent could have pushed back the frontiers of knowledge, blazed new trails, and obtained results of such classical clarity and simplicity.

A characteristic feature of a great researcher is his belief in new trends in the technical development of society -- trends that are barely apparent and perceptible to his contemporaries. The correct anticipation of the paths of progress and a total understanding of the trends of social development give faith in the eventual triumph of new ideas that are initially often formulated in a logically imperfect form. "Carlyle, in his famous treatise on heroes, calls great men originators. This is a very felicitous term. The great man is an originator exactly because he sees farther than the others and wants to be stronger than the others. He solves the scientific problems left outstanding by the previous development of the human mind and society; he points out the new social needs created by the previous development of social relations."*

This definition of the great originator fits K. E. Tsiolkovskiy closely.

In Tsiolkovskiy's works mathematical formulas and calculations do not obscure the original and clearly formulated technical ideas. As with any other immortal work, the greatness of which is revealed and emphasized by the test of time, the attentive reader will perceive

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*G. V. Plekhanov. K voprosu o roli lichnosti v istorii (On the Role of the Personality in History). Sochineniya (Works), Vol. VIII, p. /305.

in the writings of Konstantin Eduardovich that mighty and unique creativeness and insight into the laws of nature and technology characteristic of the Russian classics.

In his well-known letter to J. V. Stalin, Tsiolkovskiy wrote: "I transmit all my works on aviation, rocketry and interplanetary travel to the Party of Bolsheviks and to Soviet Authorities -- the genuine leaders of the progress of human culture. I am confident that they shall successfully complete these works."

We can confidently state that the scientific legacy of K. E. Tsiolkovskiy, bequeathed to the Bolshevik Party and Soviet Government, will not be preserved in the manner in which "archivists preserve ancient writings." Soviet science is multiplying the scientific achievements of the founder of rocket dynamics. The revolutionary sweep and bolshevist spirit of determination in the solution of new problems, which the Communist Party has instilled into the Soviet people, are a guarantee of the successful materialization of Tsiolkovskiy's most audacious dreams.

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Volume II of the Collected Works of K. E. Tsiolkovskiy contains all the major writings of this scientist on rocket dynamics. The writings are arranged in chronological order, starting with "Free Space" which was written in 1883 when Konstantin Eduardovich was a young man. This youthful work of Tsiolkovskiy's enables us to trace the development of his ideas on the principle of reaction propulsion. The brief historical notes on Tsiolkovskiy's writings and on the bibliographical sources of quotations in the text were prepared by Engineer B. N. Vorob'yev, who has also written a brief survey of the contents of the articles on rocket dynamics not included in this volume. This concerns articles in newspapers and periodicals, repeating almost literally the text of the principal works published here in full. We have endeavored to adhere as closely as possible to the original text of Tsiolkovskiy's articles, preserving his distinctive literary style, numbering of formulas, and polemical remarks. Many of the scientific results presented in the articles of Konstantin Eduardovich have since become obsolete (e.g. the data on the upper layers of the atmosphere, drag at high sonic velocities, atomic energy, etc.). Wherever this occurs, it is brought to the reader's attention by the editor in brief footnotes. Some of Tsiolkovskiy's statements pertaining to life on interplanetary space ships, his reflections on the social structure of the populations of other planets, and certain remarks on biology have since either been refuted by modern science or become debatable. In all such cases we have inserted appropriate footnotes or abridged the text slightly.

All the mathematical arguments have been carefully verified, and the notation modernized. In a few cases the terminology has been corrected.

In working on this volume I have received much help from the Scientific Secretary of the Commission for Developing the Scientific Legacy and Preparing the Publication of the Works of K. E. Tsiolkovskiy, OTN AN SSSR (Division of Technical Sciences, Academy of Sciences USSR), Engineer B. N. Vorob'yev, to whom I wish to express my sincere gratitude.

Professor A. Kosmodem'yanskiy

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REACTION FLYING MACHINES

FREE SPACE*

Definition of Free Space

Sunday, 20 February, 1883

By free space I mean a medium within the confines of which the force of gravity either does not act at all on observed bodies or has only an extremely feeble effect compared with terrestrial gravity at the surface (the gravity which we humans experience).

Since the observed bodies are contained in free space, it is natural to call them free. Such a medium, in theory, may have no boundaries and in this case I shall call it boundless. The actual existence of free space appears inconceivable, since gravitational forces cannot be entirely eliminated.

Extent of Free Space

On the basis of the laws of gravity, however, I shall explain how such a medium may be approximately** obtained by artificial means within the universe and even on our own Earth.***

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*MS published for the first time. Cf. Appendix, item 3 (editor's note).

**Underscored by the author. Hereafter all words emphasized by the author will be underlined (editor's note).

***In this volume the spelling convention for the planets (earth, sun, moon) is the same as that adopted K. E. Tsiolkovskiy, i.e., in some articles the names begin with a lower-case letter and in others with a capital letter (editor's note).

What is more, such a medium not only can be obtained but actually exists, and not only by way of an exception. Shortly I will show that the greater part of the astral space visible to us is, roughly speaking, free space.

Stars are located in free space, and much of the universe is free space.

Let us visualize the universe, bestrewn with stars and planets.

Observations by astronomers show (the following figures are taken from Arago's popular astronomy) that the center of gravity of the solar system is moving at about 8 kilometers per second. The motions of other stars also differ little from the motion of our Sun. Thus, the highest of the velocities recorded, the velocity of Arcturus, is approximately 80 kilometers (per second).

Were the velocity of Arcturus never to change in magnitude and direction, it might be concluded that Arcturus moves by inertia and is not acted upon by the gravitational attraction of the surrounding stars. Or perhaps, the attraction exerted by some of the stars cancels out the attraction of other, opposing stars.

In this case, the space of Arcturus might be termed a zone of balanced gravitational forces.

The phenomena in such a zone are exactly the same as those occurring in a completely gravitationless medium. Therefore, in this sense, it may be said that the space of Arcturus is a free space. But it may be that Arcturus does not move uniformly; it may even be that several thousand years ago it was completely stationary and only the influence of the stars gave it its 80-kilometer velocity. In this case we must assume that the resultant of the stellar gravitational forces is not zero but has a certain value.

I shall now attempt to determine this value. If the resultant has a definite value, then, at least in the course of a few thousand years, the magnitude and direction of the resultant can not have changed. In fact, the angular positions of the stars have remained nearly unchanged since antiquity, so that the resultant of the forces exerted by these stars can not have changed either, in direction or intensity.

Thus, for several thousand years (say, 3,000), Arcturus has been acted upon by a constant gravitational force which has imparted to it a velocity of not more than 80 kilometers per second.

If we assume this acceleration to be constant, it is not difficult to compute it and compare it with the acceleration of bodies at the Earth's surface.

The acceleration of Arcturus per second is $\frac{80 \cdot 1000}{3000 \cdot 365 \cdot 24 \cdot 60 \cdot 60}$

(i.e.) approximately 1/1,000,000 = 0.000001 m.

As for the acceleration of a body at the Earth's surface, it is about 10 meters. This exceeds the foregoing figure by a factor of 10: $\frac{1}{1\ 000\ 000}$ = 10,000,000.

Therefore, gravity at the Earth's surface is ten million times greater than the attraction that causes Arcturus to move.

In all likelihood, however, Arcturus has been subject to a nearly constant force acting in a nearly constant direction for millions, if not trillions of years and, therefore, the magnitude of this force is billions of times smaller than the magnitude of gravity at the Earth's surface.

21 February

The effect of gravitational attraction on the other stars is much weaker than its effect on Arcturus which may possibly exist close to another star. Thus, [the velocity of] the Sun, as I noted before, is about 8 kilometers [per second].

Most heavenly bodies (stars), then, occupy a space in which they are virtually alone, since they are only very weakly influenced by the surrounding stars.

Thus, the universe is a free space and the stars are free bodies.

Of course, after millions of years their mutual influence must manifest itself, as must the curvilinearity of their paths -- the first sign of the influence of gravity -- but over periods of several centuries their motions may not differ appreciably from the motion which they might execute if they existed in free space.

Although a star regarded as a whole is located in free space, this cannot be said regarding the parts of the star, which are subject to more or less considerable mutual gravitational attraction.

Thus, bodies lying on the surface of the Sun exist in a medium, the gravity of which exceeds terrestrial gravity by 28 times.

In general, gravity manifests itself markedly only with respect to bodies separated from a star's surface by a distance that is not very large compared with the radius of the star. As the distance between a body and the star's center increases, however, gravity rapidly weakens. Thus, at a distance of one thousand radii from the star's center, the gravitational attraction of the star is reduced by as many as 1,000,000 times as compared with the attraction at the surface.

As for interstellar distances, these are vast not only compared with the diameters of heavenly bodies but even compared with thousands of these diameters, so that it is understandable how the volume of the regions of barely appreciable or even nugatory gravity (as compared with terrestrial gravity) may exceed many times over the volume of the regions of appreciable gravitational attraction.

A Point in Nature for Observations of Free Space

Imagine that a star, Sirius, for example, has disappeared without a trace and in its stead there has appeared a group of bodies, the combined mass of which is not more than a thousand or a million tons. In this case their mutual attraction may be disregarded; everyday experience on Earth does not show how small this attraction is -- it shows only that it is inappreciable or negligible.

Thus, we need not yet concern outselves with the theory of gravity. Accordingly, the said group of bodies will exist in free space.

Instead of destroying the star -- without a trace, we could locate our group somewhere in between the stars, provided it remained at a sufficiently large distance, so that, seen from its surface, all heavenly bodies, including our own Sun, would seem like tiny stars. This method of locating a point for the observation of free-space phenomena is much more natural than the one first mentioned.

It may not even be necessary to create an interstellar group, since, doubtless, myriads of groups of this kind are scattered throughout the universe, and we could pick out one of them simply by looking for it. Would the search be so very difficult?

Furthermore, in our own solar system a multitude of such groups is revolving about the sun, as indicated by the occasional penetration of the Earth's atmosphere by aerolites. The only reason why we cannot observe them through telescopes in extra-atmospheric space is their smallness.

Consider this fact above the solar system: the Sun is unique, the planets are few (8), the satellites are more numerous, the asteroids even more numerous (500)* and stony bodies (aerolites) exist in incalculable numbers, since sometimes the number of these

*Editor's note: According to recent data: 9 planets, 29 satellites and up to 1,600 asteroids.

bodies flying through the Earth's atmosphere in a single night is so enormous that they resemble falling snow.

In general, the smaller the size of a heavenly body the greater its numbers. If there are so many suns in the universe, then the number of planets should be correspondingly greater, and the number of asteroids -- little planets -- greater still.

They are all bodies existing close to the Sun and subject to its gravitational attraction. But what about the comets? Do not they reach the Sun from infinity and leave it for infinity, completely overcoming the effect of gravity?

Comets themselves consist partly of a group of bodies. Accordingly, solid, dense bodies may also describe parabolas or hyperbolas and hence leave the Sun for infinity to wander forever along a straight course through free space.

22 February

Practical Importance of Free-Space Phenomena

First of all, I shall try to expound in the simplest and most concise manner the phenomena characteristic of free space.

My selection of a distant observation point does not necessarily imply that the phenomena charactistic of free space cannot be encountered elsewhere. Although free space exists only in interstellar space, completely analogous phenomena (as I will show in various parts of this work) are encountered not only at every step in our solar system but even near the Earth's surface and on that surface, under our very nose. We shall see that every man has been in a relative free space for the duration of half a second, although most of those who have experienced this have not the least understanding of free-space phenomena.

Description of the Scene

We are in interstellar space, whence all suns seem like stars of varying brilliancy, and whence from among the bodies of our own solar system the only one visible is the Sun itself, in the form of a dull, tiny star. It takes a beam of light from Earth (assuming that it is visible through extraordinary telescopes) one hundred years to reach the spot where we stand, so that, through these marvelous telescopes pointed at the Earth's surface, at Europe, we shall be viewing the happenings of the French Revolution and, 20 years later, the invasion of Europe by Napoleon and his army.

Look around -- you will not see our lovely blue or dark-blue sky with pale clouds scattered here and there. Nor will you see our night sky glittering with stars that twinkle as if alive. No.

You will see a somber, ink-black sphere (not a vault or hemisphere) with you yourself suspended, as it were, at its center. The inner surface of this sphere is strewn with glittering dots, infinitely more numerous than the stars visible from Earth. How desolate and woebegone this black sky appears. Its shining stars are absolutely motionless, like the gold studs in church cupolas. They (the stars) do not twinkle as they would if seen from our own planet; instead they are quite clearly visible. But here and there the blackness seems itself to shimmer; this marks the nebulas and the Milky Way which, like a broad band of light, runs in a great circle around the sphere.

Were we to have the choice, we would select a point in the universe from which the outlook was even darker.

We are now looking out from a point inside our Milky Way, which is shaped like a disk or ring and consists of separate stars. The Milky Way is not unique -- there are a myriad galaxies of the kind*; seen from the Earth, they resemble misty spots sometimes visible only through a telescope.

If we were to travel to one of these nebulas, we would find it to consist of a multitude of stars and a Milky Way, and, seen from there, our own Milky Way would look like a mere misty spot.

Let us select a point outside all these stellar disks. Looking from it, we shall no longer behold glittering tiny stars; instead we shall only see blackness and misty -- whitish or yellowish -- spots, each representing a Milky Way.

But this would be going too far; let us be satisfied with the starry sky.

23 February

Selecting a Base

Note that some of the misty spots may be genuine nebulas of the comet type, since even the strongest telescopes cannot detect any individual stars in them.

Here we are then. If we are to observe phenomena, the bodies observed must be displaced, and displacing a body means exerting pressure on it, which in turn means that it exerts pressure on you and, when this happens, you move in the direction in which this pressure is exerted; you move together with the body that serves as your support and which I shall call a base.

The motion of the base to which the phenomena observed are referred, introduces a complication. To eliminate this complication, the base must be made fixed, independent of the motion of the bodies observed and the observers, who must sometimes use it for support; otherwise we shall encounter phenomena referred to a moving base, i.e., we shall observe relative rather than absolute phenomena.

To what then should our base be attached or affixed? To another body? And what about that body itself?

A rowing boat and a steamship float motionlessly on a calm sea near the shore. The rowing boat is not moored; if you leap from it onto the shore the boat will begin to rock and float away; if you leap down from a steamship, its motion is more difficult to observe, but with time it too will float a little farther away from the shore.

Leap as little as a foot from the Earth. Do you imagine that it has not acquired or changed motion while you were in the air? In theory the velocity which your impetus or jump has imparted to it can be exactly determined. But, of course, this velocity, this motion, is billions upon billions of times smaller than that which you yourself acquired thanks to the resilience of your leg muscles.

If the mass of our base were fairly considerable compared with the mass of the observers and the bodies observed, it might be considered practically motionless, just as a barge in calm water is motionless although people walk on it (the barge).

If we take as our base a cast-iron sphere 100 meters in diameter, the force of gravity at its surface (on the basis of the known coefficients of gravitational attraction) will be 100,000 times less than at the surface of the Earth.

Such a level of gravitational attraction can be ignored, and the base may be regarded as motionless in relation to the action of masses 100 or 1,000 times greater than the mass of the human body.

However, gravity depends not only on mass but also on the shape and position of the mass, on its form and density. It can be rigorously demonstrated that a mass of arbitrary size can exert a gravitational attraction of arbitrary smallness on the bodies observed.

The attraction exerted by our iron sphere may sometimes violate to a greater or lesser degree the rigorousness of the phenomena of pure free space.

A difficult shape, more advantageous from the standpoint of the stability and immobility of base, as well as from the standpoint of reducing gravity to an almost infinitely negligible value, may be selected. This will be explained in the chapter on Newtonian gravity.

Although, for simplicity, I am assuming the base to have the form of a cast-iron ball or even cube, in the subsequent description of free-space phenomena, I shall refer to a rigorously free space rather than to a system of gravitational attraction which essentially cannot be entirely avoided.

Free space is a limit to which natural phenomena can only tend; they may appear to reach this limit, but this is attributable solely to errors in observation or to too short an observation period.

A body is called motionless if all its parts are motionless. If only three points of a body, not lying in the same straight line, are motionless, then all the other points of the body will also be motionless.

In order for a body on Earth to be motionless (of course, with respect to Earth), it must be supported by another motionless body, as otherwise the observed body would begin to move toward the center of the Earth at an accelerating rate.

The observed body and the supporting body, i.e., the one that makes the observed body motionless, exert an equal and opposite pressure on each other.

The accelerated motion of the observed body, or rather its potential for accelerated motion, is the cause of this mutual pressure; were there no potential for accelerated motion, there would be no pressure either.

On Earth, this pressure causes the collapse of rotten posts, beams, and trees, badly constructed buildings, and tilting walls and columns. It breaks the chair on which I sit. This pressure prevents the erection of buildings and other structures of arbitrary height and shape.

Indeed, because of gravity walls and pillars must be made vertical, and it is gravity that gave birth to the art of architecture.

Gravity prevents me from standing a pencil on its pointed end.

I shall show in the proper place that gravity more or less restricts the size of plants and animals and even the height of planetary mountains.

It is gravity that causes most of the great heavenly bodies, the Sun, the stars, and the planets and satellites, to have a nearly perfect spherical shape.

24 February

In free space a body will never move spontaneously away from the position it occupies if at any given moment in the past it became motionless. Once motionless, it will remain eternally motionless unless acted upon by some force. For example, if an observed body is motionless and separated by one millimeter from its base, then no matter how much time elapses, it will always remain at this distance. Therefore, in free space an observed body does not exert pressure on a support, and vice versa.

For this reason, if human habitations were needed in free space, they would never collapse from structural weakness, no matter how big they were.

Entire mountains and palaces, of any shape and size, could be suspended in free space without any support and without any connection with a support.

If I tread on the point of a needle at the Earth's surface, it will pierce my foot; but if I do this in free space, my body will not exert any pressure on the needle. In fact, in free space I could stand on the tip of a bayonet as unconcernedly as on a ploughed field.

On Earth I could not lift more than 4 poods, whereas in free space a thousand poods would not strain my hand or even my little finger.

You could direct a barrage of five-pood iron balls at me from all directions, but they would not crush me, as they would on Earth.

Since in free space there is no falling, or more exactly no accelerated motion in one preferred direction, no one would need support. There would be no need for either floors or staircases, chairs or beds.

Any part of free space would serve as a splendid bed and an excellent chair.

In free space there would be no need for tables, closets, and other furniture, since any objects could be freely suspended in space without resting on any support or being in contact with other bodies.

On Earth, mattresses and pillows serve to prevent the concentration of the weight of the body at a few points and spread the pressure over as large an area as possible; thus, thanks to pillows, the pressure on any part of the head is neither high nor low but average. In free space, clearly, there would be no need for either pillows or mattresses, since any part of free space would serve as the softest of featherbeds.

In free space there is neither top nor bottom; for example, there is no bottom, because bottom is the direction towards which bodies move at an accelerating rate. But in free space an initially motionless body can never be suspended from or lie on anything.

For the same reason, in free space there are no vertical or horizontal lines or planes. The weight at the end of a plumbline will not stretch the string tight in any direction. There are neither precipices nor mountains. A stone will not plummet into the abyss, and neither will a careless animal; the stone will not roll down the mountainside, and the careless animal will not slip. Just as the moon hangs above the Earth without falling onto it, so a man may unconcernedly hang above a chasm, however dangerous this may be on Earth. He will, of course, hang without a rope, like a hovering bird, but without the latter's wings, like a well-balanced dirigible.

Precipices and mountains are thus no longer obstacles to movement. The same applies to man-made fences. In free space one cannot say: I rise, I descend, I am above, you are below; and neither can one say: the lower floor, the tall tree. In free space a house painter would not have to lash himself to a pipe for fear of slipping, falling to the pavement and breaking a limb.

In free space the pendulum does not swing and the clock does not tick. But time can be kept perfectly by means of a pocket watch or other timepiece in which the pendulum motion is produced not by gravity but by the resilience of a steel spring.

On Earth in the daytime men mostly assume an upright or seated position, and at night, a horizontal position. But in time any position fatigues him, especially a standing position. In free space, by contrast, it is impossible to decide whether a man is standing, lying down, standing upside down, or raising or lowering his hand.

The consequences of any possible position that he may assume will be completely indifferent to him; none will fatigue him, or all will fatigue him in exactly the same degree.

Suppose my feet touch the base, which now takes the form of a plane. Were I to touch it with my head, I would assume a position perpendicular to the base and I would appear to be standing on my head.

But my blood would not rush to my head, and my face would not become purple, and my veins would not dilate, overflow with blood and grow bluish, and neither would I feel the discomfort or vexation of this position as I would if I were to stand on my head on Earth.

On the contrary, I would feel more pleasure than if I were lying on a thin rubber mattress full of air rather than feathers.

Now the problem is how to define and name the various directions assumed by man or some other elongated object in free space.

For example, Sirius, or another star very close to us (to the base) glows brightly but steadily, sluggishly, without twinkling, sending rays of light toward the observer from a black sky.

It is frightful in this limitless chasm devoid of all familiar objects: there is no Earth underfoot, and neither is there the familiar sky. With equal lack of concern, without losing equilibrium, a man can align his body either parallel to the star's rays, with his head or feet pointing at the star (here we already have two directions), or perpendicular to these rays, or at an angle to them.

This direction can be measured in degrees, just as astronomers determine the latitude and longitude of a star.

Friday, 25 February

Concerning the Disadvantages of Free Space

This description stresses the advantages of free space.

The main thing is that any structure, including natural structures -- living organisms -- may be of any size irrespective of its mechanical strength.

I will have much more to say in the proper place about the advantages and disadvantages of free space compared with the gravity-ruled system in which we (humans) now live.

There is one disadvantage, one question, which I shall not now resolve in detail.

I have stated that an inanimate object in free space, once motionless, is always motionless. But what about a man or an animal? Will their organs, their limbs, to which Earth gave birth, will these limbs of theirs help them to move from the spot, if there is no support at hand? In free space no support is needed to be in equilibrium.

But is it possible to shift the center [of gravity] of one's own body even slightly without some form of support? Think well!

For the time being, now that I have stirred your curiosity, I will merely say: it is not. In this situation an animate object is just as helpless as an inanimate one.

No amount of willing, no matter how passionate, no wriggling of arms and legs, wrigglings, incidentally, that are extremely easy to perform in free space, nothing of this nature is capable of displacing the center [of gravity of the human body].

Rectilinear and Uniform Motion in Free Space

When all the points of a body move along straight lines and cover equal distances in equal intervals of time, or when the distance covered is directly proportional to the time, I shall call the motion of the body rectilinear and uniform.

A free body, i.e., a body existing in free space, once it acquires rectilinear and uniform motion, retains this motion without any change for an indefinite time, i.e., it will never accelerate, decelerate or change direction unless acted upon by a force.

Imagine a motionless Earth and a railroad train traveling at full speed.

The rails are straight and parallel, i.e., the train moves in a plane. The train's motion will be rectilinear and uniform. Suppose that the rails suddenly end and are followed by endless space.

If the speed of the train is less than 11.17 kilometers (10 versts) per second, on tumbling into the abyss, it will describe a certain ellipse, which will cause it to...(illegible -- Editor) and on striking the earth it may fly to pieces.

If, however, we assume that beyond the point at which the rails end there exists free space, then, no matter how small the train's momentum, no matter how low the speed it acquires, it will never lose this speed; it will travel for all eternity through free space at one and the same speed in one and the same direction; its passengers, with every minute, will be separated by an increasing distance from their native planet.

When a body moves, even on the horizontal surface of the Earth, work is done more or less systematically in overcoming the friction due to terrestrial gravity.

This work is proportional to the distance traversed and, moreover, in many cases it increases greatly as a result of an increase in the rate of motion.

Thus, the movement of a ship or a fish in water and the movement of a dirigible or a bird in the air excite a resistance that is proportional at least to the square of the velocity of the body. This is why the velocities attainable by terrestrial bodies are so restricted.

The friction acting on a solid body, and hence the work, is reduced by means of wheels and lubricants, but is never totally eliminated, no matter what the velocity of the terrestrial body, no matter how smooth and horizontal its path, no matter how true and light its wheels and axles are -- invariably, sooner or later, the body expends all its reserves of energy, its entire velocity, and must halt.

If it is not to halt, a continuous expenditure of force is required. For example, a steamship and a steam locomotive, when in motion, continually absorb the force or, more exactly, the energy contained in firewood or coal.

On Earth a trip around the globe is, even now, not only very lengthy (three months) but also accompanied by [considerable expense] and even involves all sorts of hazards to life and limb. In free space, however, vaster and incomparably more rapid trips do not even cost the price of a pillow. Or, more precisely, travel through any arbitrarily vast expanse of space in any desired direction requires work only in initiating the motion, the amount of work depending solely on the velocity and mass of the free moving body.

And besides, even these losses can be made good, on the cessation of motion or the termination of the trip, since in free space the motion of a body is excellently preserved for an infinite time. Movement is possible in any direction: from the base, toward the base, and parallel, perpendicular or at an angle to its surface. This is different from on Earth where precipices and mountains, impassable tropical forests and swamps, seas studded with drifting icebergs, constitute -- at least until aeronautics is more developed -- insuperable obstacles; where movement is mostly over surfaces that are either horizontal or inclined at very low angles to the horizon; where the room for maneuver is limited and stifling, being confined by the sky above and the Earth beneath. Gravity will not allow us to travel upward, except at the risk of breaking our neck; and the Earth will not let us travel downward, being so heavy that it caves in on top of man-made excavations. There are also many other constraints imposed by gravity.

Friday evening, February 26

Description of Motion

How great is the obstacle presented by the Earth is evident from the fact that men cannot burrow deeper than 2 versts below the surface.

Imagine in free space several motionless bases, settlements occupied, let us suppose, by space dwellers (as I shall call the inhabitants of free space whether they exist or not), possibly hundreds of thousands of versts apart.

Suppose a space dweller has to travel from his settlement to a neighboring settlement. Or suppose an enormous mass of matter, for example, a palace, has to be transported from one settlement to another.

Then the space dweller, along with his goods and palace, acquires in some manner (which I shall discuss later) a certain desired velocity in the direction of the other settlement, which will then be reached by the mass moving along a straight line, without a road, without resting on any support, without the least bumpiness, moving as quietly as if there were no motion at all and yet perhaps as rapidly as the wind, as the lightning, as the motion of Earth.

Only by observing the surrounding bodies (if any), whether at rest or in motion, can the space dweller detect that he himself and his belongings are in motion.

And in such a situation you, an earth dweller, who have never experienced such gentle motion, would be firmly convinced that you yourself were completely motionless, while other bodies hurtled past you, although it might well be they that were motionless.

We have become so accustomed to our awkward earthbound motion with all its thunder and cacophony and jarrings and bumpings of all sorts that we consider these shocks, unnatural in a different life, as the true symptoms of motion, without which there can not even be motion, as it were. For thousands of years we have been traveling through space in a wheelless chariot at a speed of 27 versts per second, and perhaps even faster, without any jarring and noise. But not until Galileo and Copernicus did we become aware of this motion, because our back did not ache. In general, if the motion is smooth, we either completely overlook it or ascribe it to surrounding objects, for example, to the river banks, when we sail in a boat. The Earth's motion was long (until Galileo and Copernicus) ascribed not to the Earth itself but to the Sun and the stars. Is it easy to convince a man that the Earth, along with his village, is traveling faster than his horse-drawn cart? He would say: but where are the customary signs of motion, the jolts and the clatter?

Free Center of a Body

In any body a unique point, which I shall call the center of inertia of the body and which coincides with the body's center of gravity, can be found by experiment or calculation; if this point in a solid and (initially) motionless body is acted upon for some time by one or several forces of arbitrary direction and intensity, the body will acquire rectilinear and uniform motion, once the forces cease to act.

Thus, we have a method of imparting rectilinear and uniform motion to bodies located in free space.

We know what the center of gravity of a body is: the body, when rigidly fixed at this particular point without losing the ability to rotate about it, remains in equilibrium or in a state of motionlessness even when acted upon by the gravity of the Earth or some other planet, provided that at some time in the past it became motionless, i.e., does not rotate. It is this particular point that must be acted upon by a totally arbitrary force or the resultant of several forces, if the body is to acquire rectilinear and uniform motion, after the forces cease to act.

27 February

The center of inertia of most known bodies lies inside the body; in such cases the force must act along a line passing through its center.

For example, in order for a sphere to acquire rectilinear uniform motion, the force must act along a diameter. But sometimes the center [of inertia] may lie on the surface of the body or even, which happens quite often, outside this surface, for example, in the case of a ring, a hollow sphere, a glass, or a barrel. Such a center, located outside the material of the body itself, may be termed immaterial.

In this case the immaterial center can be made material. Thus, if a material diameter is attached to a hoop, the force may be applied to the middle of this diameter in order to impart rectilinear uniform motion to the hoop. A force may also act along a line passing through the center and meeting some material point of the body, which point may also serve as the point of application of the force.

But how, for example, can rectilinear uniform motion be imparted to a ring perpendicular to its plane without adding a material diameter? How can motion in the direction of the axis of symmetry be imparted to a barrel, the lid and bottom of which have been removed? To achieve this, we can operate with two or more parallel or non-parallel forces applied to material points of the body, the theoretical resultant of these forces passing through the immaterial center in the direction desired.

In practice, a force never acts in isolation, i.e., is never separated from matter; in nature there are no forces -- whether attractive or repulsive -- that are divorced from matter.

The forces of attraction, resilience (a steel spring), muscle power (an animal), magnetism, electricity -- they all, as we know from physics, are conditioned by the action of celestial or earthly bodies; the planets and the sun; a magnetized or electrified body, and so on.

That from which a force emanates may be termed a support. However, that on which the force acts may also be termed a support and is an active force itself. For while the Sun acts upon the Earth, the Earth also acts upon the Sun; if a magnet acts upon iron, the iron itself attracts the magnet; if I were to leap off the Earth, the Earth itself would leap off me, although its leap would be infinitesimally small in comparison with mine -- exactly as many times smaller as its mass is larger than the mass of my body.

In practice, for me and my actions, the Earth constitutes a support. In general, the support is the greater of the interacting masses.

Thus the Sun may be said to support the planets, and the gun -- the bullet, even though a gun recoils when the bullet is fired. In theory, however, there is no essential difference between the support and the body supported. It is only in order to distinguish between two bodies that I shall term them thus (the choice depends on me). Sometimes, instead of the supported body I shall refer to the observed body, although there is no reason why both bodies should not be observed.

I mentioned previously that if one body (let us call it the support) has an enormous mass compared with the mass of the other, supported body, the support acquires a negligible velocity relative to the velocity of the body supported. But in free space, motion may also be imparted to a body by means of a moving support of insignificant mass.

28 February

Motion of Support and Observed Body

Imagine two motionless bodies existing close to one another in free space.

They will not change their position spontaneously. There is no motionless support. Let us assume that some velocity in some direction must be imparted to one of the bodies. If we introduce some force between these bodies, for example, a compressed lightweight steel spring, the ends of which rest against the free centers [of inertia] of the bodies, then when the spring uncoils both bodies will clearly be endowed with rectilinear and uniform motion [Fig. 1]. The spring, which we will assume to be attached to one of the bodies, acted on both bodies with identical force and for the same length of time. The greater of the bodies, i.e., the body with the greater mass, offers greater resistance and therefore acquires a smaller velocity than the smaller body, which acquires a higher velocity. The acquisition of velocity may thus be compared to the acquisition of velocity by a rowboat owing to the thrusting aside of water by the oars. In both cases the support is unstable.

This is an exact expression of the laws of motion of bodies that repel one another either by their inherent elasticity when compressed or by the elasticity of a lightweight spring. I say "lightweight," although in free space a pound weighs as much as a feather; I used the term to denote a low mass.

And so:

1) The centers of a body, before and after it moves, always lie along a single straight line.

2) The smaller of the masses acquires a velocity which exceeds the velocity of the greater mass by as many times as the mass of the greater body exceeds the mass of the lesser.

Center of Inertia of Moving Bodies

Here I consider it needful to give a simple but precise definition of the center of inertia of several unconnected and even moving bodies.

Consider a system of moving or stationary bodies. The problem is to find their common center [of inertia] at any given time. Suppose all the bodies instantaneously come to a halt at that very moment. Let us now join them all together in a single whole by means of a strong, hard, but inertialess substance, without changing their position in any way. The laws of inertia, the manifestations of which in free space I have already discussed, consist in that a body

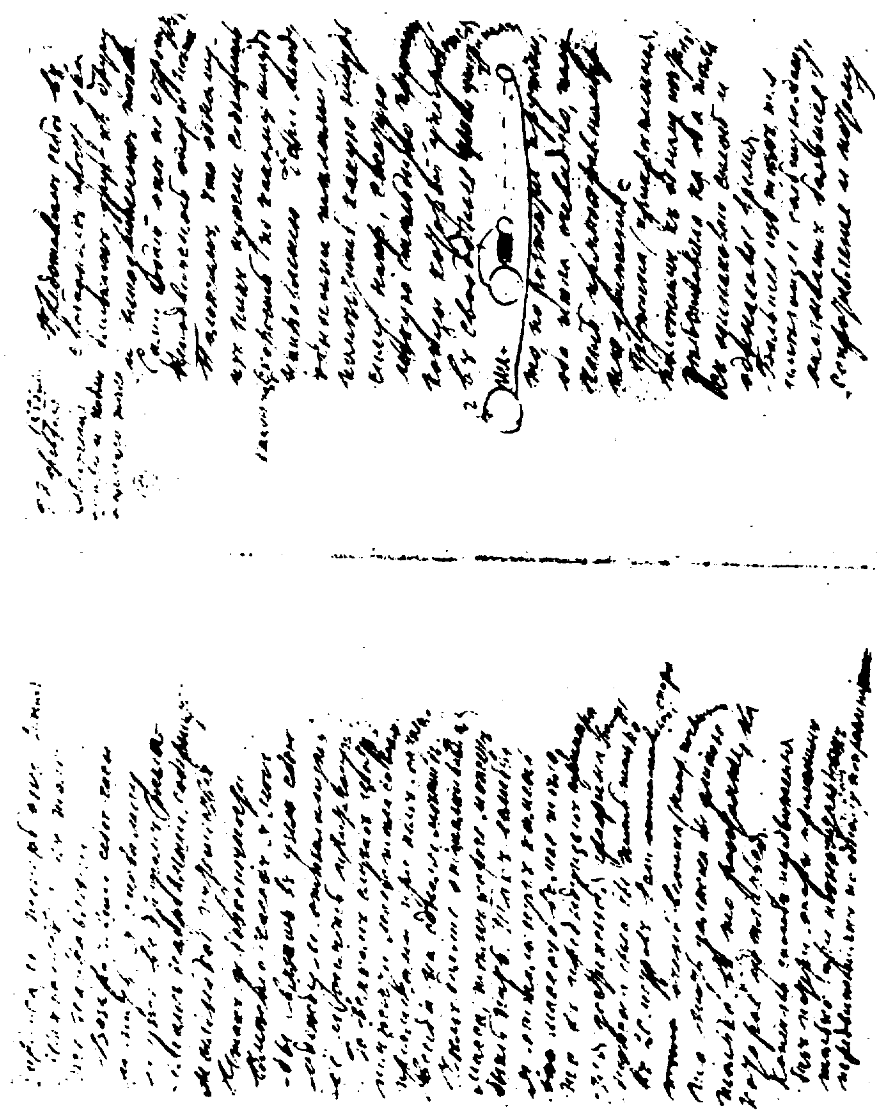

Fig. 1.

cannot spontaneously begin to move or change its form of motion, e.g. accelerate or turn sideways. I have fused the given system together with an inertialess substance, i.e., a substance which does not obey the laws of inertia -- it offers no resistance at all when motion is imparted to it. Such an inertialess substance would approximately exist if a body of extraordinary strength yet of extraordinarily low density, as hard as steel and as tenuous as the tail of a comet, were to be found in this world.

If in this fused inertialess mass we were now to find a point which, whenever an arbitrary force were applied to it, would cause this mass to acquire rectilinear and uniform motion, this point would be the center of inertia of the system at the time when we brought all the bodies of the system to a halt. The center [of inertia of a system of moving bodies coincides with the center of gravity of this system. Of course, both the center of inertia and the center of gravity in free space can be found both theoretically and empirically. Later we shall again find it useful to determine the center of inertia of an arbitrary number of moving bodies.

Here are some applications to free space of the laws of motion of two interacting bodies. I am 60 meters away from the base. Except for the base there is nothing else around me. But in my hands there is a stone, with a mass of one kilogram. I must reach the base. With all my strength, I hurl the stone in the direction opposite to that in which I wish to move. The stone is given a velocity of 10 meters. Since my body weighs 100 kilograms, it is repelled toward the base at a velocity 100 times less than the velocity of the stone, i.e., at a velocity of 1/10 meter or a decimeter. I will thus cover the 60 meters separating me from the base in (60:1/10) = 600 seconds or 10 minutes. As for the stone, it will fly through space until (even if it takes a thousand years) it encounters and is attracted by some bulky mass. It is fairly difficult to coordinate one's muscles so as to avoid being thrown into rotational motion when hurling the stone away.

1 March

There are two of us and we are on the line joining two bases. You will see our position from the sketch [Fig. 2]. One of us must reach one base, and his companion the other. There are no other bodies around us save for an overcoat with which we do not want to part. Our own bodies have the same mass and the same strength. We, as it were, prepare ourselves to leap, and press against each other's heels with equal force. Now our legs simultaneously straighten and we fly at the same velocity in opposite directions. Were two men thus

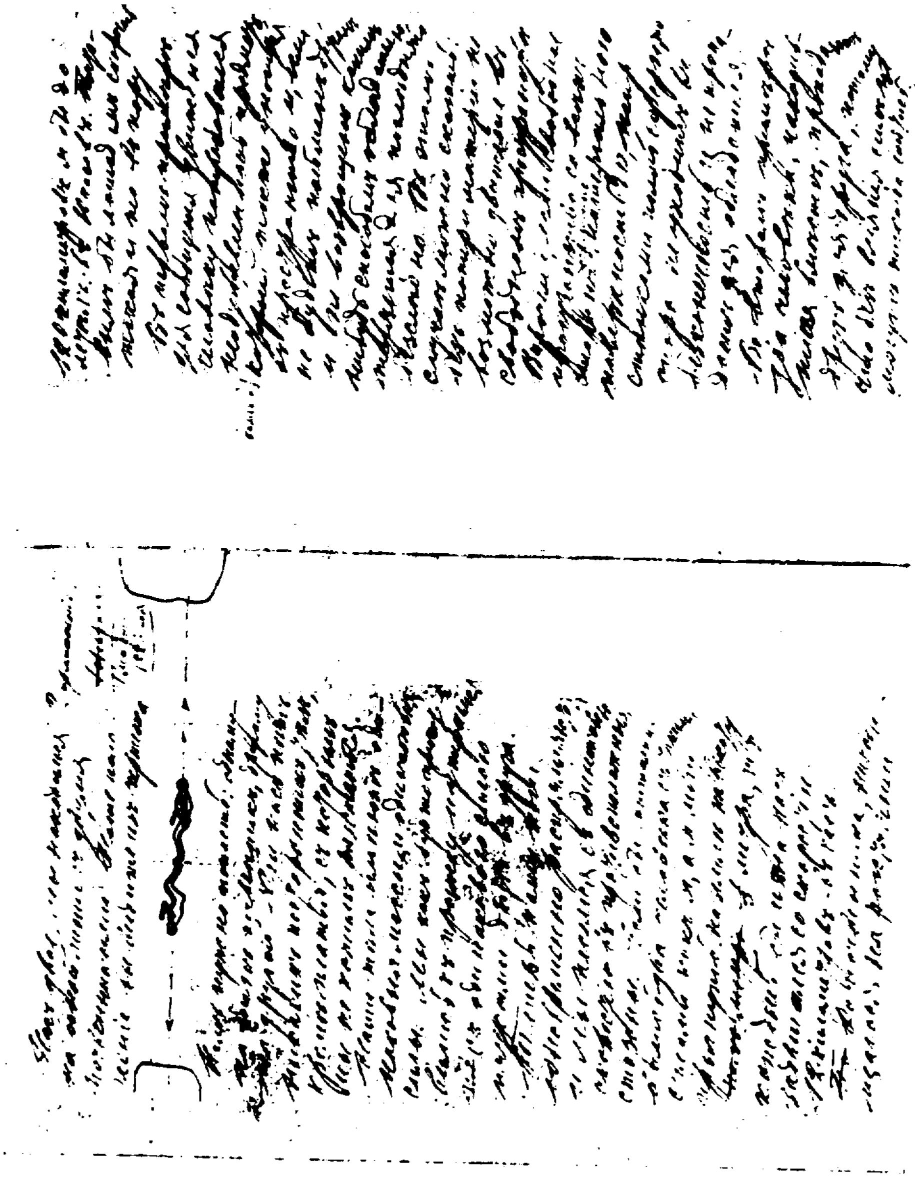

Fig. 2.

to thrust each other apart exerting the same force as I can, and I can jump one-third of a meter high on Earth, then each of us would begin to move at a velocity of 12 kilometers per hour. I would reach the base, 120 kilometers away, in 10 hours. This kind of speed would be proper for horses. In the first example, an inanimate object (a stone) was needed in order to impart motion to a human body; this object then flew away into space and, unless captured by another and returned in some way to its owner, was irretrievably lost.

In this case it may be said: motion in free space is impossible without loss of matter.

If, however, the free space is bounded on all sides by a material surface, e.g. by the walls of a hollow sphere, the object does not escape to infinity and is not forfeited by its owner.

In the second example, the two men have lost each other, because they cannot come together again except under the influence of extraneous forces. In both examples, the motion of both the "support" and the supported body is infinite.

Here is a third example, in which the motion, though not infinite, is not accompanied by loss of matter (support); the matter may be recovered whenever desired and re-used a thousand times for the same purpose [Fig. 3].

I am thirsty; 10 meters away a flask of water is freely suspended in space. In my pocket I have a watch and in my hands I hold a ball of fine string, the mass of which can be disregarded. I attach the free end of the string to the watch and fling the watch in the direction opposite to that of the flask. The watch recedes rapidly; the ball of string unwinds, while I myself float gradually toward the flask. At last I can touch it, whereupon I halt the flight of my watch by gripping the thread running through my fingers. I come to rest and drink the water. The watch has a mass one thousand times less than the mass of my body; therefore, it has traveled a thousand times further than I myself. I traveled 10 meters, so the watch traveled 10,000 meters or 10 kilometers.

I begin to reel in the watch and wind the string back onto the ball. After winding in the string which clearly was 10,100 meters long and grasping the watch, I again find myself in my original position 10 meters from the flask of water. Having recovered the watch and string, I can repeat my little trip in any other desired direction, ad infinitum. Instead of the watch, I could tie the string to a piece of my clothing and fling it away, in order later to pull it back. Always the center of gravity of my body, along with all the objects I carry on me, will remain in the same spot. The greater the mass thrown away, the shorter I can make the string.

Thus, were I to push away from me a stone with the same mass as my own body, I would need a piece of string only 20 meters long in order to reach the flask (10 meters). If the support is very large

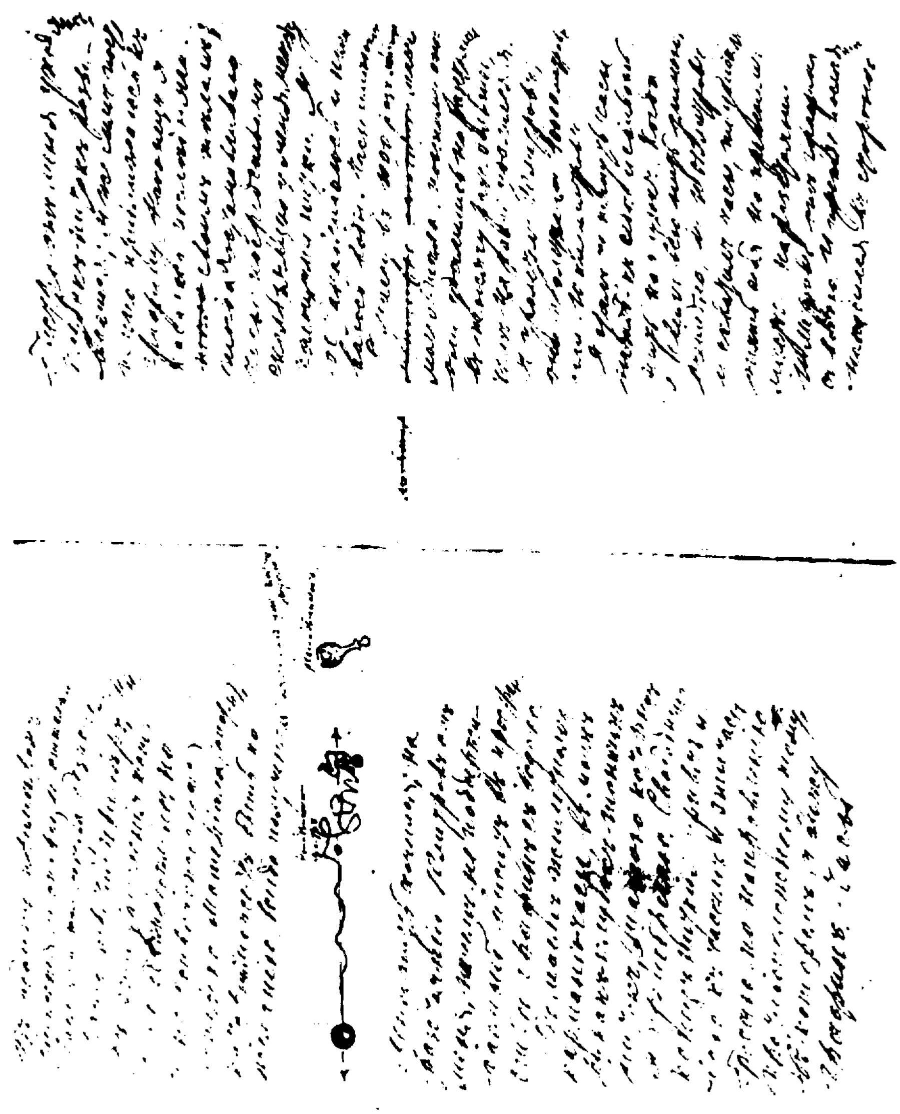

Fig. 3.

(e.g. a base), the string need be only as long as the distance I want to cover. Of course, this method of moving without losing the object that supplies the thrust is applicable only when the movement in various directions is of limited extent.

2 March

Velocity of Bodies in Free Space Moving Under the Action of Forces Expressed in Terrestrial Units of Measure (Weight)

When a support has a comparatively very insignificant mass, the velocity of the repelled body is many times smaller than the velocity of the support, but, nevertheless, the velocity of the repelled body may still be arbitrarily large. For example, if the support has a mass 100 times less than that of the repelled body and if the velocity of the support is 10 kilometers per second, then the velocity of the repelled body will be 100 times smaller, namely (10 km.1000 = 10,000 m : 100 = 100) 100 meters.

The support may be assumed to be a cannon ball and the repelled body, the cannon. Given the above figures, the cannon will acquire a velocity of 100 meters.

Now that I have described the method of imparting rectilinear and uniform motion to a body by means of a fixed base (or support), I must sketch the effect of the muscles of an animal and other ... [illegible -- Editor] forces on the motion of large and small bodies. On earth the strength of a man's arm is measured by the weight it is capable of lifting. Thus, it is said that the arm has a strength of 10 or 100 kilograms. This method is also used to measure other terrestrial forces: the resilience of a spring, gas pressure, the elasticity of solids and liquids, magnetism, etc. But in free space there is no weight, so how can force be measured in free space?

One kilogram of matter is acted upon by a force equal to one unit of weight. In one second this unit force, as shown by terrestrial experience, imparts to unit mass a velocity of 10 meters. Now let us assume that in free space the force of an arm, when exerted constantly and in one direction on unit mass (kilogram), also imparts to it a velocity of 10 meters per second.

Here two forces: weight and muscular force, acting separately on identical and initially motionless masses, have produced the same results -- a velocity of 10 meters.

Clearly, these forces are equal.

Thus, a force acting in free space can be estimated from the velocity which the body acquires at the end of one second*. On Earth due to gravity a single unit of force always acts on a unit of matter; we thus find 100 units of force always acting on 100 units of matter; and 1/100 of a unit of force acting on 1/100 of a unit of matter.

Therefore, on Earth gravity gives all bodies, whatever their size, one and the same velocity per second. In free space, however, a unit of matter may be acted upon by 10 units of force, and then the velocity acquired per second increases tenfold (100 meters). Conversely, if a unit of mass acquires during a single second a velocity of 100 meters, it may be concluded that it is acted upon by a force of 10 units. On Earth, on a horizontal surface of ice, the same conclusion may be drawn concerning the force exerted by a hand from the velocity acquired by a sled.

In free space one unit of force may act on 100 units of mass.

Here one unit of force is distributed among 100 units of mass, therefore we have one-hundredth of a unit of force per unit of mass. This one-hundredth of a unit of force imparts to each unit of mass a velocity ten times smaller than that imparted by a whole unit, i.e., a velocity of 1 meter (10:10 = 1).

Therefore, given a fixed force, the velocity is inversely proportional to the mass moved.

And conversely, the force acting on the mass must be determined not only from the velocity acquired by the mass in one second but also from the magnitude of the mass. Force is proportional to mass that has been given a specific velocity. On Earth, under the action of a constant gravitational force, the velocity acquired by a mass is proportional to the time (as experiments show).

Again, in order to determine the force that brings a free body into motion, the velocity acquired by this body in one second must be known. To this end the actual velocity of the body must be divided

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*On the basis of the theorem of momentum with respect to a point moving in a straight line, we have: $mv - mv_0 = \int_{t_0}^{t} F dt$. If $F = \text{const.}$, $v_0 = 0$, and $t - t_0 = 1$, then $v = \frac{F}{m}$. Therefore, if the mass m is known, the magnitude of the force may be determined from the velocity acquired by the body after the force has acted for one second. (editor's note).

by the time the force acts. From all this we can derive two conclusions and construct two formulas.

1. The velocity of a free body is directly proportional to the magnitude and duration of action of the force, and inversely proportional to the body's mass:

$$\text{Velocity} = \frac{\text{force x time}}{\text{mass}} \cdot 10 \text{ meters}$$

2. The force acting on a free body is directly proportional to the velocity and mass of the body but inversely proportional to the time

$$\text{Force} = \frac{\text{velocity x mass}}{10 \text{ m x time}}$$

10 m/sec^2 is called the Earth's acceleration (g). Therefore the formulas may be rewritten thus:

$$\text{Velocity} = \frac{\text{acceleration x force x time}}{\text{mass}} \qquad (1)$$

$$\text{Force} = \frac{\text{velocity x mass}}{\text{acceleration x time}}. \qquad (2)$$

From the first formula we can mathematically derive the second and three others; altogether, five formulas.

One of the formulas makes it possible to determine the mass of a body in free space

$$\text{Mass} = \frac{\text{acceleration x force x time}}{\text{velocity}} \qquad (3)^*$$

In free space the mass of water can be readily determined from its volume alone. This formula also serves to determine the mass of any body. However, on Earth, different forces, including weight, are measured not only with instruments based on the phenomenon of gravitational attraction, e.g. a simple decimal balance, but also by instruments not based on this phenomenon. One of the most frequently used force gauges, or dynamometers, is based on the phenomenon of the elasticity of a steel spring. This instrument is termed simply a dynamometer or spring balance. Instruments based on the phenomenon of gravity are unsuitable for free space. As for dynamometers, they are quite suitable, in their present form, for measuring forces in free space.

Thus a spring balance may be used to measure in free space the force exerted by the muscles or limbs of an animal.

On Earth I can raise my own body by means of my arm muscles. In free space, when my arm muscles contract, the spring balance indicates a tension of 65 kilograms, i.e., exactly equal to the weight of my body on Earth. A dynamometer based on the pressure of a certain gas might be developed for free space. And lastly, there are centrifugal machines.

Let us now consider the effect of a force of 10 kilograms (65 kilograms is too fatiguing) exerted by an individual on different masses.

A man acts on a mass in one direction by means of a string, the tensile strength of which should be equal to or exceed the force exerted by his muscles -- 10 kilograms. At the end of the first

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*When F = const., we have $v_0 = 0$, $mv = Ft$; $m = \frac{P}{g}$ and, therefore, $\frac{P}{g}v = Ft$. Hence $P = \frac{F \cdot g \cdot t}{v}$. Thus, Tsiolkovskiy here calls the weight of a body its mass (editor's note).

second, under the action of this force, a mass corresponding to a weight of 100 kilograms acquires a velocity of 1 meter.

If the force now ceases to act, the mass will begin to move uniformly at the velocity of 1 meter per second. Here is a table indicating the result of the action of a continuous force of 10 force units on 100 mass units:

Time in sec	$\frac{1}{100}$ $\frac{2}{100}$ $\frac{3}{100}$ $\frac{99}{100}$ 1,2,3,$3^{1}/_{2}$,4,10,1000,3600,86 400
Velocity in m/sec	$\frac{1}{100}$ $\frac{2}{100}$ $\frac{3}{100}$ $\frac{99}{100}$ 1,2,3,$3^{1}/_{2}$,4,10,1000,3600,86 400
Distance in m	

This kind of motion is called "uniformly accelerated."

On Earth there is a limit to the smallness of a force that can shift a large mass. On Earth, in order to overcome friction, a definite portion of the mass itself is required. In free space, however, by means of a spider's web and a stress just large enough not to break its delicate strands, mountains of matter may be moved and given, sooner or later, any desired velocity, large or small.

Halting or Changing of Original Motion of a Body by Means of a Moving Support

If a body, which we shall call the observed body, already has rectilinear and uniform motion, then, by means of a support (linked to the observed body and initially sharing its motion), this motion may be altered, i.e., accelerated, retarded or even completely annihilated. Moreover, not only the velocity but also the direction of the observed body may be changed. All this requires the repulsion of the observed body from the support. Although the motion of the free centers of the support and the observed body is thereby changed, their common center will retain its original motion. In order to impart new velocities to the support and the observed body, we must add to their original identical motion the motion which they would acquire due to the action of the repelling, separating force if they were originally motionless, since the same force produces the same results whether the bodies are at rest or in identical rectilinear uniform motion.

The following examples will throw more light on what has been said above.

4 March

I am rushing through space at a speed of 10 meters per second. On my way I encounter a mass of fire or rather a mass of incandescent matter. Unless I succeed in changing my motion, I shall inevitably burn or be overcome by the heat. I must either halt at a safe distance from the fire or reverse my translational motion or, finally, pass on one side of the fire. I can change or annihilate my motion only with the aid of a support. A 65-kg lead sphere is flying beside me. I weigh exactly the same. A strong steel spring is compressed between the center of my body and the center of the sphere.

If the spring were released, thanks to its elasticity it would impart equal velocities of, say, 10 meters to me and to the sphere, supposing that initially we were stationary.

I am approaching the fire and let us now assume that I wish to halt and observe it.

I arrange the spring as illustrated in the drawings, i.e., so that the line of centers -- of my body and of the sphere -- coincides with the direction of motion and the sphere is facing the fire.

Before the spring is released the sphere and I have a translational velocity of 10 meters; the action of the spring gives me a reverse velocity of 10 meters (-10). If the acquired velocity is added to the initial velocity, we obtain zero or the absence of motion.

$$10 + (-10) = 0.$$

Thus, I halt before reaching the fire and calmly observe it. Clearly, the lead sphere has begun to approach the fire with redoubled velocity:

$$10 + 10 = 20.$$

Were the spring stronger, I would rebound, i.e., would fly back whence I came -- I would reach that stationary base from which I had departed.

For example, if, assuming I were stationary, the spring could give me a backward velocity of 11 meters, after the release of the spring, and assuming I had a direct (translational) velocity of 10 meters, I would acquire a backward velocity of 1 meter.

$$(10 + (-11)) = -1 \text{ meter.}$$

As for lead, it would move in an incandescent mass at a velocity of 21 meters (10 + 11 = 21).

Were the spring somewhat weaker, for example, were it capable of imparting to an initially stationary body a velocity of only 9 meters 999 millimeters

$$(\text{mm} = \frac{1}{1000} \text{ meter} = 0.001 \text{ meter}),$$

I would not lose all my translational velocity -- there would still remain a velocity of 1 millimeter in the direction of the fire.

If when the spring is released the distance to the fire is one kilometer, I will reach the fiery mass after 1,000,000 seconds (1,000 : 0.001 = 1,000,000), i.e., after more than 11 days.

Thus, in this case I am bound to fly into the fire, even though slowly.

7 March Evening

To pass to one side of the fire, the centers must be so arranged that the line between them is perpendicular or at least oblique to the original direction of motion. When the spring is released, the velocities and directions of both bodies change, so that they bypass the fire.

The path of each body constitutes an open polygon with one angle. This means that in the presence of a single support the total path of the traveling body (which I call the observed body) consists of two straight lines, because, on rebounding, the body changes direction only once.

Polygonal Uniform Motion with the Aid of Moving Supports

In the presence of several supports, however, the traveling body may change its motion several times. For example, if five bodies are in my neighborhood, I may change my motion quite arbitrarily five times -- until I lose all my supports.

Of course, if I immediately push all the supports away, I will change my motion only once -- so the supports must be pushed away successively. In the latter case, the path of my body will consist of as many angles as there are supports, and as many straight lines as there are supports +1.

Thus, in the presence of five supports, the trajectory of my body, after all five supports have been lost, will have five angles and will consist of six (5 + 1) lines.

Clearly, if the supporting bodies are pushed away along the same line as that along which the traveling body has been moving, the trajectory of this body will continue in the same straight line. However, the velocity must still change as many times as there are supports. Therefore, even if there are many supports, e.g. 100, the path of the traveling body may consist of 1,2,3,..., 101 lines but not of more than 101.

So far it is understood that the force pushing the bodies apart always acts on the free centers of these bodies or, to put it in terrestrial terms, on their centers of gravity. Thus, each body, no matter how many times it may change its motion, will always have rectilinear and uniform motion; this means that its translational motion lacks even the smallest admixture of rotational motion, because all the points move at the same velocity along straight lines.

8 March Evening

Thus we see that with the aid of a sufficient number of supports the path of a body in free space may be made arbitrarily tortuous; so that, if a given body must circumvent a large number of obstacles, in theory there is no reason why it should not do so. In every case, however, the body's path represents the perimeter of an open or closed polygon.

Common Center of Inertia of Several Interacting Bodies

I have given some idea of the free center of inertia of moving bodies and said that it coincides with their center of gravity. I also mentioned that the common center of two interacting bodies, despite the arbitrarily different motions of these bodies, always has the same velocity and direction; if, however, this common center is stationary, it will always remain stationary, despite the motions of the corresponding bodies.

This also remains true when the number of supports or interacting bodies is arbitrarily large.

Therefore, although the few or many supports and, most important, the traveling body for which the others serve as supports, may move in the most different directions at the most different velocities, there always remains a point, called the free center of inertia of these bodies, which never changes its motion, i.e., never changes its direction and velocity; if, however, this center at some moment becomes stationary, it will always remain stationary, despite all the possible effects of interaction of the bodies involved.

Sunday, 27 March Evening

A man hanging in free space and lacking any support at all may assume every position that he is capable of assuming on Earth, but the center of gravity of the particles of his body is bound to remain exactly where it was before the interaction of the limbs under the influence of the muscles.

This interaction may be continuous, maintaining the body in a state of constant vibration or motion, but the center of gravity (or the free center) will never be induced to move or vibrate because of it. When the limbs cease to interact, all the parts of the body will come to absolute rest.

28 March Morning

Curvilinear Motion with the aid of a Gas or Liquid or even a Solid Support

When a body has a countless number of supports from which it continuously rebounds, the body changes its motion continuously, so that its path may take the shape of a curve. Then the velocity of the body also changes continuously and may either increase or decrease.

Suppose we have a barrel full of highly compressed gas. If one of its ....(illegible -- Editor) spigots is turned on, the gas will gush out from the barrel in a continuous jet; the gas pressures, which pushes the gas particles out into space, will at the same time continuously cause the barrel to recoil.

This will result in a continuous variation in the motion of the barrel.

If, for example, the barrel is stationary, and the jet of gas is pushed out along a line linking the free center of inertia of the body with the orifice of the spigot, or if the barrel is in rectilinear motion coinciding in direction with the jet, the barrel will be given accelerated or decelerated rectilinear motion by the recoil effect of the gas. But if the barrel originally has a motion that does not coincide with the direction of the outflowing gas particles, its motion will be parabolic, assuming that the gas gushes out at a constant rate. By means of a sufficient number of spigots (six), the discharge of gas can be so regulated that the motion of the barrel or hollow sphere can be completely controlled by the manipulator, i.e., the barrel may be caused to describe any desired curve governed by any desired velocity law. It may, for example, describe a uniform circle, even though there is no central attracting force. At any rate, the common free center of the body and the escaping molecules will always retain its original motion or its original immobility. A change in the motion of the barrel is possible only so long as some of the gas has not yet escaped. But since gas is being continuously lost and since normally this loss is directly proportional to time, arbitrary motion may only be sustained for a limited period -- for minutes, hours or days, after which it becomes rectilinear and uniform. In general, uniform motion along a curve or rectilinear nonuniform motion in free space involves the continuous loss of matter (support). Polygonal motion also involves periodic loss of matter.

29 March Morning

However, if the main body and the supports are linked together by long, thin wires, then, even though the motion of the bodies is more or less restricted, depending on the length of the wires, the supports and the main body can all be brought together again in a single system.

The free centers of the bodies will either be frozen in their original positions or will continue the uniform and rectilinear motion which they had upon interacting.

Theorem. Any body, the large or small solid parts of which can attract or repel one another, any such plastic and initially motionless body can assume any shape in any direction.

30 March Morning

Rotational Motion

Suppose we connect any two points of a body together so that they cannot move. If now, by means of a force, motion is imparted to the body, this motion will be rotational. The straight line passing through the points we have connected is termed the axis; it too is stationary.

All the points lying outside this axis describe circles. The farther these points lie from the axis, the greater their velocities and the longer their paths. Points equidistant from the axis describe equal circles and, at a given instant, move at the same velocity.

Rotational motion is called uniform if all the points equidistant from the axis move uniformly, i.e., if these points cover equal paths in the same time or if the body rotates through the same number of degrees in equal intervals of time. In free space rotational motion may also take place about an unattached axis freely suspended in space. Such an axis may simply be called a free axis. I shall now consider the rotational motion of a solid body about a free axis.

Not every straight line drawn through a body is a free axis, i.e., a free body will not rotate about just any unattached straight line. It is known that the rotation of flywheels and machines is sometimes accompanied by the wobbling of the axis or the machine itself. This happens when the actual axis of the flywheel does not coincide with its free axis.

Free Axes

A free axis should pass through the center of inertia, or center of gravity, of a body.

Every body was at least three mutually perpendicular free axes. But there may be only three or more than three or even countless axes. Thus, in the case of a uniform sphere the free axis is a diameter. We can easily visualize any body with a given number of free axes, so long as there are at least three of them. A free axis sometimes lies outside the material of the body concerned, and then it may be termed immaterial. For example, we find axes of this kind in a torus or an empty bottomless tub.

Later I shall discuss the free axes and rotation of soft bodies of variable shape (plastic), as well as the axes of a system of unconnected bodies.

If an unattached and completely unsupported body in some way acquires rotational motion about a free axis in free space, this motion, which -- unless extraneous forces intervene -- is always uniform, can never cease of itself. Conversely, if the body is not given rotational motion, it will never acquire it spontaneously.

1 April Morning

A Method of Imparting Stable Rotation to a Body with the aid of Stationary Support

Rotational motion about an unattached axis may be imparted to a body in different ways.

For example, if a stationary support is available, we may fix any two points lying on a free axis of the given body and then apply some arbitrary force to impart to the body motion about these points.

If, when this force ceases to act, we cautiously remove the two bearings that kept the axis fixed, the body will acquire uniform rotational motion about a free, stationary and completely unattached axis.

This method is suitable if the free axis is a material one, i.e., if several points of the free axis are located in the material of the body concerned. But rotational motion can be imparted to a body also without first fixing the free axis.

Imagine a straight line at right angles to a free axis; imagine on this line two points equidistant from the axis; suppose we pass a plane through the straight line and the axis.

Imagine now that the two points are acted upon by equal but opposite forces in a direction normal to the plane.

When these forces cease to act, the body will acquire uniform rotational motion about a free unattached axis. This method is applied to bodies lacking a material.

In a word, stable rotation may be imparted to a body also by means of a force couple.

2 April

Imparting Stable Rotational Motion with the aid of a Moving Support

Imagine two stationary, separate and totally unconnected bodies. Suppose one of the bodies somehow -- provided this involves the use of the other body as a support -- acquires rotational motion; then the other body will rotate in the opposite direction. The free axes may assume any (desired) position but they must be parallel.

By the velocity of rotational motion of a solid body I mean the velocity of points of the body unit distance from the axis. This is the same thing as the angular velocity. The ratio of such velocities depends on the shape and mass of the bodies. The greater the mass of a body and the greater the distance between the particles that compose it and the axis, the more difficult it is to bring it into motion and the lower the angular velocity it acquires. And vice versa.

Rotational Inertia

The angular velocity ratio is equal to the inverse ratio of the moments of inertia

$$\frac{S_{k_2}}{S_{k_1}} = \frac{\text{moment of inertia of first body}}{\text{moment of inertia of second body}} .$$

I said that the moment of inertia depends on the distribution of the masses; therefore, although the mass of the support may be insignificant, its moment of inertia, or resistance to rotational motion, may be arbitrarily great, so that in the limit it may be regarded as fixed mass. In parallel (rectilinear) motion the resistance (inertia of rectilinear parallel motion) depends only on the mass, to which it is directly proportional, in no way depending on the shape of the material. In rotational motion inertia depends on the distribution of the masses with respect to the axis.

3 April. Morning

A Method of Imparting Stable Rotation by Means of a Moving Support

Here is how stable rotational motion might be imparted to two stationary bodies. The axes are parallel; the forces act in some plane perpendicular to the axes. The four points of application of two equal and parallel forces are equidistant from a line connecting the axes and lying in this plane. Of the two forces: one strives to bring its points of application together, while the other, equal to the first, strives to drive its points of application further apart. Clearly, under these conditions each body will be acted upon by a couple imparting stable rotational motion. The bodies rotate in opposite directions like two meshing gear wheels. This is exactly the way in which stable rotational motion is imparted to bodies when the axes are parallel.

Rotation of a Man

With the aid of a toy, like the toy wolf to which children impart motion by means of a spring or string, with the aid of such a projectile, a man might set himself in rotational motion in free space. The box enclosing the spring must be held firmly in the hand, so that the free axis of the toy wolf lies in the same line as one of the free axes of the human body. Now, if the spring is released, it will impart motion not only to the toy wolf but also to the man. Depending on the orientation of the axis of the toy wolf, the man may rotate about the longitudinal axis of his body or about one of two transverse axes. In the last two figures the rotation is in the plane of the drawing.

If the mass of the toy wolf is 200 times less than that of the man, and its moment of inertia, 10,000 less, the angular velocity of the toy wolf will be 10,000 times greater than the angular velocity of the man. And conversely. Thus, if the toy wolf makes 100 revolutions per second, the man will make only (100/10,000) = = 1/100 revolutions, i.e., he will make one complete revolution in 100 seconds or $1^2/_3$ minutes.

This seemingly slow rotation is, nevertheless, much more rapid than the rotation of the Earth, which takes 1,440 minutes.

With a movement of the hand one can impart rotation to a support and, at the same time, to one's own, initially motionless body; the only problem here is how to perform this maneuver without imparting translational as well as rotational motion to the bodies.

Perception of Rotation

The centrifugal force accompanying the slow rotation described above is so insignificant compared with the muscular force that it may be considered nonexistent. However, when the rotation is faster, this force is not only perceptible to the senses (the arms rise to form a straight line, the legs open) but may even do harm -- may even tear a man to pieces. Very slow rotation is more easily perceived from the apparent reverse rotation of surrounding stationary bodies.

It would seem not as if one's own body was rotating, but as if the dark surrounding firmament was rotating in the opposite direction about points lying in a straight line with the eye.

The Dispute about the Rotation of the Earth

The impression would be the same as that obtained in Antiquity and the Middle Ages, when men would not admit that the Earth was rotating at all and saw only the rotation of the crystal blue sky. This was so until the time of Galileo, who was nearly burned at the stake for heresy.

4 April

Rotation of a Building or Projectile

Imagine a stationary building containing different objects that are also stationary. Inside the building is a wheel, the free axis of which coincides with one of the free axes of the building, taken as a whole together with the objects it contains.

Suppose a muscular force or some other force present in the building imparts rapid or slow rotation to this wheel; then the people in the building will immediately perceive this rotation from the apparent motion of the stars which calmly and in a regular sequence float past the windows. Only two stars seem to be fixed; through these (polar) stars passes a straight line parallel to the axis of rotation of the building, a diameter of the dark sphere.

If the rate of rotation of the wheel is increased, then the rate of rotation of the building will increase by an equal amount; if the velocity of the wheel is reduced to one-tenth, the velocity of the building will also be reduced to one-tenth.

If the wheel stops, the building too will stop; if the direction of rotation of the wheel is reversed, the building too will begin to rotate backward. For a given position of the axis of rotation of the wheel, the position of the axis of rotation of the building is also fixed; but nothing prevents us from turning the building about this axis through any desired number of degrees. Let us assume that the moment of inertia of the wheel is 360 times less than the moment of inertia of the building; then, if the wheel makes a single revolution and then stops, during the same time the building will make 1/360 of a revolution and will also stop. If the wheel makes 90 revolutions, the building will cover 90/360 of a circle, i.e., rotate through 90 degrees.

The building may contain more than one wheel.

By means of one wheel the building may be rotated about one free axis, and by means of another wheel about another. When describing a machine for traveling through free space, I shall show that the building, by means of internal forces alone and without loss of matter, can be made to assume any position, but without shifting the free center of inertia.

With some dexterity two persons, initially motionless, can impart to one another, by the force of their muscles, a backward rotational motion. The rotation, of course, will take place about free and parallel axes. At different times during this rotation the two persons will now face one another, now look in opposite directions. The stopping or deceleration of one will involve the stopping or deceleration of the other, and vice versa.

9 April

Description of Machine. Stability of Machine. Stable Cycloidal (Straightline) Motion. Unstable (Circular) Motion.

The machine for traveling through free space, which I shall presently describe, will serve to transport men and various objects through an absolute trackless void, i.e., in the absence of a fixed support, in any desired direction.

Absolute Void and Free Space

Imagine an iron or steel sphere capable of withstanding the pressure of the air it encloses [Fig. 4].

This sphere is provided with numerous circular openings: to the right, to the left, in front, behind, on all sides.

These openings, which serve as portholes, are hermetically

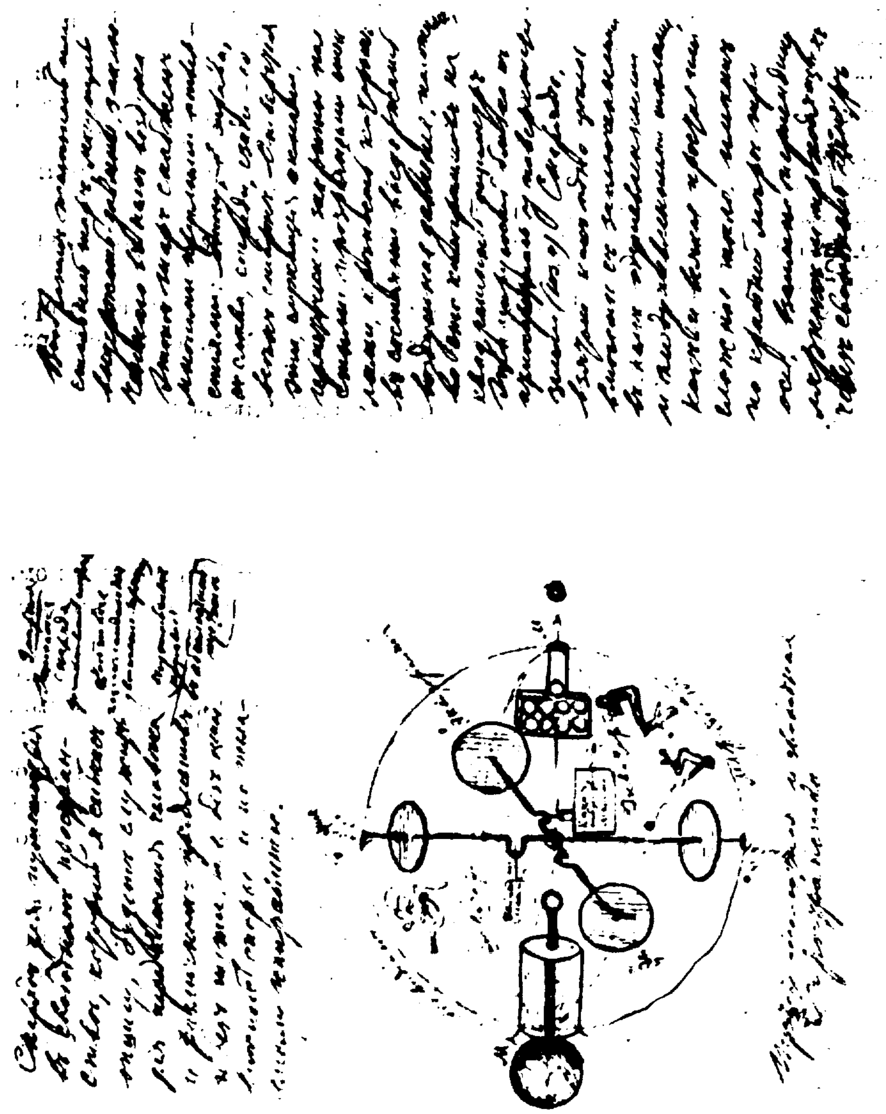

Fig. 4.

sealed with thick transparent glass capable of withstanding an air pressure of, say, one hundred kilograms per square decimeter.

This pressure is close to atmospheric pressure at the Earth's surface. The projectile, taken as a complex whole together with the animate and inanimate bodies it contains, like any simple or complex body, has at least three axes that are mutually perpendicular and pass through its free center.

We shall call one of these axes (P, P_1) polar; a second (M, M_1), meridional; and the third (E, E_1), equatorial.

Three planes may be passed through these axes.

The plane passing through the last two -- the meridional and equatorial -- axes will be called the equatorial plane, and its intersection with the sphere, the equator.

The plane passing through the polar and meridional axes will be called the meridional plane, and its intersection with the sphere, the meridian.

10 April

In order to turn the meridional plane without changing the position of the equatorial plane, we have a material axis, coinciding with the polar axis, that can rotate together with rollers or wheels (a single wheel also is possible) fastened concentrically to its ends.

A propulsion device is attached to each end of the meridional axis (in the plane of the equator). One device (M), a sort of cannon, serves to shoot a cannonball in the direction of the meridional axis.

The other, designed for the same purpose, also takes the form of a thick barrel with a corresponding cannonball of considerable size and density.

This cannonball, however, is not propelled by gunpowder or some other explosive, like the first projectile, but by some less powerful force, for example, by a coiled spring or a human hand. Attached to this cannonball is a very long thread which prevents it from receding to infinity, whereas any cannonball fired from the first cannon is lost to the traveler forever, unless retrieved and returned by others.

The first cannon serves to propel the entire machine along a straight line over an infinitely large distance, while the second serves to propel the travelers through distances limited by the length of the thread, by means of which the cannonball is pulled back into place, just like the machine itself.

These propulsion devices (cannon) permit movement in only one direction.

The polar axis with the rollers at the end enables the sphere to rotate about this axis, while at the same time rotating the meridian and both propulsion devices, which will nevertheless remain in the plane of the equator.

Manually or with some small machine, I now cause the polar axis to rotate; consequently, the sphere will also revolve, but in the opposite direction and only so long as the polar axis is kept moving by manual or mechanical means or by inertia.

When the cannon has turned through the desired number of degrees in the equatorial plane, I stop the axis instantaneously, and the sphere, with the cannon and meridian, stops too.

Now all that remains to be done is to fire the cannon, and the sphere, together with travelers, will begin to race away in the boundless equatorial plane in the chosen direction.

In order to rotate the equator (of the sphere) itself or the cannon in the meridional plane, we use another axis with rollers like the polar axis, but this time coinciding with the equatorial axis.

By means of the polar axis the cannon can be given any position in the plane of the equator, while by means of the equatorial axis it can be given any position in the plane of the meridian. The first axis rotates the meridian of the sphere, and the second, its equator.

Clearly, with the aid of these two axes, a cannon can be positioned as desired in space, and therefore the sphere can move in any direction. The movements of the cannon are similar to the movements of the barrel of a theodolite. Since this barrel can be pointed at any star, by analogy the cannon can be pointed in any desired direction and the sphere with its occupants dispatched toward any star.

Attainment of Stability for the Purpose of Traveling in the Absolute Void of Free Space

If the mass of the sphere is not very great compared with the mass of the people it contains, any movements of the passengers will cause corresponding changes in the motion of the sphere. The resulting unnecessary rotation of the sphere entails unnecessary rotation of the cannon. In any case, this unnecessary rotation can be arbitrarily reduced.

The point is that the faster a disk spins, the more difficult it is to alter its axis or plane of rotation through the application of a force.

Imagine that the traveling sphere contains two rapidly rotating disks*, the axes or planes of which are at right angles to one another (or merely inclined to one another).

Then the incorrect (noncentral) action of forces on the sphere containing the gyrating axes with the disks, roughly speaking, imparts parallel, rather than rotational motion to the sphere and axes. Thus, by means of a special pair of disks we can make the stability of the sphere the greater the faster the disks rotate. With the aid of stationary support, rapid motion can be communicated to these disks without rotating the sphere. However, this can also be accomplished with the aid of a moving support. In this case, stability is achieved by means of two pairs of disks, the axes of each pair either coinciding or being parallel, while the disks themselves, rotate in opposite directions.

If we imagine that in the middle of this sphere for traveling in the absolute void of free space the axes are cut in half, each half, together with its own disk, being capable of rotating independently of the other, we obtain a machine which can not only travel in the direction desired by its passengers but also vary its stability.

In fact, having given the cannon a definite (desired) latitude and longitude, as described, whereupon the disks are stopped, we can now give them opposite and equal angular velocities (if their moments of inertia are equal).

This will not cause the cannon to change its direction, but it will give it, together with the sphere, greater stability. This stability will be the greater the greater the rate of rotation of the disks, so long as this rotation is not so tremendous as to cause the disintegration of the disks by centrifugal force.

11 April Morning

Conditions for the Storing of Gases and Liquids in Free Space

I will now mention the storage of gases and liquids in free space, because without these types of matter no organic life is possible -- no organic life similar to that on Earth, and hence no human

*In modern terminology, two gyroscope rotors (editor's note).

existence. Now, as I will show later, the conquest of free space by man is not absolutely impossible.

I speak of insignificant -- compared with the mass of the earth -- amounts of matter, the mutual attraction of which -- without seriously contradicting Newton's law of gravity -- I shall completely ignore; otherwise the space would not be free.

Newtonian gravitational attraction alone is quite capable of maintaining the various gases and volatile liquids (water) in a constant state and at a considerable density, as we can observe on the planets; but this is not my point; I am not concerned with the effect of enormous masses of matter on gases.

Physics distinguishes two types of liquids: at normal temperatures some liquids hardly evaporate at all, even in a vacuum, like most solids; these include olive oil and sulfuric acid. Other liquids, however, evaporate, diminishing in mass and volume.

To preserve the latter in liquid form, they must -- just as when certain volatile bodies have to be preserved in solid form (ice) -- be placed in a covered, sufficiently strong, solid vessel.

If the internal volume of the vessel is greater than the volume of the liquid placed in it, the remaining space becomes filled with the vapor of the liquid. The density and pressure of this vapor will depend on the ambient temperature.

The same can be said of the storage of volatile solids (ice). The volume of the vessel may be so large that all the liquid or solid placed in it will turn into vapor or gas. As regards storing non-evaporating liquids, however, there is no need to enclose them between solid walls -- they can exist, without changing, in the same quantity and form as most solids, so long as a given liquid does not come in contact with various solid or liquid bodies in such a way that the laws of capillarity begin to operate.

As I noted previously, when not in contact with solids or liquids of another type, liquids of either kind assume a compact spherical shape that depends on the molecular properties of the liquid. Is it not the same force that also confers on the suns and planets the shape of true droplets? Calculations show that the molecular forces of a droplet of water or of some other solid or liquid are incomparably greater or, as they say, infinitely larger, than would ensue from the law of gravitational attraction, which gives rise to the spherical shape of celestial bodies.

Mutual contact between solids and liquids causes the liquids to assume most varied shapes. Here the effects of capillarity manifest themselves strikingly, since in free space, unlike on Earth, these effects are not counteracted by gravity.

12 April

Pascal's Law. The Barometer. The Siphon. The Spirit Level. The Surveyor's Level.

In free space, Pascal's law of the transmission of pressure in a liquid contained in a closed vessel manifests itself in all its purity. But siphons will not work, even in a gaseous medium, which is natural considering that the flow of the liquid jet from the siphon depends mainly on gravity, while atmospheric pressure, or -- in free space -- gas pressure, merely gives a liquid jet cohesion, preventing it from breaking up.

Were the liquid particles connected by the same cohesive force as the links of a chain, the siphon would work in a vacuum without a gaseous medium.

Similarly, fountains of all kinds fail to work in free space, although in physics textbooks their activity, like that of the siphon, is usually ascribed not to gravity, which is the reason for the existence of these devices, but to atmospheric pressure, the role of which is secondary.

In the same way, in free space, mercury (column) barometers, levels, all sorts of spirit gauges, salimeters, areometers, hydrostatic balances, and so forth, are also useless. Although more or less considerable gas pressures can exist in free space, these pressures can be measured only as pressures, not as weight, which is absent in free space. Thus barometers, aneroids, and manometers with compressed air or some other elastic body are suitable for this purpose.

In an ordinary barometer transferred from Earth to an air medium in free space, due to gas pressure, the mercury will immediately fill the entire tube, no matter what its length -- a meter or an even kilometer. In general, any device that is not based on the law of gravity can be employed in free space with even greater success than on Earth. For example, a thermometer, or machines based on levers and other devices for multiplying force or speed, such as: pulley blocks, hydraulic and lever presses, etc.

12 April

Archimedes' Law. The Airship and Birds. Ships and Fish.

A body immersed in a gas or liquid in free space will, clearly, never move if it was initially at rest and is not exposed to any force.

Nor will it experience the horrendous pressure exerted on bodies immersed deep down in the terrestrial seas, which is measured in millions of kilograms per square meter. At a depth of 10 kilometers the pressure is 10^6 kg per square meter.

In fact, the pressure of seawater one kilometer below the surface is already more than 1,000,000 force kilograms per square meter of surface area of a body submerged at such a depth. According to Archimedes' law, any body immersed in a liquid medium loses weight, becoming lighter by an amount equal to the weight of the volume of liquid it displaces. Since the weight of the latter is zero in free space, the loss in weight is also zero. In the void of free space the body weighed zero and when immersed in the liquid it lost none of its weight, therefore its weight remains equal to zero while in the liquid.

Thus, although Archimedes' law is applicable to free space, in free space we shall observe neither the sinking nor floating. Let me describe this more graphically. A lump of iron or wood on the surface of or immersed in a liquid neither sinks nor floats but remains where it is. If there were a sphere of water several dozen meters in diameter, a man could stand on its surface without sinking in.

I ignored capillarity, although it would force the water -- though very slowly -- to wet the man and slowly invest him. But the force of capillarity is so weak that even a fly's strength is sufficient to overcome it, and, moreover, even this weak force depends on complete contact.

As for structures moving in a liquid medium, there is no need for, say, the volume of a boat or ship to correspond to its weight. It (the ship) will not sink, however great its volume and small its weight. A piece of platinum immersed in a gas, even a gas as dense as air, will neither sink nor rise therein; the same applies to a light sphere filled with hydrogen, which (on Earth, for example) would rapidly ascend in an air medium of parallel and equal forces.

Gravity, in all fairness, observes a certain hierarchy of position: the less dense liquids occupy the higher places, and the denser liquids, the lower places. Gravity classifies bodies according to their density: at the bottom, mercury; then comes water; then oil; and lastly, air.

Free space in no way observes this hierarchy: mercury, water, oil and air are mingled in free space in the most fortuitous manner. In a gravitational medium the lighter and hotter unrestrained bodies move in a single definite direction, which accounts for the so-called natural ventilation and draft of furnaces, lamps, candles, and samovars. In free space this natural draft and ventilation are impossible; furnaces would at once begin to smoke furiously and go out; likewise, lamps and candles would not burn even a minute without artificial replenishment of the air. In free space, chimneys of enormous height would be completely nonsensical. Samovars, too, would not be worth buying. Gravity, however, is not so important -- it is difficult to destroy, but its little blessings are easily acquired (as I shall show later).

13 April

Machines designed for moving through the air of free space will be adapted not for combatting gravity -- a struggle that is very arduous and has still not been won on Earth, so that man still cannot fly -- but solely for cutting an aerial path. A bird with bound wings, when hurled into the aerial medium of free space, does not hurtle to the ground like a stone, as it would on Earth, but moves commensurately with the force with which it was hurled, like a boat repulsed from the shore in still water. Any body with an axis of that is flung in the direction of this axis will move in the gaseous medium of free space along a straight line at a diminishing velocity which, however, in theory never diminishes to zero, although it approaches zero ever more closely. The distance traversed will also increase infinitely with time.

As for a body flung in a random manner, it will move along a curved path and, therefore, at a slower speed.

Only the path of a sphere is always rectilinear.

In order for the motion of a body to be uniform, it must be acted upon by a constant force equal to the resistance encountered by the body during its motion through the fluid medium.

Conditions for the Growth and Reproduction of Plants

We know, in general, what is necessary for the growth and reproduction of plants. They need certain gases (nitrogen, oxygen, etc., but mainly carbon dioxide), liquids and their vapors (especially water), solids in comminuted form and (at least to a small degree) soluble in water. Every plant needs: a temperature that does not transcend certain limits, and sunlight or electric light.

But gravity! Is this a necessary condition for plant life?

I do not think so, because, as experience shows, a change in the direction and force of gravity, induced by centrifugal force, does not destroy the process of plant life. (I shall have more to say about this later).

We have seen that gases and liquids, as well as solids, can be preserved under definite conditions in free space without a change in state. What is more, I shall show later that the creation of a relative gravity of arbitrary strength in free space is quite easy and inexpensive. I mention this in the event that gravity should prove to be a necessary prerequisite of the vegetative process.

But I chose a site for observing free-space phenomena much too far from the Sun; here it shines like a star and, as we know, starlight is insufficient for plant growth. I have already stated, though I have yet to prove it, that free-space phenomena may be observed not only at the same distance from the Sun as our Earth but even at the very surface of the Sun, that is, at a distance which would probably suffice to fuse iron and coal.

At any rate, there would not be a shortage of sunlight.

Thus, assuming that light has access to a hermetically sealed but transparent (glass) vessel containing all the necessities of growth, and given a suitable temperature, the plant inside the vessel would grow beautifully and produce seeds and offspring.

It would be extremely interesting to perform on Earth experiments which would reveal the exact density and pressure of gases and vapors at which the growth process proceeds most successfully.

Do plants absolutely require that dense atmosphere of oxygen and nitrogen which, as we see, surrounds them on Earth? In an absolute void, a gas is the easier to store, the more rarefied it is, because the lower its pressure, the thinner and more transparent the walls of the containing vessel may be.

The mean pressure and volume of the carbon dioxide in air is (according to Mendeleyev) 2,500 times lower than the pressure and volume of the latter (air).

Should my planned experiment show that the amount of oxygen and nitrogen could be the same as the amount of carbon dioxide -- a gas the importance of which for the viability of plants seems to be greater and much more understandable than the importance of nitrogen, and which, after nitrogen and oxygen, is the most abundant of constituents of air -- we would arrive at the pleasing (at least to the visionary) conclusion that the thinnest and therefore most transparent walls could prevent the dissipation of the gases that plants need to live.

Shape and Size of Plants

Although I believe that gravity is not indispensable to plants, it undoubtedly affects their shape.

Thus, the main stem that characterizes most plants is more or less vertical, i.e., coincides with the direction of terrestrial gravity; plants with main stems deviating from the vertical have been grown experimentally. Further, owing to the weight of the upper part, the lower part of a tree decays and disintegrates, or may simply break. And, in general, a tree can only grow to a certain height.

In free space, on the other hand, the directions of growth of main and secondary stems and tree trunks clearly depend only on random, nugatory influences and therefore are indeterminate and can be easily controlled by man who, thus, will be able to shape them as desired.

Moreover, in the absence of oppressive gravity, a plant may grow to any size desired; it may be even several hundred kilometers long and thick, though that might be too much of a good thing.

But here is the rub: does not gravity favorably affect the diffusion or flow of sap?

Yes, it does; but I do not think that gravity is a necessary or even a favorable influence on this flow in any part of the tree, because the reason for the flow of the sap is to be found in the laws of diffusion and capillarity, which manifest themselves even more clearly in the absence of gravity.

Indeed, theory shows that if water rises one centimeter in a glass tube on Earth owing to capillary forces, then on the Moon, in the same tube, it would rise six centimeters; on Vesta, 30 cm; and on Atalanta, 400 cm or 4 m.

Clearly, in free space, the water would completely fill the glass tube however long that tube might be.

We also know of experiments on the diffusion of gases and liquids, in which no gravitational effect has been observed.

It may also be that plant species capable of surviving in a nearly absolute void could be evolved through artificial or natural selection.

It may be that such species exist on the Moon where no terrestrial species can exist in view of the absence or extreme rarefaction of the atmosphere.

Conditions for the Viability of Animals. Their Shape and Size.

Given the feasibility of the existence in free space of the plants that provide man with food and, by decomposing carbon dioxide, with the gas (oxygen) necessary for all life processes, clearly man himself could also exist in free space, even if his organism were not deliberately modified through artificial selection and transformation.

Actually, human beings in their present form are suited for existence in a medium of parallel and equal forces, and, had there been no gravity on Earth, would have been completely changed or at least modified by natural selection; the old form would have proved unsuitable in the struggle for existence under the new conditions, because it would no longer have been ideal in relation to the new environment.

Legs, which are needed for movement in a gravitational environment, are completely unnecessary in free space where, of a certainty, they would atrophy or evolve into a more useful appendage, e.g., a prehensile appendage such as claws, for gripping or thrusting, so as to facilitate uniform motion in a trackless environment.

This apparatus, assuming blind natural selection and non-rational beings, would assume horrific proportions, since in free space there would be no gravity to restrict the size of these organs or limbs, so that they might serve both as a means of avoiding danger and as a means of foraging swiftly for food and dealing telling blows.

Even within the sphere of the solar system there are many places characterized by free-space phenomena.

There is no logical reason not to assume that these spaces are populated by beings who would appear extremely strange to us, beings whose gigantic size, inherent in free space, we may perhaps some day observe, as we improve our telescopes.

With this far from complete sketch I conclude, for the time being, my description of the phenomena of free space.

Later on, I shall have more than one occasion to review these phenomena.

Once I have shown that free space is not so infinitely remote and inaccessible as it might seem, free-space phenomena will merit the more serious attention and interest of the reader.

EXPLORATION OF THE UNIVERSE WITH REACTION MACHINES*

Heights reached by balloons; their size and weight; the temperature and density of the atmosphere

1. So far small unmanned aerostats carrying automatic observation equipment have risen to altitudes of not more than 22 km.

Above this height the difficulties of ascending to higher altitudes by balloon increases rapidly.

Suppose an aerostat is required to climb to an altitude of 27 km carrying a load of 1 kg. The air density at an altitude of 27 km is about 1/50 of the density at the surface (760 mm pressure and $0^{o}C$). This means that at this altitude a balloon must occupy a volume 50 times greater than on the ground. At sea level, it is filled with, say, at least 2 cubic meters of hydrogen, which at the given altitude will occupy 100 cubic meters. At the same time, the balloon will lift a load of 1 kg, i.e., the automatic instruments, and the balloon itself will weigh about 1 kg. Assuming the diameter of the envelope to be 5.8 m meters, its surface area will be at least 103 square meters. Therefore, every square meter of the material, including the reinforcing mesh sewn into it, should weigh 10 g.

One square meter of ordinary writing paper weighs 100 g, while one square meter of cigarette paper weights 50 g. Thus even cigarette paper would be five times heavier than the material needed for our balloon. Such a material could not be used in the balloon, as an envelope made from it would tear and allow the gas to leak at a rapid rate.

Large balloons may have thicker envelopes. Thus, a balloon

Editor's note:
*First published in the periodical "Nauchnoye obozreniye" (Science Review), No. 5, 1903, under the title "Issledovaniye mirovykh prostranstv reaktivnymi priborami (Exploration of the Universe with Reaction Machines). In 1924 this article was published in Kaluga as a separate brochure. It was included in the "Izbrannyye trudy" (Selected Works), Book II, 1934, published by ONTI. K. E. Tsiolkovskiy regarded his "Issledovaniye mirovykh prostranstv reaktivnymi priborami" Part II (Issledovaniye 1911-1912) as a continuation of this article. See also Appendix, Point 11.

with the unprecedentedly large diameter of 58 meters would have an envelope, one square meter of which would weigh about 100 g, i.e., about as much as ordinary writing paper. It would lift a load of 1,000 kg, which is much more than an automatic recorder would weigh.

If we reduce this load to one kilogram, using the same gigantic aerostat, we can make the envelope twice as heavy. In general, such a balloon, while expensive, would be perfectly feasible. At an altitude of 27 km it would occupy a volume of 100,000 cubic meters, and the surface area of its envelope would be 10,300 square meters.

And yet, how miserable these results seem! A mere 27 km.

How then could the instruments be raised higher? The aerostat would have to be still larger. But here it should not be forgotten that as the size increases the forces acting on the envelope dominate more and more over the resistance of the material.

Raising instruments beyond the limits of the atmosphere by means of an aerostat is, of course, inconceivable; observations of shooting stars reveal that those limits lie no higher than 200-300 km. In theory, the top of the atmosphere may even be set at 54 km, if we base our calculations on a decrease in air temperature by 5°C per kilometer, which is fairly close to reality, at least with respect to the accessible layers of the atmosphere.*

I present a table of altitudes, temperatures and air densities calculated on this basis. It shows how rapidly the difficulties increase with altitude.

The divisor in the last column indicates the degree of difficulty in constructing a balloon.

2. Let us now consider another possible means of reaching high-altitudes -- cannon-launched projectiles.

In practice, the initial velocity of a shell does not exceed 1,200 m/sec. Such a projectile, if launched vertically, would rise to an altitude of 73 km, if the ascent took place in a vacuum. In air, however, the height reached would be much lower depending on the shape and mass of the projectile.

If the shape of the projectile were suitable, it might reach a considerable height; but instruments could not be housed inside the projectile, since they would be smashed into fragments on its return to Earth or even while it was still moving through the barrel of the cannon. The danger would be less if the projectile were shot from a

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*It is now known that the decrease in temperature continues only as far up as the boundary of the troposphere, i.e., up to 11 km.

TABLE

Depth of atmosphere * in km	Temperature in °C	Air density
0	0	1
6	- 30	1 : 2
12	- 60	1 : 4.32
18	- 90	1 : 10.6
24	- 120	1 : 30.5
30	- 150	1 : 116
36	- 180	1 : 584
42	- 210	1 : 3900
48	- 240	1 : 28 000
54.5	- 272	0

*Editor's note: According to recent data, in the stratosphere, between 11 and 35 km, the temperature is constant and equal to -56.5°C. In the region between 35 and 50 km a rise in temperature to -30-35°C is observed.

tube, but even then it would still be enormous. Suppose, for the sake of simplicity, that the gas pressure on the projectile was uniform, so that the acceleration was W m/sec^2. Then the same acceleration would also be imparted to all the objects inside the projectile, objects forced to share the same motion. As a result, inside the projectile there would develop a relative, apparent gravity,* equal to W/g, where g is acceleration due to gravity at the Earth's surface.

The length of the cannon L may be expressed by the formula

$$L = \frac{V^2}{2(W - g)},$$

whence

$$W = \frac{V^2}{2L} + g,$$

where V is the velocity acquired by the projectile on leaving the muzzle.

It is clear from the formula that W, and hence the increase in relative gravity in the projectile, decreases with increasing barrel length if V is constant, i.e., the longer the cannon the greater the safety of the instruments during the firing of the projectile. But even if the cannon were, in theory, extremely long, which is not feasible in practice, the apparent gravity in the projectile, as the latter accelerates through the barrel, would

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* g force (Editor's note).

become so enormous that the sensitive instruments would hardly be able to withstand it. This would make it all the more impossible to dispatch a living organism in the projectile, should this be found necessary.

3. Let us assume that we have succeeded in building a cannon approximately 300 m tall. Suppose it has been erected next to the Eiffel Tower which, of course, is the same height, and let the projectile, under the uniform pressure of the gases, attain a muzzle velocity sufficient to carry it beyond the limits of the atmosphere, e.g., to an altitude of 300 km above the surface. Then the velocity V required for this purpose may be calculated from the formula

$$V = \sqrt{2g \cdot h}\text{*} ,$$

where h is the maximum altitude (we obtain approximately 2,450 m/sec). From the last two formulas, on eliminating V, we obtain

$$\frac{W}{g} = \frac{h}{L} + 1;$$

where W/g expresses the relative or apparent gravity within the projectile. From the formula we find it to be equal to 1001.

Therefore, the weight of all the instruments inside the projectile would increase by more than a thousandfold, i.e., an object weighing one kilogram would experience a pressure of 1,000 kg

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*In these calculations air resistance was not taken into account (Editor's note).

due to the apparent gravity. There is hardly any physical instrument that can withstand such a pressure. And what a tremendous shock would be experienced by a living organism in a short-barreled cannon and during the ascent to an altitude of more than 300 km!

In order not to lead anyone astray by the words "relative or apparent gravity," let me say that by this I mean a force dependent on the acceleration of a body (for example, a projectile). It also appears during the uniform motion of a body, provided this motion is curvilinear; it is then termed centrifugal force. In general, relative gravity always appears whenever a body is acted upon by some mechanical force that disturbs its inertial motion. Relative gravity operates as long as the force engendering it continues to act; once the latter ceases to act, the relative gravity disappears without a trace. If I term this force gravity, it is only because its temporary effect is exactly the same as that of a gravitational force. Just as every material point of a body is subject to gravitation, so relative gravity affects every particle of a body enclosed in a projectile; this is because relative gravity depends on inertia, by which all the material parts of a body are equally affected. Thus, the instruments inside the projectile will become 1,001 times heavier. Even if they could be preserved intact through this terrifying, though momentary (0.24 sec) intensification in relative gravity, there would still be many other obstacles to the use of cannons as a means of reaching the celestial space.

First and foremost, there is the difficulty of building such cannons, even in the future; second, there is the tremendous initial velocity of the projectile. Actually, in the dense lower layers of the atmosphere the projectile would lose much of its velocity owing to air resistance; now this loss in velocity would also considerably reduce the altitude reached by the projectile. Besides, it is difficult to obtain a uniform gas pressure on the projectile, as the latter moves through the cannon barrel, so that the intensification of gravity will be much greater than calculated (1,001). Finally, the safe return of projectile to Earth would be more than doubtful.

Rocket versus cannon

4. Thus, the tremendous increase in gravity alone is definitely enough to dispel any notion of using cannons for our purpose.

Instead of cannons or aerostats, I propose the use of reaction machines to explore the atmosphere. By reaction machine I mean a kind of rocket, but a specially designed rocket on a grandiose scale. The idea is not new, but the calculations yield such remarkable results that they simply cannot be ignored.

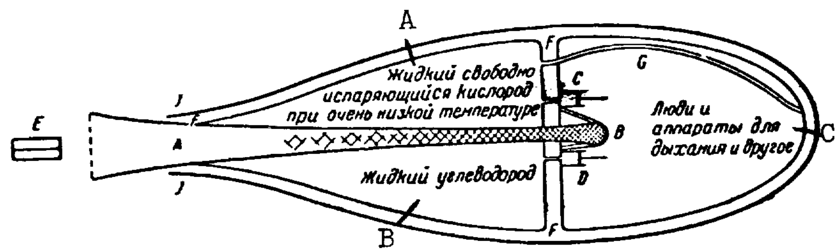

Fig. 1.

A - Freely evaporating liquid oxygen at very low temperature.
B - Liquid hydrocarbon.
C - Crew, breathing apparatus, etc.

I am far from having investigated every side of the matter, nor have I attempted to solve the practical problems relating to the feasibility of the concept; however, it is already possible to behold, across the veil, such tantalizing and significant glimpses of the distant future as could hardly be dreamed of.

Visualize the following projectile: an elongated metal chamber (the shape of least resistance) equipped with electric light, oxygen, and means of absorbing carbon dioxide, odors, and other animal secretions; a chamber, in short, designed to protect not only various physical instruments but also a human pilot (we shall consider the problem in its broadest terms). The chamber is partly occupied by a large store of substances which, on being mixed, immediately form an explosive mass. This mixture, on exploding in a controlled and fairly uniform manner at a chosen point, flows in the form of hot gases through tubes with flared ends (Fig. 1), shaped like a cornucopia or a trumpet. These tubes are arranged lengthwise along the walls of the chamber. At the narrow end of the tube the explosives are mixed: this is where the dense, burning gases are obtained. After undergoing intense rarefaction and cooling, the gases explode outward into space at a tremendous relative velocity at the other, flared end of the tube. Clearly, under definite conditions, such a projectile will ascend like a rocket.

Automatic instruments are needed to control the motion of the rocket, as I shall call it, and the force of the explosion in accordance with a predetermined schedule.

Schematic view of the rocket

The two liquid gases are separated by a partition. The place where the gases are mixed and exploded is shown, as is the flared outlet for the intensely rarefied and cooled vapors. The tube is surrounded by a jacket with a rapidly circulating liquid metal. The control surfaces serving to steer the rocket are also visible.

If the resultant of the explosion forces does not pass through the center of inertia of the projectile, the projectile will rotate and, therefore, will not be suitable. Now, it is quite impossible to attain a mathematically precise coincidence of this kind, because the center of inertia is bound to fluctuate owing to the motion of the substances contained by the projectile, in the same way as the direction of the resultant of the gas pressure inside a cannon barrel cannot be mathematically fixed. So long as the projectile is still in the air, it can be guided with control surfaces like a bird, but what can be done in an airless medium where the ether can not provide any appreciable support?

If the resultant is as close as possible to the center of inertia of the projectile, the rotation will be fairly slow. But as soon as it commences, we can shift some mass inside the projectile until the ensuing displacement of the center of inertia causes the projectile to incline in the opposite direction. Thus, by sensing the movements of the projectile and shifting a small mass inside it, we can cause the projectile to swing now in one, now in the other direction, so that the general direction of action of the explosives and the general direction of motion of the projectile do not change.

It may be that manual steering of the projectile will be not only difficult but even infeasible. In this case, it will be necessary to resort to automatic control.

The Earth's gravitational attraction cannot be used as the principal regulating force, since the projectile will be governed only by relative gravity due to the acceleration W, the direction of which will coincide with the relative direction of the outflowing gases or be directly opposite to their resultant pressure. And since this direction varies with the rotation of the projectile, the relative gravity is unsuitable as the basis of a guidance system.

On the other hand, it is possible to use a magnetic needle or the strength of the Sun's rays focused by means of a biconvex lens. Whenever the projectile rotates, the small, bright image of the sun will change its relative position in the projectile, thus causing the expansion of a gas, or creating a pressure or an electric current, and hence the movement of a counterweight to restore the direction of the projectile, so that the light spot again falls on a neutral, insensitive part of the mechanism.

There should be two such automatically actuated masses.

Another basis for the guidance system of the projectile could be a small chamber with two disks rapidly rotating in different planes. The chamber is suspended so that its position or, more exactly, direction is independent of the direction of the projectile. When the projectile rotates, the chamber (if we ignore the friction) retains the same absolute direction (relative to the stars) thanks to its inertia; this property manifests itself to a high degree when the chamber disks rotate rapidly. If fine springs attached to the chamber changed their relative position during the rotation of the projectile, this change could be used to excite a current and produce a shift in the position of the counterweights.

Lastly, rotation of the mouth of the tube might also serve as a means of keeping the projectile on course. The simplest means of steering the rocket would be dual control surfaces mounted externally, close to the mouth of the tube. As for preventing the rotation of the rocket about its longitudinal axis, this can be accomplished by rotating a plate located in the gas flow and aligned with the direction of this flow.*

*It is noteworthy that here Tsiolkovskiy anticipates the development of modern exhaust control vanes (Editor's note).

Advantages of the Rocket

5. Before expounding the theory of the rocket or similar reaction-propelled devices, I shall try to interest the reader in the advantages of the rocket as compared with the cannon-launched projectile:

a) Our device, compared with the gigantic cannon, is as light as a feather, relatively cheap, and comparatively easy to realize.

b) The pressure of the explosives, being fairly uniform, creates a uniform acceleration which develops a relative gravity; we can adjust the magnitude of this temporary gravity as desired, i.e., by regulating the force of the explosion, and make it arbitrarily small or many times greater than normal terrestrial gravity. If we assume for simplicity's sake that the force of the explosion diminishes in proportion to the mass of the projectile plus the mass of the remaining, still unexploded fuel, the acceleration of the projectile, and hence the relative gravity, will be constant. Thus, with respect to apparent gravity, a rocket can safely be used to dispatch not only measuring instruments but also human beings, whereas a cannon-launched projectile, even one shot from a colossal cannon as tall as the Eiffel Tower, involves a 1,001-fold increase in relative gravity in ascending to 300 km.

c) Another important advantage of the rocket is that its velocity can be made to increase at a desired rate and in a desired direction; it may be kept constant; or it may uniformly decrease, thus making possible a safe landing. Everything depends on a reliable explosion regulator.

d) At take-off, when the atmosphere is dense and the air resistance at high speeds enormous, the rocket moves comparatively slowly and therefore the losses due to air resistance are low; moreover, the rocket does not become overheated.

The velocity of a rocket increases only very slowly; but later on, as it ascends to more and more rarefied layers of the atmosphere, it can be made to increase more rapidly, until, finally, in airless space the velocity reaches a maximum. Thus, the work done in overcoming air resistance is reduced to a minimum.

The Rocket in an Atmosphereless, Gravitationless Medium

The Mass Ratio of the Rocket

6. First let us consider the effect in an atmosphereless, gravitationless medium. As regards the atmosphere, we shall consider only its resistance to the motion of the projectile, disregarding its resistance to the expulsion of exhaust gases. The effect of the atmosphere on the explosion is not altogether clear; on the one hand, it is favorable, since the exploding substances receive some support from the material medium, thus contributing to an increase in the rocket's velocity; on the other hand, the density and pressure of the atmosphere interfere with the expansion of the gases beyond certain known limits, so that these gases do not acquire the velocity they would acquire if expelled in a void. The latter effect is unfavorable, since the increase in the velocity of the rocket is proportional to the velocity of the expelled explosion products.

7. Let us denote by M_1 the mass of the projectile together with all it contains, except the supply of explosives; by M_2, the total mass of the explosives; and, lastly, by M, the variable mass of the explosives remaining in the projectile in unexploded form at a given instant.

Thus, the total mass of the rocket at the commencement of the explosion will be: $(M_1 + M_2)$; some time later, however, it will be expressed by the variable $(M_1 + M)$; and finally, when the explosion ends, by the constant M_1.

In order for the rocket to attain its maximum velocity, it must expel the explosion products in a fixed direction relative to the stars. Therefore it must not rotate and, in order for it not to rotate, the resultant of the explosive forces -- which passes through their center of pressure -- must at the same time pass through the center of inertia of the whole complex of speeding masses. We have already solved the problem of how to accomplish this in practice.

Thus, assuming the optimal expulsion of the gases in a single direction, we obtain the following differential equation based on the law of conservation of momentum:

$$dV\ (M_1 + M) = V_1 dM. \tag{8}$$

9. Here dM is an infinitely small mass of explosive material expelled from the mouth of the tube at a constant (relative to the rocket) velocity V_1.

10. I should point out that on the basis of the law of relative motion, given the same conditions, the relative velocity of the exhaust elements is the same throughout the period of the explosion. dV is the increment in the velocity of the rocket together with the remaining unconsumed explosives; this increment, dV, is due to the expulsion of an element dM at the velocity V_1. We shall determine the latter in the proper place.

11. Separating the variables in equation (8) and integrating, we obtain

$$\frac{1}{V_1}\int dV = -\int \frac{dM}{M_1 + M} + C, \tag{12}$$

or

$$\frac{V}{V_1} = -\ln\ (M_1 + M) + C. \tag{13}$$

where C is a constant. When $M = M_2$, i.e., before the explosion, $V = 0$; thus we find

$$C = +\ln\ (M_1 + M_2); \tag{14}$$

and hence

$$\frac{V}{V_1} = \ln\left(\frac{M_1 + M_2}{M_1 + M}\right). \tag{15}$$

The velocity of the projectile will be a maximum when M = 0, i.e., when the entire fuel supply M_2 has been burned; then, putting M = 0 in the preceding equation, we have

$$\frac{V}{V_1} = \ln\left(1 + \frac{M_2}{M_1}\right). \qquad (16)$$

Hence we see that the velocity V of the projectile increases without limit with increase in the amount M_2 of explosives. This means that we can attain different final velocities for different voyages, depending on the store of explosives taken on board. Equation (16) also shows that a definite quantity of explosive is consumed, the velocity of the rocket does not depend on the rate or uniformity of the explosion, so long as the particles of exhaust material move at the same velocity V_1 with respect to the projectile.

17. However, as the quantity M_2 increases, the velocity V of the rocket increases ever more slowly, though without limit. It increases more or less as the logarithm of the increase in the amount of explosives M_2 (if M_2 is large compared with M_1, i.e., if the mass of the explosives is several times larger than the mass of the projectile).

18. Further calculations will be of interest, once we have determined V_1, i.e., the relative and final velocity of the explosion products. Since a gas or vapor leaving the mouth of the tube is much rarefied and cooled (if the tube is sufficiently long) and may even solidify -- turn into particles of dust rushing at terrific speeds -- it may be assumed that, when an explosion occurs, the entire energy of combustion or chemical combination is transformed into the motion of the combustion products or into kinetic energy. In fact, imagine a given amount of gas expanding in a void, without any restrictions: it will expand in all directions and, consequently, cool until it turns into droplets of liquid or a mist.

This mist will turn into minute crystals, no longer due to expansion but rather to evaporation and radiation into space.

On expanding the gas will release all its manifest and part of its latent energy, which will ultimately be converted into rapid motion of the minute crystals in all directions -- since the gas expanded freely. If, however, the gas is forced to expand in a tubular chamber, the tube will orient the motion of the gas molecules in a fixed direction, which is the method we use to propel our rocket.

It would seem that the energy of molecular motion is converted into kinetic motion as long as a substance remains in the gaseous or vapor state. But this is not quite so. In fact, part of the substance may turn to liquid; this involves the release of energy (latent heat of vaporization), which is transmitted to the part remaining as a vapor, thus delaying its transition to the liquid state.

We can observe an effect of this kind in a steam cylinder when steam does work owing to its own expansion and the valve from the boiler to the cylinder is closed. In this case, whatever the temperature of the steam, part of it turns into a mist, i.e., the liquid state, while the rest remains as a vapor and continues to do work, borrowing the latent heat of the condensed and liquefied fraction.

Thus, the molecular energy will continue to be transformed into kinetic energy at least until the liquid state is reached. Once the entire mass turns into droplets, the conversion to kinetic energy will cease almost completely, because the vapors of liquids and solids have only an insignificant pressure when the temperature is low, and their practical utilization is difficult, requiring enormous tubes.

In addition, an insignificant part of the energy is lost, i.e., is not converted into kinetic energy, due to friction against the walls of the tube and the radiation of heat from the heated parts of the tube. However, the tube can be encased in a jacket through which a liquid metal is circulated; this liquid metal will convey heat from the intensely heated end of the tube to the end cooled by the rarefaction of the vapor. Thus, the losses due to radiation and conduction can also be recovered or minimized. In view of the short duration of the explosion, which takes 2 to 5 min at most, the loss due to radiation is negligible, even without any special precautions; the circulation of the liquid metal in the tube jacket is more important for another purpose: the maintenance of a uniformly low tube wall temperature, i.e., the preservation of the mechanical strength of the tube. Despite this it may happen that part of the tube will melt, oxidize, and be carried away by the gases and vapors. To prevent this, the inside walls of the tube could be lined with some special refractory material: carbon, tungsten, etc. Some of the carbon may burn away, but the relatively cool metal tube will suffer little loss of strength.

As for the gaseous product of combustion of carbon -- carbon dioxide -- this will only intensify the thrust of the rocket. Some kind of crucible material, some mixture of substances, might be used. However, I shall not attempt to solve these and other problems pertaining to reaction-propulsion machines.

In many cases I am limited to guesses or hypotheses. I am not deluding myself and I am perfectly aware that I am not solving the problem in its entirety, that a thousand times more work than I have done must be invested in its solution. My aim is to arouse interest by pointing out its great future significance and the feasibility of a solution....

The liquefaction of hydrogen and oxygen involves no special difficulty. Hydrogen could be replaced by liquid or liquefied hydrocarbons, for example, by acetylene or oil. These liquids must be separated by a partition. Their temperature is very low; therefore it would be expedient to allow them to surround either jackets with circulating liquid metal or the tubes themselves.

Experience will show which is better. Some metals become stronger when cooled; these are the metals that should be employed, copper, for example. I do not recall this clearly, but it seems that experiments on the resistance of iron in liquid air have revealed that its strength at such low temperatures is virtually dozens of times greater. I cannot guarantee the reliability of these experiments, but, in relation to the problem discussed here, they deserve the most diligent attention.* (Why not cool ordinary cannon in the same way before firing, since liquid air is now so easily obtainable.)

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*The author mentions a metal, iron, which has proved to be unsuitable with regard to its strength at low temperatures, as already pointed out by R. Lademann in his article "Zum Raketenproblem" (On the Rocket Problem) in the issue of 28 April 1927 of the periodical ZFM.

The author replies in the appendix to the book "Kosmicheskaya raketa, opytnaya podgotovka" (The Space Rocket -- Experimental Preparations):

"Concerning the increase in the strength of iron at the temperature of liquid air, in 1903 I merely repeated information that I had read elsewhere, and I shall certainly not insist that it is true, once it has been proved to be untrue. In practice, the explosion tube could not attain such a degree of coldness. It is cooled by oil which, in turn, is cooled by liquid air. It is enough if the tube does not melt or burn, the petroleum does not boil, and the liquid air does

Liquid oxygen and liquid hydrogen, when pumped from tanks and supplied in a fixed ratio to the narrow inlet of the tube, where they progressively combine, constitute an excellent explosive. The water vapor obtained from the chemical combination of these liquids will expand at a tremendously high temperature in the direction of the wide end or mouth of the tube, until it cools to a liquid racing toward the outlet in the form of an ultrafine mist.

19. Hydrogen and oxygen in the gaseous state release 3825 calories on combining to form 1 kg of water. By the word "calorie" I mean the amount of heat required to raise one kilogram of water through 1°C.

This figure (3825 calories) will be somewhat lower in the present case, since the oxygen and hydrogen are in the liquid rather than in the gaseous state, to which this particular number of calories relates. In fact, the liquids must first be heated and then converted to the gaseous state, which requires some expenditure of energy. In view of the insignificant amount of energy required, as compared with the chemical energy, we shall not reduce this figure (the question has not been completely clarified by science; but we are merely taking oxygen and hydrogen as an example).

Assuming the mechanical equivalent of heat to be 427 kgm, we find that 3825 calories corresponds to 1633 kgm of work; this is enough to raise the explosion products, i.e., one kilogram of matter, to an altitude of 1633 km above the surface of the Earth, that the force of gravity is constant. This work, converted into motion, corresponds to the kinetic energy of a mass of one kilogram moving at a velocity of 5700 m/sec. I know of no group of substances that, on combining chemically, could release such a tremendous amount of energy per unit mass of the resulting product. Moreover, some substances on combining do not form volatile products at all, which is not at all suitable for our purposes. Thus, silicon, on burning in oxygen ($Si + O_2 = SiO_2$), releases an enormous amount of heat, namely, 3654 calories per unit of mass of the resulting product (SiO_2) but,

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not vaporize too quickly. There is no need to reach the temperature of liquid air in the explosion tube." (Editor's note in "Izbrannyye trudy K. E. Tsiolkovskogo" (Selected Works of K. E. Tsiolkovskiy). Book II. "Reaktivnoye dvizheniye" (Reaction Propulsion). Moscow, ONTI, 1934).

unfortunately the product is non-volatile.

Having taken liquid oxygen and hydrogen as the most suitable materials for creating an explosion, I gave a somewhat exaggerated figure for their chemical energy per unit mass of product (H_2O), since in a rocket the explosive substances must be in the liquid and not the gaseous state and, moreover, at a very low temperature.

I consider it pertinent to console the reader with the thought that we may expect not only this energy (3825 calories) but an incomparably greater energy in the future, if and when our still embryonic ideas are found to be feasible. In fact, on considering the amount of energy produced by various chemical processes, we find that as a general rule, though naturally with some exceptions, the amount of energy per unit mass of the products of chemical combination depends on the atomic weight of the combining elements: the lower the atomic weight, the greater the heat released during chemical combination. Thus, the formation of sulfur dioxide is accompanied by the release of only 1250 calories, and the formation of cupric oxide by only 546 calories, whereas when carbon dioxide CO_2 is formed, the carbon releases 2204 calories per unit mass of CO_2. Hydrogen combining with oxygen, as we have seen, releases even more (3825).

To relate these data to the idea I have just formulated, let me remind you that the atomic weights of the elements named are: hydrogen, 1; oxygen, 15; carbon, 12; sulfur, 32; silicon, 28; copper, 63.

Of course, many exceptions to this rule can be cited, but in general it is valid. In fact, if we imagine a series of points the abscissas of which express the sum (or mathematical product) of the atomic weights of the combining elements, and the ordinates -- the corresponding energy of chemical combination, then, on drawing a smooth curve through these points (as close to them as possible), we observe a steady decrease in the ordinates with increase in the abscissas, just as our theory suggests. For this reason, if at some time so-called simple substances prove to be complex and are separated into new elements, the atomic weights of these elements should be smaller than those of the simple substances known to us.

Accordingly, newly discovered elements, upon combining chemically, must release an incomparably larger amount of energy than bodies currently considered simple and having a comparatively large atomic weight.

The very existence of the ether with its almost infinite expansibility and the enormous velocity of its atoms implies that these atoms have an infinitesimally small atomic weight and infinite energy when they combine.

20. However this may be, for the time being we cannot count on more than 5700 m/sec as the maximum V_1 (see 15 and 19). With time, however, who knows, this figure may increase several times over.

Assuming 5700 m/sec, we can calculate from formula (16) not only the velocity ratio V/V_1 but also the absolute value of the final (maximum) velocity V of the projectile as a function of its $\frac{M_2}{M_1}$ ratio.

21. It is evident from formula (16) that the mass of the rocket together with all passengers and equipment, M_1, may be arbitrarily large without thereby detracting in any way from the velocity V of the projectile, so long as the supply of explosives, M_2, increases in direct proportion to M_1.

Thus, projectiles of any size with any number of passengers may be given any desired velocity. However, as we have seen, an increase in the velocity of the rocket is accompanied by an incomparably more rapid increase in the mass of the explosives. Therefore, though it may be easy to increase the mass of a projectile destined for outer space, it is correspondingly difficult to increase its velocity.

Flight Velocities as a Function of Fuel Consumption

22. From equation (16) we obtain the following table.

23. From this table it is clear that the velocities attainable by reaction propulsion are far from negligible. Thus, when the mass of explosives exceeds 193 times the mass M_1 of the projectile (rocket), the velocity during the final moments of the explosion, when the entire supply of explosives M_2 has been consumed, is equal to the velocity of the Earth around the Sun. It should not be supposed that such an enormous mass of explosives requires a commensurate amount of high-strength material for the vessels in which it is stored. In fact, hydrogen and oxygen in liquid form develop high pressure only if the vessels containing them are closed and if the gases themselves get heated due to the influence surrounding, comparatively warm bodies.

$\frac{M_2}{M_1}$	$\frac{V}{V_1}$	Velocity m/sec	$\frac{M_2}{M_1}$	$\frac{V}{V_1}$	Velocity m/sec
0.1	0.095	543	7	2.079	11 800
0.2	0.182	1 037	8	2.197	12 500
0.3	0.262	1 493	9	2.303	13 100
0.4	0.336	1 915	10	2.398	13 650
0.5	0.405	2 308	19	2.996	17 100
1	0.693	3 920	20	3.044	17 330
2	1.098	6 260	30	3.434	19 560
3	1.386	7 880	50	3.932	22 400
4	1.609	9 170	100	4.615	26 280
5	1.792	10 100	193	5.268	30 038
6	1.946	11 100	Infinite	Infinite	Infinite

In the present case, the liquefied gases must have a free outlet to the tube into which they flow constantly in liquid form and where, on chemically combining, they explode.

The continuous and rapid flow of gases, corresponding to the evaporation of the liquids, cools the latter until their vapors exert hardly any pressure on the surrounding walls. Thus, the vessels containing the explosives need not be made very massive.

24. When the mass of the explosives is equal to the mass of the rocket ($\frac{M_2}{M_1} = 1$), the velocity of the latter is nearly twice as great as would be necessary for a stone or cannon ball, launched by "Selenians" from the surface of the Moon, to leave the Moon forever and become an Earth satellite, a second Moon.

This velocity (3920 m/sec) is nearly enough for bodies launched from the surface of Mars or Mercury to leave these planets forever.

If the mass ratio $\frac{M_2}{M_1} = 3$, then, when the entire supply of explosives has been consumed, the projectile will have attained a velocity almost great enough to cause it to revolve like a satellite about the Earth beyond the limits of the atmosphere.

If $\frac{M_2}{M_1} = 6$, the velocity of the rocket will be nearly great enough for it to leave Earth forever and revolve around the Sun like an independent planet. If the supply of explosives is big enough, the asteroid belt and even the heavy planets could be reached.

25. It is evident from the table that even if the supply of explosives is small, the final velocity of the projectile will still be adequate for practical purposes. Thus, if the fuel supply accounts for only 0.1 of the rocket's weight, the velocity will be 543 m/sec, which is sufficient for the rocket to ascend to 15 km. The table also shows that if the supply is small, after completion of the explosion the velocity will be approximately proportional to the mass of the fuel (M_2); therefore, in this case, the maximum height will be proportional to the square of this mass (M_2). Thus, if the supply of explosives is equal to half the rocket's mass ($\frac{M_2}{M_1}$) = 0.5, the rocket will fly far beyond the limits of the atmosphere.

Efficiency of Rocket During Ascent

26. It is of interest to determine the fraction of the total work done by the explosives, i.e., their chemical energy, that is transmitted to the rocket.

The work done by the explosives may be expressed as $\frac{V_1^2}{2} M_2$; the mechanical work done by a rocket with the velocity V may be expressed in the same unite: $\frac{V^2}{2} M_1$, or, on the basis of formula (16)

$$\frac{V^2}{2} M_1 = \frac{V_1^2}{2} M_1 \left\{\ln\left(1 + \frac{M_2}{M_1}\right)\right\}^2.$$

On dividing the work done by the rocket by the work done by the explosives, we obtain

$$\frac{M_1}{M_2} \left\{\ln\left(1 + \frac{M_2}{M_1}\right)\right\}^2.$$

From this formula we can derive the table of energy utilization by the rocket.

From the table and the formula it is clear that when the amount of explosives is very small, the utilization (efficiency) is equal to $\frac{M_2}{M_1}$, i.e., the smaller the smaller the relative amount of explosives.*

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*In fact, $\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} \ldots$ Therefore, approximately, $\frac{M_1}{M_2} \left\{\ln\left(1 + \frac{M_2}{M_1}\right)\right\}^2 = \frac{M_1}{M_2} \cdot \frac{M_2^2}{M_1^2} = \frac{M_2}{M_1}.$

$\frac{M_2}{M_1}$	Utilization	$\frac{M_2}{M_1}$	Utilization
0.1	0.090	7	0.62
0.2	0.165	8	0.60
0.3	0.223	9	0.59
0.4	0.282	10	0.58
0.5	0.328	19	0.47
1	0.480	20	0.46
2	0.600	30	0.39
3	0.64	50	0.31
4	0.65	100	0.21
5	0.64	193	0.144
6	0.63	Infinity	Zero

Further, as the relative amount of explosives increases, the utilization increases and reaches a maximum (0.65) when $M_2/M_1 = 4$.

Any further increase in the proportion of explosives will gradually but steadily reduce their utilization. When the supply of explosives is infinitely large, the utilization falls to zero, just as when the supply is infinitely small. It is also clear from the table that when M_2/M_1 ranges between 2 and 10 the utilization exceeds one half, i.e., more than half the potential energy of the explosives is transmitted to the rocket in the form of kinetic energy. In general, from 1 to 20 it is extremely high and close to 0.5.

Rockets Under the Influence of Gravity. Vertical Ascent

27. We have determined the velocity acquired by the rocket in a gravitationless vacuum as a function of the mass of the rocket, the mass of the explosives and their energy of chemical combination.

We shall now consider the effect of gravity on the vertical motion of the projectile.

When not influenced by gravity, the rocket can acquire dizzy speeds and can utilize a considerable proportion of the explosive energy. This also holds true in a gravitational environment, so long as the explosion is instantaneous. But this kind of explosion is not suitable for our purposes, since it would result in a lethal shock which could be endured neither by the projectile nor by the equipment and passengers. Clearly, we need a slow explosion; but if the explosion is slow, the useful effect diminishes and may even vanish.

Suppose the explosion is so weak that the resulting acceleration of the rocket is equal to the Earth's acceleration g. Then throughout the explosion the projectile will hang motionlessly in the air without support.

Of course, it will not acquire any velocity, and the utilization of the explosives, in whatever quantity they are present, will be zero. Thus, it is extremely important to analyze the effect of gravity on the projectile.

Determining the Acquired Velocity. Examination of the Numerical Values Obtained. Maximum height.

When a rocket moves in a gravitationless medium, the time t during which its entire supply of explosives is consumed, is

$$t = \frac{V}{p}, \qquad (28)$$

where V is the velocity of the projectile on completion of the explosion, and p is the constant acceleration imparted to the rocket by the explosives per second.*

In this simple case of uniform acceleration the force of the explosion, i.e., the amount of fuel expended during the explosion per unit of time, will not be constant, but will continually diminish in proportion to the decrease in the mass of the projectile as its supply of explosives is depleted.

29. Knowing p, or the acceleration in a gravitationless medium, we can also determine the apparent (temporary) gravity inside the rocket during its acceleration or during the explosion.

Taking the force of gravity at the Earth's surface as unity, we find the temporary gravity to be p/g, where g is the Earth's acceleration; this formula shows how many times the pressure acting on the base of all the objects in the rocket exceeds the pressure that acts on the same objects when placed on the living room table under normal conditions. It is highly important to know the value of relative gravity in the projectile, since it affects the reliability of the instruments and the health of those setting out to explore the frontiers of space.

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*It is assumed that the mass of the rocket varies in accordance with an exponential law; then the acceleration p due to the thrust will be constant (Editor's note).

30. Under the influence of a constant or variable gravity of any intensity, the time taken to consume a given supply of explosives will be the same as when there is no gravity at all; it can be expressed by formula (28) or by the following formula:

$$t = \frac{V_2}{p - g} , \qquad (31)$$

where V_2 is velocity of the rocket on completion of the explosion in a gravitational medium with constant acceleration g. Here, of course, it is assumed that p and g are parallel and opposite; p-g expresses the visible acceleration of the projectile (with respect to the Earth), which is the result of two opposite forces: the force of the explosion and the force of gravity.

32. The action of the force of gravity on the projectile in no way affects the relative gravity inside the projectile, and here the formula p/g still applies. For example, if p = 0, i.e., if there is no explosion, there is no temporary gravity, because p/g = 0. This means that if the explosion ceases and the projectile moves in some direction solely due to its own momentum and the gravitational attraction of the Sun, Earth, and other stars and planets, an observer inside the projectile will himself apparently be completely weightless, and not even the most sensitive spring balance will register when used to weigh any of the objects present inside the rocket along with the observer. On falling or rising inside the rocket under the action of inertia, even at the very surface of the Earth, the observer will not experience the least heaviness unless, of course, the projectile encounters some obstacle in the form of, say, the resistance of the atmosphere, water or solid earth.

33. If p = g, i.e., if the pressure of the exploding gases is equal to the weight of the projectile (p/g = 1), the relative gravity will be equal to terrestrial gravity. If it was stationary at the outset, the projectile will remain stationary throughout the explosion. If, however, the projectile had a certain (upward, lateral, downward) velocity before the explosion, this velocity will remain absolutely unchanged until the entire supply of explosives is consumed; thus the body, that is, the rocket, is balanced and moves as if by inertia in a

gravitationless medium.

On the basis of formulas (28) and (31) we obtain

$$V = V_2' \left(\frac{p}{p - g} \right). \qquad (34)$$

Hence, knowing the velocity V_2 that must be acquired by the projectile after the explosion, we can calculate V, from which, with the aid of formula (16), we can also determine the necessary amount of explosives M_2.

From equations (16) and (34) we obtain:

$$V_2 = - V_1 \left(1 - \frac{g}{p}\right) \cdot \ln \left(\frac{M_2}{M_1} + 1\right). \qquad (35)$$

36. From this, as from the preceding formula, it follows that the velocity acquired by the rocket is smaller in the presence of gravity than in its absence (16). The velocity V_2 may even be zero despite an abundant supply of explosives if $(p/g) = 1$, i.e., if the acceleration imparted to the projectile by the explosives is equal to the terrestrial acceleration, or if the gas pressure is equal and directly opposite to the effect of gravitational attraction (cf. formulas (34) and (35)).

In this case the rocket will stand motionless for a few minutes without rising and, once the supply of explosives has been consumed, will fall like a stone.

37. The greater the value of p in relation to g, the greater the velocity V_2 acquired by the projectile, given a specific amount of explosives M_2 (formula (35)).

Therefore, if the aim is to climb higher, p must be made as large as possible, i.e., the explosion must be as energetic as possible. This, however, requires, first, a sturdier and more massive projectile and, second, sturdier equipment and instruments inside the projectile, because, according to (32), the relative gravity inside the projectile will be extremely large and, in particular, dangerous to any human observer aboard the rocket.

At any rate, on the basis of formula (35) in the limit

$$V_2 = - V_1 \cdot \ln\left(\frac{M_2}{M_1} + 1\right),$$

i.e., if p is infinitely large or the explosion instantaneous, the velocity V_2 of the rocket in a gravitational environment will be the same as in a gravitationless environment.

According to formula (30), the explosion time is independent of gravity; it depends solely on the ratio M_2/M_1 and the rate of explosion p.

39. It is important to determine this rate. Suppose in formula (28) $V = 11{,}100$ m/sec (22) and $p = g = 9.9$ m/sec^2, then $t = 1133$ sec.

This means that in a gravitationless medium the rocket would fly for less than 19 minutes with uniform acceleration, even if the amount of explosives were six times the mass of the projectile (22).

In the event of the explosion occurring at the surface of our planet, however, the rocket would stand motionless for the same period of time.

40. If $M_2/M_1 = 1$, then, according to the table, $V = 3920$ m/sec; therefore $t = 400$ sec or 6-2/3 min.

When $M_2/M_1 = 0.1$ $V = 543$ m/sec, $t = 55.4$ sec, i.e., less than a minute. In this case the projectile would stand motionless at the Earth's surface for 55-1/2 sec.

Hence we can see that an explosion at the surface of a planet, and in general in any medium that is not free of gravity, may be completely ineffective -- even if it occurs over a prolonged period of time -- if it is of insufficient force; in fact, the projectile then remains stationary and will have no translational velocity unless some has been previously acquired (it will then move over a certain distance at uniform speed). If this motion is upward, the projectile will do some work. If the original velocity is horizontal, the motion will also be horizontal; then no work will be done,* but the projectile could serve the same purpose as a locomotive, steamship or steerable aerostat. The projectile could function in this way only for a few minutes, while the explosion takes place, but even during such a short period of time it could traverse considerable distances, particularly when moving above the atmosphere. However, we do not consider that the rocket is of any practical value for flights through the air.

The time during which a projectile can remain in a gravitational medium proportional to g, i.e., to the force of gravity.

Thus, on the Moon the projectile could stand motionless, without support, for 2 hours if $\frac{M_2}{M_1} = 6$.

41. In formula (35) for an environment with $\frac{g}{p} = 10$ let us put $\frac{M_2}{M_1} = 1$; we then calculate $V_2 = 9990$ m/sec. Accordingly, the relative gravity will be 10 g, i.e., throughout the explosion time (about 2 min), a person weighing 70 kg will experience gravity ten times as great as on Earth, and, on a spring balance, will weigh 700 kg. This gravity can be safely endured by the traveler only if he observes special precautions: if he is immersed in a special fluid, under special conditions.

On the basis of formula (28) we can also calculate the explosion time, or the duration of the period of intensified gravity; we obtain 113 sec, i.e., less than 2 min. This is very little, and it is amazing that in such a negligible interval of time a projectile could acquire a velocity nearly sufficient to leave the Earth and move around the Sun like a new planet.

We found $V_2 = 9990$ m/sec, i.e., a velocity only slightly less than the velocity V acquirable in a gravitationless medium under the same explosion conditions (22).

But since during the explosion the projectile also climbs to a

*If no allowance is made for the work done in overcoming atmospheric drag (Editor's note).

certain height, the idea suggests itself that the total work done by the explosives is not less than in a gravitationless medium.

44. We shall now consider this question.

The acceleration of the projectile in a gravitational medium may be expressed as: $p_1 = p - g$.

At a distance of not more than several hundred versts from the Earth's surface we can assume that g is constant; this does not introduce any appreciable error, and moreover the error will be on the safe side, i.e., the actual figures will be more favorable than those calculated.

The height h reached by the projectile during time t (explosion time) will be

$$h = \frac{1}{2} p_1 t^2 = \frac{p - g}{2} \cdot t^2. \qquad (45)$$

Eliminating t, in accordance with equation (31) we obtain

$$h = \frac{V_2^2}{2 (p - g)}, \qquad (46)$$

where V_2 is the velocity of the projectile in a gravitational medium after the entire supply of explosives has been consumed.

Now, on eliminating V_2, from (34) and (46) we obtain

$$h = \frac{p - g}{2p^2} \cdot V^2 = \frac{V^2}{2p}\left(1 - \frac{g}{p}\right),$$

where V. is the velocity acquired by the rocket in a gravitationless medium.

Efficiency

The useful work done by the explosives in such a medium may be expressed by:*

$$T = \frac{V^2}{2g}. \tag{48}$$

On the other hand, depending on the height reached by the projectile and its velocity at the end of the explosion, the work T_1 done in a gravitational medium may be expressed as

$$T_1 = h + \frac{V_2^2}{2g}. \tag{49}$$

The ratio of $\frac{T_1}{T}$ (T being the ideal value) is thus

$$\frac{T_1}{T} = \frac{2hg + V_2^2}{V^2}. \tag{50}$$

On eliminating h and V by means of formulas (46) and (34), we find

*The calculations in formulas (48) and (49) are for a projectile with a weight equal to unity (Editor's note).

$$\frac{T_1}{T} = \left(1 - \frac{g}{p}\right), \tag{51}$$

i.e., the work done in a gravitational medium by a given mass of explosives M_2 is less than in a gravitationless medium: this difference $\frac{g}{p}$ is the smaller the higher the exhaust velocity of the gases or the greater the pressure p. For example, under the conditions of note 41 the loss is only 1/10, while the utilization, according to (51), is 0.9. When p = g, or when the projectile hovers in the air, lacking even a constant velocity, the loss will be complete (1) and the utilization will be zero. The utilization will also be zero if the projectile has a constant horizontal velocity.

52. In note 41 we found V_2 = 9990 m/sec. Applying formula (46) to this case, we find h = 565 km; this means that during the explosion the projectile will travel far beyond the limits of the atmosphere and at the same time acquire a velocity of 9990 m/sec.

Note that this velocity is less than that in a gravitationless medium by 1110 m/sec or exactly 1/10 of the velocity in a gravitationless medium (22).

Hence it is clear that the loss of velocity obeys the same law as the loss of work (51). Strictly, this also follows from formula (34) which, after transformation, yields

$$V_2 = V\left(1 - \frac{g}{p}\right), \text{ or } V - V_2 = V \cdot \frac{g}{p}.$$

From (51) we find

$$T = T_1 \cdot \left(\frac{p}{p - g}\right), \tag{56}$$

where T_1 is the work done on the projectile by the explosives in a gravitational medium with an acceleration equal to g.

In order for the projectile to perform the necessary work of climbing, overcoming atmospheric resistance, and acquiring the desired velocity, the total work done must equal T_1.

Having calculated all these forms of work, we find T from formula (56). Knowing T, we can calculate V, i.e., the velocity in a gravitationless medium, from the formula

$$T = M_1 \cdot \frac{V^2}{2g}.$$

Knowing V, we can also calculate the required mass of explosives from formula (16).

Thus, we find

$$M_2 = M_1 \left[e^{\sqrt{\frac{T_1 p}{T_2 (p - g)}}} - 1 \right].$$

In the calculations, for the sake of brevity, $\left(M_1 \frac{V_1^2}{2g}\right)$ has been replaced by T_2.

Thus, knowing the mass of the projectile M_1, together with all it contains apart from the fuel M_2, the mechanical work T_2 done by explosives when their mass is equal to that of the projectile M_1, the work T_1 which must be done by the projectile during its vertical ascent, the acceleration due to the explosion p and gravity g, we can also determine the amount of explosives M_2 required to lift the mass M_1 of the projectile.

The ratio $\frac{T_1}{T_2}$ in the formula will not change if we reduce it by

M_1, so that T_1 and T_2 may be construed as the mechanical work T_1 done by a unit mass of the projectile and the mechanical work T_2 done by a unit of explosives, respectively.

In general, the gravity g may be construed as the sum of the accelerations due to gravity and the resistance of the medium. But gravity steadily decreases with increasing distance from the Earth's center, so that an increasing fraction of the mechanical work of the explosives is utilized. On the other hand, atmospheric resistance, while very insignificant in comparison with the weight of the projectile, as we shall see, reduces the utilization of the energy of the explosives.

Further, it can be seen that the latter losses, which continue for some time as the projectile races through the atmosphere, are abundantly offset by the gain due to the decrease in gravitational attraction at the considerable distances (500 km) at which the explosion ceases.

Thus, formula (20) can be boldly applied to the vertical flight of a projectile, despite the complications due to the variation in gravity and the resistance of the atmosphere $g = 9.8$.

Gravitational Field. Vertical Return to Earth

59. First let us consider the process of stopping in a gravitationless medium or a momentary halt in a gravitational medium.

Suppose, for example, that, owing to the force produced by the explosion of some (not all) of the gases, a rocket acquires a velocity of 10,000 m/sec (22). Now in order to stop it, we must give it the same velocity but in the opposite direction. Clearly, in accordance with (22), the remaining amount of explosives must be five times greater than the mass M_1 of the projectile. Therefore, on completion of the first part of the explosion (in order to acquire translational velocity) the projectile must have a supply of explosives, the mass of which may be expressed as $5M_1 = M_2$.

60. The total mass including the explosives will be $M_2 + M_1 = 5M_1 + M_1 = 6M_1$. This mass $6M_1$ must have been given a velocity of 10,000 m/sec by the original explosion, and this requires an additional amount of explosives which should also be five times greater (22) than

the mass of the projectile plus the mass of the explosives needed to stop the rocket, i.e., $6M_1 \times 5$; thus we obtain $30\ M_1$ which, together with the explosives needed for stopping the rocket, makes $35\ M_1$.

Using the symbol $q = \frac{M_2}{M_1}$ to denote the number of times the mass of the explosives exceeds the mass of the projectile, we may express as follows the above reasoning concerning the total mass of explosives $\frac{M_3}{M_1}$ needed to acquire and annihilate a given velocity as follows:

$$\frac{M_3}{M_1} = q + (1 + q) \cdot q = q\ (2 + q),$$

or, adding and subtracting one from the second part of this equation, we obtain

$$\frac{M_3}{M_1} = 1 + 2q + q^2 - 1 = (1 + q)^2 - 1. \qquad (61)$$

whence we find

$$\frac{M_3}{M_1} + 1 = (1 + q)^2. \qquad (62)$$

This last expression is easy to remember.

If q is very small, the amount of explosives is approximately 2q (because q^2 will be negligible), i.e., twice as much as needed solely for acquiring a given velocity.

63. On the basis of the above formulas and table (22) we compile the following table:

In a Gravitationless Medium

V, m/sec	$\frac{M_2}{M_1}$	$\frac{M_3}{M_1}$	V, m/sec	$\frac{M_2}{M_1}$	$\frac{M_3}{M_1}$
543	0.1	0.21	11 800	7	63
1 037	0.2	0.44	12 500	8	80
1 493	0.3	0.69	13 100	9	99
1 915	0.4	0.96	13 650	10	120
2 308	0.5	1.25	17 100	19	399
3 920	1	3	17 330	20	440
6 260	2	8	19 560	30	960
7 880	3	15	22 400	50	2 600
9 170	4	24	26 280	100	10 200
10 100	5	35	30 038	193	37 248
11 100	6	48	∞		∞

It is evident from this table that if we wanted to acquire and lose a very high velocity an impossibly large supply of explosives would be needed.

From (62) and (16) we have

$$\frac{M_3}{M_1} + 1 = e^{\frac{-2V}{V_1}}, \text{ or } \frac{M_3}{M_1} = e^{\frac{-2V}{V_1}} - 1.$$

Note that the ratio $-\frac{2V}{V_1}$ is positive, because the velocities of the projectile and the gases are opposite in direction and therefore differ in sign.

64. If we are in a gravitational medium, then, in the simple case of vertical motion, the process of coming to a halt descending to Earth will be as follows: when, owing to its acquired velocity, the rocket has risen to a certain altitude and stopped there, its earthward fall will begin.

When the projectile reaches the point in its flight where the action of the explosives ceased, it is subjected again to the action of the remainder in the same direction and order. Clearly, when the explosives cease to act and the entire supply is consumed, the rocket will come to a halt at the Earth's surface, whence the flight began. The method of ascent is exactly the same as the method of descent, the only difference being that the velocities are reversed at every point along the path.

Coming to a halt in a gravitational field requires more work and explosives than in a gravitationless medium, and therefore q [in formulas (61) and (62)] must be greater.

Denoting this greater value of q by q_1, on the basis of the foregoing, we find that

$$\frac{q}{q_1} = \frac{T_1}{T} = 1 - \frac{g}{p}, \tag{65}$$

whence

$$q_1 = q\left(\frac{p}{p - g}\right);$$

substituting q_1 for q in equation (62), we obtain

$$\frac{M_4}{M_1} = (1 + q_1)^2 - 1 = \left(1 + \frac{pq}{p - g}\right)^2 - 1, \qquad (66)$$

here M_4 denotes the amount or mass of explosives needed to ascend from a given point and return to the same point for a rocket coming to a complete stop and traveling in a gravitational medium.

67. On the basis of this last formula we can compile the following table, assuming that $p/g = 10$, i.e., that the pressure of the explosives is 10 times greater than the weight of the rocket together with the remaining explosives.

Gravitational Field. Oblique Ascent

68. Although a vertical ascent would appear to be more expedient, since the atmosphere is then traversed more rapidly and the projectile rises to a greater height, the work done in rising through the atmosphere is very insignificant compared with the total work done by the explosives and, moreover, given an oblique ascent it is possible to construct a permanent observatory that would travel for an indeterminate length of time around the Earth, like the Moon, beyond the limits of the atmosphere. Furthermore, and most important, in an oblique ascent far more of the explosive energy is utilized than in a vertical ascent.

Let us first consider the special case of horizontal rocket flight [Fig. 2].

In a Gravitational Field

V, m/sec	$\frac{M_2}{M_3}$	$\frac{M_4}{M_1}$
543	0.1	0.235
1 497	0.3	0.778
2 308	0.5	1.420
3 920	1.0	4.457
6 260	2	9.383
7 880	3	17.78
9 170	4	28.64
10 100	5	41.98
11 100	6	57.78
11 800	7	76.05

Denoting by R the resultant of the horizontal acceleration of the rocket, by p the acceleration due to the explosion, and by g the acceleration due to gravity, we have

$$R = \sqrt{p^2 - g^2}. \qquad (70)$$

On the basis of the latter formula,* the kinetic energy acquired by the projectile during time t equals

$$\frac{R}{2} \cdot t^2 \cdot \left(\frac{R}{g}\right) = \frac{R^2}{2g} \cdot t^2 = \frac{p^2 - g^2}{2g} \cdot t^2, \qquad (71)$$

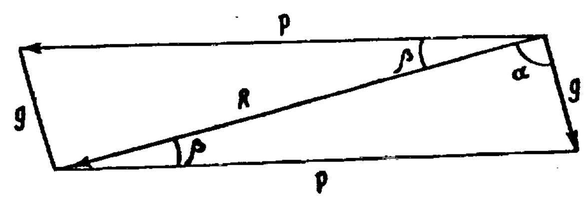

Fig. 2.

where t is the explosion time. This is also the total useful work done on the rocket. In fact, if we assume the direction of gravity to be constant (which in practice is true only for a short trajectory) the rocket does not climb at all. The work done by the explosives on the rocket in a gravitationless medium is**

$$\frac{p}{2}\, t^2\, \frac{p}{g} = \frac{p^2 t^2}{2g}. \qquad (72)$$

Dividing the useful work (71) by the total work (72), we obtain

*Here Tsiolkovskiy calculates the work done by the resultant referred to unit weight of the rocket (Editor's note).

**Tsiolkovskiy calculates the work done by the reaction force referred to unit weight of the rocket (Editor's note).

the efficiency for horizontal flight

$$\left(\frac{p^2 - g^2}{2g} \cdot t\right) : \left(\frac{p^2}{2g} \cdot t\right) = 1 - \left(\frac{g}{p}\right)^2. \qquad (73)$$

As before, the air resistance has not yet been taken into account.

From this last formula it is evident that the loss of work as compared with a gravitationless medium may be expressed by $(\frac{g}{p})^2$. Hence it follows that this loss is much smaller than during a vertical ascent. Thus, for example, if $\frac{g}{p} = 1/10$, the loss will be 1/100 or 1%, whereas in a vertical ascent it would be expressed by $\frac{g}{p}$, i.e., would equal 1/10, that is, 10%.

74. Here is a table in which β is the angle of inclination of the force p to the horizon.

Horizontal Motion

$\frac{p}{g}$	$(\frac{g}{p})^2$	$\frac{g}{p}$	$\beta°$
1	1	1	90
2	1 : 4	1 : 2	30
3	1 : 9	1 : 3	19.5
4	1 : 16	1 : 4	14.5
5	1 : 25	1 : 5	11.5
10	1 : 100	1 : 10	5.7
100	1 : 10 000	1 : 100	0.57

Oblique Ascent. Work done in Lifting the Projectile Referred to the Work in a Gravitationless Medium. Loss of Work.

75. Now let us solve the general problem -- for any angle of inclination of the resultant R. A horizontal trajectory or resultant is undesirable, since a projectile flying horizontally must travel a vastly greater distance through the atmosphere and do a correspondingly greater amount of work in cutting through the air.

Thus, let us keep in mind that α, the angle of inclination of the resultant to the vertical, is greater than a right angle; we have

$$R = \sqrt{p^2 + g^2 + 2pg \cos \gamma}, \qquad (76)$$

where $\gamma = \alpha + \beta$ (obtuse angle of parallelogram) in accordance with the sketch.

Further

$$\gamma = \alpha + \beta; \ \sin \alpha : \sin \beta : \sin \gamma = p : g : R \qquad (77)$$

and

$$\cos \alpha = \frac{R^2 + g^2 - p^2}{2Rg}. \qquad (78)$$

The kinetic energy is expressed by the formula (71), where R is found from equation (76). The vertical acceleration of the resultant R

$$R_1 = \sin (\alpha - 90°) R = - \cos \alpha R. \qquad (79)$$

Therefore, the work done in lifting the projectile will be

$$\frac{R_1}{2} t^2 = \frac{-\cos \alpha}{2} Rt^2, \tag{80}$$

where t is the explosion time for the entire supply of explosives. The total work done on the projectile in a gravitational medium [in accordance with (71) and (80)]

$$T_1 = \frac{R^2}{2g} t^2 - \frac{Rt^2 \cos \alpha}{2} = \frac{Rt^2}{2} \left(\frac{R}{g} - \cos \alpha\right). \tag{81}$$

Here ascent of the projectile through unit height in a medium with an acceleration of one g is taken as the unit of work. If $\alpha >$ $> 90°$, in the case of the ascent of the projectile, for example, then $(-\cos \alpha)$ is positive, and vice versa.

In a gravitationless medium the work will be $\frac{p^2}{2g} t^2 = T$, in accordance with (72), (let us not forget that the explosion time t is independent of the gravitational forces).

Taking the ratio of these two values of the work, we obtain the efficiency of the explosion as compared with its efficiency in a gravitationless medium, namely:

$$\frac{T_1}{T} = \frac{Rt^2}{2} \left(\frac{R}{q} - \cos \alpha\right) : \left(\frac{P_2}{2g} t^2\right) = \frac{R}{p} \left(\frac{R}{p} - \frac{g}{p} \cos \alpha\right). \tag{82}$$

Eliminating R in accordance with formula (76), we find

$$\frac{T_1}{T} = 1 + \frac{g^2}{p^2} + 2 \cos \gamma \cdot \frac{g}{p} - \cos \alpha \cdot \frac{g}{p} \sqrt{1 + \frac{g^2}{p^2} + 2 \cos \gamma \; \frac{g}{p}}.$$

Formulas (51) and (73), for example, are merely special cases of this formula, as may be readily ascertained.

84. We shall now find a use for this formula. Assume that a rocket is ascending at an angle of 14.5° to the horizon; the sine of this angle is 0.25; this means that the atmospheric resistance is four times greater than the value for vertical flight, since it is more or less inversely proportional to the sine of the angle of inclination (α - 90°) of the trajectory to the horizontal.

85. The angle $\alpha = 90 + 14^1/_2 = 104^1/_2°$; cos α = 0.25; knowing α we can also find β. In fact, from (77) we find

$$\sin \beta = \sin \alpha \; \frac{g}{p};$$

thus, if $\frac{g}{p} = 0.1$,

$$\sin \beta = 0.0968; \; \beta = 5^1/_2°,$$

whence

$$\gamma = 110°, \; \cos \gamma = 0.342.$$

Now we calculate the efficiency to be 0.966. The loss is 0.034 or about 1/20 or, more accurately, 3.4%.

This loss is one-third of the loss in a vertical ascent, not a bad result, especially if we consider that, even in an oblique ascent ($14^1/_2°$), the atmospheric resistance is still less than 1% of the work /98
done in lifting the projectile.

86. We propose the above table for various approaches: the first column shows the inclination to the horizontal; the last column, the loss of work; β is the deviation of the direction of the pressure exerted by the explosives from the actual line of motion (69).

87. For very small angles of inclination (α -90°) the formula can be much simplified, by replacing the trigonometric values by their arcs and making other simplifications.

We then obtain the following expression for the loss of work:

$$x^2 + \delta x\left(1 - \frac{x^2}{2}\right) + \delta^2 x^2\left(x - \frac{\delta}{2}\right),$$

where δ denotes the angle of inclination (α -90°), expressed as the length of its arc, the radius of which is equal to unity, and x denotes the ratio g/p. On discarding the small quantities of higher orders, we obtain for the loss

$$x^2 + \delta x = \left(\frac{g}{p}\right)^2 + \delta\,\frac{g}{p}.$$

Let us put δ = 0.02 N, where 0.02 is the part of a circle corresponding to roughtly 1° ($1^1/_7$) and N is the number of these new degrees. Then the loss of work may be roughly expressed as

$$\frac{g^2}{p^2} + 0.02\,\frac{g}{p}\,N.$$

From this formula we can readily compile the following table, assuming that

$$\frac{g}{p} = 0.1:$$

Oblique Motion

Degrees				Utilization	Loss
$\alpha - 90$	α	β	$\gamma = \alpha + \beta$		
0	90	$5^3/_4$	$95^2/_3$	0.9900	1 : 100
2	92	$5^2/_3$	$97^2/_3$	0.9860	1 : 72
5	95	$5^2/_3$	$100^2/_3$	0.9800	1 : 53
10	100	$5^2/_3$	$105^2/_3$	0.9731	1 : 37
15	105	$5^1/_2$	$110^1/_2$	0.9651	1 : 29
20	110	$5^1/_3$	$115^1/_3$	0.9573	1 : 23.4
30	120	5	125	0.9426	1 : 17.4
40	130	$4^1/_3$	$134^1/_3$	0.9300	1 : 14.3
45	135	4	139	0.9246	1 : 13.3
90	180	0	180	0.9000	1 : 10

N	0	0.5	1	2	3	4	5	6	10
Loss	1/100	1/91	1/83	1/70	1/60	1/55	1/50	1/45	1/33

Hence we see that even at large angles (up to 10°) the discrepancy between this table and the previous, more accurate one is quite small.

We could have considered many other factors too: the work done by gravity, the resistance of the atmosphere; we still have not explained how the explorer could spend a long, even unlimited, time in an environment without even a trace of oxygen. We have not even mentioned the heating of the projectile during its short flight through the atmosphere, nor have we given a general picture of the flight itself and of the extremely interesting phenomena that would (theoretically) accompany it. We have scarcely outlined the magnificent prospects of eventually attaining this still distant goal. Lastly, we could also have considered the subject of rocket trajectories in outer space.

THE EXPLORATION OF THE UNIVERSE WITH REACTION MACHINES*

THE "ROCKET" REACTION MACHINE OF K. E. TSIOLKOVSKIY

1. Preface

For a very long time, like everyone else, I regarded the rocket as little more than a toy with a few more or less trivial applications.

I do not remember exactly how I got the idea of making computations relating to rockets.

It seems to me that the first seeds of thought must have been sown by the fantastic novels of the famous Jules Verne; they set my brain working in a definite direction. I mused; musing led to more serious mental activity. Of course, it would never have come to anything if there had been no support forthcoming from the side of science.

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*This paper was first published in the journal "Vestnik vozdukhoplavaniya" (Herald of Aeronautics) in 1911. In this volume it appears in slightly abridged form. See also Appendices, note 16 (Ed.). When first published, it included an editorial footnote, which we reproduce below.

Editor's note. This interesting paper by one of Russia's foremost aeronautical theoreticians, K. E. Tsiolkovskiy, is devoted to the problem of reaction machines and flight outside the atmosphere.

The author himself draws attention to the grandiose nature of his conception, which is not only far from realization but has still to crystallize in more or less concrete form.

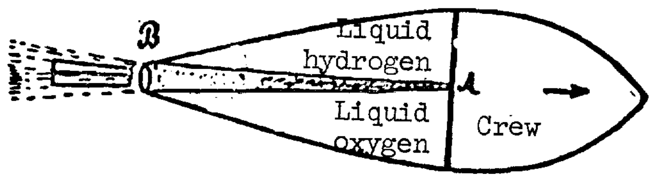
The mathematical arguments on which the author bases his subsequent conclusions give a clear indication of the theoretical feasibility of the idea. But the difficulties, unavoidable and enormous, that surround the extraordinary and unfamiliar situation which the author attempts to explore permit us to follow his arguments only in the mind.

In a letter to the editors, K. E. Tsiolkovskiy expresses his own views on his work as follows:

2. Resumé of my work to 1903

Having worked on the theory of reaction machines since 1896, I came to the following conclusions.

Externally, my projectile looks like a wingless bird that cuts easily through the air.



Sketch of K. E. Tsiolkovskiy's reaction machine.

"I have worked out various aspects of the problem of ascending into space with the aid of a reaction machine, rather like a rocket.

The scientifically based and frequently verified mathematical conclusions indicate the feasibility of an ascent into space with the aid of such machines and, perhaps, the establishment of settlements beyond the confines of the Earth's atmosphere.

It may be that hundreds of years will pass before my ideas are actually realized and mankind makes use of them to extend its control beyond the face of the Earth to include the entire universe. (However, they have already begun to be used for warlike purposes. CF. "Vestnik vozdukhoplavaniya" 1911, No. 2, p. 25.)

At present, almost all of the Sun's energy goes to waste (the Earth receives two billion times less than the Sun gives out). What is so strange about the idea of utilizing this energy? In any case, can there be anything wrong with giving expression to such ideas, if they are the fruit of serious thought? ...."

Most of the interior space of the projectile is taken up with two substances in liquid form: hydrogen and oxygen. The two liquids are separated by a tank wall and are only gradually mixed. The remaining, smaller part of the chamber is reserved for an observer and the various pieces of equipment necessary to sustain life, perform scientific experiments, and control the "rocket" (as I call my reaction machine).

On being mixed in the narrow part of a gradually expanding pipe, rather like a wind instrument, the hydrogen and oxygen combine chemically to form steam at an extremely high temperature. This is capable of tremendous expansion and rushes out of the wide end of the pipe at terrific speed in the direction of the pipe or the longitudinal axis of the chamber.

Ordinarily, the steam exerts a pressure in the same direction as that in which the rocket moves. When the rocket stops or decelerates, the situation is reversed. When the rocket accelerates, the motion of the steam is opposite to that of the rocket; when the rocket decelerates, the contrary is true. I speak here of the apparent motion of the steam relative to the rocket.

The blast pipe, which follows the longitudinal axis of the rocket, passing through its center of inertia, is cooled by the low temperature of the liquid hydrogen and oxygen surrounding the pipe or its housing. These freely evaporating liquids have a temperature of about 200-250°C below zero and prevent the pipe from melting under the extremely high internal temperature. Since the explosion lasts only a matter of a few minutes, the losses of cold liquid due to evaporation are quite small.

The rocket is prevented from spinning by various automatic devices, so that the direction of the longitudinal axis and the direction of flight will be the same: the path of the rocket will be a straight line.

The simplest way of controlling the direction of the rocket is by swiveling the end of the funnel or a control surface in front of it. This would deflect the gases in another direction, and the projectile would turn or adjust its course.

The energy of chemical combination of hydrogen and oxygen is enormous. A considerable part of it, namely up to 0.65 (65%), is transferred to the rocket, i.e., converted into motive force. The remainder (35%) is consumed in moving the steam. The rocket can utilize this considerable part of the energy of the explosive gases only in a gravitationless medium; in the field of gravity such a level of utilization is only possible in the case of an instantaneous explosion, which is quite unsuitable from a practical point of view. The slower the explosion, the longer the rocket remains in the field of gravity, and the more powerful the latter, the less the utilization of the energy of the explosive gases.

In a gravitationless medium the utilization does not depend on time and the order of the explosion.

Thanks to the accelerating motion of the rocket, an apparent (while the acceleration lasts) or temporary internal field of gravity is set up. This will be the greater, the more rapid the explosion, or the greater the pressure of the gases rushing out of the pipe. In relation to its effects inside the projectile, this relative gravity is in no way different from natural gravity. In the case of an instantaneous explosion it is infinitely large, and therefore both the rocket itself and everything in it would be destroyed and lost. This is why an instantaneous or excessively rapid explosion is out of the question.

If the temporary gravity accompanying the explosion is 10, i.e., 10 times greater than at the surface of the Earth, it will be possible to realize 0.9 (90%) of the maximum utilization of explosive energy in a gravitationless medium, i.e., $0.65 \times 0.9 = 0.585$, or more than 58% of the total potential chemical energy contained in the mixture of hydrogen and oxygen.

If the flight of the rocket is inclined to the vertical, a much greater amount of stored energy is utilized. In the limit, when the flight is horizontal, the utilization reaches a maximum, namely 0.99 or 99%, if the temporary gravity inside the rocket is equal to 10. If the flight path of the rocket is inclined at an angle of 14.5° to the horizon, the slight resistance of the atmosphere is merely quadrupled as compared with vertical flight, whereas at this inclination the utilization is 0.965. This gives 0.627 (0.65×0.965) of the total chemical energy of the explosive gases.

Maximum utilization (65%) is only obtained, both in the field of gravity and in a gravitationless medium, when the amount of explosive mixture is 4 times greater than the weight of the projectile with all its contents; otherwise the utilization is less than 65%. Given this ratio (4) of the amount of explosives to the weight of the projectile (1), the latter acquires a velocity of 9 kilometers per second. The projectile may also acquire an arbitrarily high or an arbitrarily low velocity, but then a lesser amount of the energy of the explosive material would be used. The percentage utilization is the smaller, the more the relative amount of explosives deviates from 4.

At a ratio of between 1 and 18 the energy utilization is more than 48%; the corresponding velocities in a gravitationless medium fluctuate between 3.9 and 16.9 kilometers per second. The latter velocity is more than enough to overcome the attraction of the Sun and the Earth and set the rocket wandering among the stars if launched in the direction of annual motion of the Earth.

Actually, the calculations give two main launching velocities: 14 and 74 kilometers per second. The latter figure relates to launching in a direction opposite to that in which the Earth moves, and the former to launching in the direction of its annual motion. Thus, even a ratio of 12 is enough to enable the rocket to escape from the solar system.

Theoretically, the rocket can raise a mass of any desired magnitude. For example, to raise 200 kg, not less than 2400 kg of explosive fuel would be needed to escape the Sun.

Note that oxygen can be obtained cheaply from the atmosphere by liquefying air and then evaporating the nitrogen. This is already being done. Hydrogen can be obtained by liquefying illuminating gas. The more complex products with a higher molecular weight liquefy first, and hydrogen remains in gaseous form. It is even possible to leave the marsh gas, since with oxygen it also gives volatile compounds (water, carbon dioxide) suitable for rocket propulsion. Thus, factory-produced hydrogen and oxygen need not be particularly dear. The liquefaction of hydrogen is difficult (as of now), but it can be replaced with equal or even greater advantage by liquid or liquefied hydrocarbons such as ethylene, acetylene, etc.

The vessels for storing gases in liquid form need not be especially strong; they need only be slightly stronger than the tanks used for storing water on Earth.

Moreover, compared with an ordinary cannon, the blast pipe can be extremely light, since in an artillery piece the explosion is almost instantaneous, and an enormous amount of explosive is detonated in a mere fraction of a second, whereas in our blast pipe only a comparatively negligible fraction of the store of explosives is expended in the same interval of time, the full duration of the explosion being several minutes (1-20 minutes).

If, for example, the weight of the projectile with all its contents is 1,000 kg and the temporary gravity is equal to 10, then the pressure at the base of the pipe, i.e., its narrowest section, will be less than 10 tons (metric). We shall assume that the area of the base of the pipe or the area of the normal section at its narrowest part is 100 cm^2; then the pressure of the exploding gases at the base of the pipe will be less than 100 atmospheres. In other parts of the pipe, the pressure will be the less, the further they lie from the base and the greater the expansion. It is now easy to compute that the maximum thickness of the walls of a steel pipe need not exceed 5 mm.

It is still not possible to say anything definite about the material of the blast pipe. Of course, everyone knows that iron melts like wax in an oxyhydrogen flame. But the melting point of iron is only 1300°C. There are substances with higher melting points: thus, tungsten metal has a melting point of 3200°C. The same thing applies to the explosive elements: I have taken oxygen and hydrogen merely as an example.

In the computations I have assumed that the temporary gravity in the rocket is 10; but the actual figure is in our hands, and we can also make it only slightly greater than at the surface (1), particularly if the ascent is inclined to the vertical or horizontal. Thus, if the projectile is launched horizontally and the relative gravity is equal to 3, the utilization of the explosive materials, relative to an instantaneous explosion, will be 0.89 (89%). At the same time, as we shall see later, there is a means of protecting objects and living organisms even against enormous gravitational forces.

Let us imagine something absolutely impossible: we shall assume that over thousands or millions of versts there extends a beautiful, sheer or inclined track (for example, a cogwheel track or something of the sort) with coaches, machines, and all the equipment necessary for comfortable travel beyond the limits of the atmosphere. In raising ourselves up this track through a known height, we do a certain calculable amount of work. If we use motors to accomplish this ascent, however modern they may be, we shall utilize not more than 10% of the chemical energy that we carry with us in the form of fuel.

As we have seen, in order to ascend to the same height, but without ladders or hoists, with the aid of my projectile, we would utilize, if rationally employed, at least 50% of the chemical energy of combination of hydrogen and oxygen. Thus, if we relied on the imaginary vertical tracks, we should use at least 5 times more fuel than in a reaction machine. This conclusion is valid only for an ascent to a height of not less than 700 versts (1 verst = approx. 1 km), when a considerable part of the energy of the explosives is utilized.

The result may be quite deplorable if the relative gravity is small and the ascent short. Thus, if the temporary gravity is equal to 1, and the position of the blast pipe is vertical, the result, achieved at the cost of a comparatively enormous expenditure of explosives, is twenty minutes standing still at the same height. If the acceleration of the rocket is somewhat greater (temporary gravity somewhat greater than unity, i.e., terrestrial gravity), it takes about 20 minutes to ascend a few arshines!!!

It is these pitiful reaction phenomena that we usually observe on Earth. That is why they have never inspired anyone to dream or investigate. Only reason and science were capable of drawing attention to the possibility of a transformation of these effects on an almost inconceivably grandiose scale.

Here are the principal formulas on which all these conclusions are based:

$$V = + V_1 \; L_{nat} \left(1 + \frac{M_2}{M_1}\right)^{*}. \qquad (16)$$

Here L_{nat} stands for natural logarithm; V is the velocity of the projectile or rocket when the mass of explosives has finished reacting; M_1 is the mass of the projectile with all its contents excluding the explosive materials, the total mass being equal to $M_1 + M_2$; V_1 is the relative velocity of an element of the cooled (by expansion) combustion products, as they rush out of the mouth of the blast pipe. In relation to the rocket this velocity does not depend on time or place. The formula relates to a gravitationless medium. The utilization of the absolute energy of the explosive materials be the rocket in a gravitationless medium may be expressed by:

$$\frac{M_1}{M_2} \cdot \left\{L_{nat} \left(1 + \frac{M_2}{M_1}\right)\right\}^2.$$

When $\frac{M_2}{M_1}$ is small, the utilization is equal to $\frac{M_2}{M_1}$. Then equation (16) may be expressed as follows:

$$\frac{V}{V_1} = \frac{M_2}{M_1}; \qquad (26)$$

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*The formulas included here are given in their final form; the numbering is taken from the manuscript to which the author refers above. (Ed.).

$$t = \frac{V}{p}. \qquad (28)$$

t is the duration of the explosion in such a medium; p is the constant acceleration of the projectile due to the action of the explosion. The relative or temporary gravity, developing in the projectile, may be expressed by the ratio $\frac{p}{g}$, where g is the acceleration due to gravity at the surface.

$$t = \frac{V_2}{p - g}, \qquad (31)$$

where V_2 is the final velocity (after the explosion) of a rocket ascending vertically from the Earth.

$$V = V_2 \cdot \left(\frac{p}{p - g}\right); \qquad (34)$$

$$V_2 = - V_1 \left(1 - \frac{g}{p}\right) L_{nat} \left(1 + \frac{M_2}{M_1}\right); \qquad (35)$$

$$p_1 = p - g, \qquad (44)$$

where p_1 is the acceleration of the projectile in the field of gravity for vertical flight.

In this case the height (h) of ascent is given by the formula:

$$h = \frac{1}{2} p_1 \cdot t^2 = \frac{p - g}{2} \cdot t^2. \tag{45}$$

g is assumed constant, since by the time the explosive materials are exhausted the projectile has only risen to an inconsiderable height compared with the radius of the Earth.

$$h = \frac{V_2^2}{2 (p - g)}; \tag{46}$$

$$h = \frac{V^2}{2p} \cdot \left(1 - \frac{g}{p}\right); \tag{47}$$

$$\frac{T_1}{T} = 1 - \frac{g}{p}. \tag{51}$$

Here T_1 is the useful work done by the explosive materials in the field of gravity, and T the same in a gravitationless medium.

$$\frac{M_3}{M_1} = (1 + q)^2 - 1; \; q = \frac{M_2}{M_1}. \tag{62}$$

This equation gives the relative amount of explosives $\left(\frac{M_3}{M_1}\right)$ needed not only to acquire a velocity in a gravitationless medium but also to lose it by reversing the direction of the explosion. If q is small, then $\frac{M_3}{M_2} = 2q$.

The same thing applies to an ascent in the field of gravity and a safe return.

$$\frac{M_4}{M_1} = \left(1 + \frac{pq}{p - g}\right)^2 - 1. \qquad (66)$$

Again, if q or $\frac{M_2}{M_1}$ is small,

$$\frac{M_4}{M_1} = 2q \cdot \left(\frac{p}{p - g}\right).$$

When the motion of the rocket is horizontal, the useful work is much greater than when it is vertical. Its relation to the useful work in a gravitationless medium may be expressed as:

$$1 - \left(\frac{g}{p}\right)^2. \qquad (73)$$

The losses are $\left(\frac{g}{p}\right)^2$, whereas in vertical flight the losses are $\frac{g}{p}$.

The formula

$$1 + \left(\frac{g}{p}\right)^2 + 2 \cos \gamma \cdot \frac{g}{p} - \cos \alpha \cdot$$

$$\cdot \frac{g}{p} \sqrt{1 + \frac{g^2}{p^2} + 2 \cos \gamma \cdot \frac{g}{p}} \qquad (83)$$

gives the utilization for an inclined ascent in the field of gravity in relation to the energy acquired by the rocket in a gravitationless medium. Here α is the angle between the direction of the rocket's path and the downward vertical; β is the angle between the rocket's path and the direction of the explosion or the direction of the blast pipe*; α is greater than a right angle, β is less; $\gamma = \alpha + \beta$.

It is easy to show that formula (83) gives both special cases, i.e., (51) and (73).

The above expression can be simplified, if the inclination of the rocket's path to the horizon does not exceed 10°; we then get

$$1 - \frac{g^2}{p^2} - 0.02 \cdot \frac{g}{p} N,$$

where 0.02 is the part of a circle (radius = 1) corresponding roughly to one degree $\left(\frac{1 \cdot 1°}{7}\right)$.

N denotes the number of such degrees.

Here N denotes in degrees the inclination of the trajectory of the rocket to the horizon.

3. The work done by gravity in connection with escape from a planet

By means of a very simple integration we can obtain the follow-

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*β is the angle between the direction of the flight velocity of the rocket and the reactive force. Cf. Fig. 2 of the preceding article. (Ed.)

ing expression for the work T needed to project a unit of weight from the surface of a planet of radius r_1 to a height h:

$$T = \frac{g}{g_1} \cdot r_1 \left(1 - \frac{r_1}{r_1 + h}\right).$$

Here g denotes the acceleration of gravity at the surface of the planet in question, and g_1 the acceleration of gravity at the surface of the Earth.

Let us make h in this formula equal to infinity. Now we find the maximum work done in moving a unit of weight from the surface of the planet to infinity and obtain:

$$T_1 = \frac{g}{g_1} \cdot r_1.$$

Having noted that $\frac{g}{g_1}$ is the ratio of gravity at the surface of the planet to terrestrial gravity, we see that the work needed to move a unit of weight from the surface of the planet to infinity is equal to the work done in raising the same weight from the surface through a distance equal to one radius of the planet, if we assume that the force of gravity does not diminish with increasing distance from the surface.

Thus, although the space permeated by the gravitational force of any planet is infinite, this force is like a wall or sphere of negligible resistance surrounding the planet at a distance equal to its radius. Surmount this wall, break through this elusive, uniformly dense shell, and gravitation is vanquished throughout its infinite domain.

From the latter formula it is clear that the limiting work T_1 is proportional to the force of gravity $\left(\frac{g}{g_1}\right)$ at the surface of the planet and its radius.

For equally dense planets, i.e., for planets with the same density, that of Earth (5.5), for example, the force of gravity at the surface, as is known, is proportional to the radius of the planet and may be expressed in terms of the ratio of the radius of the planet (r_1) to the radius of the Earth (r_2).

Hence, $\frac{g}{g_1} = \frac{r_1}{r_2}$ and $T = \left(\frac{r_1}{r_2}\right) \cdot r = \frac{r_1^2}{r_2}$.

Thus, the limiting work (T_1) diminishes extremely rapidly with decrease in the radius (r_1) of the planet, namely, as its surface area.

Hence, whereas for the Earth ($r_1 = r_2$) this work is equal to r_2, or 6,366,000 kilogram-meters, for a planet with a diameter 10 times smaller, it is only 63,660 kilogram-meters (unit of weight -- 1 kg).

But even for the Earth, from one point of view, it is not very great. For example, if we take the calorific value of oil as 10,000 calories, which is fairly close, the energy of combustion may be expressed as mechanical work equal to 4,240,000 kilogram-meters per kilogram of fuel.

It follows that the work needed to enable a unit of weight to escape from the surface of our planet is potentially contained in one and a half units of weight of oil.

Thus, in relation to a man weighing 70 kilograms, we need 105 kilograms of oil.

We merely lack the skill to exploit this mighty source of chemical energy.

It becomes more and more understandable how a moderate amount of explosive material, comparable with its own weight, could enable a projectile to overcome completely the force of terrestrial gravity.

According to Langley, a square meter exposed to the normal rays of the Sun receives 30 calories or 12,720 kilogram-meters per minute.

In order to obtain all the work needed for a weight of 1 kilogram to overcome terrestrial gravity, we need the energy of a square meter exposed to the Sun's rays for 501 minutes or rather more than 8 hours.

All this is very little, but when we compare human strength with the force of gravity the latter seems to us enormous. Thus, let us assume that every second a man climbs 20 cm (about 4.5 vershocks = 20 cm) up a well-built ladder. Then he will have done the limiting amount of work only after 500 days of hard toil, if we allow him 6 hours rest a day. By using one horsepower the work can be reduced to a fifth. By using 10 horsepower we can cut the time to ten days, and by working continuously to about a week.

With the work done by an airplane (70 HP) one day would be enough.

For most asteroids and the moons of Mars the work needed to overcome gravity completely is surprisingly small. Thus, the moons of Mars are not more than 10 kilometers in diameter. If we assume that they have the terrestrial density of 5.5, the work T_1 will be not more than 16 kilogram-meters, i.e., equivalent to reaching the top of a birch tree 8 sagenes (17 meters) high. If intelligent beings appeared on our Moon or on Mars, it would be much easier for them to overcome gravity than it is for the inhabitants of the Earth.

Thus, for the Moon T_1 is 22 times smaller than for the Earth. On the larger planetoids and planetary satellites the conquest of the space surrounding these bodies would be easy with the aid of the reaction machines I have described. For example, on Vesta T_1 is 1000 times smaller than on Earth. The diameter of Vesta is 375 versts. The diameter of Metis is about 100 versts, and T_1 is 15,000 times less.

But these are the biggest asteroids; the majority are 5-10 times smaller. For them T_1 is millions of times less than on Earth.

From the above formulas we find that for any planet

$$\frac{T}{T_1} = \frac{h}{h + r_1} = \frac{\frac{h}{r_1}}{1 + \frac{h}{r_1}}.$$

Here we have the ratio of the work T done in ascending to a height h above the surface of a planet of radius r_1 to the total maximum work T_1. From this formula we find that when:

$$\frac{h}{r_1} = \frac{1}{10},\ \frac{1}{5},\ \frac{1}{4},\ \frac{1}{3},\ \frac{1}{2},\ 1,\ 2,\ 3,\ 9,\ 99,\ \text{infinity}$$

$$\frac{T}{T_1} = \frac{1}{11},\ \frac{1}{6},\ \frac{1}{5},\ \frac{1}{4},\ \frac{1}{3},\ \frac{1}{2},\ \frac{2}{3},\ \frac{3}{4},\ \frac{9}{10},\ \frac{99}{100},\ 1$$

The first row gives the height in terms of the radius of the planet; the second the corresponding work, taking the work required to overcome gravity completely as unity. For example, in order to move from the surface of the planet to a distance of one radius, it is necessary to do half the total work, and to escape to infinity only twice as much.

4. Velocity necessary for a body to escape from a planet

Since we have often given the velocities acquired by a rocket due to the action of an explosive mixture, it would be interesting to learn what these velocities must be in order to overcome the resistance of gravity.

Once again, I shall omit the routine calculations used to determine these velocities and confine myself solely to the conclusions.

Thus, the velocity V_1 needed for a rocket to rise to a height h and acquire thereafter the velocity V is equal to:

$$V_1 = \sqrt{V^2 + \frac{2gr_1h}{r_1 + h}}.$$

If we now put V = 0, i.e., if the body rises until its motion is arrested by gravity, we find:

$$V_1 = \sqrt{\frac{2gr_1h}{r_1 + h}}.$$

When h is infinitely large, i.e., if there is no limit to the ascent, and the final velocity is zero, then the corresponding velocity at the surface of the planet must be:

$$V_1 = \sqrt{2gr_1}.$$

From this formula we compute for the Earth: $V_1 = 11{,}170$ meters per second, or a speed five times greater than that of the fastest artillery shell as it leaves the muzzle.

For our Moon, $V_1 = 2373$ meters, i.e., close to the velocity of a shell and the velocity of the hydrogen molecule. For the planet [asteroid] Agatha with a diameter of 6 versts and a density not greater than that of the Earth (5.5), V_1 is less than 5.7 meters per second; we find almost the same velocity (V_1) for the satellites of Mars. On these bodies of the solar system it is easy to gain enough momentum to free oneself forever from their gravitational field and become an independent planet.

For planets with the same density as the Earth, we get:

$$V_1 = r_1 \sqrt{\frac{2g_1}{r_2}},$$

where g_1 and r_2 relate to the terrestrial globe. From this formula it is clear that in this case the limiting launching velocity (V_1) is proportional to the radius r_1 of the planet in question.

Thus, for the largest planetoid Vesta, the diameter of which is close to 400 kilometers, we find that $V_1 = 324$ meters per second.

This means that even a rifle bullet will leave Vesta forever and become an aerolite circling about the Sun.

The last formula is convenient for the purposes of a rapid survey of the launching velocities from planets of equal densities but different size. Thus, Metis, one of the large asteroids, has a diameter one fourth of that of vesta; thus, the velocity will be as many times less, i.e., about 80 meters per second.

A perpetual orbit about a planet calls for half the work and a velocity $\sqrt{2} = 1.41...$ times less than that needed to escape to infinity.

5. Flight times

We shall not present any very complex formulas for determining the flight time of a projectile. The more so as this is not a new problem but one that has been solved, so that we would only repeat what is already known.

We shall make use of only one extremely simple conclusion, suitable for solving the simplest problems relating to the duration of rocket flights.

The time t for an initially stationary body to reach a planet (or the Sun), assumed to be concentrated in a single point (the mass being the same), is given by:

$$t = \frac{r_2}{r_1}\sqrt{\frac{r_2}{2g}}\left\{\frac{r}{r_2}\sqrt{\frac{r_2}{r} - 1} + \arcsin\sqrt{\frac{r}{r_2}}\right\}.$$

where r_2 denotes the distance from which the body begins to fall; r is the extent of its fall; r_1 is the radius of the planet; and g is the acceleration of gravity during this time at its surface.

The same formula, of course, also expresses the time taken to ascend from $r_2 - r$ to r_2, when the body loses its own velocity.

If we put $r = r_2$, i.e., if we determine the time taken to reach the center of the concentrated planet, we obtain from the last formula:

$$t = \frac{\pi}{2} \cdot \frac{r_2}{r_1}\sqrt{\frac{r_2}{2g}}.$$

Under ordinary conditions, this formula will also give, approximately, the time of descent to the surface of the planet or the time taken by a rocket to ascend from the surface and come to rest.

On the other hand, the total period of circular rotation of any body, for example, a projectile, about a planet (or the Sun) is

$$t_1 = 2\pi \frac{r_2}{r_1} \sqrt{\frac{r_2}{g}},$$

where r_1 is the radius of the planet with the acceleration g at its surface, and r_2 is the distance of the body from its center.

On comparing the two equations, we find:

$$t_1 : t = 4 \sqrt{2} = 5.657.$$

Therefore, the ratio of the period of any satellite to the time it takes to fall to the center of the orbited planet, assumed to be concentrated in a single point, is 5.66.

Thus, in order to determine the time taken by any celestial body (e.g. our rocket) to fall to the center (or, approximately, to the surface) about which it rotates, the period of the circular orbit of this body must be divided by 5.66.

Thus, we see that the Moon would fall to the Earth in 4.8 days, and the Earth to the Sun in $64^1/_4$ days.

Conversely, a rocket launched from the Earth and coming to rest at the distance of the Moon would fly for 4.8 days, i.e., almost 5 days.

Moreover, a rocket launched from the Sun and coming to rest due to its powerful gravitational attraction and lack of velocity at the distance of the Earth would arrive after about 64 days or rather more than two months of flight.

6. The resistance of the atmosphere

Let us determine the work done in cutting through the air by a rocket in ordinary, rectilinear, uniformly accelerated flight; we must also take into account the variable density (d) of the atmosphere at different heights.

The latter is equal (see my "Aerostat i aeroplan," 1905) to:

$$d = d_1 \left\{1 - \frac{d_1 h}{2\,(A + 1)\cdot f}\right\}^{2A+1}, \qquad (1)$$

where

$$A = \frac{d_1 M T_1 C}{f}. \qquad (2)$$

In these formulas d_1 is the density of air at sea level ($d_1 = 0.0013$); h is the height of the projectile or the height of the part of the atmosphere in question; f is the air pressure per unit area at sea level (f = 10.33 tons per sq. meter); M is the mechanical equivalent of heat (M = 424 meter-tons); T_1 is the temperature of absolute zero ($T_1 = 273$); C is the specific heat of air at constant volume (C = 0.169); so that A = 2.441, and the first formula assumes the form:

$$d = d_1 \left(1 - \frac{h}{h_1}\right)^{a}; \qquad (3)$$

where

$$a = 2A + 1 = 5.88, \qquad (4)$$

and h_1 = 54,540 meters and represents the theoretical limiting height of the atmosphere under the conditions assumed. Actually, if in formula (1) $d = 0$, h will express the height of the atmosphere; but then from (1) we get:

$$h = \frac{2\ (A + 1) \cdot f}{d_1}. \qquad (5)$$

Denoting this height by h_1, we get equation (3).

Although this value of $54^1/_2$ kilometers is extremely small, as is clear from observations of shooting stars, there is no doubt that the atmosphere above 54 kilometers is already so rarefied that its resistance can be neglected. In fact, if we compute the density of the atmospheric envelope at this height, assuming the temperature to be constant, with the value at sea level, and, hence, that the atmosphere is infinite, even in this case we find $d/d_1 = 0.001$, i.e., at this height the air is 1000 times more rarefied, and thus, above 54 kilometers, there remains no more than one thousandth (0.001) of the mass of the entire atmosphere.

But owing to the fall in temperature this residual mass is incomparably less.

The differential of the work (T) done by the resistance may be expressed as

$$dT = Fdh, \qquad (6)$$

where F denotes the resistance of the air to the motion of the projectile. It is equal to

$$F = \frac{KSdV^2}{2g \cdot U}. \qquad (7)$$

where K is a coefficient, which, according to Langley, is equal to 1.4; S is the area of the greatest cross section of the projectile; d is the density of the air at the point where the rocket is located at the moment in question; d, of course, is a variable, because the density of the air falls quickly with increase in altitude; V is the velocity of the projectile; g is the acceleration of terrestrial gravity at the surface of the planet (g = 9.8); U is the efficiency or shape factor of the rocket, a number indicating by how many times the drag is reduced thanks to the birdlike shape of the projectile as compared with the drag of an area equal to its greatest cross section; this U is also a variable which, as numerous experiments have shown, increases with increase in the velocity V of the moving body; it is worth noting that it also increases with the dimensions of the body.

However, we shall assume U to be constant, since its dependence on the velocity V is a very debatable question.

Furthermore, since the aerodynamic drag is small compared with the pressure of the explosive propellants on the rocket (about 1% or less), the velocity V of the projectile may be taken as equal to

$$V = \sqrt{2\ (p - g) \cdot h}, \tag{8}$$

where (p - g) is the true acceleration of the projectile per second. This assumption, by increasing the velocity, increases the work done by the resistance of the atmosphere and, hence, balances the error due to reducing the height of the atmosphere.

On the basis of the third equation and the last three formulas, we get:

$$dT = b \left(1 - \frac{h}{h_1}\right)^a \cdot h \cdot dh; \tag{9}$$

where

$$b = \frac{Kd_1 S\ (p - g)}{Ug} \tag{10}$$

and

$$a = 5.88. \tag{4}$$

Integrating by parts and determining the constant, we find

$$T = b \left\{ \frac{h_1^2}{(a + 1)(a + 2)} \left[1 - \left(1 - \frac{h}{h_1} \right)^{a+2} \right] - \right.$$

$$\left. - \frac{h_1 h}{a + 1} \left(1 + \frac{h}{h_1} \right)^{a+1} \right\} . \qquad (11)$$

Putting $h = h_1$, we obtain the total work (T_1) done by the resistance of the atmosphere, namely:

$$T_1 = \frac{bh_1^2}{(a + 1)(a + 2)}. \qquad (12)$$

Let us put: $k = 1.4$, $d = 0.0013$, $S = 2$ sq. meters, $\frac{p}{g} = 9.8$ meters, $U = 100$; then $b = 0.0003276$, $a = 5.88$, and $h_1 = 54,540$ meters. Now from (12) we get: $T_1 = 17,975$ meter-tons.

The work done by 1 ton of explosive materials in obtaining 1 ton of water from hydrogen and oxygen is equal to 1,600,000 meter-tons. If the projectile with all its equipment and passengers weighed a ton, and the supply of explosive materials was equal to six times that amount, i.e., 6 tons, the rocket would incorporate a potential energy of 9,600,000 meter-tons. More than half this energy is converted into mechanical work serving to propel the rocket.

Therefore, in this case the work done by the resistance of the atmosphere is only about 1/300 of the work done by gravity. We can reach the same result by comparing the work done by the resistance of the atmosphere (17,975) directly with the total work done by gravity (6,336,000). We obtain about 1/353.

Below we present a table showing, for the assumed conditions: the time in seconds from the beginning of vertical flight, the corresponding velocity of the rocket in meters per second, the height in meters, and the density of the surrounding air, taking the density at sea level as unity and assuming a uniform fall in temperature with height of 5°C.

t	V	h	d
0	0	0	1
1	90	45	-
2	180	180	-
3	270	405	-
5	450	1125	1:1.13
7	630	2205	-
10	900	4500	1:1.653
15	1350	10,125	-
20	1800	18,000	1:10.63
30	2700	40,500	1:10.63
40	3600	72,000	close to zero
50	4500	112,500	"
70	6300	220,500	0
100	9000	450,000	0
113	9900	574,600	0

Given a 6 to 1 ratio of explosive material, the explosion will last a total of 113 seconds, while at the end of this interval the body will acquire a velocity of 9990 meters and will have risen to a height of 575 kilometers; the remainder of the ascent will be governed by the forces of inertia.

The work done by the resistance of the atmosphere is very small; but in vertical flight the losses due to gravity are not so small, in fact, the former are 35 times less than the latter. Therefore it is preferable to incline the flight path of the rocket so that, at the expense of a certain increase in a comparatively small quantity, i.e., the drag, we get a simultaneous reduction in a comparatively large one, i.e., the loss of energy due to gravity.

It is easy to see that the work done by the resistance of the atmosphere is approximately proportional to $\operatorname{cosec}^2 (\alpha - 90°)$, where $(\alpha - 90°)$ is the angle of inclination of the trajectory of the rocket to the horizon.

In a gravitationless medium, again given a six-to-one ratio of explosive material, 0.63 of all the stored energy is utilized.

Eliminating, in the worst case, 8% of this figure, we find that in the case of inclined flight it is possible to utilize 58% of all the chemical energy of the explosive material.

The work done by the drag can be reduced several times, if the flight is begun from the top of a very high mountain or if the rocket is raised by means of an airship to a considerable height and launched from there. Thus, starting the flight from a height of 5 versts halves the work done by the drag, while starting the flight from a height of 10 versts cuts it down to one quarter.

7. Description of Flight

Relative phenomena

Space travel may still be very far off, but let us assume that everything is ready: invented, built, and tested. We have already taken our places in the rocket and are prepared for the ascent, while our friends look on.

We relate phenomena to the rocket, our friends to Earth, the astronomers of Mars to their own planet, and so on. All these phenomena are relative and quite different, since every phenomenon depends, among other things, on the motion of the body to which it is referred.

Once on our way, we shall experience some very strange, quite wonderful and unexpected sensations, which I shall begin by attempting to describe.

The signal has been given; the explosion has been touched off to the accompaniment of a deafening roar. The rocket shudders and starts on its way. We feel as though we have grown dreadfully heavy. The 4 poods (144 pounds) that I normally weigh have become 40 poods. I am thrown to the floor, shaken to pieces, perhaps dead; in no fit state to make observations! There are means of enduring this terrible heaviness, but only all wrapped up, so to speak, or in a liquid (more concerning this later).

Immersed in a liquid, we would likewise scarcely be inclined to make observations. However this may be, gravity in the rocket has clearly increased by ten times. We can deduce this in various ways: from the behavior of spring balances or dynamometers (a pound of gold suspended from the hook has become 10 pounds), from the accelerated oscillation of a pendulum (more than three times as fast), from the increased rate of fall of bodies, from the decrease in the size of droplets (tenfold reduction in diameter), from the fact that everything is heavier, and from many other consequences.

If the density of the Earth were to increase by ten times or if we arrived at a planet where the gravitational attraction was ten times greater than on Earth, we would be quite unable to distinguish between phenomena in the rocket and on the planet with the intensified gravity. It might be less in the rocket, but then the explosion would last longer and, for the same expenditure of material, the rocket would rise to a lesser height or acquire a lower velocity. We shall examine the case of a vertical ascent, when the direction of relative gravity is the same as on Earth. In inclined flight we might note a change in the direction of relative gravity by not more than 90°, and in the most favorable case by 75-80° relative to the direction on Earth at the point in question.

If, in these circumstances, we looked out of a window in the rocket, the Earth would appear to us like an almost vertical wall, extending on one side into the sky and on the other into the abyss.

The sensation of intensified gravity will last 113 seconds or about 2 minutes, until the noise of the explosion dies away. Then, in the ensuing dead silence, the sensation will vanish as quickly as it appeared. Now we have risen beyond the limits of the atmosphere, to a height of 575 kilometers. The force of gravity has not only diminished, it has vanished without trace; we do not even experience the terrestrial gravity which, though as familiar as the air we breathe, is by no means as vital. 575 versts .... so very little, practically at the surface of the Earth, and gravity can hardly have diminished very much. It hasn't, but we are concerned with relative phenomena and under these conditions gravity doesn't exist.

The force of the Earth's gravitational attraction acts identically on the rocket and on the bodies it contains. Therefore there is no difference between the motion of the rocket and its contents. They are being carried away by the same current, the same force, and for the rocket there is, as it were, no gravity.

This will be apparent in many ways. Any object not attached to the rocket will leave its place and hang suspended in the air, without touching anything, and if two objects do come in contact, they will not exert any pressure on each other or on their support. We ourselves will not necessarily be in contact with the floor either but will be capable of assuming any attitude or orientation. We shall be able to stand on the floor, on the walls or on the ceiling, upright or at an angle, and to float in the middle of the rocket, like fish, but without any effort and without touching anything. No two objects will exert pressure on each other, unless they are clamped together.

Water will not flow from bottles, and the pendulum will not swing, but will hang sideways. A huge mass suspended from the hook of a spring balance will not extend the spring, and the instrument will always read zero. Balances will also be useless, the balance arm will assume any position, irrespective and regardless of the equality or inequality of the weights in the pans. There will be no means of selling gold by weight. Ordinary earthly methods of determining mass will be ineffective.

Oil, shaken from the bottle with some difficulty (impeded by the pressure of the air that we breathe in the rocket), will assume the form of a quivering sphere; after a few minutes the quivering will stop, and we shall have a splendidly accurate sphere of liquid; if we divide this into parts, we shall get a series of smaller spheres of different sizes. These will all move in different directions until they strike and wet the surface of the walls.

The mercury barometer will rise to the top and the mercury will fill the entire tube.

It will not be possible to siphon water.

If gently released, an object will not fall, and if pushed, it will move uniformly and in a straight line, until it hits the wall or encounters some other object, whereupon it will continue to advance but at a reduced speed. In general, it will simultaneously rotate, like a child's top, since it is difficult to give something a push without at the same time making it spin.

We have a feeling of well-being, lightness, as if we lay on the softest of featherbeds, but the blood tends to run to the head, which for the plethoric might be harmful.

We are capable of observing and thinking. Although the Earth's mighty hand continuously retards the ascent of the rocket with dreadful force, i.e., terrestrial gravity does not relax its grip for a moment, in the rocket we feel as we would on a planet, the gravitational attraction of which had been miraculously annihilated or paralyzed by centrifugal force.

Everything is so quiet, nice and peaceful. We open the outside shutters on all the windows and gaze through the thick glass in all directions. We see two skies, two hemispheres, together forming a single sphere, at the center of which we seem to stand. We are, as it were, inside a ball consisting of two differently colored halves. One half is black and contains the stars and the Sun; the other is yellowish with numerous light and dark spots and vast, duller spaces. This is the Earth we have just left. It does not look convex, as if it were a sphere, but, in accordance with the laws of perspective, concave, like a round bowl into the depths of which we gaze.

Our flight began in the month of March at noon on the equator, accordingly the Earth occupies almost half the sky. If we had started in the morning or the evening, we would see it covering a quarter of the sky in the form of a gigantic curved sickle; leaving at midnight, we would see only a zone or ring shining with a purple light, the color of dawn, and cutting the sky in two, one half being starless, almost black, very slightly reddish, the other black as pitch and sprinkled with innumerable, comparatively very bright but untwinkling stars.

As we rise and draw away from the surface of the Earth, this zone becomes smaller and smaller, but at the same time brighter and brighter. In this form, or in the form of a sickle or bowl, the terrestrial sphere appears to diminish, whereas (absolutely) we are able to survey an increasingly large part of its surface. Now it appears to us like an enormous dish which, gradually diminishing, turns into a saucer and, further on, into a shape like the Moon.

Strictly speaking, there is no up or down in the rocket, since there is no relative gravity, and a body left without support does not tend to any one wall of the rocket; however, subjective sensations of up and down do remain. We are aware of up and down, but their position varies with the direction of our body in space. Where our head points is up, where our feet point is down. Thus, if we turn so that our head is towards Earth, it appears to be above us; if we turn our feet in the same direction, we plunge it into the abyss, since it appears to be beneath us. This is a majestic and initially horrifying state; then we get used to it and, in fact, lose our sense of up and down.

The onlookers on Earth heard the rocket roar and saw it free itself from the gound, soaring like a meteorite only in the opposite direction and with 10 times as much energy. The upward velocity of the rocket continually increases, but it is difficult to observe this owing to the rapidity of its motion. After 1 second the rocket has already risen to a height of 45 meters, in 5 seconds it has reached a height of 1 verst, in 15 seconds 10 versts; already it appears as no more than a thin vertical streak, climbing rapidly. After 30 seconds it has risen to 40 kilometers, but we can still follow it with the naked eye, because, owing to its increasing speed, it has become white hot (like an aerolite) and its protective, heat-resistant and nonoxidizing skin shines like a star. This starry flight has lasted over a minute; now everything gradually disappears, since, having left the atmosphere behind, the rocket is no longer affected by atmospheric friction, so it cools and slowly ceases to shine. Now it can only be spotted with the aid of a telescope.

The heat has not penetrated to us, seated inside the rocket, since we are protected by an insulating layer and, moreover, since we have at our disposal a powerful cooling agent: the evaporation of the liquid gases. Finally, protection was only necessary for one or two minutes.

The apparent absence of gravity in the projectile will persist, provided that there is no explosion and the rocket does not spin: it is neutralized even near the Earth's surface; the rocket may follow a trajectory taking it an enormous distance from our planet -- there will be no gravity; the rocket may race around the Sun, fly to the stars, and fall under the weak or powerful influences of all the suns and all the planets -- none of the effects of gravity will be noticed; all the phenomena associated with the absence of gravity will be observed in and around the rocket, just as before. This conclusion is not completely accurate, but it is approximately true; it is impossible to confirm the effect of its inaccuracy, not only within the confines of the rocket but tens, hundreds, and sometimes even thousands of versts around it. A certain small influence is also exerted by the gravitational attraction of the rocket itself, its crew, and the objects they have taken along with them. But this mutual interaction is very slight and can be detected only in the displacement of strictly stationary (of course, relatively) bodies in the course of time. If an object is moving, even only very slightly, the effect of Newtonian gravity can no longer be detected.

8. Around the Earth

By controlling the explosion, it is possible to raise the rocket merely to some predetermined height; then, having lost almost all our velocity, in order not to fall back to the planet, we can turn the rocket with the aid of rotating bodies mounted inside it and initiate a new explosion in a direction perpendicular to the first.

This will again create a relative gravity, but in this case we can limit it to a very small value; all the well-known gravitational effects reappear; again they vanish; peace and quiet supervene, but this will already have been enough to prevent the rocket from falling; it will acquire a velocity normal to the radius vector, i.e., along a circle, like the Moon, and, again like the latter, will revolve eternally about the Earth (cf. my chapter on "The trajectories of a projectile and its velocity").

Now we can relax completely, since the rocket has assumed a "stable" position: it has become a satellite of the Earth.

From the rocket we can see the huge globe in one or another of its phases, like the Moon. We can see how the Earth revolves, how it presents all its different aspects in succession in the course of a few hours. The closer it is to the rocket, the larger, the more convex, and the more extended along the horizon it will seem, the brighter the satellite (rocket) will shine, and the more rapidly the satellite will circle its mother planet -- the Earth. This distance may be so small that a circuit around the Earth takes only two hours, and different points on the surface will be visible for a few minutes, at various angles, and very close. This sight will be so majestic, so enthralling, and so infinitely varying that I wish with all my heart that you and I could see it. In the course of every such two-hour circuit the rocket grows dark; this lasts for less than an hour; then, for rather more than an hour, the sun shines, only to give way to darkness again.

If we wanted more light, i.e., a longer day, we would either have to move further away from the Earth or follow not an equatorial but a meridional course, one that intersected the North and South Poles. In these circumstances, i.e., when the orbit of the rocket is normal to the rays of the Sun, we would get a long day, lasting a month or more, even comparatively close to the planet. The view of the Earth would be even more exciting, enchanting and unexpected, since the edges of the illuminated zone would be visible in relief and in rapid motion. The Poles would be a particularly splendid sight.

We would be unconscious of the motion of our own rocket, just as we are unaware of the motion of the Earth (when we are on it), and it would seem as though the planet itself were racing around us together with the entire magic horizon: we would feel that the rocket was at the center of the universe, as the Earth once seemed to be.

9. The Trajectories of a Projectile and Its Velocity

If the rocket were launched vertically and the Earth did not rotate, the relative trajectory of the rocket would be a very simple one, namely, a straight line, its length depending on the amount of explosives used.

This would also be the trajectory of a rocket launched from the poles of a rotating planet, neglecting the effect of other heavenly bodies. When the amount of explosive material is eight times greater than the mass of the rocket, its trajectory, provided it is launched from the surface of the Earth, will be open-ended, infinite, and the rocket will never return to Earth, assuming, of course, the absence of heavenly bodies or their gravitational fields.

The minimum velocity needed to escape from the Earth to infinity is 11,170 meters per second, or more than 10 versts per second.

The rotation of the medium and small planets of the solar system, including the Earth, is not enough to have much effect on the straightness of the trajectory. In fact, the trajectory becomes an extremely elongated ellipse, if the projectile returns to Earth, or a parabola or hyperbola, if it escapes completely.

In speaking of the trajectory of a rocket, we did not have in mind the comparatively short section corresponding to the duration of the explosion, which, however, is also close to a straight line, if the direction of the explosion does not change.

At first, during the explosion, the rocket accelerates rapidly. Later, the velocity changes more slowly -- solely under the influence of gravity. Thus, when the rocket is rising or moving away from the center of the planet, the velocity it acquired during the explosion decreases; if it is approaching the planet or falling, it increases.

Over an infinite distance in the course of an interminable period of time the velocity of the rocket approaches closer and closer either to zero or to some constant value. In either case the rocket never stops and never returns to Earth, if we disregard the resistance of the ether and the forces of attraction exerted by other heavenly bodies.

However, there is more advantage to be derived from an inclined than a vertical takeoff. In the case of an initially (i.e., during the explosion) horizontal flight the trajectory of the rocket is some second-order curve tangent to the Earth at the launching point. The focus of this curve will lie at the center of the Earth. If the relative amount of explosive material is insufficient (ratio less than 3-4), the flight will not succeed, and the rocket will graze the Earth or fall back like an ordinary, horizontally fired cannonball.

If the velocity imparted to the rocket by the explosion is $\sqrt{2}$ (= 1.41...) times less than the minimum needed to escape to infinity (11,170 meters per second), its trajectory will be a circle coinciding with a great circle of the Earth (equator or meridian). This case too has no practical value, since the rocket, flying continuously in the Earth's atmosphere, will lose all its velocity due to the atmospheric drag and fall to Earth. However, if there were no atmosphere or if the rocket began its flight from the top of a mountain that rose above the surface of the ocean of air, the trajectory of the rocket would be circular and perpetual; like the Moon, it would never fall to Earth.

Accordingly, the velocity needed to achieve a circular orbit can be calculated as approximately 8 kilometers per second or 7904 meters per second.

If we utilize the rotation of the Earth and launch the rocket from the equator in the direction of motion of the equatorial points of the globe, the required velocity is reduced by 465 meters (the maximum rate of rotation of points on Earth), i.e., will be 7441 meters. Clearly, the gain is not very great. The relative amount of explosives required may be expressed by a number between 3 and 4 (if the weight of the rocket is taken as 1).

The work done in achieving a circular orbit is exactly half the minimum required to escape from the planet to infinity.

If the velocity of the rocket is increased still further, we get an ellipse, extending gradually beyond the limits of the atmosphere. Additional increases in velocity will stretch the ellipse more and more until it turns into a parabola; in this case the work and the velocity needed to overcome the force of gravity will be the same as for a final escape in the radial direction (for the Earth 11,170 meters per second).

At still greater velocities the trajectory of the rocket becomes an hyperbola. In all these cases the rocket is seriously affected by the resistance of the atmosphere; for this reason rocket trajectories tangential to the Earth are also without practical value.

We have seen that the most favorable trajectory for a rocket is one inclined at 20-30 degrees to the horizon. Under these conditions, the rocket loses only 7 percent of the energy that it would acquire in a gravitationless, airless medium. The trajectory is the same, i.e., some second-order curve (ellipse, parabola, hyperbola), but in this case the curve is not tangential to the surface of the Earth. If the amount of explosive material is insufficient or quite small, then, after describing part of an ellipse and reaching its maximum range, the rocket will return to Earth. Here the rocket must consume some more of its supply of explosives to arrest its motion somewhat, otherwise it will be destroyed. If the rocket rises only to a modest height above the Earth, the total amount of explosives needed for the ascent and safe return will be twice as much as for the ascent alone; for longer flights it will be three times as much, for still longer flights four times as much, and so on (cf. equation (66))*.

If we wanted the rocket to remain for ever outside the atmosphere in space, by making it a permanent satellite of the Earth, then, at the maximum distance from Earth (at the apogee), we would again have to use a small amount of explosives to increase its velocity. If this point is not far from the surface of the Earth, the velocity required by the rocket is close to 8 kilometers per second, and the total weight of explosives will exceed the weight of the remaining mass of the rocket by only 3-4 times. But however far away we established our observation station, even though it were a million versts from the center of the Earth, the amount of explosives would be less than that needed for escaping from the planet to infinity along a straight line or parabola. In fact, it could be expressed by a number less than 8.

Of course, by means of more explosives, a circular orbit can be transformed into an elliptic one, and the latter, as described, back into a circular orbit of greater radius. Thus, we can change the radius of our circular orbit at will, i.e., approach or draw away from the Earth as desired.

If, having already achieved a circular orbit, we initiate a very weak, but constant explosion in the direction of motion of the rocket, then, while the explosion lasts, its trajectory will develop into a spiral orbit, the equation of which will depend on the law of the explosion.

The further trajectory of the rocket, following the termination of the explosion, will be some second-order curve, for example, a circle, that depends on us. If the explosion acts to reduce the velocity of the rocket, the spiral will develop inside the original circular orbit, and the rocket will approach the Earth.

In the case of motion in a spiral, almost perpendicular to the direction of gravity, roughly the same percentage (up to 65%) of the energy of the explosives is utilized as in a gravitationless medium; the same applies to the process of converting an elliptic into a circular orbit.

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*See preceding article, p. 194. (Ed.).

If the launching angle of the rocket is inclined to the vertical, the influence of the Moon on its elliptic path will be the greater the more elongated the orbit and the closer the projectile approaches to the Moon, which, in its turn, depends on the relative amount of explosive material consumed and the relative position of the Moon and the rocket. It may happen -- or the motion of the projectile can be so calculated -- that, under the influence of lunar gravitation, it completely abandons its orbit and lands on the Moon.

The rate of fall will be not less than 2373 meters per second, i.e., twice the speed of a cannonball. However, this speed is far less deadly than in falling to the surface of the Earth. The energy of such a fall is 22 times greater than the corresponding energy for the Moon.

If we take into account the rate of motion and rotation of the Moon, as well as the motion of the projectile, we can also compute the small amount of explosive material needed for a safe landing on the lunar surface. I may say that the total amount of explosives needed for a safe journey to the Moon can be expressed as a number not greater than 8. At a comparatively short distance from the Moon the velocity of the rocket must be continuously reduced by means of an explosion. Everything should be so calculated and so controlled that at the moment of contact with the surface of the Moon this relative velocity is equal to zero. The task, of course, is rather delicate, but perfectly feasible. An error in calculation could be corrected by restarting the explosion, provided a sufficient supply of explosives was carried.

In the event of a miss, i.e., if the rocket passed close to the Moon without actually touching its surface, it would not become a satellite of the Moon, but, having approached it, would draw away again to revolve around the Earth, describing a very complex curve passing sometimes close to the Earth, sometimes close to the Moon. There remains the possibility of it falling onto either the one or the other. As it approached closest to the Moon, it would be possible to burn some more fuel and thus make it a perpetual lunar satellite. Then, by various means, it could be transferred from this circular orbit, to land on the lunar surface or move further away from it.

From this description it is clear that the rocket can become a perpetual satellite of the Earth, moving around it, like the Moon. The distance of this artificial satellite, the Moon's little brother, from the Earth's surface can be arbitrarily small or great; the motion is eternal, since the resistance of the ether is not noticeable even for the small, low-density bodies, mostly like aerolites, entering, in all probability, into the composition of comets. If small bodies encountered resistance from the ether, then (not to mention anything else) how could the rings of Saturn have existed for millions of years, consisting, as the astronomers assure us they do, of small, isolated solid bodies, racing around Saturn at an astonishing speed?

A number of rockets orbiting the Earth, with all the equipment needed to enable rational beings to exist, might serve as a base for the further dissemination of humanity. Having established a series of rings around the Earth, like the rings of Saturn (perhaps these too are the work of living beings; otherwise it is difficult, if not impossible, to account for their existence; if there were not something rational controlling them, the rings would have formed a moon for the planet), mankind would increase one hundred- to one thousandfold its supply of solar energy, which it allows to go to waste at the surface of the Earth. And if this were not enough to satisfy its needs, it could reach out from this conquered base for the rest of the Sun's energy, which is two billion times greater than that received on Earth.

In this case, it would be necessary to exchange eternal motion around the Earth for Eternal motion around the Sun. To achieve this, it would be necessary to move still further away from the Earth and become an independent planet, a satellite of the Sun, a brother of the Earth. Thus, by means of a further explosion, the rocket must be given a velocity in the direction of motion of the Earth around the Sun, when the rocket is moving with maximum velocity relative to the Sun. The energy required for this depends on the distance between the rocket and the Earth: the greater this distance, the less the work that need be done; the sum total of the energy needed to achieve a circular orbit around the Earth and then almost total escape does not exceed that needed to escape from the Earth for ever, assuming the absence of the Sun and other heavenly bodies, i.e., a seven (7) or eightfold (8) quantity of explosives (relative to the remaining mass of the rocket).

If still more energy is expended, the circle becomes a more or less elongated ellipse, the perihelion (least distance from the Sun) of which lies approximately at the distance of the Earth from the Sun.

In the first case, i.e., assuming a medium expenditure of energy (7-8), initially, under the influence of the new impulse, the rocket flies much faster than necessary for circular motion about the Earth or even the Sun; then, owing to terrestrial gravity (the Moon is neglected), this velocity gradually diminishes, and finally, at a considerable distance from the Earth (approximately 1000 Earth diameters), becomes equal to the motion of the latter about the Sun. The Earth and the rocket will follow the same circular course at the same speed and therefore may not see each other for hundreds of years. However, the chances of such a balance lasting for centuries are slim, and to maintain a proper distance, it would be necessary now to increase, now to reduce the speed of the rocket, to prevent the Earth and other planets interfering with its motion. Otherwise there would be a risk of falling back to Earth.

In the second case, when a large amount of energy is expended and the rocket follows an elliptic path, the chances of an encounter with the Earth are also by no means negligible, but the distance achieved by the rocket can be used in order to land on some "upper" planet: on Mars or its satellites, on Vesta or some other of the 500 small planets (planetoids, asteroids).

I make no mention of reaching the most massive planets, like Jupiter, Saturn, etc., since a safe landing on one of these would require such an enormous amount of fuel that the prospect is at present extremely remote. It would be easier, however, to become satellites of these planets, especially fairly distant ones, or to reach and join the rings of Saturn. The amount of energy needed to achieve any planetary orbit (without landing on the planet) depends on its distance from the orbit of the Earth: the greater this distance, then naturally the greater the expenditure of energy. But however great this distance might be, the work required would be less than that needed to escape entirely from the solar system and wander among the stars. And even this amount of work is not as enormous as might appear at first glance. Can we seriously consider overcoming the powerful attraction of the Sun, the mass of which is 324,000 times greater than that of the Earth? Computations show that if the rocket is fired at the moment of its maximum velocity about the Sun or directly from the surface of the Earth at a favorable moment and in a favorable direction, the velocity relative to the Earth, necessary for it to escape completely from both the Earth and the Sun, does not exceed 16.3 kilometers (about 15 versts) per second, the corresponding ratio of the mass of explosives required to the mass of the rocket being 20. Under the most unfavorable launching conditions, this velocity becomes 76.3 kilometers per second, and the amount of explosives required, relative to the remaining mass of the rocket, will be appalling. The absolute escape velocity, i.e., the velocity relative to the Sun, is the same whatever the direction in which the rocket is launched. If in the favorable case the necessary energy is 25 times less, this is because we borrow it from the motion of the Earth, which must therefore be slowed down by an imperceptible amount.

A circular trajectory about the Sun can be made elliptic by increasing or reducing the speed of the rocket by means of further explosions.

In the latter case, if the speed is reduced, the perihelion of the rocket will be less than the distance between the Earth and the Sun, and then the rocket will be in a position to reach one of the lower planets: Venus or Mercury. Their mass is not very great, and a landing would not require such an impossible amount of explosives as a safe landing on Jupiter, Saturn, or Neptune. The gravitational energy of Mercury and Mars is five times less than that of our planet; the gravitational energy of Venus is 0.82 times that of the Earth. As far as the asteroids and most of the planetary satellites (moons) are concerned, the amount of explosives needed to ensure a gentle landing on their surface is quite negligible.

Theoretically, it is possible to approach even closer to the Sun and even land on it with a total loss of relative velocity. If the rocket is already revolving around the Sun, like the Earth, and at the same distance, then in order to arrest this motion a relative (reverse) velocity of about 30 kilometers per second is required. The necessary amount of explosives can be expressed as the ratio 200. The journey to the Sun would take $64^{1}/_{4}$ days or about two months.

Hence it is clear that a journey to the fiery ocean of the Sun requires a 10 times greater sacrifice (in terms of explosives consumed) than escaping from our own Sun and approaching a new one.

Just as in an Earth orbit, a continuous but extremely weak explosion can give a rocket any trajectory, it is possible to compel it to describe a given trajectory relative to the Sun, for example, a spiral, and thus reach a desired planet, approach or move away from the Sun, land on the Sun or escape it completely to become a comet wandering for thousands of years in the darkness, among the stars, eventually approaching one of them, which for the travelers or their descendants becomes a new sun.

Note that whenever the velocity of the rocket is reduced, the explosive material must be expelled in the direction of motion of the Earth; but the motion of the rocket relative to the Sun remains as before, i.e., in the direction of motion of our planet.

The plan for the eventual exploitation of solar energy will probably be as follows.

Mankind will launch rockets to one of the asteroids and make it a base for preliminary operations. They will use the material of the small planetoid and break it down to build their own structures, forming the first ring around the Sun. This ring, populated with living rational beings, will consist of moving parts, like a ring of Saturn.

Having broken up and utilized other small asteroids, in the space thus swept free, the pioneers will build for their own purposes a series of rings, somewhere between the orbits of Mars and Jupiter.

For various technical and other reasons, similar rings may be established even closer to the Sun, between the orbits of the "lower" planets.

When the energy of the Sun is exhausted, the colonists will abandon it and make their way to another more recent star that is still in its prime. Perhaps this will happen even earlier: some of the colonists may wish to seek another world or to populate the void.

Perhaps humanity will "swarm" in this manner many times. Perhaps it has already swarmed more than once before and the present population is actually less than the previous one.

There would be no need to occupy the surface of the Sun even if it were covered with a cold crust. Nor is there any need to be on the heavy planets, save for the radiation. They are difficult to reach; living on them means fettering oneself with chains of gravity sometimes heavier than on Earth, raising for oneself a series of barriers, clinging to a confined space, living a miserable life in the womb of matter. A planet may be the cradle of the intelligence, but one can not live for ever in a cradle.

10. Means of Sustaining Life During Flight

Eating and Breathing

Above all, it will be necessary to have oxygen for breathing; we shall need quite a lot of it to provide the explosion; it should be possible to carry an additional amount to take care of breathing requirements for a predetermined period of time.

Pure oxygen is not very good for breathing even in the rarefied, as opposed to the normal state. In fact, in this case its pressure on the body is insufficient, and bleeding may occur for purely mechanical reasons.

The best thing to use is a mixture of oxygen and some other harmless gas -- nitrogen, hydrogen, but not carbon dioxide which prevents the release of carbon dioxide from the lungs and skin thus poisoning the organism. A mixture of 20% oxygen and 80% nitrogen at a pressure of 1000 to 500 mm Hg is good for breathing. Nitrogen is preferable to hydrogen, since the risk of an explosion is eliminated.

Naturally, the compartment for the passengers must be hermetically sealed and strong enough to resist the gas pressure, not more than 1 kilogram per square centimeter of the chamber walls, when the rocket climbs into the rarefied layers of the atmosphere and beyond. The elongated fish- or birdlike form of the rocket, which enables it to cut easily through the air, is capable of withstanding the gas pressure and also the gravity stresses, which reach ten times the normal level during the explosion. The metallic material will prevent the loss of gas due to diffusion.

But it is not enough merely to provide a mixture of oxygen and nitrogen; it is also necessary to replace the oxygen converted to carbon dioxide and destroy, or rather eliminate, the products of respiration: carbon dioxide, ammonia, excess moisture, etc. There are many substances capable of absorbing carbon dioxide, ammonia, water vapor, and so on. A supply of these substances must be carried on board. Of course, if the journey is only going to last a few minutes or a few hours, the rocket should not be burdened with supplies, including food. The situation will be different, however, if the voyage is to last weeks and years or if there is no intention of coming back; then sufficient reserves will be indispensable.

In order to exist for an indefinite time beyond the atmosphere and out of touch with Earth, it is possible to make use of solar energy. Just as the Earth's atmosphere is purified by green plants with the aid of th Sun, so we can refresh our artificial atmosphere. Just as on Earth the leaves and roots of plants absorb impurities and in return provide food, the plants that we take with us on our journey can be put continuously to work. Just as every creature on Earth lives on the same amount of gases, liquids, and solids that never either diminishes or increases (disregarding the fall of aerolites), so we can live for ever on the supply of matter that we have taken with us. The endless mechanical and chemical cycle of matter will operate in our little world just as it does on Earth. From the scientific point of view this possibility is uncontestable; now let us consider to what extent it may be realizable in the, perhaps very distant, future.

According to Langley, one square meter of the surface normal to the direction of the Sun's rays receives each minute a quantity of solar energy equivalent to 30 calories. This means that 1 kilogram of water occupying an area of 1 square meter, on which the Sun's rays fall vertically, will be heated through 30°C in one minute, if we neglect the losses due to radiation, conduction, etc.

On converting this thermal energy into mechanical energy, we get 12,720 kilogram-meters. Thus, in 24 hours, at the distance of the Earth from the Sun, we get 18,316,800 kilogram-meters or 43,200 calories. (Each second we get 0.5 calorie or 212 kilogram-meters, i.e., a continuous flow of work equal to almost 3 horsepower.)

According to Timiryazev, in physiological experiments with plants, up to 5% of the solar energy is utilized; this is equivalent to 2160 calories per day stored in the roots, leaves, and fruits.

On the other hand, according to Le Bon, a kilogram of flour contains almost twice as much energy, so that the potential energy sotred daily by a plant corresponds to 0.5 kilogram of flour or almost a kilogram (2.4 pounds) of bread.

The same gift of the Sun, collected from a single square meter illuminated by its rays, is also equivalent to one of the following: 4 kilograms of carrots, 5 kilograms of cabbage, 2/3 of a kilogram of sugar, more than half a kilogram of rice.

In the above-mentioned experiments the five-percent saving was accumulated in all parts of the plant, though in the fruits, of course, it is less. These experiments were conducted under very favorable conditions, but our artificial atmosphere and our feeding of the plants may be even more favorable. According to Timiryazev, in the best case, the actual soil utilizes five times less, i.e., about 1% of the solar energy. Hence it is clear that artificial conditions will be as much as five times more advantageous.

Let us now turn to a direct consideration of practical conditions. A desyatina, approximately 1 hectare (10,000 sq. m.), yields annually up to 25,000 poods of bananas, which corresponds to 0.11 kg per day per square meter.

But on Earth we have clouds, on Earth we have a thick layer of air and water vapor that absorbs a great deal of energy, on Earth we have night and the rays of the Sun are generally inclined; as experiments show, the amount of carbon dioxide in the air is also unfavorable (the most favorable concentration, according to Timiryazev, is 8%, whereas in the air it is not even one tenth of one percent). Finally, what can be favorable about the primitive cultivation of plants from what are virtually wild strains. Bearing in mind what I have said, it should be possible for the gift of the Sun to be multiplied at least 10 times, and to make the productivity of one square meter of our artificial garden not less than 1.1 kg of bananas. The bread tree, according to Humboldt, is almost as productive as the banana palm.

It follows from the above that a single square meter of greenhouse space, turned towards the rays of the Sun, is enough to feed a man.

But what prevents us from reducing a large greenhouse to a compact form, i.e., fitting it into a small volume? When a circular orbit around the Earth or the Sun has been achieved, we assemble and push out of the rocket our hermetically sealed cylindrical boxes containing seeds sown in properly balanced soil. The Sun's rays strike through the transparent walls of the greenhouse and with amazing speed prepare us a lavish menu. They also give us oxygen and, moreover, cleanse the air of animal exhalations. Neither one crew nor the objects they take with them will be affected by gravity, and, accordingly, the containers for the plants need only be strong enough to withstand the internal gas pressure, due mainly to carbon dioxide and oxygen. The Earth's atmosphere contains not more than one two-thousandth (1/2000) part of carbon dioxide by volume. Nitrogen and other gases also play a part in the plants' metabolism, but the concentration, like that of oxygen, of which (according to Timiryazev) they need 20 times less than their requirements of carbon dioxide, may be extremely small without detriment to their growth.

Thus, the atmosphere of our greenhouses can be so rarefied that the gas pressure on its walls will be 1000 times less than the air pressure at sea level.

Hence, it is clear, there will not only be nothing to fear from gravity, but virtually nothing to fear from the pressure of the gases, so that for each passenger it will be possible to take, if necessary, hundreds of square meters of these narrow glass boxes with vegetables and fruits growing in them.

It is perfectly possible to work out and test here on Earth means of enabling men to breathe and eat in the isolation of space.

It is possible to determine the minimum area exposed to the Sun's rays that will suffice for breathing and eating. It is possible to search for and experiment with plants suitable for this purpose. True, conditions on Earth are by no means the same as in the ether, far from our planet, but conditions in outer space can be made to approximate those on Earth. Thus, in a gravitationless medium it is easy to arrange for day and night; it is only necessary to give the greenhouses a slow rotating motion. Then light will alternate with dark, and the relative duration of the alternating periods can be fixed arbitrarily. The motion will be perpetual, thanks to inertia. In my opinion, conditions will actually be much more favorable than here on Earth. In fact, terrestrial plants suffer badly and may even die as a result of severe temperature fluctuations during the night or in the course of the winter. They are also vulnerable to bacteria, parasitic fungi, worms, insects, rodents, and birds, to lack of moisture and exhaustion of the soil. In space these perils do not exist, because everything that is taken from the soil is restored to it, because the temperature is under our control, like the duration of the night. If the motion of the rocket is circular, there will be no seasons. If the greenhouse compartments are small, there will be no harmful bacteria and insects, since they can be destroyed by filling the compartments with pesticidal gases, by raising the temperature, or even by the action of continuous sunshine. Moreover, the hermetically sealed containers will never dry out.

The construction on Earth of experimental greenhouses, especially of a type well insulated from the atmosphere and containing a suitably rarefied medium, will be rather difficult, because very strong material and massive structures will be needed to withstand the external pressure of the atmosphere and the force of gravity. In the experimental greenhouses it will first be necessary to remain satisfied with an inside pressure the same as that outside and, hence, only with a mixture of suitable gases in the proportions most favorable for the plants. The total of the internal pressures will be equal to one atmosphere, whereas in space it will be possible to rarefy the gas mixture to the optimum degree. In these preliminary experiments the sunlight will not only pass through the glass, as in space, but also through the thick layer of the atmosphere, full of water vapor, haze and clouds which prevent the solar energy from reaching the plants in undiluted form. We, in fact, are quite unfamiliar with the true energy of sunlight, before it has passed through the atmosphere. In reality, it may possess quite unexpected chemical properties.

11. Protection Against Intensified Gravity

At the very beginning of the flight, while the explosion continues to roar, the relative gravity in the rocket will, as we have seen, be several times greater than normal, say, by a factor of 10.

The question arises whether man can safely endure such stresses for a period of several minutes. This question can be answered here on Earth, and at the same time we can work out the most favorable conditions for enabling men to endure these or even greater stresses without harm. Some time ago I carried out experiments with various animals which I subjected to the action of intensified gravity in special centrifugal machines. I was unable to kill one of them, though this was not actually my intention; I merely thought it might occur. I recall increasing the weight of a cockroach, taken from the kitchen, by 300 times, and that of a chick by 10 times. As far as I could see the experiment did them no harm.

Human experiments on intensifying the apparent gravity could best be conducted with the aid of centrifugal machines with a vertical axis of rotation and the largest possible radius, i.e., the largest possible horizontal dimensions (the less the angular velocity of the machine, the less the dizziness suffered by the subjects).

However, rotation, and the disturbed functions associated with it, does not occur in a rocket moving in a straight line. That a slow rotation not only has no ill effects but is not even perceptible, we know from the phenomenon of the rotation of the Earth, which we all experience from the day of our birth. The lasting amusement that children and even adults derive from carousels points to the same conclusion. Thus, on a carousel I once saw two young girls, employed to attract customers, who rode around on the wooden horses day and night.

The experiments on intensified gravity need not last more than 2 to 10 minutes, i.e., a period corresponding to the duration of the explosion.

I shall not attempt to derive the well known formulas on which the following conclusions are based.

By experimental means we can obtain an artificial gravity of any desired intensity; the more we slow down the rotation, the greater must be the velocity of the chamber in order to achieve the same gravity. Thus, given a radius of 100 meters, if the velocity is 100 meters per second and a complete revolution takes 6.3 seconds, we get a tenfold increase in the force of gravity. If the radius were 10 times less, then, to achieve the same intensification of gravity, the angular velocity would have to be more than three times as great; the translational or absolute velocity would be reduced in the same proportion.

By making the experiments with a centrifugal machine or by means of the rapid circular motion of a cart on inclined rails, we can determine the maximum gravity that a human subject can safely withstand over a given period of time. If, contrary to expectation, these experiments showed that even a small, say, a twofold increase in gravity was the most that could safely be withstood, all would still not be lost: firstly, because the rocket, in inclined flight, can still satisfactorily utilize the force of the explosion, even though the relative gravity is so small, and, secondly, because by immersing the subject in water and conducting the gravity experiments with him floating in a favorable position, we could certainly obtain much more reassuring results.

Let us consider what is involved. Suppose we take a very strong open or closed liquid-filled vessel and immerse in it a thin shape made of material that is very weak but equal in density to the liquid filling the vessel. Let us assume that taken separately, i.e., outside the liquid, this shape is so brittle and fragile that not only can it not be dropped without shattering but it can not even be picked up without crumpling or breaking. Now let us place it in the vessel, where it is in such perfect equilibrium with the liquid that it stays motionless wherever we put it and however we arrange it (like Plato's drop of oil in wine).

If the experiments with the centrifugal machine are performed not on a human subject but with this thin, fragile object, which outside the liquid is scarcely capable of resisting the force of gravity, the results will be very striking: the object remains intact and even motionless, whatever the increase in relative gravity.

Moreover, even without a centrifugal machine, we can dash the vessel with all our strength against the table or strike it with a hammer; provided the vessel does not break and the liquid does not splash out, our fragile shape will remain unharmed. However, it is only necessary to take away the liquid, and the entire effect breaks down; even strong objects will break if spun fast enough or exposed to sufficiently heavy blows. The same experiments can also be performed on small fish immersed in water. Hence we see that a liquid surrounding a body of the same density apparently neutralizes the destructive consequences of gravity, however great they may be.

Perhaps, if we take a liquid the density of which is equal to the average density of the human body and immerse a man in it, we shall obtain the same excellent results in our experiments on tolerance of intensified gravity. I have phrased this conclusion tentatively, because all that has been said above relates to bodies, all the parts of which have the same density. The various organs of the human body are far from possessing this property, in particular, the density of the bones and the lungs differs from that of other elements of the body. Bones immersed in a liquid will tend to sink, in the direction of relative gravity; lighter parts will tend to rise; a tension is set up between the different tissues leading to rupture and perhaps the death of the organism, if gravity is sufficiently intensified.

Thus, even if a man is immersed in a suitable liquid, his powers of safely withstanding gravity are not unlimited. The limit, in my opinion, is not less than 10 and can be determined for each individual only by experiment. The best thing would be for the subject to lie horizontally in a continuous jacket of approximately the same shape and size; then only a small amount of liquid would be needed to fill the intervening spaces. This is important from the weight-saving point of view, in connection with actual rocket travel. The mouth, nose and ears would be enclosed in a watertight hood with a tube for breathing.

Actually, there is no doubt that for a fraction of a second a man can withstand enormous gravitational forces. Thus, when someone jumps from a height, he strikes the ground. In order to annihilate the velocity acquired by the body, the ground, by virtue of its elasticity, gives it an accelerated motion in the opposite direction. Of course, the elasticity of the body also participates in this, in particular the elastic cartilage between the bones and, if the fall is properly controlled, the muscles that flex the legs. In this case the apparent gravity should be very great, because the time of impact is short, and therefore the reverse acceleration in this brief interval must be very large.

Nature herself makes use of this ability of a liquid to annihilate the destructive effect of relative gravity; thus she carefully immerses all the fragile organs of the body in special fluids enclosed in tough natural vessels. The brain swims in a fluid that fills the cranium; the mammal embryo is surrounded by a fluid before it enters the arena of life. Even commerce uses the same method for protecting delicate fruits, though the liquid is replaced with a rough equiv[illegible] -- a granular material: thus grapes are packed in sawdust

12. The Gravitationless State

Now the explosion in the rocket has ended and with it the dreadful intensification of gravity. We gratefully leave our protective jacket, wipe off the liquid that clings to our bodies, and get dressed. As if in reward for the intensified gravity we have just endured, we now find ourselves free of gravity altogether.

The question arises: does not this absence of gravity have an injurious effect upon our health? Should we not, in these circumstances too, take certain protective measures?

On Earth, when we fall or even jump, while our feet are still out of contact with the ground we are likewise, relative to our body, clothing, and the objects carried on our person, in a medium free of gravity, but the effect lasts only for a fraction of a second. During this interval of time the parts of our body do not weigh on each other, our overcoat does not weigh on our shoulders, our watch does not drag on our pocket, and our glasses do not tend to dig a crease across the bridge of our nose. On Earth, when we swim, the weight of our body is similarly almost paralyzed by the opposing action of the water. This absence of weight can even be prolonged for an indefinite length of time, if the water is warm enough. Hence it is clear that special experiments are hardly necessary to prove the harmlessness of a gravitationless medium. Perhaps such a medium might mean premature death for fat people inclined to apoplexy and the rushing of blood to the head, as lying and bathing might in time. Presumably, other mortals would quickly adapt themselves to the new order of things. For most sick and feeble people such a medium might even prove beneficial. A horizontal position often reduces the blood pressure, an effect also achieved by the absence of gravity. A lying position can not be regarded as injurious to health. For the sick and feeble it is helpful, but the healthy must modify their diet, if lying down is not to do them any harm.

Even if it should turn out that people can not, after all, live without gravity, it would be easy to create it artificially in a medium where it normally is not. All that is necessary is to set the rocket in rotation. Thus, thanks to the centrifugal force, we could create an apparent gravity of any desired intensity, depending on the size of the chamber and its rate of rotation. This transformation of the medium would cost us nothing, since the rotation of a body in an airless space and, moreover, in a gravitationless medium will continue for ever without any assistance. This apparent gravity is very convenient in that it may be made as large or small as desired and can always be eliminated and later restored; however, like natural gravity, it means that the chamber and other objects must have a certain strength, since it tends to destroy them. Moreover, the circular motion will have an ill effect on the organism, if the rate of rotation is very fast.

The effect of intensified gravity on plants was investigated long ago, but nothing special was observed, except that the direction of growth changes with the direction of gravity. The stem tends in a direction directly opposite to that of the artificial gravity. It would be interesting to know how a plant grows in the complete absence of gravity; in all probability its direction of growth would then be a question of change and the influence of the light.

13. Dreams

The Future of Reaction Machines

In an early unpublished work on reaction machines, I dreamed about future, as yet undiscovered, more elementary substances, the combination of which would, on the basis of the general laws of chemistry, be accompanied by a much greater release of energy than the combination of known simple substances such as hydrogen and oxygen, the volatile product of combination having a much higher velocity (V_1) at the outlet from the reaction pipe.

From equation (35)* it is clear that, for the same relative consumption of explosives (M_2/M_1), as (V_1) increases so does (V_2), i.e., the velocity of the rocket.

It is thought that radium, by continuously decaying into more elementary matter, liberates particles of different mass, moving at amazing, unimaginable speeds, close to the speed of light. Thus, the liberated helium atoms move at a speed of 30-100 thousand kilometers per second. Helium atoms are four times heavier than hydrogen atoms. Other particles released by radium are 1000 times lighter than hydrogen, but move at a speed of 150-250 thousand kilometers per second. The total mass of these particles (negative electrons) is considerably less than the mass of the helium atoms (positive electrons). These speeds are 6-50 times greater than the

*See preceding article, p. 187. (Ed.)

velocity (in kilometers) of the gases released from the nozzle of our reaction pipe.

Therefore, if it were possible sufficiently to accelerate the decay of radium or another radioactive substance, perhaps any substance, it could be used, other things being equal [cf. equation (35)], to give a velocity to a reaction machine such that it might reach the nearest sun (star) in no more than 10 to 40 years.

Then, in order for a rocket weighing one tone to burst all the bonds tying it to the solar system, no more than a pinch of radium would be required [cf. equation (16) on p. /77].

Of course, the further progress of science may show that all this is far from the truth, but there is no harm in dreaming about it now.

Perhaps, in the future, it will be possible to use electricity to give the particles ejected from our reaction machine an enormous velocity. Even now we know that the cathode rays in a Crooke's tube (x-rays), like the rays of radium, are accompanied by a flux of electrons, the mass of each of which, as we have pointed out, is 4000 times less than the mass of the helium atom, while their velocity approaches 30-100 thousand kilometers per second, i.e., is 6-20 thousand times greater than the velocity of the ordinary combustion products expelled from our reaction pipe.

14. What is Impossible Today may be Possible Tomorrow

There was a time, and not so very long ago, when the idea of determining the composition of heavenly bodies was considered foolhardy, even by famous scientists and thinkers. This attitude is now a thing of the past. Today the idea of the possibility of a close, direct study of the universe may seem even more absurd. To set foot on asteroids, pick up a stone on the Moon, establish mobile stations in space, form living rings around the Earth, the Moon, and the Sun, observe Mars from a distance of a few tens of versts, land on its satellites or even on its very surface -- clearly nothing could be more insane. However, the moment reaction machines come into use we shall witness the beginning of a great new era in astronomy -- an era of more intensive study of the sky. We should not be unduly afraid of the enormous oppressive force of gravity.

A shell traveling at 2 kilometers per second does not seem to us anything unusual. Why then should the idea of a projectile traveling at a speed of 16 kilometers per second and escaping for ever from the solar system into the universal void, having overcome the gravitational attraction of the Earth, the Sun, and the entire solar system, cause us such surprise? Is there such a chasm between 2 and 16? After all, the one is only 8 times greater than the other.

If one unit of velocity is possible, why should 8 such units not be possible too? Is not everything progressing, moving forward at an astonishing rate? Long ago a speed of ten versts would have seemed to our grandmothers incredible, baffling; now automobiles travel at 100 to 200 versts an hour, i.e., 20 times faster than the coaches of Newton's time. Long ago it would have seemed strange to think of using any force other than muscle, wind or water power. We could go on enlarging on this point for ever.

Today, the more advanced levels of society are leading increasingly artificial lives; and is it not in this that progress consists? The struggle against unfavorable weather, high and low temperatures, the force of gravity, wild animals, harmful insects and bacteria is surely creating a purely artificial environment.

In space this artificiality is merely taken to the extreme, but, on the other hand, the conditions are those most favorable for man.

With the passage of centuries, new conditions create a new form of beings, and the artificiality that surrounds them is gradually weakened and may finally vanish. Was it not thus when the creatures of the sea first crawled out onto dry land and became amphibians and then land-dwellers, some of which in turn became creatures of the air: birds, insects, bats? Having conquered the air, is the next step not the conquest of space? Will not the creatures of the air become creatures of space, natives of the realm of pure sunshine and the infinite reaches of the universe?

15. The Reaction Machine an Insurance Against Possible Disaster

What is the terrestrial globe? It is essentially a tremendously hot mass, solid inside due to the pressure of the outer layers, but liquid and molten nearer to the surface. Inside it is still a small sun, only outside is it at rest and covered with a thin, cool crust.

The chemical processes that still go on beneath the surface, the effect of water, and the compression of the central mass, from time to time cause the volcanic eruptions that still disturb the crust.

Who can say for certain that one evil day, after thousands of years, the potential energy of the masses forming the Earth may not be channeled into a force that will sweep every living thing from the face of the globe. The reason for the explosion might be the displacement of the internal constituents of the Earth, or their chemical combination accompanied by the liberation of an enormous amount of heat and an increase in volume. Or the reason might be the disintegration of the heavy elements, accompanied by an accumulation of elastic gases (helium, etc.) and electrons. The result -- a cataclysm destroying the organic world mechanically or by an increase in the temperature of the soil and the air. Finally, the destruction of the higher animals might also result from the release into the atmosphere of gases that interfere with respiration. In such circumstances the reaction machine might save mankind.

Even if an aerolite several versts in diameter fell to Earth it would be enough to cause loss of life. And this might happen quite unexpectedly, since such an aerolite, being a non-periodic comet, traveling through the dark regions of the universe along an hyperbolic path, can not be predicted by the astronomers long before a catastrophe can occur. There have already been cases of masses up to 4 versts in diameter penetrating the Earth's atmosphere. Here the disaster is due to earth tremors, increased temperature of the soil and the air, and many other causes.

We have seen a star flare up, be born, as it were, only once more to fade away. This dark body, resembling the Earth, or a sun that has ceased to shine, has met with catastrophe, either from the impact of gigantic meteors or, more probably, as the result of chemical and radioactive processes in its fiercely hot interior.

An unexpected increase in temperature would instantaneously destroy every living thing that has succeeded in establishing itself in the atmosphere of our planet during the thousands of years that its crust has been at rest. Disasters due to comets have long been anticipated on Earth, and not without reason, although the probability of such a disaster is extremely small. Nevertheless, however unlikely, it could happen either tomorrow or in the course of trillions of years. Comets and other random, improbable, but dangerous and unpredictable threats to life could not easily destroy at one blow all the colonists, who, thanks to reaction machines, had succeeded in establishing populated rings around the Sun....

The number of inhabitants of the globe is increasing constantly and fairly rapidly, in spite of the relatively unfavorable conditions. During the last century this increase was not less than 1% per year.

If we assume that this rate will remain constant, then in 1000 years the population of the Earth will have increased 1000 times.

What could we do with these millions, whom the Earth would be incapable of feeding?*

*Tsiolkovskiy overlooks the increase in productivity and the general progress in agriculture that is to be expected in the course of

Reaction machines will give men access to endless space and put at their disposal solar energy two billion times greater than that available to them on Earth.

But there is more than one sun, there are stars without number, and, accordingly, we shall not only acquire mastery over infinite space, but the infinite vital energy of an infinity of suns.

That other suns can be reached will be apparent from the following considerations: let us assume that a reaction machine is moving uniformly at a mere 30 kilometers per second, i.e., 10,000 times more slowly than light.

This is the speed of the Earth around the Sun. The same speed is not infrequently achieved by aerolites, which shows that it is perfectly feasible (without slackening) for small bodies. Since a ray of light from the nearest stars takes several years to reach us, reaction trains would reach them in the course of several tens of thousands of years.

Naturally, this is a very long period of time compared with the lifetime of the individual, but for mankind as a whole, as for the luminous existence of our Sun, it is negligible.

In the course of tens of thousands of years spent in traveling to another star, the human race, flying in an artificial environment, would live on supplies of potential energy borrowed from the Sun.

Granted that it is possible to transfer humanity to another sun, why these fears regarding the luminous existence of our own star which is still shining? Eventually it will grow dark and become extinct, but during the hundreds of millions of years of its glory and splendor mankind will be able to accumulate the store of energy needed to transfer life to another center.

The gloomy views of the scientists concerning the inevitable end of all life on Earth due to its cooling as a result of a fall in the Sun's temperature should not, to my mind, rank as immutable truth.

In all probability, the better part of mankind will never succumb, but will move constantly from sun to sun in search of fresh energy. After many decillions of years, we shall perhaps be living near a sun that has not yet begun to shine, but exists only in a primordial state, in the form of nebulous matter destined for higher things.

If even now we are able to believe in an eternal future for mankind, what will our attitude be in several thousand years, when our knowledge and understanding will have grown!

1000 years. His arguments are one-sided and can not be accepted as a satisfactory solution of the problem. (Ed.)

Thus, there is no end to life, nor to understanding and the development of mankind. Its progress is eternal. And if this is so, it is impossible to doubt that even immortality will be achieved.

So let us go boldly forward, workers of mankind, great and small, in the knowledge that of all we do nothing will vanish without trace, but bring us great rewards in the infinite future.

EXPLORATION OF THE UNIVERSE WITH REACTION MACHINES*

(Supplement to Parts I and II of Work of Same Title)

Being anxious to obtain more support for my public-spirited endeavors, I have cited everything I know that might inspire confidence in my work.

It is difficult to work alone and in adverse circumstances for many years without receiving recognition or encouragement.

From the articles concerning "rockets" it is clear that with our present technology we are still far from attaining the required velocities.

Now, however, I would like to popularize my ideas, to offer explanations, and refute the view that the "rocket" is something far beyond our grasp.

Below are some of the theorems I have already proved; here I shall dwell only on those that may seem not entirely convincing.

Theorem 1. Suppose that gravity does not diminish as a body moves away from a planet. Suppose further that the body rises to a weight equal to the radius of the planet. Then the body will have done work equal to that required to overcome the gravity of the planet completely.

For the planet Earth, for example, and a mass of one ton this work is equal to 6,366,000 meter-tons. If the projectile, described by Esnault-Pelterie, works for 24 minutes and weighs one ton, it can be readily calculated that in one second its engine will do work on the "rocket" equivalent to 4,420 meter-tons or 58,800 horsepower, not 400,000 as calculated by Pelterie**.

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*First published privately by the author as a separate brochure in Kaluga, 1914. This edition omits the prefatory part of the article, in which Tsiolkovskiy cites a number of press references to his earlier writings (Editor's note).

**Cf. the article of K. Ye. Veygelin in Priorda i lyudi (Nature and Mankind). No. 4, 1914. Without a doubt, I am here correcting misprints rather than any mistake by Esnault-Pelterie.

In my calculations the explosion is more rapid, lasting only 110 sec. Thus, in one second the one-ton projectile must do work equivalent to 57,860 meter-tons or 772,600 horsepower. You may well ask whether this is possible. A projectile weighing only one ton, or 61 poods, doing work equivalent to nearly one million horsepower!

The lightest modern engines develop at most 1000 horsepower per ton (1000 kilograms).

But the point is that I am referring not to ordinary engines but to projectiles resembling artillery shells.

Imagine a cannon 10 meters long firing a one-ton projectile at a velocity of one kilometer per second.

This is not far from reality. Whan then is the work done by the charge on the projectile? It is easily found to be about 50,000 meter-tons -- and that within a small fraction of a second. The mean velocity of the projectile in the barrel is at least 500 m/sec. Therefore, the projectile travels a distance of 10 meters 1/50 sec. This means that the work done by the cannon in one second is 2,500,000 meter-tons or about 33,300,000 horsepower.

This shows that the useful work done by the cannon is 566 times greater than that done by Esnault-Pelterie's rocket, and 43 times greater than that done by my reaction machine.

Thus, from the quantitative point of view, there is nothing in common between reaction-propelled projectiles and ordinary engines.

Theorem 2. In a gravity-free medium, when the direction of the explosion is fixed, the final velocity of a "rocket" is independent of the force and speed of the explosion and depends only on the quantity of explosives (in relation to the mass of the "rocket"), their quality, and the design of the explosion tube.

Theorem 3. If the quantity of explosives is equal to the mass of the "rocket," then nearly half the work done by the explosives is transmitted to the rocket.

This is easily verified by visualizing two spheres of identical mass separated by a compressed spring. On being released the spring will distribute the energy it contains equally between the two spheres.

If, for example, we have a projectile with a nozzle from which an equal mass of hydrogen is ejected at zero temperature, the latent energy of the hydrogen will be divided in two, one half being transmitted to the projectile. The velocity of hydrogen molecules is known to be about two kilometers per second. Therefore, the projectile will be given a velocity of approximately 1410 m/sec. But if we take into account the heat capacity of hydrogen or the rotational motion of the two atoms of which every hydrogen molecule is composed, the projectile will be given a velocity of about 2 kilometers per second.

Now it is no longer difficult to believe in my calculations, from which it follows that when hydrogen combines chemically with oxygen the velocity of the newly formed water molecules bursting out of a fixed tube exceeds 5 kilometers per second, while the velocity imparted to a moving tube of the same mass exceeds 3-1/2 km/sec. In fact, were the entire heat of combustion to be transmitted to the compound, i.e., to the water vapor, its temperature would reach 10,000°C (if it did not expand); then the velocity of the vapor particles would be approximately 6 times greater than at zero degrees (+273°abs.).

The velocity of molecules of water vapor at zero temperature is known to exceed 1 km/sec; therefore, the formation of water vapor from oxygen and hydrogen entails a velocity of up to 6 km/sec, thanks to the chemical reaction.

This, of course, is merely a rough and simplified reworking of my previous calculations.

Thus, when the mass of the detonating gas is equal to the mass of the "rocket," a velocity of 3-1/2 kilometers per second is quite natura, and in fact, this figure is a very modest one.

Theorem 4. If the mass of the rocket plus the mass of the explosives increases in a geometric progression, the velocity of the "rocket" will increase in an arithmetic progression.

This law may be expressed by two series of numbers:

Mass:	2,	4,	8,	16,	32,	64,	128 ...
Velocity:	1,	2,	3,	4,	6,	6,	7 ...

Suppose for example that the mass of the rocket plus the explosives is 8 [units]. I expel 4 units of explosives and obtain a velocity which I will take as unity. Then I expel 2 more units of explosives and obtain yet another unit of velocity; finally, I expel the last unit of explosives and obtain yet another unit of velocity; altogether 3 units of velocity.

This theorem implies that the velocity is far from proportional to the mass of the explosives; it increases extremely slowly, but without limit.

There is an optimal relative amount of explosives for which the energy of the explosion is optimally utilized. This is a figure close to 4.

Nevertheless, the absolute velocities of the "rocket" are the greater the larger the supply of explosives. Below the supply of explosives is compared with the corresponding velocities in kilometers per second:

1,	3,	7,	15,	31,	63,	127,	256	(mass of explosives)
3-1/2	7	10-1/2,	14,	17-1/2,	21,	24-1/2	28	(velocities)

Theorem 5. In a gravitational medium, for example, on Earth, when a "rocket" ascends vertically, part of the work done by the explosives is forfeited; this fraction will be the greater the closer the pressure of the exploding gases on the rocket to the weight of the rocket.

If, for example, the "rocket" together with all its contents weighs one ton and the pressure of the explosives on the rocket is also one ton, there is no or zero utilization of energy, i.e., the explosion is pointless, since the "rocket" stands still and no energy is transmitted to it.

That is why I assume the pressure acting on the "rocket" to be 10 times greater than the weight of the rocket together with its contents.

Esnault-Pelterie, assuming the rocket to weigh one ton (61 poods), assigns one-third, or 20 poods, to the explosives. If the explosive were radium and released its energy millions of times more rapidly than is actually the case, then interplanetary travel would be assured.

I myself dreamed of radium. But recently I made some calculations which showed me that if the particles (alpha and beta) emitted by the radium were oriented in a parallel beam in the same direction, the radium would lose only about one-millionth of its own weight....This made me reject the idea of radium. All sorts of discoveries are possible, and dreams may unexpectedly be translated into reality, but I would prefer to stand on solid ground as far as possible.

Esnault-Pelterie calculated that 20 poods of detonating gas could transmit to the "rocket" only 1/130 of the work needed to liberate it from gravity.

According to my calculations, an even smaller fraction is transmitted, namely, only 1/540. The reason is not that the proportion (one-third) of explosives is low, but mainly that Pelterie assumed the pressure exerted by the gases on the projectile to be only one-tenth greater than the weight of the "rocket." This is 100 times less than what I assume.

On the basis of the last theorem (5), we saw that an explosion in a gravitational medium may even be without results if the pressure exerted by the gases on the device is only equal to its weight.

Actually, the proportion of explosives (one-third) assumed by Esnault-Pelterie far from being the most favorable (4); for this reason, according to my tables, the projectile would acquire a velocity of not more than 1-1/2 km/sec, even if the gas pressure were the same as that which I calculated. But since the pressure on Pelterie's projectile is 9 times less, it will be utilized 10 times less and the velocity will be only about 0.5 km. Now, more than 11 km/sec are required to overcome terrestrial gravity; therefore, this velocity should be 22 times higher, and the energy required for this will be 484 times greater.

Again I repeat that the errors which I observed in Esnault-Pelterie's report are probably as often happens, mere misprints; but I consider it worthwhile correcting them.

To my mind, the successful construction of a reaction machine involves tremendous difficulties and requires years of preliminary work and basic and applied research, but still these difficulties are not so great as to confine us to dreaming about radium and still nonexistent effects and materials.

Is it possible to take along the necessary supply of explosives, even when it exceeds the weight of the "rocket" by dozens of times?

Imagine that one-half of an elongated, spindle-shaped "rocket" is filled with freely evaporating liquid explosives.

These substances are under the influence of the intense relative gravity created by the accelerated motion of the "rocket," and therefore they exert greater pressure on the walls of the "rocket" than when the "rocket" is stationary on Earth. Calculations show that for a sufficiently strong (6) steel rocket 10 meters long, when the relative gravity exceeds 5 times that on Earth, the weight of the explosives can be 50 times the weight of the "rocket" and its contents. This even applies to ordinary materials and a high safety factor. Theory also shows that as the size of the "rocket" increases, the relative supply of explosives required decreases, and vice versa.*

*If we bear in mind the useful load, the weight of guidance systems, engine controls, and other "passive" load elements, the relative weight of the fuel will be less for small rockets than for large ones (Editor's note).

Therefore, it is expedient to make the "rocket" as small as possible -- 10 meters is definitely long enough.

Another important question is the temperature of the explosive materials.

Calculations show that assuming free expansion of the reaction products of detonating gases (as in our explosion tube), the maximum temperature of these products should reach 8,000°C.

In practive, however, not even lime will melt in hot detonating gas. Therefore, the temperature is far from being so high. The phenomenon of dissociation is the reason for this.

When hydrogen and oxygen begin to combine chemically, the sharp rise in temperature prevents the greater part of the molecules from combining chemically, since chemical combination is impossible at high temperatures. Water begins to decompose into hydrogen and oxygen even at 1,000°C. Deville has found the decomposition temperature of water vapor to lie between 900 and 2500°C. Therefore it is conceivable that the maximum temperature of hot detonating gas is 2500°C.

But finding materials that can withstand such a temperature is not an impossible task. Here are a few melting points known to me: nickel, 1500°C; iron, 1700°C; indium, 1760°C; tungsten, 3200°C; and carbon will not even melt at 3500°C. On the one hand, the explosion tube should be intensively cooled and, on the other, investigators should search for substances that are both tough and refractory.

A search for the most suitable explosives should also be instituted. Of all the known chemical reactions, the greatest amount of heat is liberated when hydrogen combines with oxygen. Below are the figures on the amount of heat released per unit weight of certain substances when they combine with oxygen. Hydrogen, when water is is formed, yields 34,180 calories, and when steam is formed, 28,780; carbon, when carbon dioxide is formed, yields 8,080; and hydrocarbons from 10,000 to 13,000 calories. But the figures that matter most to us are those corresponding to unit mass of the combustion products: only these give us a clear idea about the suitability of a given fuel for use in "rockets." We find that the number of calories per unit mass of water vapor is 3200; carbon dioxide, 2200; and benzine, 2370. In general, burning hydrocarbons release more calories per unit mass than carbon, i.e., more than 2200 calories, though not as much as 3200. The more hydrogen there is in a hydrocarbon, the more suitable it is for use in "rockets." Materials yielding nonvolatile combustion products, such as calcium oxide or lime, can not be used.

A gas in liquid form, preferably oxygen, would be useful as a means of cooling the explosion tube. As for hydrogen in liquid form, it could be replaced by liquid or easily liquefiable hydrocarbons. We must search for the hydrogen-carbon compounds that contain as much hydrogen as possible and absorb heat on being formed, like acetylene, for example, which, unfortunately, contains little hydrogen. In this respect, turpentine is more satisfactory and methane, or marsh gas, even more so; the latter, however, has the disadvantage of being difficult to liquefy.

It would also be worthwhile to look for compounds of the same kind so far as oxygen is concerned.

We should look for weak compounds of oxygen with itself (such as ozone) or with other substances, which would provide strong and volatile products on combining with the elements of hydrocarbons and release a great deal of heat.

If we use benzene or benzine for the "rocket" instead of hydrogen, then, in the event that the mass of explosives is equal to the mass of the "rocket" together with all that it contains, we shall find the exhaust velocity of the particles rushing out of the explosion tube to be not 5700 meters but only 4350 meters per second. And the velocity of the "rocket" will then be only 3100 meters per second. We shall thus now obtain the following table of masses and velocities:

Mass of explosive:	1,	3,	7,	15,	31,	63,	127 ...
Velocity of rocket in km:	3,	6,	9,	12,	15,	18,	21 ...

These velocities are also sufficient for interstellar travel.

Hydrocarbons are advantageous, because they give very volatile products: water vapor and carbon dioxide; moreover, a liquid hydrocarbon at normal temperature does not absorb a considerable amount of heat when heated, like liquid and very cold pure hydrogen.

The weight of the explosion tube is an important problem. To solve it we must know the pressure of the gases inside the tube. This question is very complicated and requires an elaborate mathematical argument (which I am preparing for print). Here we shall touch upon it only lightly.

Imagine the inlet of an explosion tube, into which flow liquid gases (say, hydrogen and oxygen) in specific proportions. Only a part of the atoms combines chemically, because the soaring temperature (2500°C) prevents the other atoms from combining. Assuming the density of the mixture of gases to be unity, we find that their pressure --

taking into account the elevated temperature -- will not exceed 5000 atmospheres or approximately 5000 kg/cm^2 of surface of the tube inlet.

As the gases move and expand within the tube, their temperature should decrease; but this will take some time, since the falling temperature immediately revives the chemical reaction, which again raises the temperature to 2500°C. Thus, up to a point, as the gases expand their temperature remains constant, being maintained by the heat of combustion.

After the atoms have combined completely and steam forms, a rapid drop in temperature commences. Calculations show that a sixfold increase in volume means that the absolute temperature is halved. On this basis, I compiled the following table of expansions and corresponding absolute and ordinary temperatures (approximate):

Expansion	1	6	36	216	1296	7776
Absolute temperature	2800	1400	700	350	175	87
Centigrade temperature	+2500	+1100	+400	+50	-125	-213

This shows that a 200-fold expansion corresponds to an almost total release of heat, which is converted to work of translational motion on the gases and the "rocket." Upon further expansion, the gas turns to liquid and even to ice crystals which race from the tube at a dizzying speed.

Such is a rough picture of the phenomena in the explosion tube.

Let us assume, for simplicity's sake, that the tube is cylindrical and let us determine its maximum thickness and the area of the bottom.

Suppose we assume the weight of the "rocket" together with the passengers and all its equipment and supplies to be one ton; and the weight of explosives, 9 tons.

We shall assume that the pressure acting on the rocket is 5 times its weight. The relative gravity of the "rocket" and all its contents will be 5, i.e., 5 times greater than terrestrial gravity. The passengers should be in a prone position, immersed in a container of water. Then their bodily safety can be definitely guaranteed.

Thus, the gas pressure acting on the rocket, or on the bottom of the tube, will be 50 tons, or 50,000 kg. And since the gases at the tube inlet produce a pressure of 5000 kg per square centimeter, the area of the bottom of the tube will be 10 cm^2. The wall of the tube, assuming it is made of the best steel and assuming the usual safety factor of 6, will be 4.5 cm thick, for an inside diameter of 3.6 cm. This means that the outside diameter will be less than 13 cm, and the inside diameter less than 4 cm.

The weight of [one] decimeter of such a tube will be about 10 kg, and of one meter 100 kg, but we should bear in mind that the weight of the tube should sharply decrease with increasing distance from the base, since gases expand rapidly and the pressure diminishes proportionately, not to mention the decrease in temperature, which commences not directly at the tube inlet but at a short distance from it.

Nevertheless the tube will obviously account for much of the "rocket's" weight.

Therefore, an effort should also be made to find materials much stronger than ordinary steel, since steel may not really meet our requirements, if only because it is not heat-resistant enough.

Determining the total weight of the tube without resorting to advanced mathematics is difficult. I shall leave this question for a more detailed treatise.

Somehow the explosives must be delivered to the tube; this requires a tremendous amount of work and is one of the major difficulties. But there is no need to shut one's eyes to it. If the "rocket" weighs one ton and explosives 9 tons, the acceleration of the "rocket" will be 50 m/sec and the pressure acting on it during an oblique (more favorable) ascent will be approximately 50 tons. We assumed the gas pressure per cm^2 to be 5 tons. Now, on the basis of these data, we find that the explosion must continue for about 200 sec, if we wish to attain a velocity of 10 km/sec; accordingly, we must supply the tube with approximagely 45 kg of explosives per second.

The rate of flow of explosives, assuming their mean density to be unity, will thus be about 45 m/sec. The work done in squeezing them into the tube inlet under the enormous pressure prevailing there will be 2250 meter-tons per second or 30,000 horsepower!

This result is one which no present-day engine can conceivably achieve. Therefore, we must abandon the thought of using conventional pumping techniques. It is simplest to introduce a certain charge into the tube and explode it and let it volatilize. Then, in the absence of pressure in the tube, insert and explode another charge, and so on. This should be done by a machine, and at an exceptionally rapid rate. Here, too, difficulties may be discerned.

Note that the useful work done by the explosives in our projectile will average at least 400,000 horsepower, or 13 times the work of forcing the explosives into the tube. Could not this material be introduced by utilizing the energy of the explosion itself, in the same way as Dzhiffar's injector rams water into a steam boiler thanks to the pressure of the steam it contains?

At the inlet of the tube itself there should be a branch pipe through which the gases could return to the inlet and, by virtue of their great velocity, entrain and ram into the inlet a continuous stream of explosives.

Without a doubt, this would be perfectly feasible if structural materials of suitable strength and heat resistance could be found.

In view of the gigantic force exerted by the gas on the "rocket," a force equal to 5 and more tons per ton of "rocket," the problem of steering the rocket can not be an easy one. By bending the outlet end of the explosion tube and thus altering the direction of the exhaust gases, we can produce a lateral pressure and, hence, a change in the orientation of the rocket. But the total pressure acting on the rocket is so great that, by the time the tube outlet (or a rudder attached to it) has been deflected, the rocket will already have deviated considerably from its course or even turned upside down. Rockets, and projectiles designed for military purposes in general, are stabilized by being spun rapidly about the longitudinal axis. With our "rocket" this cannot be done, because the rotation would generate a centrifugal force, which living creatures could not endure. But stability could be achieved if two rapidly rotating bodies with mutually perpendicular axes of rotation were housed inside the rocket. This would increase the "rocket's" weight and thus is not a tempting solution. The goal could be achieved more simply and economically if the explosion tube could be given several turns some parallel to the longitudinal axis of the "rocket" and others perpendicular. Although the mass of the gas jet is negligible, this is compensated by its remarkable velocity, which may reach 5 kilometers per second.

If, for example, the gas density is 400 times less than the density of a rotating disk, while the gas velocity is 20 times greater than the velocity of the disk, the resistance to rotation of the "rocket" owing to the action of the gases will be the same as that produced by the disk if the masses are the same.

Even educated people entertain very confused notions concerning the effects occurring in an ascending "rocket." Writers of works of fantasy either omit to describe the accompanying phenomena or describe them incorrectly.

The apparent gravity inside the "rocket" depends on the acceleration imparted to it by the gas pressure. Thus, if this acceleration is 50 m/sec, the apparent gravity will be 5 times greater than terrestrial gravity, since the acceleration due to the latter is 10 m. Therefore, during the explosion, the gravity in the rocket will be intensified for 3-4 minutes; after the explosion ceases, this gravity will be destroyed, as it were, since the acceleration due to the explosion will fall to zero. Intensified gravity can be easily endured by entering a sturdy vessel shaped like a man's body and containing a little water. There is a need for carrying out preliminary experiments with the aid of a large centrifuge which would also generate an apparent gravity.

Similar experiments should be performed with the aim of determining the respiratory and nutritional requirements of a man traveling in a "rocket" through airless space.

The foregoing is enough to give some idea of the design of a space-travel projectile. This is the right place to include a rough sketch and brief description of the "rocket."

The left-hand, rear half of the "rocket" consists of two chambers separated by a partition (not shown in sketch).

The first chamber contains freely vaporizing liquid oxygen. This oxygen has a very low temperature and surrounds a part of the explosion tube and other components exposed to high temperatures.

The other chamber contains hydrocarbons in liquid form. The two black dots at the bottom (almost in the center) show the pipes supplying explosives to the explosion tube in cross section. Two branch pipes run from the mouth of the explosion tube (around the two dots). These branch pipes carry furiously racing gases, which entrain more liquid explosives and force them into the mouth of the explosion tube by analogy with Dzhiffar's injector or steam-jet pump.

Freely evaporating liquid oxygen in the cold, gaseous state flows through the space separating the two envelopes of the "rocket," thus preventing the interior of the "rocket" from being heated by its rapid motion through the air.

The explosion tube makes several turns along the "rocket," parallel to the longitudinal axis, followed by several turns at right angles to this axis. The object is to reduce the instability of the rocket or improve its steerability. These turns followed by the rapidly moving gas are a substitute for massive rotating disks.*

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*K. E. Tsiolkovskiy later discarded this design (Editor's note).

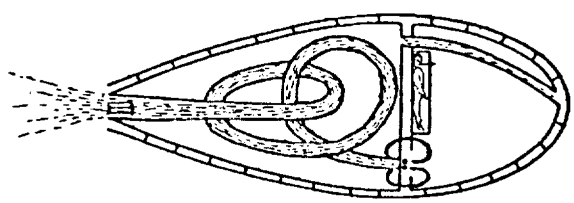
The right-hand forward compartment is isolated, i.e., enclosed on all sides, and contains:

1. Gases and vapors necessary for breathing. 2. Facilities for protecting living organisms against a gravity 5 or 10 times greater than normal. 3. Food supplies. 4. Controls, notwithstanding the prone position in water. 5. Substances for absorbing carbon dioxide, miasmas and noxious exhalations in general.

K. Tsiolkovskiy

EXPLORATION OF THE UNIVERSE WITH REACTION MACHINES

(Supplement to Parts I and II of Work of Same Title)



Sketch of Rocket

Price: 15 kopecks

Kaluga, 61 Korovinskaya Road

Published Privately by the Author

Kaluga, 1914

Cover page of brochure published by K. E. Tsiolkovskiy in 1914 showing a section through his rocket (page is half actual size).

I shall now make some additional rough calculations to compare artillery pieces with the rocket tube. Although I have read that shells have been experimentally fired at a velocity of as much as 1200 m/sec, in practice a velocity of 500 m is satisfactory. If the air resistance is ignored, an artillery shell fired vertically can ascend to 12-1/2 km. If fired at an angle of 45°, it will cover the maximum horizontal distance, namely, 25 km (23 versts). In the first case, the shell will fly for about 100 sec, and in the second, for 70.

At a velocity of 1000 meters, however, the maximum altitude will be 50 km and the maximum horizontal distance covered will be 100 km, the flight time being twice as long.

Using a 14-inch gun with a barrel 10 m long and firing a projectile weighing one ton, we find that the mean pressure per square centimeter of barrel will be about 1250 kg, or 1250 atm. On doubling the velocity of the projectile, the mean pressure will reach 5000 atm. The maximum pressure, of course, is much higher. Therefore, the pressure in the barrel is close to the pressure we assumed for the "rocket" (5000 atm).

Assuming that our gun fires a mass of explosives weighing one ton, and that the projectile travels through the barrel in 1/25 sec (muzzle velocity: 500 km), we find that an average of 25 tons of explosives is expended per second.

In our "rocket," on the other hand, only 45 kg, or only 1/555 times as much explosives is expended. Naturally, the explosion tube of the rocket is commensurately less massive.

The explosion tube of the "rocket" ejects not heavy shells but merely gas molecules. Naturally, their velocity greatly exceeds that of the shells, reaching 5 kilometers per second. The velocity imparted to the "rocket" is of the same order. The hot gases transmit only a small part of their energy to the shell, and only while in the barrel at that. On emerging from the barrel, these gases still have a tremendous pressure and high temperature, as indicated by the thunder and flash that accompany the firing of the gun. The flaring explosion tube of the "rocket" is so long that the temperature and pressure of the gases emerging from its outlet are quite negligible. Thus, in the "rocket" the energy of the chemical reaction is almost fully utilized.

THE REACTION MACHINE AS A MEANS OF FLIGHT THROUGH THE VOID AND THROUGH THE ATMOSPHERE*

Those of my readers who are interested in this extremely important problem should turn to my work "Issledovaniye mirovykh prostranstv reaktivnymi priborami" (Exploration of the Universe With Reaction Machines).** Here I shall merely present a short extract from that article with the object of clarifying some of the problems relating to the use of reaction machines for atmospheric flight. A reaction machine resembles a rocket, in which gases are ejected in one direction, while the rocket is propelled in the other.

The functioning of a reaction machine is virtually independent of the surrounding medium. A rocket would ascend in an airless void just as well as in air.*** The thrust of the reaction machine is devised from the substances it ejects. Physically, these substances may be in any of the three possible states -- it does not matter. It is simplest to eject gases or vapors. Explosives, which release gases at high temperatures, are the most suitable for reaction machines, since substances in gaseous form are ejected with the greatest velocity, thereby contributing to optimal performance. The main elements of a reaction machine are as follows:

1) Compartment for passengers, cargo, and necessary equipment.

2) Separate compartments for two liquids****, the gradual combination of which forms the expelled gases.

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*First published in the periodical "Vozdukhoplavatel." (The Aeronaut), No. 2, 1910, St. Petersburg. Cf. Appendices, Note 14 (Editor's note).

**"Nauchnoye obrazovaniye" (Scientific Education), No. 5, May, 1903. Unfortunately, the article was very carelessly published.

*** The action of the explosives is also more or less independent of the environment.

****The substances may also be in another state.

3) A small chamber in which these two liquids combine.

4) A smoothly expanding tube through which the gases formed by the combination of the liquids are directed. The gaseous products of the chemical reaction are ejected from the flared mouth of this tube.

5) Steering apparatus.

6) Facilities for absorbing the products of the travelers respiration and for supplying him with oxygen in the event that the trip takes him through airless space.

There follow certain mathematical conclusions concerning the conditions for the optimal performance of such a machine in airless space, which also apply in part to its performance in the atmosphere.

The action of the machine is such that it either hovers in the air (or in a vacuum) or moves in some direction.

Let us first determine the hovering time in a gravitational medium (dynamic field).

1. In general, the performance of the reaction machine will be the better the greater the energy of chemical combination per unit mass of products formed.

2. The performance also improves as the mass of explosives increases in relation to the mass of the projectile.

Let us assume that we are using very high-energy explosives in liquid form.

If now the mass of explosives is equal to the mass of the reaction machine plus all its contents, the rocket will hover at the Earth's surface (or several hundred versts above it) for 6-2/3 minutes. If the mass of explosives is six times the mass of the machine, the hovering time will be 19 minutes. If the mass ratio is only 0.1, the hovering time will be 55.4 sec, i.e., about a minute. If we take less energetic liquid explosives or steam ejected under a terrible pressure the hovering time will be even shorter.

The hovering time is inversely proportional to the force of gravity; thus, it will be the greater the further the surface of the Earth; on the Moon, for example, the hovering time will be 6 times greater, because the lunar gravity is just 6 times less. In other words, the reaction machine could hover there for about 2 hours rather than 19 minutes.

While the machine is in equilibrium it can, of course, be given a translational velocity and, in the course of 19 minutes, it could traverse 100 or more versts.

Now let us turn to another effect of the reaction machine: the acquisition of translational velocity.

In the following table:

$M_2 : M_1$	0.1	0.5	1.0	2	3	4
V	543	2308	3920	6260	7880	9170
$M_2 : M_1$	5	6	8	10	50	193
V	10 100	11 100	12 500	13 650	22 400	30 038

$M_2 : M_1$ denotes the ratio of the mass of explosives to the mass of the reaction machine together with all its contents; V is the velocity in meters per second, imparted to the machine in the course of the explosion or after the entire supply of explosives has been consumed.

From this table we see that the velocities obtained by the reaction method are far from negligible.* Thus, assuming the relative mass of explosives to be 193, the velocity of the projectile will be

*The mass of the reaction machine can be arbitrarily large.

equal to the velocity of the Earth's rotation about the Sun. If the supply of explosives is equal to the mass of the projectile, the velocity of the latter will still be twice as high as that required for a stone hurled from the Moon's surface to leave that surface forever and become a satellite of the Earth. The same velocity is nearly sufficient for bodies hurled from the surface of Mars or Mercury to leave that surface forever.

Given a mass ratio of 3, the velocity of the projectile will be nearly enough for it to orbit the Earth outside the atmosphere, like a satellite.

When $\frac{M_2}{M_1} = 6$, the projectile will leave the Earth forever and become a satellite of the Sun -- an independent planet, one of the Earth's brothers. If the proportion of explosives were still higher, it would be possible to reach the asteroid belt and even the heavy planets.

All this depends upon an instantaneous explosion in a gravitational medium or a slow explosion in the absence of gravity.

The greater the gravity, the closer the flight will be to the vertical, and the slower the explosion the lower will be the final velocity compared with the value given in the table.

If the projectile carries human passengers and sensitive instruments, the explosion must be slow, lasting several minutes; but even with such a completely safe explosion the resulting velocity imparted to the projectile will differ very little from that given in the table; it will be approximately one-tenth less, i.e., 0.9 of the original value (see table).

THE SPACESHIP*

If an object is acted upon from below by a force greater than its own weight, the object will not only rise but experience a continuous acceleration. After some time, the body may attain a velocity sufficient for it to leave the Earth and even the solar system forever.

This is the basis for interplanetary and interstellar, i.e., intersolar travel.

A relative velocity (i.e., relative to the Earth considered as stationary) of 11.2 kilometers (11 versts) per second is quite sufficient for a projectile to overcome the Earth's gravitational pull and wander along the annual path or orbit of our planet, while a relative velocity of 16-1/2 kilometers (or 16 versts) is sufficient for the projectile to escape forever from the gravitational restraint of the Sun.

(Note that all the figures and arguments presented here are based on calculations contained in my published and unpublished writings.)

In escaping from the Sun, it is necessary to make use of the diurnal, and especially the annual motion of the Earth. Otherwise, the enormous velocities required prove less feasible. We can avail ourselves of the kinetic energy of the terrestrial sphere, harness it so as to achieve the maximum velocity at the minimum expense. Of course, in this case the relative motion imparted to the spaceship cöincide in direction with the motion of the point on Earth at which the spaceship is located.

Perpetual orbiting of the Earth outside the atmosphere requires a velocity of at least 8 kilometers per second. Such a projectile could be likened to a little Moon.

These velocities will not appear excessive if we consider that artillery shells reach a velocity of 2 kilometers per second, while the combustion products of the most energetic explosives achieve an exhaust velocity (in a vacuum) of 5 kilometers per second.

Thus, the problem reduces to exerting on a body a force several times greater than its own weight. For example, for a body weighing one ton the force should be two, three or ten tons.

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*First publication of 1924 MS. CF. Appendices, Note 26 (Editor's note)

If, however, the barrel of the gun is short, e.g., 60 kilometers long (a kilometer is just a little less than a verst), the force required to achieve a velocity of 11 kilometers per second will be 100 times greater than the normal weight of the projectile and all it contains. Then the weights of the bodies inside will increase a hundredfold. A traveler weighing 100 kilograms (6 poods) will weigh 10 tons, or more than 600 poods, in the barrel of the gun, during the explosion. His hand, normally weighing 10 pounds, will now be subject to a gravitational pull of 25 poods [approximately 425 kg]. Such a force could hardly be endured by even a heavily protected human being.

Besides, a gun with a barrel 60 km long is hardly feasible even if it rested against a mountain.

If the barrel were 600 kilometers long, the apparent gravity in the projectile would increase tenfold. Even this gravity can be withstood by a human being, provided he is immersed in a liquid of the same density as the mean density of his body.

I shall now explain the significance of the liquids as a means of protection against the destructive effects of increased gravity. Suppose that you are immersed in a liquid of the same density as the mean density of your body. You are breathing through a small tube extending beyond the surface of the liquid. Your weight vanishes, as it were, being balanced by the pressure of the liquid. You neither rise nor fall, but remain in equilibrium, whatever the depth (I shall neglect the nonuniform compression of the liquid and the different parts of the body). Now suppose that the relative or absolute gravity increases a thousandfold. You will continue to be in equilibrium and you will not be aware of the intensified gravity. It will not exist for you. Actually, although the weight of your body has increased a thousand times, the pressure of the liquid surrounding you has increased by the same factor. This means that equilibrium has not been disturbed.

Obviously, liquids will protect man against the terrible consequences of a formidable increase in gravity. It is not for nothing that nature has domiciled in water the most primitive and least viable organisms. The enormous weight of whales does them no harm, since it is offset by the water in which they live. In the higher animals the brain floats in a fluid, as do delicate embryos. This gives protection against shock and rupture, and against forces exerted during leaping and falling.

This measure would be effective even in the presence of the fiercest gravity, if the animal's body were completely uniform in density. Unfortunately, this is not true of man and the other higher animals. Bones are much denser than muscles, and muscles are denser than fat. As gravity increases, the bones are pulled downward, while the fat tends upward. This difference in pressures would destroy any organism, if the gravity were sufficiently great.

Only experiment can serve to determine the maximum relative gravity that can be withstood by man without danger to his health under various specific conditions. I consider a tenfold increase in gravity possible; but then the gun barrel would have to be 600 kilometers long. Inevitably, a barrel so long would have to be positioned horizontally along the Earth's perimeter. The cost of the project would be fantastic, its feasibility dubious. Moreover, the resistance of the air to horizontal or slightly inclined flight at a tremendous initial velocity would destroy the greater part of the kinetic energy of the projectile, so that, on emerging above the atmosphere, it would lack sufficient velocity.

Electromagnetic and other firing systems would inevitably produce the same unfortunate results.

Velocity can also be acquired by thrusting aginst the air, like an airplane or dirigible. But these velocities are very much less than what is required. The airplane's velocity of 100 meters per second or 360 kilometers per hour amounts to only 1/120 (less than 1%) of the velocity required to overcome terrestrial gravity completely. With such a velocity one could not even rise above the atmosphere.

It is hardly likely that the ordinary, unmodified airplane could be given a cosmic velocity. First of all, the propeller, even though made from the very best structural materials, could not (whatever its diameter) be given a tip velocity of more than 200-400 meters per second. Thus, the speed of airplanes must be restricted to 100-200 meters per second, i.e., 360-720 kilometers per hour.

But they could be modified, fitted with some other, propellerless drive, namely, special turbines through which air is expelled. This method would appear to provide unlimited velocity; moreover, there is an unlimited supply of material to be expelled, namely, air taken from the atmosphere, which would also provide oxygen for fuel. At higher altitudes, however, the oxygen disappears and is replaced by hydrogen.* It may be that hydrogen, too, would prove useful as a fuel.

It is even simpler to propel airplanes by means of a supply of explosives. But then the airplane becomes a gigantic rocket.

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*According to the latest information, the composition of the atmosphere hardly changes at all with altitude (verified to altitudes of the order of 120 km) (Editor's note).

This method would appear to be inferior to that suggested above. In fact, it would be necessary to take on board stores not only of fuel but also of oxygen, the weight of which is 8 times greater than that of the lightest fuel -- hydrogen. Such a vehicle, compared with that discussed above, would be burdened with 9 times as much potential energy in the form of explosives.

Theoretically, at some level of the atmosphere there whould be an explosive mixture of oxygen, nitrogen and hydrogen. True, this mixture must be very thin, but it could be condensed with the aid of special centrifugal pumps. Then the rocket could be launched without large stores of fuel and could freely acquire tremendous velocities in the rarefied layer of air, while moving parallel to the Earth's surface.

Having reached a speed of eight or more kilometers per second in the very thin atmosphere, the rocket could leave it behind and, like the Moon, race for eternity around the Earth.

Lastly, there is a third and most attractive method of acquiring velocity. This consists in the transmission of energy from the outside, from Earth.

The projectile itself need not carry "material" energy, i.e., extra weight, in the form of explosives or fuel. This energy could be transmitted to it from the planet in the form of a parallel beam of shortwave electromagnetic rays. If the wavelength were not more than a few dozen centimeters, this electromagnetic "light" could be transmitted to the airplane in the form of a parallel beam by means of a large concave parabolic mirror and thus provide the energy needed to expel particles of air or a store of inert material and thus attain cosmic velocities while still in the atmosphere.

This parallel beam of electrical or even luminous energy (solar rays, for example) should itself exert a pressure (the existence of which is still in doubt), likewise capable of imparting sufficient velocity to the projectile. In this case no store of inert material would be needed. The latter method would appear to be the best. Indeed, a power station of almost unlimited size, generating enormous amounts of electrical energy, could be built on Earth.

This station would transmit energy to the space vehicle, which would utilize it and thus be relieved of the need to carry heavy supplies of fuel. The vehicle would then carry only human passengers and whatever was necessary to preserve and support life during the trip or during an endless voyage through space. This would much simplify the problem of interplanetary travel and the colonization of the solar system.

But all this is to hypothetical (dubious) and scarcely amenable to calculation. Moreover, if it is necessary for the projectile to carry a store of inert material for expulsion, would it not be more reasonable to use explosives for this purpose, since these would provide not only thrust but precious energy.

At high altitudes, however, it is best to use rarefied air as the material for expulsion; this air, of course, will have to be condensed in special centrifugal compressors. If the first cosmic velocity (about 8 versts per hour)[sic] is achieved in this extremely thin air, the projectile, following a spiral path, will emergy from the atmosphere and become a tiny, but permanent satellite of the Earth. From this point on it is easy to achieve any desired increase in velocity for purposes of further space travel. External energy will no longer be needed: the solar energy surrounding the projectile will suffice.

If we use only the pressure of a beam of electric or other rays, the question arises whether this pressure would suffice, and whether the beam might not burn the projectile together with all it contained or merely kill the passengers.

The edge of the square parabolic reflector should be at least 12,600 meters or 12.6 kilometers (12 versts). This cannot be considered feasible at present. Moreover, the beam, with a temperature of several thousand degrees at the focal point, would instantaneously melt even the toughest parts of the spaceship. Moreover, how could the energy flux be continually trained on the moving projectile as it continually changed its position ? This method of imparting velocity raises quite a few difficult problems, the solution of which I shall leave to the future

But the pressure of sunlight, electromagnetic waves and helium particles (α-rays) can even now be applied in the ether to projectiles that have overcome the Earth's gravitational pull, have risen above the atmosphere, and merely need a further increase in velocity. The point is that in the airless void a moving projectile can acquire further velocity with arbitrary slowness. Thus, no monstrous bursts of energy are needed, and the insignificant pressure of light and positive and negative electrons (and α-rays) can be utilized.

I have indicated the magnitude of the velocities needed to overcome the gravitational pull of the Earth, the planets, and the Sun, but I have not calculated the amount of energy involved. Only by determining the work done by gravity can we envision the energy that must be released by a spaceship. Simple integration (a special mathematical technique) will show that this energy is the same as that required by a vehicle or anything else to rise to a height of one Earth radius (half-diameter), assuming gravity to be constant and nondecreasing.

Actually, with increasing distance from the planetary surface, gravity is 4 times less at one, and 9 times less at two Earth radii. More concisely, gravity decreases with increasing distance from the center of the planet as rapidly as the attraction exerted by a magnet, which becomes inperceptible at a distance of a few steps. Now it is possible to understand why the work done by gravity is not infinite but, on the contrary, of a definite and not very considerable magnitude (like the work done in pulling a nail away from a magnet).

If a body weighs one ton (64 poods), the total work done by terrestrial gravity, as this body is removed to an infinitely increasing distance, will be 6,367,000 meter-tons, i.e., it can be expressed numerically as [the product of the weight of the body and the radius of the planet].

Compare this work with that available to man at present. One ton of hydrogen, on burning in oxygen, releases 28,780,000 large calories, the equivalent of 12,300,000 meter-tons. Thus, if this energy could be entirely converted into mechanical work, there would be twice as much as is needed to enable one ton of fuel or some other substance to escape the Earth's gravity completely and travel toward infinity.

Petroleum will provide up to 13,000,000 calories or 5,560,000 units of work, i.e., the energy of petroleum is not quite enough for its mass to escape terrestrial gravity.

True, in the ether there is no oxygen and therefore, as far as rockets are concerned, we should have to take along a supply of oxygen. In general, we would ferry to the rocket fuel, oxygen and, of course, the spaceship itself together with its passengers and equipment.

One ton of a mixture of hydrogen and oxygen, which react to form water, will release 1,600,000 meter-tons of work. This is only one-fourth of that needed to overcome the weight of the combustion products (water) alone. Benzine and oxygen release 1,010,000 meter-tons per ton. This is less than one-sixth of the energy needed.

The energy of radium and other such substances is gigantic, but it is released so slowly as to be quite impractical.* Thus, one ton of radium releases about one billion meter-tons in 2000 years, i.e., a million times more than coal in forming a ton of products (carbon dioxide).

But one kilogram of radium provides about 130 large calories per hour, equivalent to 55,640 kilogrammeters of work or about 15.5 kilogrammeters per second. Therefore, a kilogram of radium continuously provides the work of a laborer if ideally utilized.

*At the time when this article was written, notions about intratomic energy were insufficiently developed and the potential of chain reactions was unknown (Editor's note).

Under these conditions, one ton of radium provides about 155 horsepower. Therefore, in terms of weight, radium is 6 times less productive than airplane engines, which develop 1,000 horsepower per ton. Besides, the quantity of radium required could not be found, i.e., not enough is being mined, and, in addition, its cost is enormous, so that there is still no radium engine, and the ideal utilization of radium is still impossible.

But it is possible to utilize negative (alpha) and positive (beta) electrons, i.e., cathode and anode (or canal) rays, especially the latter, if their velocity can be many times reduced (e.g., 100 times). At present the lower velocity limit is several hundred kilometers per second. Even this velocity cannot insure the efficient utilization of their energy, since it greatly exceeds even the maximum escape velocity (16 versts per second) required to travel to other suns.

I am referring to the use of electricity, the action of which is always accompanied by the ejection of helium nuclei and electrons. The Franklin wheel effect demonstrates that their speeds can be greatly reduced by the ambient medium, whereupon they develop an appreciable pressure. This pressure can be utilized directly, even in a highly rarefied medium. Its utilization in a vacuum is more difficult, since it then becomes inperceptibly small. The electrical force, on the other hand, could be made infinitely large and thus could provide a mighty flux of ionized helium, which could be harnessed to meet the needs of a spaceship.*

But let us abandon these dreams for the time being and return to our prosaic explosives.

It appears that even the most energetic explosives, under ideal conditions, are incapable of overcoming their own weight completely.

Nevertheless, I shall proceed to show that, if present in sufficient quantities, under certain conditions explosives can impart to spaceships any desired velocity and thus make space travel possible.

Suppose there is no gravity and two bodies of equal mass are held apart by a compressed spiral spring. When the spring is released, the two bodies, previously motionless, acquire different velocities. The same thing, more or less, would occur, if we replaced one of the bodies with an equal mass of compressed gas flowing through a tube in a single direction. For the moment let us confine ourselves to a single hollow sphere fitted with a flared tubular outlet and containing a compressed gas or a superheated volatile liquid. The gas

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*This reasoning is highly approximate (Editor's note).

will rush out in one direction, and the equally massive vessel will be propelled in the other. The speeds, as I noted before, are only approximately equal. In order to attain greater velocities, instead of gas or steam, we could use explosives such as gunpowder, nitrocellulose, or dynamite.

In a vacuum the velocity of the exhaust gases may reach 5 kilometers per second if the tube is sufficiently long. This means that our projectile, if its mass is equal to that of the explosives, can be given an almost identical velocity.

But suppose the mass of the explosives is three times that of the rocket together with all its other contents. Taking the weight of the rocket as unity, the weight of the explosives will be 3 ($2^2 - 1 = 3$). If we first explode two units, the other two units will be given a velocity of 5 kilometers per second. Then, we explode another unit and obtain our increment of 5 kilometers in the velocity of the projectile. Now the projectile will have a velocity of 10 kilometers. Let us now suppose that the supply carried by the rocket is 7 units ($2^3 - 1 = 7$) and that we start by exploding 4 of these. The remaining 4 units are given a velocity of 6 km/sec. Then we explode two more units. The remaining two units are given another 5 km/sec, or a total of 10 km/sec. Lastly, we explode a single unit. The empty rocket is thus given another velocity increment of 5 km/sec, so that its velocity is now 15 km/sec.

The ratio of the supply of explosives to the mass of the $2^4 - 1 = 15$; $2^5 - 1 = 31$; $2^6 - 1 = 63$; and in general, $2^n - 1$. The corresponding velocities of the spaceship at the end of the explosion will be: $5 \times 4 = 20$; $5 \times 5 = 25$; $5 \times 6 = 30$; $5 \times n$ km/sec, respectively.

Clearly, these velocities increase without limit; however, even interstellar travel does not require a velocity of more than 17 km/sec.

In our reasoning we ignored the gravitational effect. Now, in a gravitational medium, part of the work done by the explosives is forfeited. This part will be the smaller the more rapid the explosion, and the nearer the course of the projectile to the horizontal.

Thus, assuming an instantaneous explosion, there will be no loss of energy. Nor will there be any losses if the direction of the explosion is normal to the gravity effect (i.e., to its direction, or vector), however weak the force of the explosion may be.

But here we encounter two obstacles. In the event of an instantaneous explosion, if it were feasible at all, the relative gravity within the projectile would be infinitely large and therefore would kill any living being and destroy the entire contents of the spaceship as well as the spaceship itself.

When the direction of the explosion is horizontal, the rocket falls back to the planet before it can acquire the necessary gravity-annihilatiag velocity. (At a velocity of 8 kilometers per second in the neighborhood of the Earth the centrifugal force and the gravitational force are equal, so the projectile, revolving around the Earth outside the atmosphere, becomes a sort of moon.) Moreover, in the case of an horizontal explosion and nearly horizontal flight, the thickness of the atmosphere traversed increases many times over. This will cause a large part of the work done by the explosives to be wasted in overcoming the drag. Thus, both extremes are unsuitable.

Calculations show that the optimum angle of flight with respect to the horizon is between 20 and 30°*. Then the resistance of the atmosphere is not very great, the relative gravity inside the rocket is small, and the loss of energy due to gravitational attraction is not significant.

Thus, it would seem that a projectile of any mass can acquire an escape velocity, even when carrying a relatively small supply of explosives.

But, once again, the apparent ease with which this can be accomplished is an illusion. Calculations show that if the explosion proceeds gradually as in an ordinary rocket or in the latest rockets being planned by Oberth and Goddard, the weight of the vessel containing the explosives will be very large in proportion to their mass. In fact, in all the rocket systems with which I am familiar, the gas pressure developed during the explosion is transmitted to the entire inner surface of the container, which must therefore be made very strong and heavy. How can such a rocket be light in weight?

The gas pressure developed by the most energetic explosives reaches 5000 atmospheres or 5 tons per sq. cm. Suppose we use one or several containers of the optimum cylindrical-spherical shape, made of the strongest and lightest material (strength 100 kg per mm^2, density 8). Lightweight magnesium and aluminum alloys melt and are quite unsuitable. If the safety factor is reasonable (4) and the strength of the material is not affected by the rise in temperature,

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*If the rocket can be guided, it is best for it to penetrate the atmosphere at an angle of 90° and then change direction as desired. For jet planes the optimum angle depends on the ratio of initial thrust to initial weight (Editor's note).

calculations show that the weight of the container (or boiler) will be 30 (thirty) times greater than the weight of the explosives it contains. Here the density of the explosives is taken as unity (density of water). If, for example, we have one ton of explosives with the density of water, the best boiler containing them will weigh 30 tons. If the explosives have twice this density, the container will be 15 times heavier. Conversely, as explosives in the form of liquid hydrogen and oxygen are on the average twice as light as water, the vessel containing them will weigh 60 times as much.

If we assume a pressure of only 2500 atmospheres and take the density of the explosives as unity, then the container will likewise weigh 15 times as much. Tantalum is extremely strong and heat-resistant. Its tensile strength at a density of 10 (according to Mendeleyev) reaches 250 kilograms per mm^2. This material, if used for the containers, will make it possible to reduce their relative weight by a further 50%. Thus, in the limit, the relative weight of the container may descend to 8. This means that, even if we ignore the weight of the rocket with all its contents other than the container and the explosives, i.e., if we consider the rocket to consist solely of the containers and explosives, such a rocket cannot lift the explosives if the mass ratio is more than 1/8. Moreover, if, in addition to the container, the rocket must also lift an additional load weighing half as much as the container, the weight of the explosives can be only 1/16 of the weight of the rocket.

For a rocket of practical dimensions, we may assume the mass of the explosives to be 10% of the mass of the rocket with all its contents.

What altitude can be attained by a projectile with such a minimum supply of energy? Disregarding drag and gravity, we find that my table gives a velocity of 543 meters*. This corresponds to an ascent to an altitude of about 15 kilometers.

The pressure developed by gunpowder, nitrocellulose, and other explosives may be less than that specified, but their effect, or energy, is not so great.

In any case, as we shall see, a higher proportion of explosives and greater velocities are possible, even for a very simple rocket.

The refinements of Goddard's rocket do not affect the problem

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*Exploration of the Universe with Reaction Machines, this volume, Russian p. 82 (Editor's note).

in any way. Theory shows that the number of containers, even if inserted one inside the other, and the order of the explosion do not condition any reduction in weight.

Compressed "constant" gases, no matter how elastic, yield the same result, i.e., the weight of the compressed gas is at least 8 times less than the weight of the containers.

But substances may exist which develop low pressures at high densities. For example, heated water and other liquids and liquefied gases. Thus, superheated water has considerable potential energy and may yield, instead of 5000 atmospheres of pressure, one, ten, one hundred or more atmospheres.

This would greatly reduce the weight of the containers, but, unfortunately, the latent energy of water is extremely small compared with that of explosives. The most exact calculations show that under the most favorable conditions superheated water could lift itself and the boilers higher than 60 kilometers. Moreover, the suitability of superheated water (water at as much as 200°C) for this purpose has still to be tested, so that these calculations may be inapplicable for purely practical reasons. Although the velocities imparted by hot water are far from cosmic, water heated to 150-200°C may prove useful for the initial experiments.

Is there a way out? There appears to be a very simple one. The most energetic explosives must be used, but they must be exploded in a special small, but extremely strong container, which I shall term the explosion chamber, or the admission section of the explosion tube. The gas pressure will affect only this chamber and its continuation -- the explosion tube, through which flow the explosion products, gradually expanding and cooling owing to the transition from random thermal energy to kinetic energy, i.e., to an ordinary jet of gas.

The volume of the table and explosion chamber is very small. Therefore, their mass cannot be very great either. It is definite and does not increase with increase in the supply of explosives. The containers holding the explosives are not exposed to pressure, except that which develops during the acceleration of the rocket due to their intensified relative weight. These containers or tanks may be very light, particularly if the projectile is of the multi-chambered (bulkheaded) design with many explosion tubes.

But the design of such a rocket, in which the supply of explosives may be many times greater than the weight of the projectile with all its other contents, is complicated. The explosives must be pumped continuously into the explosion chamber. In a gravity environment the explosion must proceed very rapidly. Here no procrastination is possible. The quantity of materials exploded per second is large, and the pressure is several thousand atmospheres. Naturally, the work of pumping is correspondingly enormous. We shall presently consider its extent and feasibility.

TABLE 1

Time in seconds after launching	Troposphere						
	0	1	2	3	5	7	10
Velocity, km/sec	0	0.03	0.06	0.09	0.15	0.21	0.30
Distance traversed, km	0	0.046	0.183	0.413	1.15	2.25	4.6
Height, km	0	0.023	0.91	0.26	0.57	1.12	2.3
Air density and remarks	1	Troposphere. Normal composition of air. Precipitation clouds.					
Time	90	100	120	150	170	200	220
Velocity	2.7	3	3.6	4.5	5.1	6	6.6
Distance	371	459	660	1030	1330	1830	2220
Height	185	230	330	515	660	915	1110
Air density, gravity, remarks	0.000006 Black sky. Geocoronium hydrogen*		0.000002 Black sky.			Void--ether	
Time	370	380	390	400	420	450	470
Velocity	11.1	11.4	11.7	12.0	12.6	13.5	14.0
Distance	6184	6235	6287	7339	7980	9290	10 140
Height	3100	3117	3143	3669	3990	4645	5070
Gravity	0.45			0.41	0.38		0.31

*Modern meteorology does not confirm the predominance of hydrogen in the upper layers of the atmosphere (Editor's note).

[Table continued next page]

[Table continued]

Time in seconds after launching	Stratosphere						Hydrogen	
	15	20	30	40	50	60	70	80
Velocity, km/sec	0.45	0.60	0.9	1.2	1.5	1.8	2.1	2.4
Distance traversed, km	10.3	18.3	41.3	73.4	115	165	225	294
Height, km	5.1	9.1	20.6	36.7	57.5	82.5	112	147
Air density and remarks	0.5	0.3	0.06	0.006	0.000020 Stratosphere. Shooting stars. Noctilucent clouds.			
Time	250	260	270	280	290	300	320	350
Velocity	7.5	7.8	8.1	8.4	8.7	9.0	9.6	10.5
Distance	2870	3101	3340	3596	3858	4130	4700	5620
Height	1435	1550	1670	1798	1929	2065	2350	2810
Air density, gravity, remarks	void--ether	0.66	Gravity 0.61					0.5
Time	500	520	550	570	600	620	650	700
Velocity	15.0	15.6	16.5	17.1	18.0	18.6	19.3	21.00
Distance	11 470	12 460	13 880	14 900	16 510	17 600	19 380	21 480
Height	5735	6230	6940	7450	8275	8800	9690	11 240
Gravity		0.26		0.21		0.18		0.13

Note that the explosion may be brought about by either of two means: 1) a ready-made explosive, e.g., gunpowder, dynamite, etc.; or 2) two or more substances stored separately, for example, petroleum and an oxygen-rich substance which, on being mixed in the explosion chamber, produce an intense jet of gases. The latter technique is in every respect more practical. As for the former, it is very hazardous, involving the possibility of the instantaneous detonation of the entire store of explosives. Henceforth we shall assume that two or more liquids are mixed together in the explosion chamber, liquids that under normal conditions, prior to mixing, exert a negligible pressure.

Thus, in order to attain cosmic velocities, the space rocket must be rather complicated in design. It must be fitted out with continuous-action pumps or injectors and motors for driving them.

This idea of a special explosion chamber will not work if we use superheated water or compressed or liquefied gases, since these develop pressure throughout their mass. As for heating them as they are pumped into the explosion chamber, this is impossible because of the extraordinary and unavoidable rapidity of the process. Thus, in the cold state, at low pressures, these substances are unsuitable, since they cannot be rapidly heated in the explosion chamber, while, if used in hot state, they require heavy containers.

This means that superheated water is suitable only for preliminary experiments and tests designed to provide experience in controlling the explosion, varying the velocity, direction, etc. This will cost relatively little and can be accomplished readily, that is, so far I see no technical difficulties in the way.

Let us return to our modified spaceship. In design it bears the same relation to the old rocket as the boilers of Watt's time bear to Serpolet's steam generators, in which water is supplied to fine heated tubes, where it instantaneously evaporates. The space inside these tubes is extremely small, and therefore in theory the weight of the steam generator can be extremely small compared with the heavy cylindrical boilers still being used to this day.

As my calculations show, when the space rocket is launched at an angle of 30° to the horizontal, almost all the energy of the explosives is utilized, that is, gravity and atmospheric resistance absorb only a small part of this energy and the process is almost as successful as in a gravity-free environment. In the rough calculations presented in this article, I shall disregard these losses and assume a rocket acceleration of 30 m/sec. The relative gravity inside the rocket may be three times greater than on earth. In a prone position, a healthy young man could endure this without having to be immersed in water. But in no circumstances should the use of protective devices be ignored.

The table shows approximately (as always in this article): time in seconds from the moment the spaceship begins to move, the corresponding velocity in kilometers per second, the distance traversed and the height achieved, both in kilometers. The fifth row shows the density of the atmosphere, its composition, and the force of gravity.

By studying this table attentively, we can get a picture of the rocket's flight.

When launched at an angle of 30° to the horizontal, the rocket continuously accelerates. After 15 seconds the velocity reaches 0.45 kilometer (450 meters) but by now the resistance of the atmosphere is only half as great, since the projectile has climbed to 5 kilometers -- an altitude at which the air density is half that at sea level. After a further 5 sec the density diminishes to one-third, as the rocket reaches an altitude of 9 kilometers traveling at a velocity of 600 meters. Now the composition of the atmosphere begins to change: the percentage of lighter gases (e.g., nitrogen, hydrogen, argon, etc.) increases somewhat, and that of heavier gases (e.g., carbon dioxide)decreases. We have now flown above the region of clouds, vapors, and precipitation (the troposphere). All around us extends the dry, bright, dark-blue sky. Thirty seconds after the start of the flight the velocity reaches nearly one kilometer (900 meters) per second, and the air resistance is very slight, since the projectile has reached an altitude of 20 kilometers, where the density of the air is 0.06, i.e., where the air is 17 times thinner than below.* We are now flying through the stratosphere where we occasionally catch a glimpse of cirrus clouds. This is the region of shooting stars (the region where they burn up and vanish) and noctilucent clouds. We shall have flown through it within approximately one minute of the start of the flight, reaching an altitude of 80 kilometers and an atmosphere already rarefied as much as 50,000 times, so that it can scarcely be sensed at all. According to Wegener, at this point the sky ceases to be blue. The velocity of the rocket reaches 1.8 km (1,800 m) per second. This is comparable to the muzzle velocity of an artillery shell.

Now the air resistance need no longer be taken into account, and therefore the rocket may incline more and more toward the horizontal, so that its path becomes increasingly circular, like the orbit

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*More accurate data on the density of the atmosphere at different altitudes can be found in tables of the international standard atmosphere (Editor's note).

of the Moon. In the table I kept this angle of inclination constant. But this is no longer necessary, once the rocket emerges at the top of the atmosphere. The very high altitudes indicated in the table are unnecessary. The main thing is for the rocket to become an Earth satellite, like a small moon revolving close to the earth. Once this is accomplished, it is easy to proceed to all sorts of further maneuvers, culminating in escape from the solar system and flight to the stars.

And so we fly through the hydrogen sphere, surrounded by a black firmament dotted with bright glowing stars. Rising above 80 kilometers, we enter the region of geocoronium with a small percentage of hydrogen -- the mysterious sphere of the aurorae.

After 150 sec, or 2-1/2 min, we leave even this gaseous medium behind and enter the absolute void -- the region of the luminiferous ether, where our motion is no longer affected by air resistance.

The velocity of the spaceship now reaches 4.5 kilometers (4500 meters) per second. It is now at a distance of 500 kilometers from the Earth's surface. But even this velocity is still not enough to make it a reliable Earth satellite. The rocket, inclining toward a circular flight path, must still continue its accelerated motion for an additional 2 minutes, making a total of 270 sec from the moment the flight began. It will then attain a velocity of 8 km/sec and soar to an altitude of 1700 versts. There the force of gravity is 35 percent less, and the rocket would have soared much higher had not it inclined toward the usual trajectory of planets and satellites and expended its energy not so much in overcoming gravity as in acquiring velocity.

At this point the explosion may be terminated. The velocity of the rocket is now no longer affected by atmospheric resistance, and its centrifugal force is equal to the Earth's gravitational pull. Now its distance from the planet will not change, and its position will be constant, to the extent that the positions of heavenly bodies can be constant.

If, however, we assume that the explosion continues, our table will show the following results. The figures for this eventuality were calculated without taking into account the decrease in gravity with increasing altitude. However, it is not the altitude, but the velocity acquired that counts. It is the velocity that makes it possible, after the explosives have burned for 370 seconds, to escape the Earth entirely and follow in its annual orbit like a sister planet.

If the explosion lasts 550 sec or 9 minutes, the velocity will not only be sufficient for the rocket to reach any planet in our solar system (provided the direction of the launching coincides with that of the Earth's annual motion) but also to overcome the gravitational pull of the Sun completely and wander among the other suns of the Milky Way. This negligible velocity will overcome the mighty pull of the Sun because it is calculated relative to the (Earth). As for the velocity relative to the Sun, it will be extremely high. In fact, we exploit the Earth's motion, thus gaining enormous additional velocity (nearly 30 kilometers per second, or altogether approximately 47 kilometers per second) while the Earth itself loses very little.

I have not yet touched upon the subjective sensations of the passengers. I shall come to this later. My present aim is a different one, and I have merely digressed in describing the atmosphere.

In my previous publications I calculated that, in order to gain a velocity of 8 km/sec and become a moonlet orbiting the Earth, a spaceship would have to take on board a store of highly energetic explosives 4 times heavier than the rocket and all its other contents.

If the projectile together with its passengers and equipment weighs one ton, the explosives will have to weigh 4 tons, or 4000 kilograms, to be consumed in 270 sec, that is, at an average rate of 15 kilograms per second. As agreed, the pressure on the vehicle will be 3 times greater than its weight together with all its contents, including the explosives. Thus, if the acceleration is constant, at the time of launching, when the rocket weighs 5 tons (1 + 4), the pressure will be 15 tons (5 x 3). At the end of the explosion, however, when the explosives have been consumed and the rocket with its contents weighs only one ton, the pressure will be 3 tons. This means that at the beginning of the flight the consumption of explosives will be 5 times greater than at the end.

For simplicity, I shall assume an average consumption of 15 kg per second and an average pressure of 9 tons. Then at the beginning of the flight the rocket will fly more slowly and at the end more quickly. This would be useful as regards reducing the losses due to the resistance of the atmosphere. It would also simplify the design of the explosion tube and chamber. On the other hand, it would make the apparent gravity irregular: at launching it would be less than 2 and would then increase steadily until it reached 9, which should not unduly affect a man immersed in liquid.

Let us assume that the maximum pressure of the exploding gases is 3000 atmospheres. Then the pressure acting on the bottom of the explosion tube will be 3 tons per cm^2. But a total of 9 tons is required. Therefore, the bottom of the cylindrical explosion tube must have an area of 3 cm^2. The flow rate required to insure the burning of 15 kilograms of explosives per second, assuming the mixture to have a density equal to that of water, will be 50 meters. The work done in forcing the mixture into the explosion tube will be 450 meter-tons (9 tons x 50 m), or 4500 metric horsepower (1 metric horsepower = = 100 kilogrammeters).

This means that, in addition to everything else, we shall need a 4500 metric HP motor to pump explosives into the explosion tube.* This is not yet feasible. In fact, even if we allotted to this motor one-half the total weight of the rocket, i.e., 500 kilograms, it would still have to be one-ninth the weight of the lightest known type.

This is one of the many obstacles to building a spaceship.

One idea that occurs to me is to insert special cartridges in the explosion tube, i.e., insert one cartridge, explode it, and wait until the tube is free of gases and gas pressure. Then insert another cartridge, and so on. The motion of the rocket would then be intermittent, irregular. This is tolerable. But the rate at which the cartridges must be inserted turns out to be impossibly fast. A cylinder of explosives 50 meters long, or 100 cartridges each half a meter long, would have to be inserted each second! If, however, the explosion tube is made 10 times bigger, i.e., if the area of the base is made 30 cm^2 (diameter 6.2 cm), the weight of the tube will increase tenfold. Then 10 cylinders of explosives, each one-half meter long, would have to be inserted each second.

In addition to all this, the shock due to the explosion would increase tenfold and become greater than the passengers or the rocket itself could endure. The result would be the same if we resorted to the use of intermittent pumps for inserting the explosives. These pumps, of course, would not have to work so hard, but the shock would remain, and the required speed of operation would be almost impossible to achieve.

Dzhiffar's injector for pumping water into boilers is powered by the steam itself. Could not this principle be applied to pumping materials into the explosion tube by utilizing the energy of the explosives themselves -- their enormous pressure and velocity?

The work done by 4 tons of explosives, based on the energy of chemical combination of hydrogen and oxygen, will be 5,600,000 meter-tons. This is equivalent to 20,700 meter-tons per second or 207,000 metric horsepower, i.e., 46 times greater than the work required to force the explosives into the tube.

Hence it is clear that, first, the work of pumping will account for only 1/46 of the total work done by explosives and, second, that the power of the explosives is gigantic and incomparably greater than that of ordinary engines. For the explosion releases 207,000 metric horsepower continuously, i.e., every second. Now, the weight of the

*Combustion chamber of a jet engine (Editor's note).

explosion tube used to achieve all this is very insignificant -- all in all, only a fraction of a ton (the entire rocket weighs only one ton). Is this possible? Assuredly, yes. For proof consider the performance of ordinary artillery. It is not difficult to calculate that a gun firing a ton of metal with an initial velocity of 2000 meters does work equivalent to 200,000 meter-tons. And this within 1/100 of a second. This means that in one second it will do 20,000,000 meter-tons or 200 million metric horsepower. This is 968 times greater than the work done by the explosion tube. Assuming that the gun weighs about 40 tons, our explosion tube should weigh about 40 kilograms, which is quite feasible, as other calculations show.

But what about pumping the explosives? Invent an injector! Until this is done, space travel will remain in the realm of pipe dreams or in the stage of calculations and trivial experiments and flights.

The development of the right injector is hampered by the extraordinarily high reaction temperature of the mixture of explosives and by the lack of sufficiently tough and heat-resistant materials. But all this will be overcome in time by human industry and ingenuity.

The control surfaces resemble those used in an airplane. They are located on the outside, opposite the mouth of the explosion tube. They operate both in air and in a vacuum. Their inclination, and hence also the inclination of the rocket, in the atmosphere depends on the drag and the pressure of the flow of combustion products. In a vacuum, on the other hand, this inclination depends only on the combustion products.

Similar surfaces, mounted separately, would also serve as a spin regulator, i.e., would cause the rocket to turn in either direction and prevent the involuntary spin due to the irregularity of the explosion and the air pressure. Their action would depend on the use of a helical plate mounted parallel with the gas flow in the tube. The purpose, of course, would be to prevent any rotation of the rocket that might be harmful to the passengers.

Let us now consider the sensations of travelers departing in a spaceship to circle the Earth like another Moon, and the sensations of those who witness their departure. It is assumed that the rocket is spaceworthy and properly designed.

The rocket contains several vessels built in the shape of a human figure, one for each traveler. The travelers lie in these vessels, horizontally with respect to the apparent gravity, and are covered with a small amount of fluid, like the brain in the cranium. Their hands are also immersed in fluid, but more freely, so that they can manipulate the handles of the instruments, which are likewise submerged. The instruments regulate the direction of the rocket, the composition of the air inside, the temperature, humidity, explosion rate, spin, and so on.

While in this submerged state, breathing through a tube, the other end of which breaks the surface of water, the travelers can not observe much during the $4^1/_2$ minutes of the explosion. Their increasing weight is greatly offset by the fluid, which is lukewarm, not chilly. The portholes are tightly covered with opaque shutters, barring any view outside. This is as it should be. But let us imagine that the travelers stand or recline in chairs and calmly look out through transparent windows. In this case they could make visual observations even during the first 270 seconds.

A high mountainous site has been selected. The ground, which slopes at 20-30° to the horizontal, has been leveled and special rails have been laid over it. The rocket stands on this track. The altitude of the site is 5-6 kilometers. The air density is half that at sea level. The track is 100 versts long. The rocket rests on the track in an inclined, nearly horizontal position. The floor, and the seats screwed to it, is nearly vertical (60-70° to the horizontal). The travelers have entered the rocket, and its airtight doors have been closed. Their position is extremely uncomfortable. They cannot sit down. They can walk only on the lower sloping (20-30°) wall, and with difficulty at that, as on a steep mountainside. But it is possible to sit on lightweight rope seats resembling a trapeze, and this is what our travelers do, swinging freely. The rocket still stands motionless.

The portholes offer a glimpse of mountains, buildings, and clouds that float above and below in the dark-blue sky. In short, a typical alpine scene.

The explosion begins. The sound is deafening, the effect nerve racking. But our heroes have nerves of steel and pay no attention to the terrible noise.

The travelers feel the thrust as the rocket starts to roll up the track, and the horizon, or the Earth's surface, seems to rotate through an angle of 60°, until it looks like a vertical wall. The floor of the rocket, on the other hand, has become horizontal. The hanging chairs have swung to the side and have become vertical in relation to the floor. The gravity has nearly doubled, pushing the travelers down into their seats, the position of which is now correct. They could rise from their seats only with tremendous effort, but so far there has been no need to do so. The portholes offer an excellent view: all around is the nearly vertical surface of the Earth with its mountains, lakes, rivers, forests and buildings -- all now miraculously clinging to an incredibly steep plane. The water does not rush out of the lakes and, despite their unnatural position, towers do not collapse. It seems as if a relief map of the Earth had been raised at an angle of 60-70° to the horizontal.

The sun has just risen, but it already seems to be high overhead.

The pressure exerted on the rocket by the explosion is constant -- 9 tons -- but since the amount of explosives is decreasing, the acceleration of the projectile grows. As a result, the apparent gravity inside it continuously increases, from $1^4/_5$ at the beginning to 9 at the end of the track, i.e., on termination of the explosion. This is clear from observations of a spring balance. A piece of gold weighing one pound, placed in the pan of the spring balance, is observed to weigh about 2 pounds at the beginning of explosion, i.e., more than it should, since not only the gold but also the pan and the spring balance weigh more. The weight of the gold is observed to increase steadily, stretching the spring more and more.

But in less than two minutes, the rocket leaps off the rails and soars freely far above the ground. Its motion can not be sensed by the travelers, apart from some shaking and vibration. But it seems to them now that the vast, upended earth is collapsing somewhere below and receding together with all its mountains, seas and cities.

The clock with an ordinary Huygens pendulum begins to tick away at a terrible rate, the pendulum making three oscillations in the time it normally required to make two. This is clear at a glance but can be verified by consulting a pocket watch, which continues to run true. The mercury in the barometer falls to nearly half its original level, although the aneroid, or round vacuum barometer, shows the pressure of the gases inside the rocket to be unchanged. The ordinary lever-arm balance shows no increase in the weight of objects, although they have become twice as heavy. This is understandable, since the balance itself has also become heavier.

It is instructive to observe this steady increase in weight, since we are accustomed to regard weight as something constant. A centrifugal machine would show that the mass of these objects remains absolutely unchanged.

Objects released from the hand begin to fall more rapidly; drops of water shrink to half their size and their volume diminishes eightfold. Waves are propagated more quickly. The faces of the travelers turn pale, and, but for their youth and good health, the ending would not be a happy one. Meanwhile, gravity has been pushing them down harder and harder against their now seemingly horizontal seats. Archimedes' law of buoyancy and loss of weight in liquids is not overthrown, but the phenomena of capillarity are affected; thus, water in thin tubes rises only half as high.

The sky darkens. Planets and the larger stars become visible, notwithstanding the bright sunshine. The Sun is twice as bright, although this is not immediately observable, and more bluish than in the atmosphere. The heat is beyond human endurance, but the travelers are protected by thick glass. The Moon, previously barely noticeable, begins to shine like freshly polished silver. The sky has long been completely cloudless. As for the clouds below, they envelope obliquely the steeply tilted surface of the Earth. Seas and continents can be seen through gaps in the clouds.

The sky grows darker and darker, and the stars increase in numbers. The Moon becomes brighter, and the Sun more dazzling. The troposphere and stratosphere have been left far behind. We have entered the region of hydrogen and geocoronium.* The sky is complete-ly black, the stars myriad, and all this seems so close that one could touch it with one's finger. The vault of the sky has become more spherical, but it would be frightening were it not for its toy-like appearance.

The stars have become many-colored, bright, but not twinkling.

We have traversed the region of geocoronium and left the atmosphere behind. The stars are even more bright and clear. The Milky Way is also visible.

The shadows cast by objects inside the rocket have become darker, but the half-light persists, since the darkest nooks in the rocket are illuminated by reflected lifht from the Earth, the equipment of the rocket, and its walls.

The Earth increasingly resembles an inverted bowl. It is seen laterally: the bowl standing almost on end. It occupies half the sky, expands, revealing an increasing number of rivers, lakes, and seas.

The surrounding space seems like a sphere, and we are at its center. One half of this sphere is the visible part of the terrestrial globe, the other half is the black sky, studded with innumerable silvery points -- the stars -- together with a brilliant Sun and a golden Moon. The whole coalesces into a sort of child's ball with one bright half, the Earth, and one black half -- the sky together with the blinding Sun. This ball seems much smaller, that is to say, its inner surface seems much closer, as it were, than the sky seen from Earth's surface.

The Earth now resembles a giant concave Moon occupying half the complete sphere.

The gravity increases so much that one of the travelers faints, another lies down on the floor, and a third, the hardiest and strongest, suggests that they save their prostrate companion by placing him in a tank of water. With enormous effort, they lift their unconscious comrade into the tank and then clamber into it themselves, all the while holding his head above water.

At once, they experience a tremendous sense of relief, and the first traveler immediately regains consciousness and is not even aware

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*Cf. note to the table on p. /166 (Editor's note).

of having fainted. The limbs become weightless and only the head feels heavy, as if it were separate from the body. The travelers roll their heads involuntarily, as if anxious to shake them off. But they can avoid even this unpleasant sensation simply by immersing their heads in the water, after putting on special goggles with extremely convex lenses, which enable them to see in and through the water, and placing in their mouths tubes that fit tightly over lips and nose. How wonderful! And it is even better to lie on the bottom of the tank. This produces a most luxurious sensation, a sort of negation of the body, like the softest featherbeds or a special chair for the feeble. A fish, accidentally present in the water, floats in it as if nothing had happened. Only the surface of the water is rippled by the continuous jolting, and there is a slight all-pervading vibration.

By the end of the explosion gravity will be 9 times greater than normal, but now there is nothing to fear.

The rocket is steered almost automatically, and the travelers rarely need to touch the controls and regulating instruments. These are all connected to fine wires or switches immersed in the water or near at hand. But when the travelers attempt to raise an arm or leg above water, they groan with the effort, their limbs feel leaden.

Four or five minutes after the journey has begun, a sudden tomb-like silence sets in, the explosion has ended.

After the deafening roar, the tumult and vibration, which even prevented the exchange of a word in a normal voice, this silence is as impressive as the monstrous din at take-off. The travelers are aware of a rumbling in their ears, they feel benumbed, as if exposed to a new world. Their faces are flushed, but this is not dangerous, since it also happened even when they were immersed in water during the period of high apparent gravity. Rupture of the blood vessels was excluded, but there was a slight variation in blood pressure.

What is to be done? They all sit stiffly in the water as if paralyzed. But the water, becoming weightless, begins to creep out of the tank and assume fantastic shapes. This brings the travelers back to life again. They rise to their feet and...their bodies begin to float through the air. Their bodies and limbs strike the roof and walls of the rocket, and this revives them further. Their first movements in emerging from the tank spattered water in all directions, and this is now flying about the rocket in the form of large and small spheres, resembling soap bubbles. But these spheres are dense, massive, gigantic drops of water.

These, however, soon end their wanderings. They adhere to and coat the walls and other objects. Loose objects, wet or covered with a thick, massive layer of water, like glass, float back and forth together with the travelers.

The inanimate objects float gently, but the passengers make movements and therefore bounce hither and thither like gas molecules.

The only sensation they now experience is astonishment, since these effects are new to them despite all that they have read about the subject on Earth.

The noise in the ears diminishes, the rocket appears to stand still, but the travelers know that it is now hurtling around the Earth like a new moonlet, at a velocity of 6-7 versts per second. It is now outside the atmosphere, 3000 to 4000 versts above the Earth. It cannot stop itself, it is now a satellite of the Earth.

Once our heroes fully recover consciousness, they begin to bring their little world into order. After sponging up the water, they lashed down the objects torn away during the period of increased gravity.

They have a sensation of blissful calm and peace. The position and orientation of their bodies inside the rocket is not fixed; it can be changed at will. But to stand still is very hard; when they manage to do so, even a slight movement of the blood, heart, intestines, a sneeze, a breath, and so on, will disturb their equilibrium and send them spinning and floating away. Even slight impulses such as air currents inside the chamber have the same effect.

All bodies have three principal forms of stable motion: rectilinear, rotational, and a combination of the two. In addition, an irregular oscillatory motion will often be present along with these ideal motions. But the oscillation is quickly suppressed and goes over into an ordinary stable spin about a "free" axis. At least three such axes can be found in even the most asymmetric body -- and their number in symmetric bodies is much greater, and in a sphere infinitely large.

The barometer rises and the mercury completely fills the tubes, leaving no voids. All kinds of balances become useless, since there is no gravity. Mass can be judged solely from the effort that has to be applied to an object in order to move it from its place and give it a certain velocity.

Inanimate and animate objects can be at rest in any position. Motion, if there were no obstacles, would never cease. The ceiling seems to be wherever one's head is, and the floor, wherever one's feet are. Therefore, each has his own ceiling depending on the direction in which the longitudinal axis of his body points.

The Earth occupies slightly less than half the entire sky and resembles a concave hemisphere with the rocket at its center. But part of the Earth is illuminated like the Moon and has the shape of a gigantic lunar sickle, while the other part is a dark, grayish color. This sickle waxes like the Moon and soon changes into a concave silvery bowl. All the phases of the Earth rapidly follow one another: from a bright red circle -- a ring, dark inside, to a shining half-sky. Then the Earth is clearly visible: all its continents, seas, oceans, islands and even cities. But part of its face will always be covered by snow-white clouds, and the perimeter will be vague, obscured by a dense layer of air and vapor. The Earth resembles a hemispheric map, but in a strange new projection. All its edges seem flattened out and misty. Maps of this kind are not used. The apparent vertical position of the Earth, which it assumed throughout the duration of the explosion, has now, of course, disappeared. To one traveler it seems to be above, in the middle of the starry ceiling; to another, on one side; and to the third, below, where it hangs like a horizontal bowl. Everything depends on the position of the body with respect to the Earth.

Our heroes are wafted freely about the rocket, whatever the orientation of their body, like fish in a tank. They move with the minimum of exertion, effortlessly. But the body itself, without action and reaction, can never move from the spot if it is originally immobile, and can never change its original motion, if it has any.

When the travelers spin owing to inertia, like a bicycle wheel, it seems to them that the rocket, the Sun, the stars, and the Earth are spinning; when they are in translational motion, they lose awareness of the direction in which the rocket is moving. Therefore, to one it seems as if the rocket is motionless; to another, that it is slowly spinning; to a third, that it is rapidly advancing; to a fourth, that it is rapidly spinning, to a fifth, that it is both spinning and advancing, and so on, depending on the traveler's own motion.

Chairs, beds, mattresses, and pillows, springs, and even legs are absolutely superfluous. Even tables and stands are not required. But, of course, everything has to be lashed down or covered with a net, so that it will not stray about the chamber. In fact, the least air current, the smallest shock will bring every object into motion until it -- very precariously -- returns to a state of rest in some improbable spot.

Unless precautions are taken, unimaginable confusion and bedlam will arise.

Were it not for the heat radiated from the Earth, the temperature in the rocket could be varied as desired: from -270°C to +150°C. But the Earth makes these extremes of cold unattainable. For example, it is difficult to obtain temperatures lower than -100°C.

A sliding outer shell, either shiny, black, or striped, is used to vary the rocket's temperature. By moving the proper levers the travelers can expose themselves to icy cold or roasting heat. Here a part is played by the action of the Sun's rays and by the loss of heat due to radiation, depending on the state of the rocket's surface. Naturally, under such conditions there is no need for clothing, footwear, or heating appliances.

Not even cooking stoves and hearths are needed. Different compartments of the rocket may be given different temperatures, as the need arises. Mirrors and lenses can be used to produce a temperature as high as that of a forging furnace, and even higher.

An expanded and elongated rocket, resembling a specially designed greenhouse, could furnish oxygen and food for its passengers, since the latter can provide the vegetation with carbon dioxide and fertilizers. In fact, in such a rocket one could raise the most fruitful plants. Here then is your source of food and oxygen. But that is a very broad topic, outside the scope of this article.

Once every 100 minutes the rocket enters the Earth's shadow for 40 minutes. Then the starry sky is particularly in evidence. But the Earth, too, glows brightly, like an enormous red wreath, dark at the center. It occupies nearly half the sky. The Sun, of course, cannot be seen. You may call this a solar eclipse or night, as you prefer. The Moon passes through its phases in the usual time. The only difference now is that it is twice as bright, because of the lack of an atmosphere.

The starry sky, the Sun, the Milky Way, the planets -- all have the customary appearance as regards shape, size and position, except that now they are very bright, untwinkling, without "rays." Even many of the spiral nebulas are visible in the form of small clouds or misty dots. The stars are much more abundant and variously colored and seem quite close, suspended from a small, black, strictly spherical surface. This is a paradise for astronomers. Their chief foe, the atmosphere, is absent. The magnification at any time may reach 10,000. Here they could make fabulous and incalculable discoveries with their gigantic telescopes, spectroscopes, and cameras.

Those who saw our heroes off and stayed behind on Earth have not, of course, experienced any of the sensations described above. They merely saw how the rocket, within seconds of being launched, disappeared from sight after bursting into a savage roar. The thunder receded and vanished. But a minute later, a loud, steady peal could be heard. At first it grew stronger, then fell and faded away. It was the rocket achieving cosmic velocity, as it cut through the air. In doing so it produced an air wave, which took a relatively long time to cover the distance to the original launching point.

Barely had this roar ceased, when the rocket reappeared, looking like a star; it had begun to glow owing to the atmospheric friction. But this star soon ceased to shine. This is all that the earthbound witnesses could see.

As for the travelers, they have sped a considerable distance from the Earth and now believe themselves to be traveling in an absolute vacuum. But they are mistaken: even here some traces of the atmosphere still persist. Therefore, their vehicle, meeting a slight resistance, describes a spiral with a very small pitch, which steadily, but extremely slowly, begins to approach the Earth. They make so many revolutions about the Earth that they begin to lose count. Nevertheless, a return to Earth is inevitable. They realize this from the fact that their "day" is growing shorter and the apparent size of the Earth is increasing.

At first, the rocket's velocity increases and the centrifugal force balances the Earth's increasing gravitational pull. But later the velocity of the projectile begins to decrease owing to the increasing density of the atmosphere and the resulting increase in air resistance. Then the travelers bring the rocket into gliding flight by raising its nose with the aid of the controls, which operate in the same way as in an airplane. They now can not only moderate their descent, but even convert it into an ascent, until sufficient velocity is lost. But this might be excessive and culminate in a loss of velocity at high altitudes and the destruction of the rocket, thus transformed into a wingless airplane. So they descend, but not so slowly as to lose a safe margin of velocity at the Earth's surface.

The travelers merely pray for their craft to descend on the sea rather than on land.

Actually, the descent is much more dangerous than in an airplane, since there are no wings and great velocity is required to balance gravity against the air resistance (in barely inflined flight) and to descend not steeply, but almost horizontally. In this case a landing in water is safest.

Fate hears their prayer and they, descending into the waves at a gentle angle, land on the sea.

Their velocity is still not all exhausted, and they coast quite a distance on the waves before coming to a stop and being taken on board the nearest steamship.

EXPLORATION OF THE UNIVERSE WITH REACTION MACHINES*

Introduction

My interest in space travel was first aroused by the famous writer of fantasies Jules Verne. Curiosity was followed by serious thought. Of course, this would have led to nothing, had it not been organized on a scientific basis.

I was still young, when I discovered the path that leads to space flight. It is the path of centrifugal force and rapid motion (see my "Visions of Earth and Sky," 1895). Centrifugal force balances gravity and neutralizes it. Rapid motion raises a body skyward and the greater the velocity the farther it will be carried. Calculations revealed to me the velocities required to overcome terrestrial gravity and reach the planets. But how to achieve them? This is the question which has obsessed me all my life, and it was not until 1896 that I decided it could most definitely be solved.

For a long time I shared the general opinion that rockets were chiefly for amusement and had little practical value. They did not even interest me as a toy. Nevertheless, from time immemorial many have regarded the rocket as a means of flight. On delving into history we find numerous inventors of this kind. Such were Kibal'chich and Fedorov. Sometimes only ancient drawings reveal the desire to employ rockets for aeronautical purposes.

In 1896 I ordered a copy of A. P. Fedorov's "Novyy printsip vozdukhoplavaniya" (A New Principle of Aeronautics) (Petrograd, 1896). It seemed unclear to me (since it contained no calculations). And in such cases I do the calculations myself, from A to Z. This is the principle underlying my theoretical investigations of the possibility of employing reaction machines for space travel. So far, no one has mentioned Fedorov's little book. It taught me nothing new, but still it impelled me to work seriously on the problem, just as the falling apple led to Newton's discovery of the law of gravity.

It is very likely that many other and more serious works on rockets have been published in the past, but remain unknown to me.

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*First published privately by the author as a separate book under the same title in Kaluga, 1926. See Appendices, Note 31 (Editor's note).

In the same year, after many calculations, I wrote the story "Vne Zemli" (Outside the Earth), which was subsequently published in the journal "Priroda i lyudi" (Nature and Mankind) and even appeared as a separate book (1920).

An accidentally preserved yellowed page with the final equations is dated 25 August 1898. But from what I have already said, it is obvious that I began to be concerned with rocket theory even earlier, in 1896.

I have never claimed to have solved the problem completely. Speculation, fantasy, and invention inevitably precede scientific calculations, until ultimately the idea is put into practice. My writings on space travel pertain to the middle phase of my creative work. More than anyone else I am aware of the chasm separating ideas from reality, since all my life long I have used not only my brain, but my hands.

However, the idea must come first; execution follows reflection, and exact calculations follow flights of the imagination.

Before sending him my manuscript (published in 1903) I wrote to M. Filippov, editor of "Nauchnoye obozreniye" (Science Review) as follows: "I have worked out certain aspects of the problem of soaring into outer space with the aid of a reaction machine resembling a rocket. Mathematical proofs, based on scientific data and repeatedly checked, point to the feasibility of using these devices to voyage into the cosmos and perhaps even found human settlements beyond the confines of the Earth's atmosphere. Hundreds of years will probably pass before the ideas I expound are used by mankind to colonize not only the Earth but the entire Universe.

Almost the entire energy of the Sun is at present going to waste, since the energy received on Earth is two (or, more exactly, 2.23) billion times less than that which the Sun actually radiates.

What is strange about the idea of utilizing this energy! Moreover, what is strange about the idea of conquering the limitless space surrounding the globe...?"

We all know how unimaginably great, how boundless the universe is. We all know that the entire solar system with its hundreds of planets is but a speck in the Milky Way. And the Milky Way itself is a speck compared with the Ethereal Island, which, in its turn, is a speck in the great Universe.

If men were to conquer and colonize the solar system, would the mysteries of the universe be revealed? Definitely not. Similarly, the sight of a small rock or shell does not reveal the mysteries of the ocean....Even if mankind had conquered another sun, explored the entire Milky Way, with its billions of suns and hundreds of billions of planets, even then we would make the same reply.

The known universe is a mere nothing, and all our knowledge, present and future, is as nothing compared with that which we shall never know.

But how pitiable is man in his delusions! It is not so long ago that rising into the air was considered a blasphemous temptation and punished with death, and the statement that the Earth revolved about the Sun was punished with burning at the stake. Is not mankind susceptible even now to similar errors?

My previously published writings are now rather difficult to obtain. For this reason, in the present edition I have combined my earlier work and my subsequent achievements.

The Spaceship Should Resemble a Rocket

The principle underlying the motion of any vehicle or ship is the same: it displaces a certain mass in one direction thus acquiring a thrust that pushed it in the opposite direction. The steamship displaces water, the dirigible and airplane displace air, man and horse displace the terrestrial globe, and reaction machines, e.g. a rocket or Segner's wheel, displace not only air but substances which they themselves contain: gunpowder or water. Were a rocket in a vacuum or the ether, it would still acquire motion, since it carries a store of matter to expel: gunpowder or other explosives, which contain both mass and energy.

Clearly, a device for travel in a vacuum should resemble a rocket, i.e., contain not only energy but also a mass against which to thrust.

Travel outside the atmosphere and any other material environment at an altitude of 300 km or even higher, between planets and suns, requires a special device which we shall term, solely for the sake of brevity, a rocket.

Note that the interstellar ether is the same material environment as air, but it is rarefied to such an extent that in no case will it serve to provide thrust. It is only nominally matter. Even celestial stones (bolides, aerolites, shooting stars) weighing several grams can move through the ether at appalling speeds (as much as 50 and more km/sec) without encountering appreciable resistance. In a word, so far as drag is concerned, the ether may be considered a vacuum. Likewise, ether currents in the form of radiant and electrical energy exert only an extraordinarily small pressure on a body. Consequently, for the present, we shall disregard them.

Explosions may serve not only to take off from a planet but also to land on it, not only to gain velocity but also to lose it.

The projectile is capable of leaving Earth, wandering among planets and stars, visiting planets and their satellites and rings and other celestial bodies, and returning to Earth, so long as its supply of energy-containing explosives permits. However, as we shall see, it is possible to land on planets that have atmospheres without consuming any explosives.

Principal Data needed to Investigate the Problem

The Gravitational Attraction that must be Overcome in Escaping from a Planet

Through very simple integration we can derive the following expression for the work T done in lifting unit mass to an altitude h_1 above the surface of a planet of radius r_1

$$T_1 = g_1 \frac{r_1}{\left(1 + \frac{r_1}{h}\right)}.$$

Here g_1 means the acceleration due to gravity at the surface of the planet and r_1 the radius of the planet.

Suppose that h in this formula is equal to infinity. We then determine the maximum work done in raising unit mass to infinity from the surface of the planet. We obtain

$$T_1 = g_1 r_1.$$

We see that the work done in raising unit mass from the surface of the planet to an infinitely great distance is equal to the work done in lifting the same mass to an altitude equal to one planet radius, if it is assumed that the gravity of this planet does not decrease with increasing distance from its surface.

Thus, although the reaches of space through which the gravitational pull of any planet continues to act are infinite, this pull may be figuratively represented by a wall or sphere of negligible resistance surrounding the planet at a distance equal to its raidus. Once one surmounts this wall, bursts through this intangible, uniformly dense envelope, one has conquered the gravitational pull of the planet throughout its limitless range.

The last formula shows that the limiting value T_1 is proportional to the acceleration due to gravity at the planet's surface and to the radius of the planet.

For equally dense planets, i.e., for planets of the same density, say, that of the Earth (5.5), the surface gravity, as is known, is proportional to the planetary radius and is expressed by the ratio of the planet's radius r_1 to the Earth's radius R.

Therefore

$$\frac{g}{g_1} = \frac{R}{r_1} \text{ and } T_1 = g\,\frac{r_1^2}{R}.$$

This means that the limiting value T_1 decreases with extreme rapidity as the radius r_1 of the planet diminishes, that is to say, as the surface area of the planet diminishes.

Thus, if T_1 equals 63,660,000 kg-m for the Earth ($r_1 = R$, $T_1 = gR$), for a planet with a diameter one-tenth as large it will equal 636,600 kg-m.

But in the case of the Earth this figure is really not so very large. In fact, if the heat value of petroleum is taken as 10,000 cal, which is quite reasonable, the energy of combustion may be expressed as mechanical work equal to 4,240,000 kg-m per kg of fuel.

Thus, the energy required for unit mass to escape from the surface of our planet is the same as that potentially contained in 15 units of petroleum. Thus, applied to a man weighing 70 kg, we obtain 1050 kg of petroleum.

The only thing missing is a knowledge of how this redoubtable energy of chemical affinity may be utilized.

Still it is becoming clearer why a quantity of explosives eight times the weight of a projectile can enable the latter completely to overcome the pull of the Earth's gravity.

According to Langley, 1 m^2 of surface exposed to ordinary sunshine yields 30 cal. or 12,720 kg-m per minute.

To obtain the energy needed to overcome 1 kg of the Earth's gravity, we need to utilize 1 m^2 of irradiated surface for 501 min, or slightly more than eight hours.

This is very little; but when a man's strength is compared with the force of gravity, the latter seems enormous.

Suppose, for example, that a man climbs a well-built ladder at the rate of 20 cm per second. Then he will do work equal to T_1 only after 5,000 days of hard climbing, assuming that we allow him 6 hours of rest daily. If one horse power is used instead, we can reduce the work to a fifth. Ten horsepower will require only 100 days or, if applied continuously, about 10 weeks.

For most asteroids and for the moons of Mars the work needed to overcome gravity completely is strikingly small. Thus, the moons of Mars are less than 10 km in diameter. Assuming that they have the same density as the Earth (5.5), the work T_1 will be not more than 40 kg-m. If sentient beings existed on the Moon or on Mars, they would find it much easier to overcome gravity than do the inhabitants of the Earth.

Thus, for the Moon T_1 is 22 times less than for the Earth. On the large planetoids and planetary satellites overcoming gravity would be child's play with the aid of the reaction devices I have described. For example, on Vesta T_1 is 1,000 times less than on Earth, because the diameter of Vesta is 400 km. The diameter of Metissa is about 107 km, and there T_1 is 15,000 times less.

But these are the largest asteroids, whereas the average asteroid is 5 to 10 times smaller and the corresponding T_1 millions of times less than on Earth. From the preceding formulas we find

$$\frac{T}{T_1} = \frac{h}{h + r_1} = \frac{\frac{h}{r_1}}{1 + \frac{h}{r_1}} .$$

for any planet.

Here I have given the ratio of the work T done in ascending to an altitude h above the surface of a planet of radius r_1 to the total maximum value T_1. From this formula I compute:

$$\frac{h}{r_1} = \frac{1}{10} \quad \frac{1}{5} \quad \frac{1}{4} \quad \frac{1}{3} \quad \frac{1}{2} \quad 1 \quad 2 \quad 3 \quad 9 \quad 99 \quad \infty$$

$$\frac{T}{T_1} = \frac{1}{11} \quad \frac{1}{6} \quad \frac{1}{5} \quad \frac{1}{4} \quad \frac{1}{3} \quad \frac{1}{2} \quad \frac{2}{3} \quad \frac{3}{4} \quad \frac{9}{10} \quad \frac{99}{100} \quad 1$$

The first row shows the ascent in planetary radii, the second row the corresponding work, taking the work done in overcoming gravity completely as unity. For example, to ascend one radius above the surface of the planet requires half the total work, and to travel to infinity only twice as much.

Necessary Velocities

It is of interest to know the velocities that must be imparted to a rocket by the explosives in order for it to defy gravity.

I shall not reproduce the calculations, by means of which these velocities are determined, but merely present the conclusions.

Thus, the velocity V_1 needed to lift a rocket to an altitude h and then to attain a velocity V

$$V_1 = \sqrt{V^2 + \frac{2gr_1h}{r_1 + h}}.$$

If we put V = 0, i.e., if the body ascends until arrested by gravity, we find

$$V_1 = \sqrt{\frac{2gr_1h}{r_1 + h}}.$$

If h is infinitely large, i.e., if the ascent is unlimited and the final velocity zero, the velocity required at the planet's surface may be expressed as

$$V_1 = \sqrt{2gr_1}.$$

From this formula we calculate V_1 = 11,170 m/sec for the Earth, which is 5 times the muzzle velocity of the fastest artillery shell.

For the Moon V_1 = 2373 m/sec, i.e., close to the velocity of an artillery shell or a hydrogen molecule. For the planet Agata, which is 65 km in diameter and has a density not greater than that of the Earth (5.5), V_1 is less than 5.7 m/sec; we find that the satellites of Mars have nearly the same velocity. On these bodies of the solar system it is sufficient to break into a run in order to overcome their gravitational attraction and become a planet oneself.

For planets of the same density as the Earth we obtain

$$V_1 = r_1\sqrt{\frac{2g_1}{R}},$$

where g_1 and R relate to the terrestrial globe. This formula shows that in this case the limiting launching velocity V_1 is proportional to the radius r_1 of the given planet.

Thus, for the largest planetoid, Vesta, the diameter of which is close to 400 km, we find that V = 324 m/sec. This means that even a rifle bullet leaves Vesta forever and becomes an aerolite circling the Sun.

This last formula helps us to make a quick estimate of the launching velocities on planets of equal density but different size. Thus, Metissa, a large asteroid, has a diameter one-fourth that of Vesta, the velocities on Metissa must therefore be correspondingly smaller, i.e., 81 m/sec.

The perpetual orbiting of a planet requires half as much work and a velocity $\sqrt{2} = 1.41 \ldots$ times smaller than the work and velocity required for escaping to infinity.

Flight time

I shall not reproduce here the extremely complex equations for determining the flight time of a projectile, particularly as this is an old problem long since solved and I would merely be repeating what is already known.

I shall just employ one very simple and useful conclusion to solve the most elementary problems of the traveling time of a rocket.

The time t taken by an initially motionless body to fall onto a planet (or the Sun) concentrated at a single point (with the same mass) will be

$$t = \frac{r_2}{r_1} \sqrt{\frac{r_2}{2g}} \left\{ \left(\sqrt{\frac{r_2}{r_1}} - 1 \right) \sqrt{\frac{r}{r_2}} + \text{arc sin} \sqrt{\frac{r}{r_2}} \right\} .$$

Here r_2 denotes the distance at which the body starts to fall; r, the distance through which it falls; r_1, the radius of the planet; and g, the acceleration due to gravity at the planet's surface during this time.

The same formula, of course, also expresses the time taken to ascend from $(r_2 - r)$ to r_2, when the body loses all its velocity.

If we put $r = r_2$, i.e., if we determine the time taken to fall to the center of the concentrated planet, we obtain from the last equation

$$t = \frac{\pi}{2} \cdot \frac{r_2}{r_1} \sqrt{\frac{r_2}{2g}} .$$

Under normal conditions, this equation also yields the approximate time taken to fall to the surface of a planet, or the approximate time taken by a rocket to ascend from this surface to the top of its trajectory.

On the other hand, the time required for a complete revolution of a given body, e.g., a projectile, around a planet (or the Sun) is

$$t_1 = 2\pi \cdot \frac{r_2}{r_1} \sqrt{\frac{r_2}{g}} .$$

where r_1 is the radius of the planet with the gravitational acceleration g at its surface, and r_2 is the distance between the body and the planet's center.

On comparing the two equations we find

$$t_1 : t = 4\sqrt{2} = 5.657$$

Therefore, the ratio of the period of any satellite to the time it takes to fall to the center of the planet assumed concentrated at a single point, is approximately 5.66.

Thus, in order to calculate the time taken by any celestial body (for example, our rocket) to fall to the center (or, approximately, the surface), around which it revolves, the orbital period of this body must be divided by 5.66.

Thus, we find that the Moon would fall to Earth in 4.8 days, and the Earth would fall to the Sun in 64-1/4 days.

Conversely, a rocket launched from Earth coming to rest at a distance equal to that of the Moon would have flown for 4.8 days or roughly 5 days.

Similarly, a rocket launched from the Sun and coming to rest, owing to the mighty gravitational pull of the Sun and the insufficient velocity of the rocket, at a distance equal to that of the Earth would take about 64 days, or more than two months, for its flight.

The Work of Solar Gravity

Let us determine the work done by solar gravity when a rocket is setting out from Earth. Of course, it would be best if the projectile were to travel in the direction of the Earth's annual rotation about the Sun, as then the revolution of our planet about its axis could also be utilized.

The work done by the rocket is made up of two components. The first corresponds to the work done in overcoming terrestrial gravity, and the second to the work done in overcoming the resistance of the atmosphere. For unit mass, e.g., one ton, the first component amounts to 6,366,000 meter-tons. If the rocket is launched in the direction of annual rotation of the Earth, it will recede from the Earth and become a satellite of the Sun, like the Earth itself. It will also have a velocity (average) of, let us assume, 29.5 km/sec. If it is to escape the Sun's gravity too, the energy of annual motion must be doubled, or the velocity multiplied by $\sqrt{2}$, i.e., increased by an amount equal to $29.5(\sqrt{2}-1) = 12.21$ km/sec. The total velocity will be $\sqrt{11.17^2 + 12.21^2} = 16.55$ km/sec. Since the rocket has no second source of thrust, it must acquire this velocity immediately on taking off from Earth. If the rotation of the equatorial points on Earth is utilized, this velocity may be reduced by an additional 465 m/sec and then totals 16,085 m/sec, i.e., approximately 16 km/sec. Such a velocity is more than sufficient to reach any planet of the solar system, and to wander for ever among the stars (suns) without ever stopping. It will not, however, suffice to fly away or, more exactly, escape for ever from our own Milky Way. Were we to begin our flight in a direction opposed to the Earth's annual rotation, an enormous velocity and a staggering amount of work would be required to overcome the gravitational pull of the Sun. In fact, in the former case we draw away from the Earth without sacrificing our principal velocity of 29.5 km/sec. If we set out from the Earth in the opposite direction, in order to escape from Sun, we must lose this velocity and then regain it together with the additional 41.7 km/sec required to overcome solar gravity, i.e., altogether 71.2 km/sec. The total velocity required will be $\sqrt{71.2^2 - 11.2^2} = 72.1$. This velocity is 4-1/2 times greater and the work 20 times greater, while the amount of explosives required is unimaginably huge. It would be less disadvantageous to launch the projectile in a direction normal to the annual rotation of Earth.

Resistance of the Atmosphere to the Motion of the Projectile

I shall now show that the resistance of the atmosphere represents work insignificant compared with the work done in overcoming gravity. Later on, I shall examine these problems more thoroughly. Suppose a projectile is launched vertically. If it accelerates at 30 m/sec, it will travel 53 km, i.e., through nearly all the atmosphere, in 33 seconds. Then the maximum velocity will be 1 km/sec. But this will be at an altitude where there is hardly any air left. We may assume that the average velocity is not more than 0.5 km. At this velocity, the pressure acting on a cross section of the rocket $4\ m^2$ in area will not, according to known formulas, exceed 100 tons.*

*The drag calculations are approximate in nature. Tsiolkovskiy's conclusion that these forces have little effect on the final velocity of a rocket with a sufficiently large takeoff weight is confirmed by modern research (Editor's note).

But since the rocket is very long, streamlined, and moves very quickly, this pressure on the plane cross section may be reduced by at least a hundred times. This means that it will not be more than one ton. Our large rocket weighs at least 10 tons, and the pressure acting on it will be 40 tons or 40 times that correspondingly to the average resistance of the atmosphere. Of course, the total work done by the projectile, or the work done against gravity, will be thousands of times greater than the work done against the resistance of the atmosphere. Hence it is obvious that the presence of air should not appreciably affect the speed of the rocket.

Available Energy

Following is a table presenting data on the amount of energy released by the combustion of different substances, referred to 1 kg of substance.

TABLE 1

Combustion, Own supply of oxygen	Large calories	Work, kg-m	Velocity, m/sec	Work ratio
H_2 and O_2, forming steam	3200	$1.37 \cdot 10^6$	5180	1.455
The same, but forming water	3736	$1.6 \cdot 10^6$	5600	1.702
The same, but forming ice	3816	$1.63 \cdot 10^6$	5650	1.730
C and O_2, forming CO_2	2200	$0.94 \cdot 10^6$	4290	1.000
Benzine H_6C_6 and O_2, forming H_2O and CO_2	2370	$1.01 \cdot 10^6$	4450	1.078

[table continued next page]

[Table continued]

Combustion, Oxygen from outside	Large calories	Work, kg-m	Velocity, m/sec	Work ratio
H_2 burns, forming H_2O	28 780	$12.3 \cdot 10^6$	15 520	13.08
C burns, forming CO_2	8 080	$3.46 \cdot 10^6$	8 240	3.673
Hydrocarbon burns, forming CO_2 and H_2O	10 000	$4.28 \cdot 10^6$	9 160	4.545
Radium	$1.43 \cdot 10^6$	$0.611 \cdot 10^{12}$	$3.44 \cdot 10^6$	$0.65 \cdot 10^6$

We have seen that the work done by terrestrial gravity per kg is $6.37 \cdot 10^6$ kg-m. It is with this figure that I shall compare the energy at man's disposal. The upper half of the table relates to the situation when we are flying in a vacuum and must carry our own supply of oxygen. In this case, the energy of the explosives is at most one-fourth as high as required to escape the pull of gravity, assuming total utilization of the energy of combustion. The corresponding velocity is half as great. The lower half of the table relates to flight in air, when we can utilize the available oxygen, and there is no need to store oxygen in the rocket. In this case, the available energy will be twice that needed, and the velocity will also be higher.*

In general, it follows that the energy of explosives is far from sufficient for these substances themselves to acquire the velocity required to escape the Earth's gravitational pull.**

Nonetheless, it can be readily demonstrated that a projectile can still be given any velocity, provided that more explosives are carried. If the supply of explosives is equal to the weight of the empty projectile, the velocity, too, will clearly approximate 5 km/sec,*** since the repelled masses are the same (see Table 1). If the relative supply is equal to 3 units, the velocity will increase to 10 km/sec. In fact, once two units of explosives have been consumed, the velocity of the rocket (together with remaining explosives) will be 5 km/sec. On burning the remainder of the explosives, we get a velocity increment of another 5 km/sec, or altogether 10 km/sec. We can likewise readily show that for supplies of explosives equivalent to 7, 15, and 31 units, we obtain velocities of 15, 20 and 25 km/sec. Now, escaping the gravitational attraction of even the Sun requires only a velocity of 16-17 km/sec.

The decay of atoms is a source of immense energy, as is evident from the last row in the table. This energy is 400,000 times greater than the mightiest chemical energy. The trouble is that it is much too expensive, inaccessible, and released extremely slowly, sometimes over thousands of years. Even if we were able to obtain a whole kilogram of radium (more than the total world production so far), the energy released by this element would give only 15 kg-m/sec, i.e., the energy of a workman. This means that such an engine, if it weighed the same as an airplane engine, would be at least 7 times less powerful. Moreover, a radium engine has still to be developed, and besides, 1 kg of radium would cost at least a billion rubles.****

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*The last column in Table 1 represents the ratio of work done by 1 kg of the given explosive to the work done by 1 kg of $CO + O_2$ on combustion in CO_2. (Editor's note in Selected Works of K. E. Tsiolkovskiy, Moscow, ONTI, 1934.

**This relates to the case in which the entire mass of the explosives must be liberated from gravity. Ibid.

***Here it is assumed that the explosive remains behind, while the empty projectile flies off at the velocity indicated. Ibid.

****This is no longer true (Editor's note).

But one cannot doubt that in time inexpensive energy sources with a rapid rate of energy release will be discovered.

The Achievement of Cosmic Velocities in General

We can achieve velocities of this kind even on our own planet. Having achieved them, we can ascend into the ether, wander among the planets and even among the stars. But unless we employ a reaction machine, our motion will resemble that of a bolide, i.e., it will not be subject to our control. Therefore, a rocket device is absolutely indispensable.

Attaining such a velocity while still on Earth offers great advantages, since, by moving over its surface we can acquire a continual influx of energy without expending our own supply.

I shall first enumerate some impractical ways of achieving cosmic velocities:

1. A projectile cannot be launched from a rotating wheel or a giant merry-go-round, since the peripheral velocity, whatever the size of the wheel, cannot exceed 500 to 1000 m/sec, which is not a cosmic velocity. Even at this velocity the wheel may burst owing to the centrifugal force. Besides no living organism could survive, even if the wheel were 1 km in diameter.

2. A short-barreled cannon is impossible, since the relative gravity inside the projectile would crush a living organism. Even a cannon with a barrel 6 km long would be too short. This holds true whether the projectile is propelled by gases, explosives or electromagnetic forces.

3. A vertical cannon is out of the question, since tall structures of this kind are impractical.

4. A horizontal cannon would also be impractical, however long it might be, since the projectile, on emerging from the cannon mouth, would lose nearly all its velocity in the dense layers of air near the ground (Table 2). From the eighth row in Table 2 it can be seen that a rocket weighing 10 tons and having a cross sectional area of 4-1/2 m^2, if traveling horizontally at a velocity of 8 km/sec, would lose 20%, of its kinetic energy in the course of a 50-km flight. But at such a velocity the rocket would travel along a curve without emerging above the atmosphere. Therefore, it would

lose velocity rapidly or rather fall to earth. At a velocity of 16 km/sec it would lose 80% of its energy. If, however, the rocket weighed less, i.e., if it weighed, say, one ton apart from the explosives, then even at a velocity of 4 km/sec it would lose half its energy. The massiveness of a projectile greatly facilitates its flight. From the tenth row in Table 2 it can be seen that placing the cannon against an extremely tall mountain would be a workable solution, since, even at a velocity of 12 km/sec, the projectile would then lose only 13.6% of its energy.

5. Cosmic velocity cannot be acquired by following a short circular track, since the centrifugal force would kill living organisms, although it might not destroy a track solidly anchored to the ground.

6. It is likewise infeasible to attain cosmic velocities on extremely long tracks running horizontally along the equator, since, as in the previous example, the air resistance would absorb all the velocity. Fitting the spaceship with wheels (to reduce friction) would not work.

Some degree of practicability attaches to a gas and, especially, an electromagnetic cannon at least 60 km long, placed with the barrel tilted against a mountainside, so that the mouth is at an altitude of 8 km, where the air is only one-third as dense.

Much has now been written about the impracticability of a short-barreled cannon, but I shall add my comment on the subject. Suppose that a man immersed in water can withstand a relative gravity 100 times greater than terrestrial gravity. Then the acceleration of the projectile in the cannon may not exceed 1000 m/sec^2 (10 x 100). To escape gravity, a velocity of 12 km/sec must be acquired in the barrel. This takes 12 sec. The average velocity of the projectile will be 6000 m/sec. In 12 sec it will have traveled 72 km, this being precisely the minimum required length of the cannon barrel. But in all likelihood this length will have to be 10 times greater, since a man immersed in a liquid could not withstand more than a tenfold increase in gravity. Short-barreled steel cannon are suitable only for firing steel or solid projectiles. And even cannon of this kind would have to be at least 100 times longer than conventional artillery, otherwise these unmanned projectiles would also be destroyed.

At first glance it appears that a gas, the particle velocity of which does not exceed 2 km/sec at normal temperatures, could not produce cosmic velocities. But that is an error which I shall now clear up.

TABLE 2

Rocket weight: 10 tons. Cross sectional area of rocket: 4 m^2. Form factor: 100. Density of air: 0.0013 of density of water. Air resistance and work for constant rocket velocity.

1.	Velocities, km/sec	4	6	8	10	12	16	17
2.	Air pressure* acting on a plane 4 m^2 in area, in tons P = = 0.0001 cm^2 x 4	6 400	14 400	25 600	40 000	576 000	102 400	115 600
3.	Pressure acting on rocket with form factor of 100, tons	64	144	256	400	576	1 024	1 156*
4.	Work done by rocket in traveling 10 km, thousands of meter-tons	640	1 440	2 560	4 000	5 760	10 240	11 560

5. If the rocket weighs 10 tons, overcoming terrestrial gravity requires at least 6,370,000 · 10 · 2 = 127,400,000 meter-tons. We multiply by 2, since at most only 50 % of the energy of the explosion is utilized.

*It should be noted that the resistances given in this book require to be increased in the case of velocities exceeding the speed of sound (Editor's note).

[Table continued next page]

[Table continued]

6. Work done against drag in relation to work done by explosives, % Distance covered: 10 km.	0.50	1.13	2.02	3.15	4.54	8.06	9.10
7. The same, but in relation to work done by rocket, %	1.00	2.26	4.04	6.30	9.08	16.12	18.20
8. The same, when the distance covered is 50 km, %	5.00	11.30	20.2	31.5	45.4	80.6	91.0
9. The same, if empty rocket weighs one ton, %	50	113	202	315	454	806	910
10. Cannon at altitude of 8 km, rocket weighint 10 tons and covering distance of 50 km: work in %	1.5	3.4	6.0	9.4	13.6	24.2	27.3

Imagine a large tank A containing hydrogen or another gas and an adjoining cylindrical barrel B (Fig. 1). The projectile is subjected to a pressure which is the more constant the larger tank A compared with the volume of cylinder B. Thus, in the limiting case, the work done on the projectile is proportional to the square root of this length. Therefore, it is infinitely large. This strange and paradoxical conclusion is explainable by the fact that the work is done at the expense of the entire mass of gas in A, and since this mass may be large, the work done on the projectile may be tremendous. After all, a great velocity is imparted only to an insignificant mass of gas in tank A has a small velocity, but on the other hand, it is cooled. It is owing to this tremendous release of heat that the work done in moving the projectile and gas in the barrel B is obtained. Clearly, maximum work and velocity are more easily achieved by heating the gas with jets of steam or by other techniques. Heating by passing an electrical current through conductors introduced into A is also expedient.

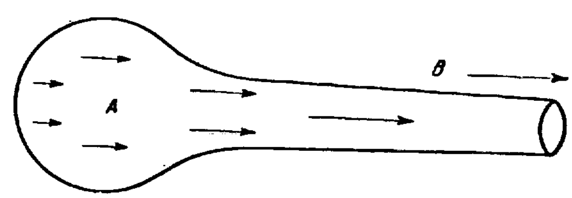

Fig. 1.

In the calculations that follow I assume the pressure acting on the projectile to be constant, i.e., I shall assume that tank A is very large, full of hydrogen, and heated. Gravity acts on hydrogen with 14-1/2 times less intensity than on air (in relation to downward compression), therefore we shall assume the gas density throughout the system to be constant, notwithstanding the great height of the cannon mouth.

We obtain the equations

$$P = p_a nF; \tag{1}$$

$$j : g_3 = P : G; \tag{2}$$

$$V = \sqrt{2j \cdot L}; \tag{3}$$

$$t = \sqrt{2L \cdot j}; \tag{4}$$

$$K = j : g_3 . \tag{5}$$

From these formulas we find

$$j = g_3 K; \tag{6}$$

$$P = (G \cdot j) : g_3; \tag{7}$$

$$n = P : (Fp_a). \tag{8}$$

$$L = V^2 : (2j). \tag{9}$$

where:

K - relative gravity inside projectile;

j - acceleration of projectile per second;

p - pressure acting on projectile;

n - number of atmospheres of pressure;

L - length of barrel in km;

t - time of residence in barrel;

F - cross-sectional area of barrel;

V - maximum velocity per second;

D - diameter of section of projectile and barrel;

p_a - 10 tons/m^2 -- 1-atm pressure;

G - weight of projectile, determined at Earth's surface;

g_3 - acceleration due to terrestrial gravity.

With the aid of these formulas I compiled Table 3.

This table shows that given a compression of 1000 atm. and a barrel 720 km long, a velocity of 380 km/sec can be attained, although only 17 km/sec is needed to overcome the Sun's gravity and wander through the Milky Way. Column 6 in the table shows that this velocity is attained at a relative gravity of 100, when the gas is compressed 100 times and the barrel is 145 km long. Column 8 shows that a velocity of 4 km is obtained for a tenfold increase in gravity at a compression of 10 atm, if the barrel is 80 km long. If the cross-sectional area of the barrel is quadrupled or the diameter doubled, then (column 14) the velocity of a given mass will be doubled, i.e., the first cosmic velocity will be attained (the velocity required to become an Earth satellite orbiting close to Earth). The length of the barrel and the degree of compression will remain the same, but the acceleration and relative gravity will be quadrupled.

Electromagnetic cannon have a great advantage, since they do not require a gas tank, are much more practical and economical, and insure a copious influx of secondary energy throughout their length, supplied by conductors from stations alongside.

As time goes on, cannon may find a great application in the mass dispatching of projectiles: for large-scale cosmic migrations of mankind, and as a complement to the rocket method. In fact, when fired from a cannon at the first cosmic velocity of 8 km/sec, a projectile

TABLE 3

Acceleration due to terrestrial gravity $g = 10\ m/sec^2$. Weight of projectile* $G = 10$ tons. Pressure of atmosphere $p_a = 10\ tons/m^2$.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
K	10	100	10	100	100	100	100	10	1000	1000	1000	1000	10 000	40
j, m/sec^2;	10^2	10^3	10^2	10^3	10^3	10^3	10^3	10^2	10^4	10^4	10^4	10^4	10^5	400
P, tons	10^2	10^3	10^2	10^3	10^3	10^3	10^3	10^2	10^2	10^4	10^4	10^4	10^5	400
n	10	100	1	10	100	100	100	10	10^3	10^3	10^2	10^2	10^3	10
L, km	720	72	730	72	32	144.5	8	80	7.2	72	72	720	720	80
t, sec	120	12	120	12	8	17	4	40	1.2	3.8	3.8	12	3.8	20
F, m^2	1	1	10	10	1	1	1	1	1	1	10	10	10	4
V, km/sec	12	12	12	12	8	17	4	4	12	38	38	120	380	8
D, m	1.13	1.13	3.57	3.57	1.13	1.13	1.13	1.13	1.13	1.13	3.57	3.57	3.57	2.26

* As can be seen from formulas (2) and (7), G represents the weight of the projectile of the Earth's surface and not the mass M erroneously introduced by Tsiolkovskiy at this point. Editor's note in Selected Works of K. E. Tsiolkovskiy, Moscow, ONTI, 1934.

falls back to Earth and shatters, because its velocity is not parallel to the equator (or meridian). The first important accomplishments, i.e., the establishment of human settlements close to the Earth but outside the atmosphere, will require a combination of the cannon and rocket methods: the projectile will first acquire a velocity of less than 8 km/sec and then increase it by an explosion, like a rocket. Since the orientation of the explosion is variable and depends on us, the projectile may acquire sufficient rotational velocity to become a moonlet orbiting the Earth.

A rocket attachment is indispensable, if a cannon-fired projectile is to orbit the Earth or approach the planets of our system. This also holds true if the projectile is to escape the Sun's gravitational and wander among the other suns of the Milky Way.

At the same time, cannon (including the electromagnetic type) of the lengths required would be tremendously expensive and (at present) are hardly feasible; moreover, a reaction machine can manage without them.

Performance of the Rocket

Compared with a cannon, a rocket is like a microbe compared with an elephant. Rocket is a term I apply to a reaction device which propels itself by expelling matter stored inside it. There is no machine or organism that does not expel matter: man continually expels vapors through his skin, and so does a steam engine, but the effect is small compared with the other forces involved, and therefore such devices cannot be termed reaction machines. A rocket resembles a toy rocket. It differs from other vehicles and ships in that the latter thrust against matter that lies outside them.

EFFICIENCY OF A ROCKET

Let us deal first with a weightless energy, such as electricity, the mass of which may be neglected. Let us also assume that the projectile is not subjected to the force of gravity or to other external forces. Then, for two fixed masses repelled by an insubstantial intermediate force, we have, on the basis of the law of conservation of momentum

$$MW + M_2c = 0. \tag{12}$$

If we assume the speed c of the rocket to be positive, then the speed of exhaust W will be negative, so that the momentum will be zero and cannot be changed by internal forces. M_1 and M_2 here denote the mass of the ejected material and the mass of the rocket.

The work done by the rocket will be

$$E_2 = \frac{M_2c^2}{2}. \tag{13}$$

The work of the ejected mass will be

$$E_1 = \frac{M_1W^2}{2}. \tag{14}$$

The rocket efficiency, or the utilization factor of the energy will be

$$\eta = \frac{E_2}{E_1 + E_2} = 1 : \left(1 + \frac{E_1}{E_2}\right) = 1 : \left(1 + \frac{M_1W^2}{M_2c^2}\right). \tag{15}$$

But obviously from equation (12) we have

$$M_1 : M_2 = - c : W. \tag{16}$$

This means that the rocket efficiency

$$\eta = 1 : \left(1 - \frac{W}{c}\right) = 1 : \left(1 + \frac{M_2}{M_1}\right). \tag{17}$$

Hence, it is clear that the smaller the mass of the rocket is, compared to the mass of the ejected material, the greater the efficiency will be. Table 4 is based on the last formula

TABLE 4

Mass of rocket M_2	10	9	8	7	6	5	4	3	2	1	0
Mass of ejected material M_1	0	1	2	3	4	5	6	7	8	9	10
Efficiency	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Same, in %	0	10	20	30	40	50	60	70	80	90	100

Clearly, from the Table, the efficiency cannot be equal to unity in practice, since the rocket must always have a certain mass. The efficiency will amount to 50% when the mass of the rocket and the mass of the ejected material is the same.

But this will not be the case when the projectile together with its fuel stores has acquired a certain velocity, for example, than acquired by means of an electromagnetic gun, by means of an explosion, or by some other means. Here we may encounter the interesting case where the utilization of the energy is 100% independently of the mass of the material ejected. In fact, if the rocket has a speed of 1 m/sec, for example, then by ejecting an elemental amount of material in the opposite direction at a relative speed of 1 m/sec we can obtain a small particle of ejected matter having zero absolute velocity. Clearly, all of the work expended was done entirely for the benefit of the projectile. In this case, in place of equation (12) we obtain

$$M_1\ (W + V) + M_2\ (c + V) = (M_1 + M_2)\ V. \tag{18}$$

Canceling out, we obtain formula (12) and all the inferences flowing from that formula. Here, V is the total initial velocity of the system prior to the ejection of material. Further, we have

$$E_2 = \frac{M_2}{2}\ (c + V)^2; \tag{19}$$

$$E_1 = \frac{M_1}{2}\ (W + V)^2; \tag{20}$$

$$\eta = 1 : \left\{ 1 + \frac{M_1\ (W + V)^2}{M_2\ (c + V)^2} \right\} \tag{21}$$

According to formulas (18) or (12), we have instead

$$\eta = 1 : \left\{1 - \frac{c \cdot (W + V)^2}{W\ (c + V)^2}\right. . \qquad (22)$$

If the rocket has a velocity increment (in the same direction, of course), then the ejected material will have a negative velocity. If, further, the velocity of the ejected material is equal to the total velocity of the rocket* $V = W$, then the numerator in formula (22) will vanish, and hence $\eta = 1$, i.e., there will be total, or 100%, utilization of the available energy. This means that it is expedient for the particles of the exhaust material to be ejected in the direction directly opposite to the motion of the projectile at the velocity of the rocket itself, and we then obtain an ideal utilization of the work done.

But what we have in mind is to obtain the greatest possible velocity of the projectile from a given stored mass of material to be ejected. It would be expedient to combine the energy with the exhaust, so that the exhaust material itself would be a source of energy at the same time. Otherwise, matters would stand worse. In fact, if we take sand, for example, as the exhaust material and carbon with oxygen (as the combination of energy with the exhaust material), we would gain less thereby than if we used combustible materials alone.

In a second case, given the same mass of exhaust material, the energy per unit of this mass will be greater, and therefore a highly speed of ejection will be obtained, and accordingly a higher rocket speed. In general, energy is material. Even electricity and light are material, not to mention explosives. In order for the projectile to attain its highest velocity, each particle of the combustion products or of any other exhaust material would have to acquire its highest relative velocity. This velocity is constant, however, for specific exhaust materials. What is the point in economizing on energy if we have no recoil. Savings in energy cannot take place here: they are both impossible and impractical. In other words: <u>we must accept the constant relative velocity of the exhaust particles as a fundamental in rocket theory</u>.

A reaction aeroplane capable of using air as the exhaust material is entirely another matter. Here it is advantageous to economize on the stored energy which, we might add, will have to be used as exhaust material also. But a machine of that type is not an

*In absolute values. (Ed.)

instrument working purely on the reaction principle.

VELOCITY OF A ROCKET USING ENERGY FROM OUTSIDE

We may even encounter a case where, in addition to the exhaust energy, we have an additional source of energy from outside. This influx of energy may be supplied from the earth during the flight of the projectile, in the form of radiant energy of a given wavelength, and also in the form of α- and β-particles, or it may be derived from the sun.

The influx of energy from the earth is an attractive prospect, but there are few data available for discussing this. The influx of energy from the sun occurs, however, when the rocket is already outside the confines of the atmosphere. In both cases a store of exhaust material is not needed, since the energy coming from outside itself contains exhaust material in the form of α- and β-particles. All that is needed to find some way to orient these particles in the direction opposite to the desired direction of the rocket. The picture will become clearer in the case where we are storing a radioactive material as the exhaust supply. The velocity of the particles will be so enormous that the store of this material may be very small compared to the mass of the rocket. Thus this last mass may be considered constant, as in the case of energy drawn from outside.

Then we have

$$\frac{dW}{W} = \frac{dM_1}{M_2}, \tag{23}$$

where W is the relative velocity of the exhaust particles, for example, alpha particles. On integrating we find, assuming the direction of the exhaust to be constant, that

$$c = \frac{W}{M_2} \cdot M_1 + c_0, \tag{24}$$

where c_0 is the initial velocity of the rocket prior to the exhaust or prior to the explosion. If this velocity is zero, then

$$c = \frac{M_1}{M_2} \cdot W. \tag{25}$$

We see from the formula that the final velocity of the machine will be proportional to the relative store of exhaust material (or, in general, proportional to the exhaust, since it is possible that no such store may be carried on board) and to the relative velocity of the exhaust (e.g., α-particles). If

$$W = 3 \cdot 10^8 \text{ m/sec}; \quad M_1 = M_2,$$

then

$$c = 3 \cdot 10^8 \text{ m/sec}.$$

This velocity is 18,000 times greater than required to overcome the gravitational attraction of the Sun. The energy associated with this motion is 324 million times greater than required. Flying at this velocity, a spaceship will reach the nearest sun or the nearest solar system in 4 years. Here we assume tapping of external energy. The M_1/M_2 ratio would have to be small for the formula to be applicable to the radioactive material. For example, if it were equal to 0.1, then 40 years would be required to reach a neighboring sun.

It is not possible to obtain so many particles from the Sun, for the influx of particles will decline almost to a vanishing point as the vehicle recedes from the sun. The known radioactive materials, moreover, decompose very slowly and do a very inadequate amount of work per second. Besides, the quantity of such radioactive materials now in the hands of mankind is negligible. But the future is unknown: the earth and the material composing it have been studied only scantily to date. Many surprises may still turn up.

Let us put, in formula (25):

$$W = 30 \cdot 10^6 \text{ m/sec, and } c = 17 \cdot 10^3 \text{ m/sec,}$$

i.e., a projectile velocity such as will be only slightly greater than that required to escape the sun forever.

Dropping the signs found in formula (16), i.e., taking the same sign for c and W, we obtain

$$\frac{M_1}{M_2} = \frac{c}{W} = 0.00057. \tag{26}$$

This means that the relative exhaust mass or relative mass of radioactive material will amount to roughly 1/2000 of the mass of the vehicle in that case. For example, if the vehicle weighs one ton, then the exhaust mass will amount to only 568 g, or less than one and a half pounds. The exhaust mass is so small that the mass of the rocket may be considered constant, and the formulas are applicable almost without error when using the future suitable radioactive materials, provided the velocities of their particles are of the same order as the velocities of the α-particles (electricity or radium).

How will the utilization of this energy be realized. We have

$$E_2 = \frac{M_2}{2} c^2; \tag{27}$$

$$E_1 = \frac{M_1}{2} W^2. \tag{28}$$

The efficiency [cf. (23)] will be

$$\eta = 1 : \left(1 + \frac{M_1}{M_2} \cdot \frac{W^2}{c^2}\right). \tag{29}$$

With the aid of (26), we obtain

$$\eta = 1 : \left(1 + \frac{W}{c}\right) = 1 : \left(1 + \frac{M_2}{M_1}\right). \qquad (30)$$

When we are dealing with radioactive materials or with energy originating outside, the ratios in the last formula will be very large, and we shall therefore have

$$\eta = \frac{c}{W} = \frac{M_1}{M_2}. \qquad (31)$$

Thus, in the case in point, when $M_2/M_1 = 1{,}765$, the efficiency will be about 1/2,000. Although its use is not advantageous, in compensation the store of exhaust material will be negligible.

Its use is more advantageous in the Franklin wheel so that the particles bring into motion a comparatively enormous mass of air (electric wind). In a vacuum, however, the utilization of this energy is so small that the wheel does not rotate, i.e., the work done is not sufficient to overcome friction. The principle of the Franklin wheel could find application in the flight of a vehicle through the air.*

CONVERSION OF HEAT ENERGY INTO MECHANICAL MOTION

Let us now turn to explosives. The source of the energy of these materials is chemical affinity. In general, they give only

*This assertion is in error. (Edit.)

heat, i.e., a random motion of particles (molecules). Special machines are required to obtain from such motion (i.e., from heat) particle motion which is coherent, aligned parallel, oriented in a single direction, in a word, simple and visible motion. For a machine operating on the reaction principle, the greatest possible portion of the thermal, or chemical, energy of the particles would have to be converted into this coherent translational motion. Then the heat would disappear, and in its place we would obtain mechanical motion, or a rapidly moving jet. A lengthy pipe is employed for this purpose. Explosions or combustion occur at one end of the pipe, and gases and vapors escape precipitously from the other end. The walls of this pipe have the property of being able to direct the random (oscillating in different directions) thermal, or chemical motion (not directly perceived, felt as heat) in a single direction, converting it into a stream much in the manner of a flowing river. But the combustion products would have to be gaseous or vaporous (volatile), with the lowest possible condensation point.

If this is so, then the gas, on expanding in the pipe, will be cooled more and more, the heat will disappear, replaced by a gas jet. If the pipe is a short one, the gas will escape at a high temperature and its energy will not be utilized properly (as is the case in rifles and guns). After emerging from the tube the gas will continue to expand and cool, but its motion will be in different directions, and this is of no advantage for our purposes. It is even worse when the explosion takes place without a pipe. An extremely long pipe is expedient, but this will act as a hindrance on the rocket with its mass, and therefore does not fit the bill either.

The absolute temperature is reduced in half on a sixfold expansion of the gases. The utilization of the heat will be 50%. On a 36-fold expansion 75% of the heat is utilized, and so on. Thus, the pipe must be so long that the gas at the exit would expand at least 36-fold; better yet, 1,300-fold. Then only 5% of the entire amount of heat energy would be lost. Substances yielding nonvolatile products, such as calcium oxide, are unsuitable: the energy is great, but it is difficult to utilize properly, since there are no gases (the gas would appear only at a very high temperature such as on the Sun) and consequently no expansion. The energy is converted to radiant energy and lost in the ether. Vaporous products, particularly in a mixture with gaseous products, are fairly acceptable. For example, in burning hydrocarbons with oxygen or with nitrogenous compounds of oxygen, gases (carbon dioxide, nitrogen) and water vapor are given off. When the expansion is vigorous, condensation to drops of water vapor is likely to occur. But in the presence of gases this vapor will transfer its heat to the gases, which will utilize its energy. The energy liberated in the freezing of water could also be used. The absolute temperature of explosing gases must attain 10,000° at the first instant, but at such a high temperature only a small portion of the elements would be in a compound state, the remaining portion being decomposed. The first and complex portion will gradually increase only when it is expanded and the temperature is lowered. The temperature of exploding materials could hardly exceed 3,000° in actual fact, therefore.

As we see, even at 95% utilization the temperature will amount to only 352°C. At that temperature the vapors cannot liquefy, so that even the latent heat of liquefaction is not utilized in such an expansion. This means that further expansion, possible only in a vacuum, will be advantageous. Then the pipe would have to be lengthened even more.

An explosion at high pressure is particularly necessary during flight through the atmosphere. The explosion cannot produce a pressure lower than atmospheric pressure, for otherwise there would be no expansion and flow. But even at a much higher pressure the utilization of the energy will be less, the lower the pressure is compared to the air pressure. If, for example, the pressure of the gases is six times greater than the air pressure, then the utilization could not be greater than 50 %. If the pressure of the gases is 36 times greater than the ambient pressure of the medium, then the utilization or efficiency would be less than 75 % (Table 5).

The problem in a vacuum is a different one. There the pressure of the exploding gases might well be small, except that the pipe would be wider while its weight would remain almost unaltered. Theoretically speaking, we lose nothing in efficiency, even at the lowest explosion pressure, provided the rocket is traveling through a vacuum. Thus, it turns out that at the beginning of the projectile's flight the pressure inside the pipe must be very high compared to the atmospheric pressure; then, to the degree that the vehicle gains altitude this pressure may become arbitrarily small. This is hardly applicable in practice, since the pipe must be first narrow and thick-walled, and then again wide and thin-walled.

We have to select a mean pressure, of course in excess of the atmospheric pressure, and maintain this pressure until a stable position, similar to the position of heavenly bodies, is reached. After that, the pressure may be arbitrarily small*.

*Here, the author neglects friction inside the pipe; owing to this friction the kinetic energy becomes converted to heat, and at very

TABLE 5

Utilization of Heat Inside Pipe

Expansion of gases	1	6	36	216	1 300	7 800	46 800
Absolute temperature or energy	10 000	5 000	2 500	1 250	625	312	156
Centigrade temperature	9 727	4 727	2 227	977	352	39	- 147
Thermal efficiency, %	0	50	75	87	95	97	98.4
Losses, %	100	50	25	13	5	3	1.6
Approximate density of gases with respect to air	100	167	28	4.6	0.77	0.13	0.12

The pressure exerted by the same explosives may range from 5,000 atm to any desired low value. The point is that the force of the explosion in a particular tube depends on the thoroughness and care with which the combustion components are mixed. The mixing may be so perfect, so compact, that the explosion will be almost instantaneous. And conversely, the explosion may proceed slowly in the case of combustion with poor mixing, when portions of the combining substances are very coarse in size. The pressure also is regulated in this manner. Thus, the more or less vigorous action of powder depends on the manner of its preparation.

At high pressures, the utilization of the energy is high, but an insuperably huge amount of work is required to force the masses into the explosion tube. Therefore, the maximum pressure inside the tube must be kept as low as possible without any great loss in efficiency. Here we gain nothing in the temperature. It is inevitably high, 3000 to 4000°C to be precise. Artificial cooling of the outer tube walls will be required.

We may now refer to the required minimum pressure. This is determined by the effect of the atmosphere, by the atmospheric pressure. If the flight is initiated from high mountains, then the atmospheric pressure may be assumed at 0.3 kg/cm^2. This will be about one third the pressure at sea level. That means that the gases must not have a pressure less than 0.3 kg/cm^2 as they escape from the pipe. At the pipe inlet the pressure must be at least 36 times greater (75 % efficiency). Thus, the maximum gas pressure must not be below 10 atm. In the lower layers, it must be at least 30 atm. In any case, the figures may be limited to 100 atm.

Let us now compute the area at the base of the cylindrical blast pipe at that pressure. If the rocket weighs one ton, and weighs 5 tons with the explosives on board, and if the pressure on the rocket due to the explosion will be double the rocket weight, then a pressure of 10 tons will be exerted on the pipe base. The area of this base will be 100 cm^2. The diameter of the circular base area will be 11.3 cm^2. We already mentioned how a lower pressure

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high gas velocities and low pressures the velocity of the gases in the pipe will be reduced again. Extremely low temperatures prevail only under certain conditions. --- Note by the editor of Selected Works of K. E. Tsiolkovskiy, Moscow, ONTI, 1934.

would result: the more coarse the explosive components, i.e., the less thoroughly they are mixed, the weaker the explosion will be. Still, in a closed space, after all, the pressure will attain an enormous value. But, in the first place, the pipe is broad and open, and in the second place the mixing is such that whatever pressure is required will be obtained. I repeat that we lose no combustion energy at all because of the weak pressure. Cooling and vigorous motion (blasts) occur in a chaotic explosion (in an explosion occurring apart in a more general mass). But this motion becomes converted to heat without doing any work, and the temperature is restored. Physicists are familiar with this. Even if the energy utilization is worse at low pressure, the fault lies with the atmosphere: it does not allow explosives to expand without limit. But in compensation, the pipe will be shorter at high pressures, and this provides savings in weight. In a vacuum, we can raise the energy utilization to almost 100% by increasing the length of the pipe; but this length will then be inordinately great. I have proved on many occasions that the work of forcing the explosive materials into the pipe is fairly large and at the maximum pressure is not feasible. To circumvent this difficulty, we may take measures so that the pressure will vary periodically at the pipe inlet, say from 200 atm to zero and back again from zero to 200 atm. This will be a wavelike process*. The average pressure may be quite large in that case, subject to the limits of human endurance. The explosives must be rammed into the pipe at the instants of weakest pressure, intermittently. Then the work of ramming will be negligible, and the utilization of the heat, or of the chemical affinity, will be far greater. In water, the jolts would not affect a human being adversely.

MOTION OF A ROCKET PROPELLED BY EXPLOSION IN A VACUUM OR IN A MEDIUM FREE FROM GRAVITY

Even though there is no advantage in imparting a relative velocity greater or lower than the absolute velocity of the projectile

*Here Tsiolkovskiy formulates the concept of a pulsed jet engine. --- (Edit.)

to the ejected material, the relative velocity of that material must necessarily be constant when explosives are employed. In general, the greater this velocity is, the greater the velocity imparted to the vehicle will be. If such is the case, then the velocity of the exhaust particles will initially be greater than the rocket velocity, and the energy utilization will be very low, but then the two velocities will become equal and the utilization will be total. Later on, the exhaust velocity will be lower and the efficiency will be less than total. In brief, the utilization of the energy, or the conversion of the energy to rocket motion, starts from zero, gradually rises to 100%, then declines continuously to zero.

We have two types of losses to face in the case of explosions. First of all, not all the heat energy is converted to recoil. But the longer the pipe and the more gaseous the exhaust products, the smaller this loss will be. It vanishes in the limit. In practice, the energy utilization must not be less than 75%. The second type of loss depends on the fact that the exhaust has a fixed relative peak velocity, which is not equal to the accelerating motion of the projectile. As we see, this loss will not amount to less than 35% at escape velocity, and the utilization will not be greater than 65% under space conditions. In a medium affected by gravitation, such as we live in on the earth, it will be less. If we assume 50% secondary utilization, the rocket will require about 35% (0.75 times 0.5) of the total potential energy of the explosives for its motion.

DETERMINATION OF ROCKET SPEED

We have, in a vacuum and in a medium free from the earth's gravitational pull:

$$W dM_1 + M_2 dc = 0. \tag{32}$$

But M_1 consists of the constant mass M_0 (i.e., the mass of the projectile, crew and passengers, supplies, and various appurtenances) and the variable mass of the explosives M_1 (which, on burning, are ejected from the rocket). This means that $M_2 = M_0 + M_1$. Now we have, in place of equation (32):

$$WdM_1 + (M_0 + M_1)\, dc = 0. \tag{33}$$

Hence

$$- W \cdot \frac{dM_1}{M_0 + M_1} = dc. \tag{34}$$

On integrating, we find

$$c = - W \ln (M_0 + M_1) + \text{const.} \tag{35}$$

(ln here denotes the natural logarithm). Suppose that at the beginning of the explosion the rocket is not moving, i.e., $c = 0$ and $M_1 = M_1'$.

$$c = W \ln (M_0 + M_1'). \tag{36}$$

Therefore

$$c = W \cdot \ln \left(\frac{M_0 + M_1'}{M_0 + M_1} \right). \tag{37}$$

The rocket will acquire its greatest velocity when the entire store of explosives is exhausted, or when $M_1 = 0$.

In that case

$$c_1 = W \ln\left(1 + \frac{M_1'}{M_0}\right). \qquad (38)$$

Clearly, from this last formula: 1) the maximum velocity c_1 of the projectile will be greater the greater the exhaust velocity W; 2) c_1 may increase without bound in response to an increased relative exhaust ratio $\frac{M_1'}{M_0}$. But this increase, which proceeds at first quite rapidly, tapers off. When the $\frac{M_1}{M_0}$ ratio is very small, $c_1 = W \frac{M_1'}{M_0}$, as can be proved with ease by any mathematician. The meaning of this is that c_1 in this case will be proportional to the store of explosives M_1'. On the other hand, in the limit when the ratio [cf. (38)] is very great,

$$c_1 = W \cdot \ln\left(\frac{M_1'}{M_0}\right),$$

i.e., the increase in the velocity will be exceedingly slow; 3) the rocket velocity will not change when $\frac{M_1'}{M_0}$ remains constant. Hence, it is clear that the escape velocity will not be dependent on the absolute value of the projectile mass. In other words, the mass of the projectile and the mass of its load can be arbitrarily large if we abstract from other conditions; 4) the final velocity will be independent of the rate of explosion. It makes no difference whether the latter proceeds uniformly or not, whether it takes a second or a decade. Even discontinuities in the process will be inconsequential.

Let dt be an element of time.

From (34), we find

$$\frac{dc}{dt} = \frac{W}{M_0 + M_1} \cdot \frac{(-dM_1)}{dt}. \tag{39}$$

The first part expresses the acceleration per second in the rocket's motion, i.e., the relative gravity generated in the rocket (even though outside there may be no gravity at all). As we can see from formula (39), it is proportional to the rate at which the materials are consumed $(-dM_1/dt)$. Moreover, to the degree that M_1 is used up the apparent gravity will be increased, since M_1 decreases and $dM_1 < 0$.

For the relative gravity to remain unchanged, there would have to be a gradual slackening in the intensity of the explosion. We will then obtain

$$\frac{-W}{M_0 + M_1} \cdot \frac{dM_1}{dt} = K, \tag{39$_1$}$$

from formula (39), and here K is the constant relative gravity.

Hence

$$\frac{-WdM_1}{M_0 + M_1} = K \cdot dt. \tag{39$_2$}$$

On integrating, we have

$$-W \cdot \ln (M_0 + M_1) = K \cdot t + \text{const.} \tag{39$_3$}$$

TIME OF EXPLOSION

When $M_1 = M_1'$, then $t = 0$; consequently

$$t = \frac{W}{K} \cdot \ln\left(1 + \frac{M_1'}{M_0}\right). \qquad (39_4)$$

When $M_1 = 0$, i.e., the entire store of explosives have been used up, then

$$t_1 = \frac{W}{K} \cdot \ln\left(1 + \frac{M_1'}{M_0}\right). \qquad (39_5)$$

This means that the total time of explosion is proportional to the resulting relative gravity, and increases with the exhaust mass.

From (39_1), we find

$$-\frac{dM_1}{dt} = \frac{K}{W} \cdot (M_0 + M_1). \qquad (39_6)$$

Hence it is clear that the least rate of explosion, or the least rate of consumption of the explosive, will take place at the end of the process, when M_1 becomes very small, and the highest rate will occur at the beginning of the process, when $M_1 = M_1'$.

In the first instance

$$-\frac{dM_1}{dt} = \frac{M_0 K}{W}, \qquad (39_7)$$

and in the second instance

$$-\frac{dM_1}{dt} = \frac{(M_0 + M_1') \cdot K}{W}. \qquad (39_8)$$

The ratio of the highest rate of consumption (at the outset) to the lowest rate (at the end) will be

$$1 + \frac{M_1'}{M_0}. \qquad (39_9)$$

The greater the M_1'/M_0 ratio, the more intensely the explosive will become used up, and conversely the rate will be almost nonconstant at a low ratio. It is inconvenient to vary the explosive force in practice, for it is simpler to withstand the effect of nonconstant gravity by immersing the passengers and other fragile objects in a liquid.

The time required for (uniform) explosion of the entire store of fuel when the rocket acceleration and relative gravity both increase, but the rate of consumption of the fuel remains the same, may be expressed in the form:

$$t_1 = M_1' \frac{dt}{dM_1}. \qquad (39_{10})$$

Here the derivative may be replaced by the rate of consumption of explosive per second. The same time, for the case of uniform acceleration of the rocket and a constant relative gravity inside the vehicle (39_1), but nonuniform rate of exhaust, will be

$$t_1 = c_1 : j = c_1 : \frac{dc}{dt}. \tag{39_{11}}$$

The derivative $j = \frac{dc}{dt}$ expresses the constant increase in the projectile velocity per second.

MECHANICAL EFFICIENCY

It would be interesting to know what part of the total work done by the moving exhaust particles will be imparted to the rocket. We have

$$E_1 = 0.5\ M_1' \cdot W^2; \tag{40}$$

$$E_2 = 0.5 \cdot M_0 c_1^2. \tag{41}$$

Hence

$$\frac{E_2}{E_1} = \frac{M_0}{M_1'} \cdot \left(\frac{c_1}{W}\right)^2, \tag{42}$$

or, on the basis of formula (38):

$$\frac{E_2}{E_1} = \frac{M_0}{M_1'} \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2. \tag{43}*$$

*Here and in what follows we find some oversights in the order in which the formulas are numbered in the author's original text. -- (Edit.)

This enables us to calculate the efficiency at not greater than 65%, and it may be assumed at 50% for attaining escape velocities. If the store of explosive is comparatively small, then we obtain, in an approximation, instead of (43):

$$\frac{E_2}{E_1} = M_1' M_0, \tag{45}$$

or, to be more precise,

$$\frac{E_2}{E_1} = \frac{M_1'}{M_0} \cdot \left(1 - \frac{M_1'}{M_0}\right). \tag{46}$$

We can arrive at a still more exact formula by using the expansion

$$\ln (1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} \cdots \tag{47}$$

It is evident from the formulas that at the beginning, when the store of explosive is small, the efficiency will increase in proportion to the store, and later will increase more slowly to attain a maximum, after which it will slowly decline and ultimately reach zero.

The ratio $\frac{M_1'}{M_0} = x$ corresponding to the maximum efficiency is determined by the equation

$$\ln (1 + x) = \frac{2x}{1 - x} \cdot x$$

and is close to 4 in value (i.e., the explosive store exceeds the weight of the rocket by 4 times), while the efficiency is 65 %. Table 6 lists values of the variables of interest for several cases.

In addition to what we derived analytically, we see from the table that the maximum utilization (up to 65 %) of the exhaust energy will occur when the weight of the exhaust material is 4 times the weight of the rocket. But the percentage of utilization is in general not small (around 50 %) when the relative quantity of the exhaust material fluctuates from 1 to 20, and the corresponding velocities, from 3 to 15 km/sec. These are entirely adequate figures for outer space flight. The two velocities tabulated refer to different explosives. The greater velocity refers to pure hydrogen and pure oxygen, whereas the lesser velocity refers to hydrocarbons and to endogenous oxygen compounds. For illustration, I have added a fifth column to indicate the maximum ascent possible (in km) in the presence of a constant gravitational pull.

Out investigation is applicable in the following cases: 1) in a gravitationless medium, for example somewhere between suns and galaxies where the gravity is close to zero; 2) on small asteroids, small moons (such as the Martian moons) and on all small celestial bodies, such as the Rings of Saturn, where gravity may likewise be neglected; 3) in orbit around the earth; 4) at any point in any solar system at any distance whatever from a celestial body if the projectile is outside the atmosphere, whether or not it has acquired a velocity which will prevent its coming into contact with the celestial body or with the atmosphere of the latter.

Later on we shall see that, in order to avoid energy losses, the direction of the explosive process must be normal to the resultant of the gravitational force.

Clearly, then, it is sufficient simply to break free from the planetary atmosphere and to become a satellite of that planet, even though at a very close distance from the planet, for further motion and travel through the entire universe to become perfectly possible. In fact, the explosion rate might be a very weak one in that case, and the energy required to bring it about might be borrowed from the Sun's energy. The supporting material would be provided by α- and β-particles, which are disseminated everywhere, or by fireballs, or by cosmic dust.

Mankind's first great step forward into outer space consists in flying beyond the atmosphere and creating a satellite of the earth. The rest is comparatively easy, even escape from our solar system. But, of course, I do not have in mind here descent onto the giant planets.

TABLE 6

Ratio of Exhaust Mass To Rocket Mass M_1'/M_0	Formula (38), When Exhaust Velocity Attains 5,000 m/sec	Formula (38), When Exhaust Velocity Attains 4,000 m/sec	Average Efficiency, % E_2/E_1 Formula (43)	Approximate Ascent in km, Under Constant Pull of Gravity
0.1	472.5	378	8.87	11.4
0.2	910	728	16.55	42
0.3	1 310	1 048	22.9	92
0.4	1 680	1 344	28.2	138
0.5	2 025	1 620	32.8	204
0.6	2 345	1 876	36.7	280
0.7	2 645	2 116	40.0	357
0.8	2 930	2 344	42.9	440
0.9	3 210	2 568	45.8	520
1	3 465	2 772	48.0	607
1.5	4 575	3 660	55.8	650
2	5 490	4 392	60.3	1 520
3	6 900	5 520	63.5	2 430

[Table cont'd. on next page]

[Table cont'd.]

Ratio of Exhaust Mass To Rocket Mass M_1'/M_0	Formula (38), When Exhaust Velocity Attains 5,000 m/sec	Formula (38), When Exhaust Velocity Attains 4,000 m/sec	Average Efficiency, % E_2/E_1 Formula (43)	Approximate Ascent in km, Under Constant Pull of Gravity
4	8 045	6 436	64.7	3 300
5	8 960	7 168	64.1	
6	9 730	7 784	63.0	
7	10 395	8 316	61.7	The ascent is actually higher, since the gravity pull slackens off
8	10 985	8 788	60.5	
9	11 515	9 212	58.9	
10	11 990	9 592	57.6	
15	13 865	11 092	51.2	
20	15 220	12 176	46.3	
30	17 170	13 736	39.3	
50	22 400	17 920	31.0	
100	26 280	21 040	21.0	
193	30 038	24 032	14.4	
∞	∞	∞		

Rocket Travel in a Medium Affected by Gravity, in a Vacuum

Let us conceive of the situation where the atmosphere has been eliminated, or imagine ourselves on the Moon or on some other planet having dry land and not surrounded by gases or vapors. We neglect the slow rotation of the planet. The flight of the projectile may be: 1) vertical flight 2) level, or 3) inclined.

Let us take up this question in more general terms (Fig. 2).

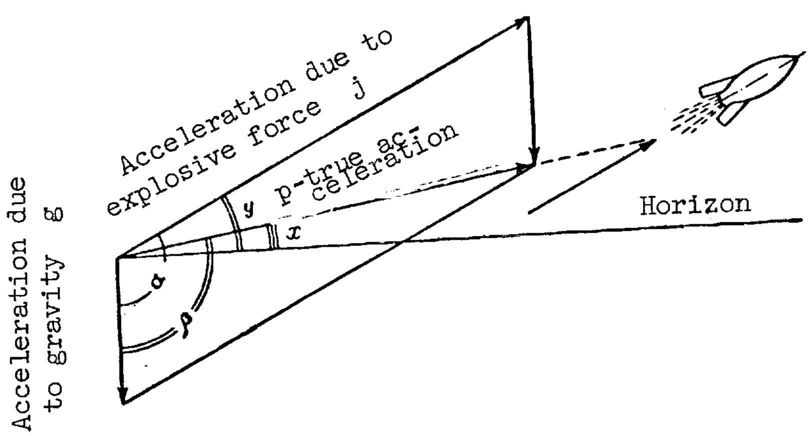

Fig. 2.

HOW TO DETERMINE THE RESULTING ACCELERATION

The rocket is acted upon by the force of gravity g expressed by the acceleration per second, and then by the force of the explosive process in the direction aligned with the long axis of the projectile, this force imparting to the projectile an acceleration per second j. Between the directions of these forces we have an angle α greater than 90°. The angle formed by the expolosion force with the horizon will be $\alpha - 90° = y$. These will be the three known quantities. The unknowns are: the direction of the rocket's motion, defined by the angle β or the angle $x = \beta - 90°$, and the value of the resultant p, i.e. the true acceleration per second of the projectile.

By trigonometry, we have (see drawing above)

$$\alpha = y + 90; \ \sin\alpha = \cos y; \ \cos\alpha = -\sin y;$$

$$\cos\beta = -\sin x; \ x = \beta - 90; \ \tan\beta = \cot\alpha;$$

$$\tan\beta = \cot x = \frac{j \cdot \sin\alpha}{g + j\cos\alpha} = \frac{j \cdot \cos y}{g - j\sin y}; \qquad (48)$$

$$\rho = \sqrt{j^2 + g^2 + 2j \cdot g\cos\alpha} = \sqrt{y^2 + g^2 + 2j \cdot g \cdot \sin y}. \qquad (49)$$

The known angle y and the unknown angle x are simpler to find than α and β, since they are less than right angles and they define the inclinations to the horizontal of the explosive force (and also of the rocket axis) and the resultant.

WORK DONE BY ROCKET AND BY EXHAUST MATERIAL; MECHANICAL EFFICIENCY

What will be the efficiency in a medium affected by gravity, in a vacuum?

$$E_2 = 0.5\, M_0 c_1^2 + A. \tag{65}$$

A is the work done in lifting the rocket, and E_2 is the work done by the rocket.

$$A = -\, l \cos \beta \cdot M_0 \cdot g = l \sin x \cdot M_0 g. \tag{66}$$

l denotes the range or the path length traversed by the vehicle.
If p and j are constant, then

$$l = \frac{c_1^2}{2p} \tag{67}$$

and, in view of formulas (65) to (67):

$$E_2 = 0.5 \cdot M_0 c_1^2 \left(1 + \sin x \cdot \frac{g}{p} \right). \tag{68}$$

Moreover

$$E_1 = 0.5\ M_1'W^2. \tag{69}$$

And from (68) and (69)

$$\eta = E_2 : E_1 = \frac{M_0}{M_1'} \cdot \frac{c_1^2}{W^2}\left(1 + \frac{g}{p} \cdot \sin x\right). \tag{70}$$

We know from trigonometry that, for any angle

$$\cos \beta = \frac{\cot \beta}{\sqrt{1 + \cot^2 \beta}}. \tag{71}$$

Hence, taking (48) into account:

$$\cos \beta = \frac{g + j \cos \alpha}{\sqrt{j^2 \cdot \sin^2 \alpha + (g + j \cos \alpha)^2}} = - \sin x =$$

$$= \frac{g - j \sin y}{\sqrt{j^2 \cos^2 y + (g - j \sin y)^2}} \tag{72}$$

Now, from (70), we may eliminate the unknown sin x. But we still have to eliminate c_1. We have

$$t_1 = \frac{W}{K} \cdot \ln\left(1 + \frac{M_1'}{M_0}\right). \tag{73}$$

This is the total time required for the explosive process when the relative gravity K is constant

But

$$K = j \text{ and } c_1 = p \cdot t_1. \tag{74}$$

Consequently, from (39_5) and (74) we have that

$$c_1^2 = p^2 \cdot \frac{W^2}{j^2} \cdot \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2. \tag{75}$$

And now, using formulas (70), (72), and (75), we find

$$\eta = \frac{p^2 \cdot M'}{j^2 \cdot M_1'} \cdot \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2 \times$$

$$\times \left[1 - \frac{g\cdot(g\cdot j\cdot \sin y)}{\sqrt{j^2\cdot\cos^2 y + (g - j\sin y)^2}\,\sqrt{j^2 + g^2 - 2j\cdot g\cdot \sin y}} \right] \quad (77)$$

When there is no gravity, $g = 0$ and $p = j$. In this case, the last formula will lead to formula (43). Using (77), we determine the efficiency in the event the explosion issues horizontally, i.e. when $y = 0$. Then we again end up with formula (43). Again, it is readily seen that when the direction of the explosion is normal to the pull of gravity (i.e. when it is directed horizontally), the utilization will be the same as when gravity is totally absent. Near the planet (at the very surface) a horizontally directed explosion would be inapplicable, since then the rocket would impinge on the ground as it dropped. But at a certain height, even if still in the air, a horizontally directed explosion would be possible, also in cases where the rocket can no longer plunge through the atmosphere because of the escape velocity it has acquired, and is starting to behave like a celestial body. The horizontally directed force is also applicable in the case of atmosphere-free planets when the projectile is moving along a smooth level path. Later, we shall also see its application to motion through an atmosphere.

We may check formula (77) using still another particular case. Assume that the projectile is moving perpendicular, i.e. that $y = 90°$ and $p = j - g$.

We then find

$$\eta = \frac{M_0}{M_1'}\left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2 \cdot \left(1 - \frac{g}{j}\right). \quad (80)$$

(This formula was derived earlier and may be found in the works printed in 1903.)

It is clear from this formula that vertical rocket motion is not advantageous, particularly so when j is slightly in excess of g.

By contrast, the greater the acceleration j due to the explosive force relative to g, the greater will be η and the lower the losses. Comparing the efficiency in a medium free from gravity (43) to the efficiency in a gravitational medium at vertical motion (80), we see that the latter efficiency is less than the first by $1/(1 - g/j)$.

The relative loss is expressed in terms of the fraction g/j. For example, when the explosive force is ten times greater than the weight of the rocket, the loss will be 0.1. But when the two forces are equal, the loss will be 100%, i.e. all of the energy will be lost with no benefit to the projectile. In fact, in that case the rocket is balanced; it will neither climb nor acquire any velocity. When the explosive force is infinite, the efficiency will be the same as in a gravity-free medium. But a powerful explosion will kill all the occupants and wreak destruction inside the vehicle. Such an explosion can be resorted to only in projectiles carrying no passengers or intricate equipment.

TABLE 7

Gravitational Medium. Vertical Rocket Motion

j/g	1	2	3	4	5	10	
Efficiency, %	0	50	66.7	75	80	90	100
Velocity, %	0	70.7	81.7	86.6	89.4	94.9	100

As we see, vertical motion will be accompanied by high energy losses, particularly when the explosive force j is a modest one. Here j must be greater than g, for otherwise no motion of any kind would result. The bottom row expresses the maximum corresponding velocity in percent. Actually, the velocity is given by the middle row, since a portion of the energy will be expended on climbing during the explosion process (this was proved in 1903).

FLIGHT OF A ROCKET IN A MEDIUM SUBJECT TO GRAVITY, IN AN ATMOSPHERE

Suppose that a rocket positioned horizontally in a medium subject to gravity is moving under the influence of a horizontally acting force. At first gravity will constrain the rocket to fall at an angle of 90° or less. More precisely, the tangent of this angle will be g/j*. But after several seconds the horizontal component of the rocket velocity will be so enormous that the vertical motion of the rocket, given a large surface area of the rocket, would become negligible compared to the horizontal component of the motion. In this way the rocket will be moving almost horizontally, as if on rails. We may calculate that the fall of the rocket could be only a very slow fall because of the resistance presented by the air, given the considerable lateral surface (vertical projection) of the projectile, and that the fall would be slowed down more and more as the velocity of the rocket increased. This will also be the case in inclined fall, when the inclination of the projectile does not exceed 20°—40°. Then the projectile will be moving as if on inclined rails, several seconds after the motion is initiated. The fall of a well-designed rocket in the absence of horizontal motion would be roughly only 20 to 30 m/sec. This figure must drop to 1 m/sec or less at an enormous velocity. What is this in comparison to the escape velocity?**

---

*We assume here an initial rocket velocity $v_0 = 0$. (Edit.)

**It seems that Tsiolkovskiy had in mind here the effect of lift in rocket flight. When zero lift obtains, the law of independent action of forces would indicate that the motion along the vertical would be independent of the motion in the horizontal direction.

HOW TO DETERMINE THE VELOCITY, ACCELERATION, FLIGHT TIME, THE WORK DONE BY THE ROCKET, THE WORK DONE BY THE EXHAUST MATERIAL, AND THE MECHANICAL EFFICIENCY, ASSUMING MOTION ON AN INCLINED PLANE

In Fig. 3 we have, approximately*

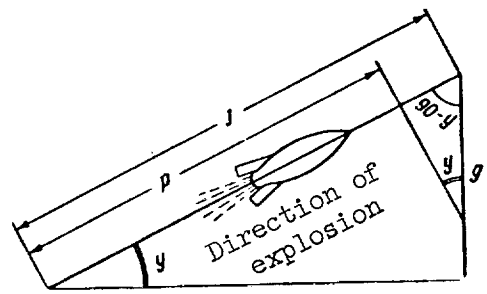

Fig. 3.

$$c_1 = p \cdot t; \qquad (83)$$

$$p = j - g \cdot \sin y; \qquad (84)$$

$$K = j:g; \qquad (85)$$

*This approximation is admissible when the values of j are large compared to g. Note by the editor of Selected Works of K. E. Tsiolkovskiy, Moscow, ONTI, 1934.

$$c_1 = (j - g \cdot \sin y) \cdot \frac{W}{j} \ln\left(1 + \frac{M_1'}{M_0}\right); \qquad (86)$$

$$t_1 = \frac{W}{j} \ln\left(1 + \frac{M_1'}{M_0}\right). \qquad (39_5)$$

In these equations, j is constant.

The formulas are even better adapted to the motion of a projectile on an inclined nonyielding plane, i.e. in accelerated motion (upward) on a mountain slope.

Let us take up the definition of the efficiency

$$E_2 = 0.5\ M_0 c_1^2 + A; \qquad (87)$$

$$A = M_c gh = M_0 g l \cdot \sin y. \qquad (88)$$

Here h is the altitude achieved by the projectile.
Hence

$$E_2 = \frac{M_0}{2} \cdot c_1^2 \cdot \left(1 + \frac{g}{p} \sin y\right). \qquad (89)$$

Further

$$E_1 = \frac{M_1'}{2} \cdot W^2. \tag{90}$$

And accordingly,

$$\frac{E_2}{E_1} = \eta = \frac{M_0}{M_1'} \cdot \frac{c_1^2}{W^2}\left(1 + \frac{g}{p} \sin y \right). \tag{91}$$

With the aid of formulas (86) and (84), we infer from the above that

$$\eta = \frac{M_0}{M_1'} \cdot \left[\ln\left(1 + \frac{M_1'}{M_0} \right)^2 \left(1 - \frac{g}{j} \sin y \right) \right]. \tag{92}$$

On simplifying formula (77), for low y angles, we also end up approximately with formula (92) [see also formula (49)].

If the rocket is flying horizontally and $y = 0$, then the efficiency found from (92) will be in accord with formula (43). Also, when $y = 90°$, we obtain from (92) the familiar formula (80). η is the mechanical efficiency which, when multiplied by the thermal efficiency (cf. Table 5), yields the total efficiency. We see that the efficiency in a vacuum (77) will in general not be the same as the efficiency in an atmosphere, or, more accurately, we refer here to a vacuum with the projectile in motion on an inclined plane.

The losses, by comparison to a gravity-free medium, will be

$$\frac{g}{j} \sin y. \tag{93}$$

TABLE 8

Medium Affected by Gravity in an Atmosphere.

Incline Motion

Angle of inclination, in deg		1	2	5	10	15	20	25	30	35
Energy losses at various j/g ratios, in %	10	0.17	0.34	0.85	1.7	2.6	3.4	4.2	5	5.7
	5	0.34	0.64	1.7	3.4	5.2	6.8	8.4	10	11.4
	2	0.85	1.7	4.25	8.5	13	17	21	25	28.5
	1	1.7	3.4	8.5	17	26	34	42	50	57

If, for example

$$g/j = 0.3; \ y = 20°; \ \sin y = 0.342,$$

Then the losses will be 5.7%. We here recommend Table 8 to the reader.

It is obvious here that it would be highly advantageous to launch the rocket in the presence of the strongest powerful explosion, were it not for the destructive effects of such a blast and the engineering difficulties. It would also be to our advantage to direct the rocket on the lowest angles, were it not for the work required in overcoming atmospheric drag. In general, the losses may be reduced to 1% even in the case of a small explosive force.

HOW TO COMPUTE ATMOSPHERIC DRAG MORE ACCURATELY

In what follows, I shall attempt a simplification of the formulas which I derived in 1911-1912. Assume the temperature of the air to be constant. As a result of this, the atmosphere is extended without limit. We then have the familiar formula

$$h = \frac{f_1}{d_1} \cdot \ln \frac{d_1}{d}, \qquad (95)$$

where f_1/d_1 is the height of the imagined atmosphere h_1 at constant density d_1; f_1 is the atmospheric pressure corresponding to d_1.

This means

$$\frac{h}{h_1} = \ln \frac{d_1}{d} \qquad (96)$$

and

$$d = d_1 e^{-\frac{h}{h_1}} \qquad (97)$$

The drag presented by the air or the pressure W on the rocket due to its motion will be

$$W = \frac{F}{a} \cdot d \cdot \frac{c^2}{2g} . \qquad (98)$$

This pressure (Poncelet) is not given in absolute units, but rather in conventional units such as tons. F is the area of rocket mid-section; a is the form factor of the rocket, i.e. a coefficient varying in inverse proportion to the drag W. In inclined rocket motion the path length l will be

$$l = h:\sin y. \qquad (99)$$

We have

$$p = j - g \sin y; \qquad (84)$$

$$c = \sqrt{2p \cdot l}. \qquad (84_1)$$

Hence

$$c = \sqrt{2(j - g \sin y)\ \iota}\ . \tag{100}$$

The elemental work required to overcome the air resistance is expressed as

$$dT = Wd\iota. \tag{101}$$

From (97), (98), (99), and (100), we infer

$$dT = \frac{Fd_1}{ag} \cdot (j - g \sin y)\ \iota \cdot e^{\frac{\iota \sin y}{h_1}} \cdot d\iota. \tag{102}$$

Here we put

$$\frac{\iota \sin y}{h_1} = \frac{h}{h_1} = x;$$

$$dx = \frac{\sin y}{h_1} \cdot\ d\iota = \frac{dh}{h_1};\quad d\iota = \frac{h_1 dx}{\sin y}. \tag{103}$$

We then find

$$dT = \frac{F\ (j - g \sin y) d_1}{a \cdot g \cdot \sin^2 y} \cdot h_1^2 \cdot x \cdot e^{-x} \cdot dx. \qquad (104)$$

We assume

$$\frac{F\ (j - g \sin y)}{a \cdot g \cdot \sin^2 y} \cdot d_1 h_1^2 = A. \qquad (105)$$

On integrating and determining the constant, we have

$$T = A \left[1 - \left(1 + \frac{h}{h_1} \right) e^{-\frac{h}{h_1}} \right] = A \left[1 - \left(1 + \frac{\ell \sin y}{h_1} \right) e^{-\frac{\ell \sin y}{h_1}} \right]. \qquad (106)$$

Taking (103) into account, we also end up with:

$$T = A\ [1 - (1 + \alpha)\ e^{-x}]. \qquad (107)$$

We now have to determine the total work done in overcoming the resistance presented by the atmosphere. To do this we must assume

$$\text{either} \quad h = \infty \quad \text{or} \quad x = \infty .$$

We now have:

$$e^{-x} = 1/e^{x} = 1\left(1 + \frac{x}{1} + \frac{x^2}{1\cdot 2} + \frac{x^3}{1\cdot 2\cdot 3} + \cdots\right). \qquad (108)$$

And accordingly,

$$(1 + x)e^{-x} = e^{-x} + x\cdot e^{-x} = e^{-x} + x:\left(1 + \frac{x}{1} + \frac{x^2}{1\cdot 2} + \cdots\right) =$$

$$= \frac{1}{e^{x}} + 1:\left(\frac{1}{x} + 1 + \frac{x}{1\cdot 2} + \frac{x^2}{1\cdot 2\cdot 3} + \cdots\right). \qquad (109)$$

It is now clear than when h or x goes to infinity, the expression (109) will go to zero. This means that the work done in overcoming the drag

$$T = A. \qquad (110)$$

The total work done in vertical motion is obtained from formula (104) on putting $y = 90°$. We then have

$$T = \frac{F\,(j - g)}{ag}\, d_1 h_1^2 . \qquad (111)$$

Comparing this work to the total work done in inclined motion, we realize that the latter exceeds the first by as many times as:

$$\frac{j - g \sin y}{(j - g) \sin^2 y} . \qquad (112)$$

When j is large or y is small, we may assume in an approximation that the work done in inclined motion will be inversely proportional to the square of the sine of the angle of inclination. This would mean that there is no inclination and we are dealing with level motion, the total work done in overcoming the resistance would be infinite. But this is incorrect, since equally dense layers of the atmosphere cannot be considered horizontal, as we had assumed, owing to the spherical shape of the earth. In other words, the formulas are invalid for low angles. Thus, if we assume the height of an atmosphere of appreciable density to be 50 km, then we readily calculate that the horizontal path is longer than the inclined path by only a factor of 15.5. If, on the other hand, we assign 5 km for the height, then the horizontal path will be longer than the perpendicular path by a factor of 155. This means that the work in the horizontal direction cannot be infinite. From formula (104) we can compute the total work done in the perpendicular motion.

Assume $F = 2 \cdot m^2$; $j = 100$ m/sec^2; $g = 10$ m/sec^2; $h_1 = 8{,}000$ m; $d_1 = 0.0013$ ton/m^3; $a = 100$. We then have T = 14,976 ton-meters. This is very little even when compared to the work done simply in the motion of a rocket having a mass of 10 tons (without counting the explosives) and escaping from the earth's gravitational pull (11 km/sec velocity). This work will exceed 60 million ton-meters. That means that it will be over 4,000 times the work done in overcoming atmospheric drag in a perpendicular climb. In launching the projectile from the highest points, at points where the air is 3 to 4 times less dense, we shall find that, in accord with formula (104), this work will decrease further in proportion to the rarefaction, i.e. again by 3 to 4 times. The work will not be greatly increased by inclined motion. From formula (112) we can calculate this on putting j = 30, j = 20, and g = 10.

We see from the second line in Table 9 that at 20° inclination the work is increased 11 times. Then, from a comparison of the second and third lines with the fourth, we see that the work involved can be calculated roughly as proportional to $1/\sin^2 y$. The greater the value of j, the more closely the approximation will correspond to exactness, and conversely. The third line indicates the increase in the work when j = 20. At low angles, the true work will be far less because of the spherical shape of the earth.

We have seen that the work done in overcoming air drag at vertical motion comprises 1/4000 of the work done in moving the rocket, while it is less than 1% at inclined motion.

The relationship between the work involved in overcoming drag and the path traversed or the height h attained is of interest. The total work is expressed by formula (104), and the remaining portion is expressed by formulas (107) and (108). It depends on the altitude reached.

Table 10 illustrates this relationship.

THE OPTIMUM FLIGHT ANGLE

By using formulas (77) and (93), we can compute the work loss due to inclined flight in a medium affected by gravity. From formula (104) we determine the corresponding loss due to the atmospheric drag. On compiling a table and determining the sum of the losses, we will find what type of inclined flight is accompanied by the least losses. This is the type that will be the optimum.

But even without recourse to tables we can roughly determine the optimum angle of inclination. The losses due to inclined motion of the projectile are expressed [cf. (93)] as

$$\frac{g}{j}\sin y \quad \text{in absolute units.} \qquad (113)$$

TABLE 9

y	10	20	30	40	50	90
T at $j = 30$	46.7	11.3	5	2.85	1.92	1
T at $j = 20$	60	14.2	6.0	3.3	2.1	1
$1/\sin^2 y$	33	8.55	4	2.42	1.70	1

TABLE 10

Relative Remaining Work Done in Overcoming
Drag, percentage*

h ...	4	8	16	24
h/h_1	0.5	1	2	3
Relative remaining work, %	91	74	41	20

*Table 10 should be revised, in view of an error committed by Tsiolkovskiy in formula (105); there the remaining relative work turned out to be a function of the angle of inclination, whereas in fact this is not so. We see from Table 10 that after flying 4 km there would remain still 91% of the entire amount of the work to be performed, and after flying 24 km, 20%.

----Note by editor of Selected Works of K. E. Tsiolkovskiy. Moscow, ONTI, 1934.

The losses due to atmospheric drag will be, in absolute units

$$Ag = \frac{F}{a} \cdot \frac{(j - g \sin y)}{\sin^2 y} \cdot d_1 h_1^2 \, . \qquad (114)$$

The work done by the rocket will be [cf. (104)]

$$E_2 = 0.5 \cdot M_0 \cdot c_1^2 = 0.5\, M_0 \cdot W^2 \left[\ln \left(1 + \frac{M_1'}{M_0} \right) \right]^2 \text{ [cf.(38)]} \qquad (115)$$

Consequently, both losses will be, in absolute units

$$E_2 \cdot \frac{g}{j} \sin y + Ag = E_2 \cdot \frac{g}{j} \sin y + \frac{F}{a} \cdot d_1 h_1^2 \cdot \left(\frac{j - g \sin y}{\sin^2 y} \right) = Z.$$

(116)

Taking the derivative of this expression and equating it to zero, we obtain an equation which is still not convenient for solving with respect to sin y.

However, the optimum angle is not a large one. We may consequently neglect the expression g sin y in the second term.

Equation (116) is thereby transformed to

$$Z = E_2 \frac{g}{j} \cdot x + \frac{F}{a} \cdot d_1 \cdot h_1^2 \cdot \frac{j}{x^2}$$

Here we have sin y = x. On differentiating this equation and putting its first derivative at zero and solving for x, we obtain

$$x = \sin y = \sqrt[3]{\frac{2 \cdot F \cdot d_1 \cdot h_1^2 \cdot j^2}{a \cdot E_2 \cdot g}} \qquad (118)$$

With the aid of (115), we find

$$\sin y = \sqrt[3]{\frac{4F \cdot d_1 \cdot h_1^2 \cdot j^2}{a \cdot M_0 W^2 \left[\ln\left(1 + \frac{M_1'}{M_0}\right) \right]^2 \cdot g}} \qquad (119)$$

Clearly, then, the optimum angle y increases with the explosion energy j and with the cross-sectional area F of the rocket, and decreases in inverse proportion to the form factor a and the ratio of the projectile mass to exhaust material mass M_1'/M. On a planet exerting a powerful gravitational attraction g it will also decrease, and the opposite is also true. In formula (119), we put: F = 2; d = 0.0013; h = 8,000; j/g = 10; a = 100; M_0 = 10; W = 5,000.

Our calculations then yield

$$\sin y = 0.167 \text{ and } y = 9°35'.$$

When j = 20, we obtain sin y = 0.057 and y = 3°20′.

But at these low angles the atmospheric drag is far less because of the earth's spherical shape. This means that the optimum angle will also be smaller.

Using formula (117), we obtain the relative loss due to both causes

$$\frac{Z}{E_2} = \frac{g}{j} \cdot x + \frac{Fd_1 j}{aE_2 x^2} h_1^2 = \frac{g}{j} x +$$

$$+ \frac{2Fd_1 j \cdot h_1^2}{aM_0 W^2 \left[\ln \left(1 + \frac{M_1'}{M_0} \right) \right]^2 \cdot x^2} \qquad (120)$$

Let us now demonstrate a simpler formula for determining the loss percentage.

On dividing the second term by the third in formula (120), we learn how many times the losses due to the effect of gravity exceed the losses due to air drag. Then, eliminating x from this relation by means of formula (119), we end up with number 2. This shows that at the optimum angle of inclination the gravitational losses due to gravity will be double the losses due to the air drag. Accordingly,

$$Z/E_2 = \frac{g}{j} \cdot x + \frac{g}{2j} x = \frac{3}{2} \cdot \frac{g}{j} x . \qquad (121)$$

Thus, at angles of 9° and 3° we find the total loss to be 0.025 and 0.0428, i.e. 2.5% and 4.3%, respectively.

From Formulas (121) and (119) we derive the total relative loss

$$L/E_2 = \sqrt[3]{\frac{27 \cdot F \cdot d_1 \cdot h_1^2 \cdot g^2}{2 \cdot a \cdot M_0 \cdot W^2 \left[\ln \left(1 + \frac{M_1'}{M_0} \right) \right]^2 \cdot j}} \qquad (122)$$

The area presented by a body varying in this manner will increase in proportion to the square of its dimensions, while the volume and the mass of the body will increase in proportion to the cube of its dimensions. The losses will therefore vary inversely with rocket size, as well as with improvement in the shape a of the projectile and with increase in j (or explosive force), but very slowly. For example, when j is increased 8 times, the losses will be cut only in half. It would be highly advantageous to fly at low j, but little would be gained, as we see. At j = 10, x = sin y = = 0.036, y = 20°10′, and Z/E_2 = 0.054. The angle is a very small one, consequently, and the losses are 5%. Actually, the losses are far less due to the earth's spherical shape.

Let us assign the value a = 50 in the formulas and, in addition, F = 2; d_1 = 0.0013; h_1 = 8,000; M_0 = 10; W = 5,000, as we did before; j will now be assigned different values.

We compile Table 11.

At a low inclination, we find, a slight acceleration will be needed, and this is quite advantageous from the technical standpoint. It is a pity that the losses incurred here will be at a maximum (as high as 14.6%).

Here we specify the acceleration for the projectile as ranging from 1 to 200 m/sec^2, corresponding to a range from 0.1 to 20 with respect to the acceleration due to gravity (10 m/sec^2). For example, for a rocket weighing 10 tons the pressure of the explosives will vary the inclination from 0.5° to 20°. The energy losses due to gravity and drag will range from 15 to 2.5%. It seems strange that the losses would be less at high inclinations; but this is accounted for by the tremendous acceleration j. The losses at low angles, on the other hand, are actually still lower considering the curvature of the atmosphere over the spherical surface of the earth.

When the mass M_0 of the rocket is 8 times less, we infer from formulas (119) and (122) that the sines of the angles and the losses (cf. Table 11) are doubled. Thus, at j = 30 the angle will be about 11°, and the losses will be about 9.5%.

Table 11 and formula (114) readily show that the approximate formulas will yield no great error even when j = 1. The error is even much smaller when j is large.

GRAVITY, RESISTANCE OF THE ATMOSPHERE, AND CURVATURE OF THE EARTH

From (101), (98), (97), and (100), we obtain, in conventional units:

$$dT = \frac{Fd_1}{ag}(j - g \sin y)\, e^{-\frac{h}{h_1}} \cdot l\,dl. \qquad (122_1)$$

For a flat earth, we infer from formula (99):

$$l = h : \sin y.$$

TABLE 11

Gravity-free acceleration of rocket j	1	2	3	4	5	6	7	8	9	10
sin y = x	0.0097	0.0154	0.0204	0.0246	0.0292	0.0326	0.0356	0.0392	0.0422	0.0453
Angle y in deg	0.56	0.88	1.17	1.41	1.68	1.86	2.07	2.26	2.43	2.60
Z/E_2 = losses, %	14.6	11.6	10.2	9.23	8.57	8.07	7.66	7.33	7.05	6.80

TABLE 11 (Cont'd)

Gravity-free acceleration of rocket j	15	20	25	30	40	50	60	80	100	200
sin y = x	0.059	0.072	0.083	0.094	0.114	0.133	0.150	0.182	0.211	0.333
Angle y in deg	3.41	4.16	4.75	5.41	6.55	7.66	8.66	10.50	12.16	19.50
Z/E_2 = losses, %	5.94	5.40	4.97	4.71	4.28	3.98	3.75	3.40	3.16	2.50

But for the true shape of the earth, this will be applicable only at not very acute angles y. We can readily derive the more accurate formula

$$h = \ell \sin y + \frac{\ell^2}{2R} = \ell \left(\sin y + \frac{\ell}{2R} \right), \qquad (123)$$

where R is the radius of the earth, for any angles whatever.

Hence, we may compute

$$\ell = - R \sin y \cdot \left(1 - \sqrt{1 + \frac{2h}{R \sin^2 y}} \right). \qquad (124)$$

We now put

$$\frac{2h}{R \sin^2 y} = X; \sqrt{1 + X} = 1 + \frac{X}{2} - \frac{X^2}{8} + \frac{X^3}{16} \cdots \qquad (125)$$

Restricting ourselves to the first three terms, we find

$$\ell = - R \sin y \cdot \left(- \frac{X}{2} + \frac{X^2}{8} \right) = \frac{h}{\sin y} - \frac{h}{2R \sin y} =$$

$$= \frac{h}{\sin y}\left(1 - \frac{h}{2R\sin^2 y}\right). \qquad (126)$$

We now solve the problem of the work done in overcoming the drag in the particular case when the flight is horizontal and $y = 0$.
We then have

$$h = \frac{l^2}{2R} \text{ and } l = \sqrt{2Rh.} \qquad (127)$$

Furthermore, from (102) we have

$$dT = \frac{Fd_1}{ag} \cdot j \cdot e^{-\frac{h}{h_1}} \cdot l\,dl = \frac{Fd_1}{ag} \cdot j \cdot e^{\frac{-l}{2Rh_1}} \cdot l\,dl. \qquad (128)$$

We now put

$$\frac{l^2}{2Rh_1} = u.$$

Then

$$l\,dl = R \cdot h_1 \cdot du, \qquad (129)$$

and, in place of (128),

$$dT = \frac{Fd_1}{ag} \cdot j \cdot R \cdot h_1 e^{-u} \cdot du = A \cdot e^{-u} du. \quad (130)$$

On integrating and determining the integration constant, we have

$$T = A(1 - e^{-u}) = A \cdot \left(1 - e^{-\frac{h}{h_1}}\right) = A \cdot \left(1 - e^{-\frac{\iota^2}{2Rh_1}}\right) \quad (131)$$

Here

$$A = \frac{Fd_1}{ag} \cdot j \cdot R \cdot h_1. \quad (132)$$

This expression also specifies the total work done in overcoming the resistance of the atmosphere.

For vertical motion we had

$$T = \frac{F(j-g)}{ag} \cdot d_1 h_1^2. \quad (111)$$

At vertical ascent of the projectile, the work done in overcoming the resistance of the atmosphere will be a fraction of that indicated in (132) and (111):

$$\frac{j}{j-g} \cdot \frac{R}{h_1} \cdot \qquad (133)$$

Here we put

$$j = 100; \quad g = 10; \quad h_1 = 8000.$$

From (133) we then obtain the figure 883, i.e. the work done in horizontal motion is almost a thousand times greater than the same work done in overcoming drag at vertical flight of the projectile. The reason for this is that a projectile with increasing velocity must fly through very dense layers of the atmosphere. Thus, a path close to a horizontal trajectory would be very disadvantageous: the work done in overcoming the drag would take up an enormous share of the vis viva [kinetic energy] of the rocket, which would fail to acquire sufficient velocity. We saw that the work done in overcoming air drag in an upward ascent accounts for about 1/4000 of the kinetic energy of the projectile (at M_0 = 10 tons). This means that the horizontal drag would take up about one-fifth (22.2%). According to Table 11, losses would be somewhat less at a half-degree (0.56°) inclination, about 15% (14.6%) to be specific. Here only 1/3 is involved in overcoming the resistance, that is, 5%. The reason for the low figure is that the acceleration is 100 times less, according to Table 11, than what we assumed. Losses due to the effect of gravity are included.

It is evident from (132) that T is largely dependent upon j and that horizontal flights are expedient at low j. Thus, we can calculate the work involved in overcoming air drag at horizontal flight of the projectile for different j values. As earlier, we assign the values

$$F = 2; \quad \alpha = 50;$$

and then [cf. (132)]

$$T = 264\,800.$$

The work done by the rocket is found from (41) and (38)

$$E_2 = 0.5 \cdot M_0 \cdot W^2 \left[\ln\left(1 + \frac{M_1'}{M_0}\right) \right]^2. \qquad (135)$$

The work done by the rocket in overcoming the earth's gravitational attraction (11 kg) at $M_0 = 10$ amounts to about $64 \cdot 10^6$. This is 240/j times greater than the drag presented by the atmosphere.

TABLE 12

Explosive force j	1	2	5	10	20	30	50	100
Losses, %	0.42	0.83	2.1	4.2	8.3	12.5	20.8	41.7

Even at an acceleration such that j = 5, i.e. half that of the earth's gravitational acceleration (g = 10), the losses will be about 2%.

ASCENT, VISITS TO PLANETS, AND LANDING ON EARTH

Suppose that a rocket has attained a certain height after losing all its velocity in straight ascent. Under the influence of gravity, it will fall back, will acquire an appreciable velocity, and will smash to pieces on the earth, despite the decelerating effect of the atmosphere. Even this decelerating effect alone is capable of destroying the vehicle or of killing any organism on board. But if we also assume that there remains a store of explosives in the rocket after the ascent is terminated, and that this store is used to retard the rate of fall to exactly the same extent as the rate of ascent, then the descent will be accomplished successfully, and the vehicle will come to rest at the very surface of the planet, i.e. it will land without mishap on the earth.

If the quantity of explosives available for the ascent must exceed by K_1 times the weight of the rocket and all its contents, then a safe landing will require a store of explosives equal to the mass of the rocket multiplied by K_1. In order to loft the mass of rocket plus the supply of explosives we will need a mass

$$M_0 + M_0 \cdot K_1 = M_0(1 + K_1). \tag{136}$$

A safe landing will additionally require a supply of explosives K_1 times greater than the mass indicated in (136), viz.

$$M_0(1 + K_1)\ K_1. \tag{136_1}$$

Together with the rocket and the first load of explosives (136), this will amount to

$$M_0(1 + K_1)K_1 + M_0(1 + K_1) = M_0(1 + K_1)^2. \qquad (136_2)$$

The mass of explosives alone will be

$$M_0(1 + K_1)^2 - M_0 = M_0[(1 + K_1)^2 - 1]. \qquad (137)$$

If, for example, $M_0 = 1$, $K_1 = 9$, then the explosives will be 99, i.e. their weight will be 99 times the weight of the rocket and all contents other than the explosives. Such an enormous fuel store is hardly feasible. Things will be even more difficult when our objective is to ascend from the Earth, land on some other planet (one with an Earth-like orbit, for example), perform ascent from that planet, and return home.

It is a different matter when the altitude to which the projectile climbs is not great, so that K_1 will constitute a small fraction. Then the fuel store will be approximately equal to

$$M_0 \cdot 2 \cdot K_1$$

[cf. formula (137)]. In this case, hence, the fuel store will be simply doubled.

But an ascent to some modest height is of no interest in terms of space flight.

Ascent from Earth and landing on a strange planet with an Earth-like orbit (there is no such planet; this is an arbitrary assumption here) requires a fuel store

$$M_0 \cdot [(1 + K_1) \cdot (1 + K_2) - 1]. \qquad (138)$$

Here K_2 denotes the relative quantity of explosives required to make the ascent or to land on the alien planet.

If we cannot procure a supply of explosives on that planet and we nevertheless wish to take off from the planet and return to Earth, then we shall have to carry, beforehand, a supply

$$M_0[(1 + K_1)^2 \cdot (1 + K_2)^2 - 1]. \qquad (139)$$

Assuming the planet to be similar to Earth in mass and volume, we find the supply to be

$$M_0[(1 + K_1)^4 - 1]. \qquad (140)$$

Here we assume $K_1 = 9$ and $M_0 = 1$. Then the supply mass will be 9.999, i.e. an amount absolutely beyond reach. This corresponds more or less to the case of Venus. Travel to Jupiter and the other massive planets is even more out of the question, since K_2 takes on enormous proportions in that case. On the other hand, travel to the asteroids, and particularly to the smaller ones, is quite within reach, since K_2 will virtually vanish in that case. Travel to any of these bodies (again assuming them to have Earth-like orbits) and the return trip to the earth require a supply in accord with formula (137).

For visiting various planets without the opportunity to refuel on those planets, and then returning to the earth, we would in general have to lay on board a supply:

$$M_0[(1 + K_1)^2 \cdot (1 + K_2)^2 \cdot (1 + K_3)^2 \cdot (1 + K_n)^2 - 1]. \quad (141)$$

If there are n such planets to be visited (including the Earth), then by equating each of them to the Earth we end up with the fuel mass figure

$$[(1 + K_1)^{2n} - 1] \cdot M_0. \quad (142)$$

It is quite evident that visiting of planets in sequence is still less feasible.

HORIZONTAL MOTION OF PROJECTILE IN AN ATMOSPHERE OF UNIFORM DENSITY AND AT AN INCLINATION TO THE LONG AXIS

We assumed [see (83) and before] that the rocket must move in the air as if on rails, i.e. that the drag presented by the atmosphere would hinder the rocket from deviating appreciably from the trajectory determined by the explosive forces and the force of gravity. We now provide confirmation of this point.

Suppose that the rocket is flying horizontally at a velocity c and that the long axis of the rocket is inclined at a certain angle ξ to the horizon. Then the normal pressure R_y on the rocket, according to familiar laws of resistance of fluid media, will be

$$R_y = \frac{d}{g} F_h \cdot K_1 \sin \xi \cdot c^2. \quad (143)$$

Here F_h is the horizontal projection of the rocket, and K_1 is the drag coefficient.

If the rocket is moving horizontally, then this means that the rocket is not falling, and the pressure on the rocket from below will be equal to the weight M_0 of the rocket. From (143) we then find

$$\sin \xi = \frac{M_0 g}{dF_h K_1 c^2} . \qquad (144)$$

For example, we put: $M_0 = 1$; $g = 10$; $d = 0.0013$; $c = 100$; $F_h = 20$; $K_1 = 1$.

We shall now compute

$$\sin \xi = 0.0385 \text{ and } \xi = 2.2°.$$

When M_0 is ten times greater, ξ will also be almost ten times greater. When c is 10 times greater, the inclination will be reduced 100 times, i.e. it will become imperceptibly small.

Let us now attempt to determine the work done in overcoming air drag at accelerated and horizontal motion of a rocket. The spherical shape of the Earth reduces the amount of this work. The horizontal pressure R_x due to air drag will be

$$R_x = R_y \sin \xi = M_0 \sin \xi = \frac{M_0^2 g}{dF_h K_1 c^2} . \qquad (145)$$

Consequently, an elemental amount of work will be

$$dT = R_x dl, \tag{146}$$

where l is the length of the path traversed.

We may assume d constant and only c to be a variable.

$$c = \sqrt{2j \cdot l}: \tag{147}$$

j is the acceleration in seconds of the rocket. From (147), (146), and (145), we now have

$$dT = \frac{M_0^2 g dl}{2d \cdot F_h K_1 j l} . \tag{148}$$

Integrating and determining the integration constant, we find

$$T = A \cdot \ln\left(\frac{l}{l_1}\right), \tag{149}$$

where

$$A = \frac{M_0^2 g}{2d \cdot F_h K_1 j} . \tag{150}$$

If we compute the work from the beginning of the path, at zero velocity, the work will be found to be unbounded, in theory. This work is not great when the rocket traverses a segment of the path l on rails while acquiring a certain velocity. In a medium of uniform density, the work will increase without bound, although slowly. In (150) we put

$$M_0 = 1; \quad g = 10; \quad F_h = 20; \quad K_1 = 1; \quad j = 10.$$

Then A = 19.2 and

$$T = 19.2 \cdot \ln\left(\frac{l}{l_1}\right). \qquad (151)$$

Suppose the projectile covers a total of 1,000 km after traversing a path of 10 km. Then

$$T = 19.2 \cdot \ln 100 = 88.3.$$

If, however, the projectile has first traversed 1 km, then T = 132.5.

This means that a comparatively, negligible amount of work, is required to keep the rocket from falling.

This work may be expressed as a function of the velocity c acquired by the projectile. From (147) and (149) we have

$$l = \frac{c^2}{2j} \text{ and } T = A \cdot \ln\left(\frac{c^2}{c_1^2}\right). \qquad (152)$$

Thus, if the rocket commences its flight at a speed of 100 m/sec, and ends its flight at a speed of 10,000 m/sec, then

$$T = 19.2 \cdot \ln (100^2) = 176.6.$$

This is now a cosmic velocity, almost freeing the rocket from the Earth's gravitational pull, but the work involved is nevertheless insignificant. If the flight were begun at a speed of 10 m/sec,

$$T = 19.2 \cdot \ln (1000^2) = 265.$$

The difference in the work here turns out to be modest. The corresponding path length l is computed from (147).

$$l = \frac{c^2}{2j} = 5 \cdot 10^6 \text{ m}, \qquad (147)$$

or 5,000 meters. (We should recall the fact that we ignored frontal resistance in these calculations.) But at such a long path, albeit a horizontal path at the beginning, the rocket becomes projected far above the Earth's surface and first plunges into rarefied air and later on into a vacuum. The work done in passing through the slightly rarefied air will be enormous because of the pronounced inclination of the projectile, while even equilibrium will be impossible in the more rarefied air, and it will be all the more impossible in a vacuum. The work required for equilibrium becomes an actually absurd quantity.

We might confine our attention to travel through a constant layer of air at velocities up to 8 km/sec, after which the centrifugal force will completely cancel out the force of gravity. But here another difficulty presents itself. At motion through a dense medium the work done against the frontal resistance of the atmosphere, even when the projectile has a sharply tapered shape, becomes uncomfortably great. In addition, after the velocity of 8 km/sec has been acquired, there is still the problem of escaping from the atmosphere on a tangent or on an ascending curve, and this again requires a good deal of work. Our calculations have only shown at this point that the work done in keeping the weight aloft is very small, but we have not succeeded yet in proving that travel through air of uniform density is the most optimum variant.

HORIZONTAL MOTION OF A PROJECTILE WITH NO INCLINATION OF ITS LONG AXIS

The projectile is moving in the direction of the force of gravity.

The falling process or, more accurately, the rate of fall in seconds, will be

$$c_y = c \cdot \sin \xi = \frac{M_0 g}{dF_h K_1 c} . \qquad (165)$$

We again assume the rocket flight to be horizontal. The symbol ξ here designates the small angle by which the projectile deviates from its horizontal motion owing to gravity and air drag. For example, let us put $M_0 = 1$; $g = 10$; $\sin \xi = 0.0037$ (at a height of 10 km); $F_h = 20$; $c = 1$; $d = 2{,}260$; $K_1 = 10{,}000$. Then $c_y =$ $= 0.6$, i.e. 60 cm/sec.

If the projectile is traveling on a tangent to the Earth, then, on the one hand, it will be receding from the Earth at a certain speed while on the other hand it will be falling or drawing closer to the Earth's surface, depending on its translational velocity and on the density of the medium. The rate of fall is given by formula (165). Eliminating d and c from that equation [cf. (97), (127), and (147)], we find

$$c_y = \frac{M_0 g e^{\frac{h}{h_1}}}{d_1 F_h K_1 \sqrt{2j} \cdot \sqrt[4]{Dh}} \tag{166}$$

We compute the rate of climb at flight on a tangent in the following manner. We have:

$$\iota = \frac{j}{2} \cdot t^2, \tag{167}$$

where t is the time, and D is the Earth's diameter. We also have:

$$h = \iota^2/D.$$

And accordingly

$$h = \frac{j^2 \cdot t^4}{4D}.$$

Hence, on differentiating, we find

$$\frac{dh}{dt} = \frac{j^2}{D} \cdot t^3 = \sqrt[4]{\frac{64}{D}} \cdot \sqrt{j} \cdot h^{3/4}. \tag{168}$$

This enables us to compile Table 13.

TABLE 13

Rocket flight time, in seconds	10	20	50	100	200	400	1 000
Speed, in m/sec, when j = 10	100	200	500	1 000	2 000	4 000	10 000
l -- path length, in km	0.5	2	12.5	50	200	800	5 000
Height $h = l^2/D$ (approximately), in meters	0.02	0.32	12.3	197	3 150	50 400	1 970 000
$\frac{dh}{dt}$ -- rate of climb, in seconds	0.008	0.064	0.554	4.43	35.5	283	4 430
Air density d	-	-	-	0.0013	0.000878	Close to zero	
Rate of fall due to gravity and air drag, in m/sec	3.85	1.92	0.77	0.385	0.280	Very large	
d_1/d	1	1	1	1	1.48	550	10^{109}

The flight is performed more or less on a tangent to the Earth. This causes an increase distance from the spherical surface (4th row). At first this increase in distance is barely perceptible. Thus, after 10 seconds have elapsed, when 0.5 km has been traversed, it amounts to only 2 cm. The rate of escape (5th row) after 10 seconds is 8 mm/sec. But after 50 seconds, when more than 12 km of path has been traversed and the rocket has climbed 12 meters, the rate of escape will exceed 0.5 m/sec (55 cm/sec). By then the rate of escape will have almost overtaken the rate of fall (7th row). Right after 50 seconds have elapsed, more or less, this last velocity becomes inappreciable compared to the rate of escape from the spherical surface. Thus, after 200 seconds, when the projectile has already gained an altitude of 3 km and acquired a speed of 2 km after flying 200 km on a tangent, the rate of climb will exceed the rate of fall (which is limited by air drag) by a factor of 127. But further out the rate of fall will begin catching up with the rate of climb and will finally exceed it, becausethe atmosphere is rarefied, and infinite velocity is required in a vacuum to arrive at a pressure or resistance on the part of the medium capable of equalizing the weight of the rocket. At that point the body will already have begun to fall solely owing to the force of gravity. Briefly, at that point we may completely ignore the resistance of the air, which is absent in a vacuum.

How will this happen? Within the first minute the rocket will begin to nose downward from the horizontal; after that the flight will become parallel to the Earth; then the escape from the Earth's surface will begin, and the flight will increasingly approximate a tangent straight line. Gravity will have seemingly no effect on the vehicle, which will be moving as if on rails. But after roughly 4 minutes (265 seconds), the air will become rarefied to such a degree that the rails will disappear, as it were, and the projectile will be now flying under the influence of the Earth's gravity, which now comes into its own; but by this time the vehicle will have climbed to an altitude of 10 km, will have flown 351 km, and will have acquired a velocity of more than 2 km/sec.

This means that some more dense part of the atmosphere will render the travel of the projectile easier, by providing it with rails on that stretch of the trajectory, thereby lightening the work (if we ignore the frontal drag on the vehicle). We assumed a rocket acceleration equal to the Earth's acceleration (10 m/sec^2). The increase in the pressure j on the projectile will make for a still less significant deviation from the tangent, i.e., it will stiffen the "rails." The flight curve can be determined accurately, but we already have given many formulas as it is. The inconvenience of such a flight tangent to the earth is that it would have to be started from some height: from towers or tall mountains, since the rocket will lose altitude during the first seconds of flight. At j = 10, as we see from Table 13, the mean rate of fall due to gravity and to air drag may not exceed 4 m/sec when the flight is started at a velocity of 100 m/sec. Thus, in 40 to 50 sec of flight, the vehicle will have descended much less than 200 meters. More probably 100 meters. After that the flight will become parallel to the Earth's surface, and still later on it will begin to recede from that surface. Thus, at a moderate explosive force (j = 10), the flight must be started from a tower 100 meters high or from a hill of the same height but with a 45° slope. When j is larger, the required height will be lower and the slope of the hill can be gentler, and vice versa. If we start by moving on a horizontal plane and acquire a velocity slightly greater than 500 m/sec in the process, then no ground elevation at all will be required, since the extent of fall will not exceed the distance covered due to the sphericity of the Earth.

CLIMB THROUGH THE ATMOSPHERE ON AN ASCENDING LINE

A tangential flight has the advantage that a very slight degree of explosive power j may be used. In the technical sense, particularly in the first experiments, this is a very important advantage. But as regards economy in the energy required to overcome air drag, flight inclined to the horizon is better. Still, the greater the inclination, the greater the explosive force j that will have to be used, whether we like it or not, since this flight is similar to climbing a mountain slope.

We have already analyzed this case, in formula (83), with respect to the air resistance. We may now add that we were correct in assuming a negligible deviation from the descent due to the resistance of the atmosphere.

We have seen that a steep climb is disadvantageous, and particularly so a straight upward climb. Here we assume a slightly inclined flight through the atmosphere. This has many advantages. First, the loss is equal to the loss incurred in climbing a mountain slope, with a decreased resulting energy loss. At a greater height, where the air can no longer serve as a supporting mass, the action of the explosives may be normal to the Earth's radius, so that, as we have proved earlier, there will be no energy losses at all. Second, a small explosive force j may be used. Third, we may resort to launchings from mountain slopes, in order to impart a sufficient preliminary velocity to the projectile, which is quite useful, as we have seen, since it is then possible to avoid a fall, particularly when the inclination of the path is sufficiently great. Fourth, some inclination of the path will greatly reduce the amount of energy spent on overcoming the frontal drag presented by the atmosphere. (As compared to a tangential or a horizontal flight.) Finally, the rocket and all of its parts need not be made particularly massive when a small explosive force is employed. Also, no special safeguards will be required for the safety of humans on board.

When the rocket is moving on an inclined ascending path, the escape from the Earth's spherical surface will depend on two factors: on the angle of inclination and on the sphericity of the planet. The first is

$$h_1 = \iota \sin y, \tag{169}$$

and the second is

$$h_2 = \iota^2/D. \tag{170}$$

Hence

$$h_1 + h_2 = \iota \sin y + \frac{\iota^2}{D} = \iota \left(\sin y + \frac{\iota}{D}\right). \tag{171}$$

The rate of fall is expressed by formulas (165) and (166) with which we are already familiar. But the angle ξ in these formulas must be interpreted as denoting a different angle expressing the deviation which is an exclusive function of the air drag and of the translational flight velocity. This angle ξ is in general extremely small.

At ascending motion, even if on a small incline y, the explosive force j can not be arbitrarily small. Its minimum value is set by the equation

$$j = g \cdot \sin y. \tag{172}$$

Then also the rocket will be positioned on a hill slope (in air). There will be no acceleration as yet, but the rate of fall will be fast. It is necessary and advantageous for j to be in excess of this rate. Here we give the least j depending on the angle of inclination y and gravity g (Table 14).

TABLE 14

y, in deg	1	2	3	4	5	6	7	8	9	10
j, in m/sec^2	0.175	0.349	0.523	0.698	0.872	1.05	1.22	1.39	1.56	1.74
j, increased 10 times	1.75	3.49	5.23	6.98	8.72	10.5	12.2	13.9	15.6	17.4

Clearly, then, when j is increased 10 times, even at an inclination of 10°, the acceleration will be only 1.7 times greater ($10\ m/sec^2$) than that due to Earth's gravity. But even at that inclination or a lesser inclination, we may confine ourselves to an incomparably weaker explosive force, roughly down to 0.1 of the force of gravity. Now this will present tremendous technical advantages, since it will enable us to begin the flights even on the basis of the present level of technology.

We derived formula (171) for a projectile gaining altitude in inclined motion.

The rate of climb (neglecting the sphericity of the Earth for the time being) will be $c \sin \xi$.

On the other hand, the rate of fall is determined by formula (165). On equating the rate of fall to the rate of climb, we find an equation from which we obtain

$$\sin \xi = \frac{M_0 g}{dF_h K_1 c^2}. \tag{173}$$

At this angle, the initial motion will be horizontal. For example, when $M_0 = 1$; $g = 10$; $F_h = 20$; $K_1 = 1$; $c = 100$, then we have $\sin \xi = 0.0385$, and angle $\xi = 2^\circ.2$. At a speed of 200 meters, the angle will be close to $0^\circ.5$.

Consequently, it is entirely possible to avoid a drop in altitude even when the inclination angle is very low, provided the initial velocity is adequate. But this velocity can be far lower when the angle of inclination is higher. For example, when the angle is increased to 8°, an initial velocity of 50 m/sec will be quite sufficient.

THE ENGINE AND ITS RATE OF FUEL CONSUMPTION

Engine Power per Ton of Rocket Weight

In Table 15, we present figures for the engine power per ton of rocket weight at different velocities and accelerations; the power is expressed approximately in thousands of metric force units (100 kg-m/sec); the rocket velocity c_1 is given in km/sec at various instants of the rocket's motion.

We find that the power of a one-ton rocket ranges from 100 to 11,000 metric force units at the minimum acceleration (and, of course, at a low angle of inclination).

When the rocket is delivering 100 kg thrust per engine, then the power will at first be close to that of aeroplane engines (100 metric force units), and will increase 110 times only on attaining the limiting cosmic velocity.

This seems strange at first glance, but we should not forget that we are dealing with reaction-type [jet] (or rocket) engines.

TABLE 15

	c_1, in km/sec	0.1	0.2	0.3	0.5	1	2	5	8	11
Acceleration j of rocket in m/sec^2, or explosive force	1	0.1	0.2	0.3	0.5	1	2	5	8	11
	2	0.2	0.4	0.6	1	2	4	10	16	22
	3	0.3	0.6	0.9	1.5	3	6	15	24	33
	5	0.5	1	1.5	2.5	5	10	25	40	65
	10	1	2	3	5	10	20	50	80	110
	20	2	4	6	10	20	40	100	160	220
	30	3	6	9	15	30	60	150	240	330
	50	5	10	15	25	50	100	250	400	550
	100	10	20	30	50	100	200	500	800	1 100

Rate of Fuel Consumption in Response to Different Explosive Force; Final Velocity and Explosion Time as a Function of the Supply of Explosives

The problem is to explode a fixed and unvarying amount of explosive in the blast pipe every second. We shall now show that this amount is quite small. For example, in Table 15, for a one-ton rocket attaining a cosmic velocity of 8 km/sec, 4 tons of explosives will be sufficient. The explosion time required to produce that velocity will be 8,000 sec, provided the average explosive force is 1 (0.1 force of gravity). This means that an average of 0.5 kg of explosive will have to be exploded per second. This is not impossible. Were the explosive force to be even ten times greater (at a greater inclination), 5 kg would have to be exploded per second. This, too, is feasible.

Table 16 shows us approximately the average quantity of explosive materials consumed per second to develop different amounts of explosive force j. The weight of the rocket is one ton.

The second cosmic velocity is sufficient to make the rocket an Earth satellite, orbiting outside the atmosphere, of course. And the third cosmic velocity is sufficient to overcome the Earth's gravity and to permit varying orbits around the earth. And for this, too, the explosive matter consumed per second would be less than 1 kg. This last velocity would be sufficient to escape forever from our solar system and wander about the Milky Way at a velocity no less than the velocity of a shell fired from a gun. Even for this the rate of explosive consumption would be less than 2 kg per second. The time required for the explosive process to go to completion would range from 1 to 5 hours. All this can be accomplished at an explosive force j 10 times smaller than the force of the Earth's gravity. At higher j, the rate of consumption of explosives per second would proportionately increase, and the explosion time would proportionately shrink. It seems strange at first that the work done by the rocket engine would increase progressively (with the projectile's velocity) while the amount of explosive material consumed per second would experience no increase. The point is that the explosive material not yet consumed will have an energy which will be the greater the higher is the velocity of the vehicle carrying it. Therefore, it will release that energy in a greater quantity than that implied by its potential chemical energy.

TABLE 16

Supply of explosives, in tons	1	4	9	30
Final velocity, in m/sec	3465	8045	11 515	17 170
Time of explosion process, in seconds	3465	8045	11 515	17 170
Time, in hours	0.96	2.23	3.2	4.8
Quantity of explosives, in kg/sec, j = 1	0.29	0.5	0.78	1.75
Same, but at j = 5	1.45	2.5	3.9	8.75
Same, but at j = 10	2.9	5	7.8	17.5

CONCLUSIONS

From the entire foregoing presentation, we may draw the following inferences. It is advantageous to begin the flight on mountains at the greatest height possible. A road with an incline not greater than 10° to 20° could be leveled on the mountain slopes. The rocket will be mounted on an automobile which will impart to it a velocity ranging from 40 to 100 m/sec in the process. After this the projectile will fly independently on its ascent path, developing a rearward pressure by exploding the materials. The inclination of the projectile will decrease as its velocity increases, and the flight will begin to approximate horizontal flight. As it emerges above the confines of the atmosphere and reaches a vacuum, its flight will become parallel to the Earth's surface, i.e., the flight will be circular. The acceleration j must have the least value, roughly from 1 to 10 m/sec. The rate of explosive consumption used in overcoming the air drag will be at a minimum. The effect of gravity will also be almost nil (with respect to energy loss). The first velocity will be that attained by the automobile, aeroplane, or other suitable land-, water-, or air-borne vehicle. The flight in a not very rarefied atmosphere will be made possible through the energy of the fuel ignited by oxygen from the atmosphere. This will mean a 9-fold saving in fuel supplies (an ideal number when pure hydrogen alone is stored as the fuel). If the rocket has not attained the cosmic velocity freeing it from the Earth's gravitational pull while in the air, it will be no longer possible to rely on the oxygen of the atmosphere in the highly rarefied layers of air.

At that point, the reserve supply of liquid oxygen or some unstable (and, if possible, endogenous) compound of oxygen with other gases (for example, with nitrogen) will be tapped. The attained velocity can then be brought up to cosmic velocity.

EARTH-BASED LAUNCHING ROCKET

Function of the Rocket. Runway. Take-off Strip. Engine. Air Drag. Friction

We have already seen that a rocket must acquire a certain velocity while still on the Earth in order to be able to immediately fly horizontally or obliquely on its ascent path. The greater this take-off velocity, the better. It would be desirable if the projectile were not to lose in the process any of its energy stored in the form of explosives. And this will be possible only in the case where our rocket is imparted a momentum by some external force: an automobile, a steamship, a locomotive, an aeroplane, a dirigible, a gas-operated or electromagnetic cannon, etc. Known techniques at our disposal could not ensure velocities greater than 100 to 200 m/sec, since neither wheels nor propellers could rotate faster than that without falling apart. Their peripheral velocities could be raised as high as 200 m/sec* -- but no higher. This means that this velocity (720 km/hr) cannot exceed the conventional means of locomotion. But this perhaps enough to start with. However, we shall strive to impart to the rocket the greatest possible amount of preliminary velocity in order to keep intact its supply of explosive for further flight after it abandons its solid-ground trajectory. It is clear hence that other special means are required for the rocket to acquire a take-off velocity greater than 200 m/sec. Gas-powered and electromagnetic cannons must be rejected for the time being as suitable tools, being inordinately expensive, running into many millions of rubles, because of their great length. In short cannons, on the other hand, everything would be smashed and all on board killed by the relative gravity (the jolt). The simplest and the cheapest approach in this case is to use some rocket unit or reaction-type machine. We mean that our space rocket must be mounted or nestled in another, auxiliary, earth-based rocket. The Earth-based rocket, without separating from the ground, would impart the required acceleration to our space rocket. A flat rectilinear upward-inclined track would be required for our earth-based rocket.

Propellers are both unfeasible and unnecessary. Their thrust will be replaced by the rearward pressure of the gases exploding inside the blast pipe. Wheels for lessening friction are unsuited. The earth-based rocket will move in the manner of a sleigh.

Friction between rigid bodies gives rise to rather intense friction, even when lubrication is employed to reduce it. For example, the coefficient of friction for iron against dry cast iron or bronze (and vice versa) is about 0.2. This means that a rocket weighing one ton will be put into motion on a horizontal plane by a force not less than 0.2 ton, or 200 kg. This is the magnitude of

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*Appreciably higher velocities are employed in present technology. (Edit.)

friction for pressures not exceeding 8 to 10 kg/cm^2 on the friction surface.

It is remarkable that the coefficient of friction decreases to one-fourth or lower as the velocity of the bodies in friction is increased (within the narrow limits of the experiment). Under ordinary pressure which does not go beyond these limits, and in the presence of generous lubrication, the coefficient of friction for the same bodies may be reduced by 5 to 10 times. Wetting the friction surfaces with water can reduce the friction in half. The coefficient of friction for metal on ice or snow (and vice versa) drops to 0.02, i.e., one-tenth that of friction between various dry metals, and is comparable, then, to the friction encountered in the presence of generous lubrication. Thus, if the rocket is moving on ice or on a level and well lubricated metallic strip, then there will be no insuperable impediments to rapid motion without wheels. For example, if a pressure of gases which is equal to the weight of the rocket ($j = 10$) is developed, then only 20 to 2% of the energy spent on moving the earth-based rocket need be lost on friction. At an acceleration of 5 m/sec^2 ($j = 5$), this loss will be 40 to 4%. When $j = 1$, 200 to 40% of the energy will be required, which is inadmissible.

However, I am aware of methods for reducing friction to almost zero, but we shall have more to say about this in another book.*

We now come to consider an earth-based rocket moving on ordinary but smooth and rigorously rectilinear rails well lubricated with tallow or grease oozing from the runners of the machine, or with ice. The latter is feasible only during cold seasons, or on high mountains where the temperature is below zero.

The shape of the earth-based rocket must be properly streamlined. The more elongated it is, the easier it will be for the rocket to cut through the medium, ignoring the friction of the air against the walls of the rocket. At an aspect ratio of 100 or 200 (i.e., when the length is many times in excess of the greatest transverse dimension of the rocket), we may even only need take friction into account. As we shall see, the projectile itself may be very long in view of the very long runway track required for the projectile to accelerate to take-off speed -- there will be room for that.

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*Cf. the book Soprotivleniye vozdukha i skoryy poyezd (Air resistance and rapid trains), Kaluga, 1927. -- (Edit.)

Special calculations and arguments, which we need not go into here, demonstrate that the coefficient of friction may not be greater than

$$\frac{dFV}{2g}, \tag{174}$$

whatever the velocity of the friction surface. We see from the formula that this limiting friction is proportional to the area F of friction surface, the gas density d, and the rate of motion V of the gas molecules. This conclusion enables us to compare gases at enormous velocities with solids, since the friction in the latter is essentially independent of the speed of the body in friction. By a transformation of formula (174), it can be readily shown that this limiting friction is, for "constant" gases and unaltered external pressure, proportional to the square root of the molecular weight of the gas and inversely proportional to the square root of the temperature of the gas. This means, for example, that at atmospheric pressure heated hydrogen offers less friction than cold air. On the other hand, cold carbon dioxide gas will present a greater resistance than heated air.

The inverse will hold at the same density of gases, i.e., gases heated and of low molecular weight will yield a high coefficient of friction. Let us consider some limiting cases.

Other arguments bring us to the formula

$$R = \frac{slb}{2g}\,dc \tag{175}$$

for the friction.

This means that the coefficient of friction will be proportional to the density d of the gas, the velocity of the rocket, and the thickness s of the air adhering to a square meter of the body moving at a speed of 1 m/sec. But unfortunately, this formula is only valid when the speed of the rocket is as many meters per second as the rocket itself is meters long. Accordingly, we must assume $l = c$ in this formula. We then have

$$R = \frac{s}{2g} l^2 bd = \frac{s}{2g} c^2 bd. \qquad (176)$$

Here, we assign the figures: 2g = 20; b = 3; d = 0.0013; moreover, I know from personal experiments that s = 0.01 (1 cm). We then find

$$R = 195 \cdot 10^{-8} \ c^2 = 195 \cdot 10^{-8}. \qquad (177)$$

Let us assume further that the weight of the entire rocket in tons is expressed by the number l. Now we compile Table 17 for various accelerations j and for various rocket speeds.

We see that even at a speed of 5 km/sec and at an acceleration of 0.1 Earth gravity (j = 1) on the part of the earth-based rocket, the losses will not exceed 10%. But here we encounter a major drawback: the rocket must be as long as 5 km. At low speeds and low rocket lengths, an insignificant percentage of the work would be absorbed. But a blunt-nosed rocket would encounter strong resistance in moving aside the air ahead of it.

The length of the earth-based rocket should not exceed 100 meters, otherwise the rocket will have a great mass, and the cost, not to mention the absolute work, required to impart the necessary velocity and to overcome air drag, will be high. This means that a heavy and costly load of explosives will be required as well. When the rocket is shorter by $\frac{c}{l}$ times than indicated in the table, each air particle will be subjected to displacement a shorter time than in the case where the velocity of the rocket is numerically equal to its length. The time is shortened by $\frac{c}{l}$ times.

The thickness s of the air layer entrained does not decrease proportionately, but approximately by $[1 + \ln(\frac{c}{l})]$ times. The air resistance decreases in the same proportion. Thus, in place of formula (176), we derive a more exact formula much better suited to any lengths of the earth-based rocket, viz.:

TABLE 17

Length, weight, and speed of earth-based rocket, in meters, tons, m/sec	1	10	100	500	1000	1500	2000	3000	5000
Friction, in kg	0.002	0.2	20	500	200	4500	8000	18 000	50 000
Resistance with respect to pressure on the rocket, in percent, at j = 10	0.0002	0.002	0.02	0.1	0.2	0.3	0.4	0.6	1
Same, at j = 1	0.002	0.02	0.2	1	2	3	4	6	10
Same, at j = 4	0.0005	0.005	0.05	0.25	0.5	0.75	1	1.5	2.5

$$R = \frac{s \cdot l}{2g} \cdot b\, dc : [1 + \ln (\frac{c}{l})]. \qquad (178)$$

We now assume the rocket to be of constant length, 100 meters to be specific. Speeds will be different. This brings us to Table 18.

The last column indicates by how many times the thickness of the adhering layer of gas, and the resistance due to friction, will decrease as a function of the variation in length (2nd row).

In formula (178), let $s = 0.01$; $l = 100$; $b = 3$. We then have

$$R = 1.95 \cdot 10^{-6} \cdot c : [1 + \ln (\frac{c}{l})]. \qquad (179)$$

This enables us to compile Table 19 giving the absolute and relative resistances in response to different explosive forces.

Clearly, then, friction absorbs no more than 17% of the work even at the lowest acceleration ($j = 1$) and at negligible rocket mass (10 tons).

We shall now resolve the problem of the length of the runway for the earth-based rocket. A segment of the runway serves to accelerate the motion, and the rest to slow down the motion and bring it to a halt. A retro-acting explosion is not an economical way to cancel out the acquired velocity. This can be done even faster, i.e., over a shorter path length, by deceleration through friction or through air resistance. The lubrication could be discontinued or the rocket could be set up at right angles to the direction of motion of the planet. Air resistance will soon cancel out the velocity of the earth-based rocket. A far shorter segment of runway would be required for braking than for acceleration, particularly if the space rocket has already taken off. The overall picture is like this. The earth-based launching rocket races forward on rails in an accelerated motion, carrying the space rocket. When the highest speed is attained and the earth-based rocket begins to decelerate, the space rocket breaks loose from the earth-based rocket by force of inertia and starts to pick up more and more speed because of the explosion already begun on the space rocket itself. The earth-based rocket, now slowing down because of the air drag

TABLE 18

c in m/sec	100	200	300	400	500	700	1000	2000	3000	4000
$\frac{c}{l}$	1	2	3	4	5	7	10	20	30	40
$\ln(\frac{c}{l})$	0	0.69	1.10	1.39	1.61	1.95	2.30	3.00	3.40	3.69
$[\ln(\frac{c}{l}) + 1]$	1	1.69	2.10	2.39	2.61	2.95	3.30	4.00	4.40	4.69

TABLE 19

c in m/sec	100	200	300	400	500	700	1000	2000	3000	4000
Pressure, in kg	19.5	23.1	27.9	32.6	37.4	46.3	59.1	97.5	133.0	167.0
Weight 100 tons, j = 10	0.02	0.023	0.028	0.033	0.037	0.046	0.059	0.098	0.133	0.167
Weight 100 tons, j = 1	0.2	0.23	0.28	0.33	0.37	0.46	0.59	0.98	1.33	1.67
Weight 10 tons, j = 1	2	2.3	2.8	3.3	3.7	4.6	5.9	9.8	13.3	16.7
Weight 10 tons, j = 4	0.5	0.6	0.7	0.8	0.9	1.1	1.5	2.5	3.3	4.2

or some other means, meanwhile slides along further down the runway but at a steadily slowing pace till it comes to rest. We shall not calculate the decelerating path length of the runway, since it may be very short. To minimize the air drag, the space rocket should constitute the forward section of the earth-based booster. The nose of the former will be open (outward), and the tail section will nestle in the earth-based rocket body. When the latter begins to decelerate, the space rocket will break loose from the earth-based rocket and leave it behind. A gaping opening is opened up in the earth-based booster in the processes, bringing about an enormous air resistance and thereby a vigorous braking action. The booster itself comes to a stop without much further trouble. The earth-based booster rocket is very long, and the tail of the space rocket comprises only a small portion of it. The remainder of the space rocket is used for storing explosives and control devices.

For compiling Table 20 (of maximum speeds for the earth-based booster), we have the formula

$$p = j - g \cdot \sin y. \qquad (180)$$

Here we see the resultant of the acceleration due to the explosive force j, the Earth's gravity (10 m/sec^2), and the angle of inclination of the path to the horizon. Further

$$c = \sqrt{2p \cdot t} = \sqrt{2(j - g \sin y) \cdot t}. \qquad (181)$$

The pressure P of the explosives exerted on the rocket is determined by the equation

$$P = G_0 \cdot \frac{j}{g}, \qquad (182)$$

where G_0 is the weight of the rocket; the pressure is expressed in

TABLE 20*

Rail length in km	1	2	5	10	50	100	200	300	500
j = 100	447	632	1000	1420	3160	4470	6324	7746	10 000
j = 50	316	447	707	1000	2236	3162	4472	5477	7071
j = 30	244	346	547	774	1732	2449	3464	4242	5477
j = 20	200	282	447	632	1414	2000	2828	3468	4472
j = 10	141	200	316	447	1000	1414	2000	2449	3160
j = 5	100	141	223	316	707	1000	1414	1732	2236
j = 3	78	109	173	244	547	774	1095	1342	1732
j = 1	45	63	100	142	316	447	632	774	1000

*Tabulated figures corrected. Note by editor of Selected Works of K. E. Tsiolkovskiy, Moscow, ONTI, 1934.

the conventional units.

We assume the runway to be horizontal (y = 0). We need only a very small incline, which will slightly reduce the velocities and air resistance listed in the table.

The time required for the motion of the earth-based rocket will be found by dividing the speed by the acceleration j. Thus, at a path length of 500 km, the time indicated in the table would range from 100 to 1000 sec. At a path length of 1 km, the time would range from 4-1/2 to 45 sec. The braking time might be very short.

The gravity generated by the acceleration would vary from 0.1 to 10 times the Earth's gravity, according to the table. Added to the latter, there would be an apparent gravity of from 1 to 10 (approximately) in rockets. The rail track somewhere on a mountain slope at high altitude could be even 500 km long (about 5° on the circumference on the Earth) so that we could even hope to attain cosmic velocities in the process. But higher gravity would require an enhanced strength on the part of the rockets, and this would entail an increase in the mass of the rockets. Finally, the work done in overcoming air drag would be increased. In other words, an acceleration j equal to the acceleration caused by the Earth would be sufficient, and then we would obtain a completely satisfactory preliminary velocity of up to 3,160 m/sec. A slight but highly effective inclined path of 10° to 20° would mean a slight decrease in the preliminary velocity.

We may also compute the explosive supplies needed for the earth-based booster rocket. If the empty weight of the booster rocket is 10 tons and the space rocket with its load is the same, then the total weight of the assembly will be 20 tons. Now we use Table 6 to compute the weight of explosive supplies, in tons, for the earth-based booster rocket, in order to obtain different velocities. The exhaust velocity W is assigned the value 4 km/sec.

TABLE 21

M_1'/M_0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.5	2
M, in tons	2	4	6	8	10	12	14	16	18	20	30	40
c_1, in m/sec	378	728	1048	1344	1620	1876	2116	2344	2568	2772	3660	4392

These velocities are entirely adequate so long as the fuel store does not exceed 50 tons. Note that rapid braking could kill the man piloting the earth-based booster rocket. It is therefore better that the latter be unmanned, controlled automatically. As for the passengers on the space rocket, they will find themselves outside the booster rocket assembly, from which the space rocket will have already separated, when the braking starts.

If the space rocket has thereby acquired an initial velocity without using up its own fuel, then it will be able to store less fuel or, conversely, will be able to attain a greater cosmic velocity using the same amount of fuel.

We have

$$dc = - W \cdot \frac{dM_1}{M_0 + M_1} \qquad (34)$$

and

$$c = - W \cdot \ln (M_0 + M_1) + \text{const.} \qquad (35)$$

When the initial velocity of the rocket is c_0, we have $M_1 = M_1''$, i.e., the mass of the exhaust material will be at its peak (the initial mass). Consequently,

$$c_0 = - W \cdot \ln (M_0 + M_1'') + \text{const.} \qquad (183)$$

Subtracting formula (183) from (35), we obtain

$$c - c_0 = W \cdot \ln \left(\frac{M_0 + M_1''}{M_0 + M_1} \right) . \qquad (184)$$

When $M_1 = 0$ we obtain the maximum speed c_1. Hence,

$$c_1 = c_0 + W \cdot \ln\left(1 + \frac{M_1''}{M_0}\right). \qquad (185)$$

Suppose that the preliminary initial rocket velocity is 3 km/sec, and we must have c = 8 km/sec. We assign to W a value of 5 km/sec. Then, we find from Table 6 the relative supply mass for the space rocket $M_1''/M_0 = 1.8$, while we need a relative supply mass of 4 (according to Table 6) in order to obtain a speed of 8 km/sec; from (185) we may find

$$\frac{M_1''}{M_0} = 1 - e^{\frac{c_1 - c_0}{W}}. \qquad (186)$$

Let us avail ourselves of this formula to compile Table 22 which will be useful for comparison.

It is evident from this table that a space rocket having a preliminary velocity will be much less overloaded with explosives than a space rocket lacking such a velocity. Then, in order to attain the higher cosmic velocity for overcoming the attraction of the Sun (17 km/sec), a supply of explosives weighing 30 times the weight of the rocket would be required. Now if the rocket has obtained a speed of 5 km/sec while still on the ground, the relative supplies will be only 10-fold the weight of the space rocket. The first cosmic velocity requires 4 times supply weight over rocket weight; if, however, a take-off speed of 3 km/sec is available, the weight of the explosives will be only 0.8 of the weight of the rocket.

TABLE 22

c_1, in km/sec.	8	11	17
c_1, -- 5	3	6	12
M_1''/M_0 (according to (186))	0.8	2.31	10.0
M_1'/M_0 (according to Table 6)	4	8	30
c_1 -- 4.	4	7	13
M_1''/M_0	1.24	3.08	12.0
M_1'/M_0	4	8	30
c_1 -- 3.	5	8	14
M_1''/M_0	1.72	4	15
M_1'/M_0	4	8	30

Shape of the Earth-Based Launching Rocket

The shape of the earth-based booster will be extremely elongated, to minimize drag effects. The elongation may reach 50. Since the rocket will not leave the Earth and the atmospheric layers above it are fairly dense, there is no need to make the rocket pressuretight. Its hull may be made similar to the fuselage of an aeroplane. It should contain a compartment for the explosives, which will be pumped into the blast pipe and ejected by the force of the explosion in the tail of the rocket. The hull will also house an engine by a gasoline motor and designed to power the pumps (this purpose can be achieved by the preliminary use of a small portion of the supply of explosives; after being utilized in the motor, these explosives can then be discharged through the explosion tube and thereby contribute to the work of reaction).

The Space Rocket

The space rocket must have a minimum mass and volume in order to be more practicable. The elongation should be 10 and no greater than that. The greatest transverse dimension will have to be no less than 1 to 2 meters. The shape will also be streamlined, but the skin will be hermetically sealed, since the rocket will move out into airless space, where the gas required for breathing might all leak through any openings.

The main skin of the rocket must be able to safely withstand a pressure of at least 0.2 atm, when it is filled with pure oxygen. Actually, we find the highest quantity of oxygen at sea level. Its partial pressure is about 0.2 atm. Its amount is in the same proportion. This is adequate from the physiological standpoint. But man can readily tolerate, or at least adapt himself to, half that amount. On mountains (at 5 to 6 km altitude) where the amount of available oxygen is half that much, a human being is still capable of living freely. Animals can tolerate a further two-fold rarefaction (at an altitude of 10 km), although with some hazard to life. At any rate, 0.5 the usual amount of oxygen will be sufficient. This means that the oxygen will be sufficient when the oxygen pressure is 0.1 atm.

The rocket's skin must be equipped with a valve opening outward, if the difference between the internal and external pressures exceeds, say, 0.2 atm. Below, at sea level, the absolute pressure in the rocket will thus be no greater than 1.2 atm, and in a vacuum the pressure inside the rocket will not exceed 0.2. Clearly, these are the limits for safe breathing. If the external pressure on the valve is increased by a controller to, say, one atm, then the pressure limits will be 1 and 2 atm. The latter figure will be at first more suitable to provide an ample supply for breathing purposes. The internal gas pressure dictates that the rocket be shaped in the form of a dirigible of circular cross sections. This is a highly expedient shape and one best suited to minimize air drag. This also will free the rocket from the need for additional internal bracing and partitions. The rocket filled to capacity with gas will resemble a complicated beam structure with excellent flexural strength and, in general, resistance to change in shape. But since it has to perform gliding flight, a task for which it is not well-suited since it lacks wings, it will be useful to link together the sides of several rocket hulls shaped like bodies of revolution. These linked sides must be braced internally by partitions. Such a complex structured rocket, resembling a corrugated sheet with several sharp tails and heads or a single, large wing is much better suited for gliding. The space rocket must also be capable of withstanding intensified gravity. This requires that the rocket components be made stronger than required to resist the forces of ordinary gravity. For example, the compartments housing the explosives must be of greater strength. But we have seen that a slightly inclined flight at a low acceleration ($j < 10$) is most advantageous. The gravity will change so little in this case that all of our calculations could boldly be based on the assumption of normal terrestrial gravity.

We also must take into account the condensation and rarefaction of the medium surrounding a rapidly moving rocket. The air will be compressed ahead of the rocket's nose, and we may therefore make this part of the rocket skin weaker or thinner; the atmosphere will be rarefied in the wake of the rocket's tail, and we can therefore make the tail section firmer or thicker. These forces operate while the rocket is in the atmosphere. They are not present in a vacuum. Nevertheless, the tail section must be made with greater strength, without weakening the forward section. This is of enormous significance to the space rocket, but of less significance to the earth-based booster rocket in view of its considerable elongation. We have seen that the total longitudinal air drag accounts for a small part of the pressure of the explosives on the rocket. The pressure normal to the rocket walls is of the same magnitude. Consequently, it will average out to a quantity not exceeding the normal gravity. Because of the large margin of strength of the rocket, these forces may be disregarded as was done with the relative gravity.

As a basis, we assume for a principal point that the difference between the internal and external pressures will dictate a spindle-shaped rocket. Consider (Table 23) the mass of the skin made from the strongest iron alloys at a four-fold safety margin in strength and at a pressure difference of 1 atm (instead of the required difference of 0.2 atm). This weight will depend primarily on the volume of the skin, rather than on the shape and aspect ratio, assuming a spindle-shaped smooth rocket shape.

TABLE 23

Rocket volume, in cubic meters	5	10	15	20	30	40	50	100
Weight of internal gas, air density in kg	6.5	13	19.5	26	39	52	65	130
Weight of rocket skin, in kg	33	65	98	130	195	260	325	650

We find that the weight of the skin will be only 5 times greater than the weight of the air, of ordinary density (0.0013), contained within the rocket. At a pressure of 0.2 atm, the strength margin will be 20, and at 0.1 atm, it will be 40. Ten cubic meters will quite suffice per person. This supply of oxygen will be adequate for one human's need over a ten-day period, if the respiration products are all absorbed within the rocket itself.

The greatest load capacity possible on a rocket at different rocket volumes is expressed approximately in tons, in the first row of Table 23. This load will be 154 times greater than the weight of the skin, for any volume. However, for small rockets the skin will then turn out to be impracticably thin, so that it will have to be made two, three, or more times thicker, despite the small volume. This will still further increase the strength margin for small rockets. But the small volume encompassed by the skin in this case will account for the bulk of the highest load capacity (154), e.g., 1%, 2%, 10%. The weight of the skin will come to less than 1% in the case of the greatest volumes. The outer, shutter-type skin making it possible to obtain temperatures in outer space from 150° in sunlight to -250° in the cold has been mentioned earlier. When the shutters are adjusted to make this skin glitter, it will offer protection against heating during flight through the air, particularly when cold gas released from the rocket interior is allowed to flow behind the outer skin and the inner, fortified skin.

Varieties of Explosives

Liquefied pure hydrogen contains less potential energy, since it is cold and absorbs energy on turning into a gas, and its chemical effect is weaker. It is difficult to liquefy and store, since, unless special precautions are taken, it will rapidly evaporate. Liquid or easily liquefiable hydrocarbons are more favorable. The more volatile they are, the more hydrogen they contain and the more suitable they are. Oxygen is useful in liquid form, the more so as it can also serve as a coolant for cooling the rocket (while passing through the atmosphere, when it gets hot) and the explosion tube. But it is best to proceed as follows: take the major part of the supply of oxygen in the form of endogenic compounds of this element, i.e., compounds are synthesized with the absorption of heat. On decomposition, they release the absorbed heat and thus increase the combustion energy. The other, smaller part of oxygen supply may be in pure liquid form and will serve first as a coolant and later for respiration and combustion. A small amount will be sufficient. Liquid gases in hermetically sealed containers develop a tremendous pressure, which only massive vessels can withstand. Therefore, to avoid this, the vessels must be perforated to allow the newly forming gases to escape. In this way their low temperature is also maintained. The performance of explosive compounds is somewhat inferior to that of pure hydrogen and oxygen. The latter yield an exhaust velocity (products of chemical combination or combustion) of 5 km/sec, while explosive compounds yield an exhaust velocity of 4 km/sec. This means that the velocity of a rocket propelled by the latter will be 20% less.

It has been proposed to use compressed gases carried in containers, or strongly heated volatile liquids, as the reaction fuel. This is quite unworkable, for the following reasons. My very exact and numerous calculations show that the weight of the fuel tanks, even of the optimum shape and material, would be at least

TABLE 24

Projectile velocity, km/sec	8	11	17
Mass of explosives, tons	4	8	30
Explosion time at j = 10, sec	800	1 100	1 700
Amount of explosives pumped, kg/sec	5	11	17
Work done in pumping, kg-m	500	1 100	1 700
Explosion time at j = 1, sec	8 000	11 000	18 000
Amount of explosives, kg/sec	0.5	1.1	1.7
Work, kg-m	50	110	170

five times the weight of the compressed air used in place of explosives. Hence it is clear that the gas expelled will always weigh 5-10 times less than the rocket. Now, as we see (Table 6), to attain the lower cosmic velocity we need a mass of explosives equal, under the most favorable conditions, to four times the mass of the rocket. Although lightweight gases are more efficient, they require vessels of greater weight. The same can be said of highly incandescent gases. Water and other volatile liquids, moderately heated, offer certain advantages and are therefore suitable for the first experimental low-altitude flights. My calculations show that ascent with the aid of compressed gases is limited to at most 5 km, and with the aid of superheated water, to at most 60 km.

So far, I know of nothing more energy-rich and more suitable than the explosives indicated above.

How then are they to be exploded and stored? If they were to be exploded as in all the known rockets old and new, the reaction following the explosion would be transmitted to the entire surface of the vessel (or storage tank), which would therefore have to be very massive. The pressure of the explosives may reach 5000 atm. In this event, calculations show that the weight of the walls will be at least 30 times greater than the weight of explosives with a density equal to (actually it is somewhat lower, which is even worse) that of water. In these circumstances, the projectile will not ascend higher than 15 km.

But we shall lose little if, by means of a moderate (i.e., not thorough) mixing of the explosives we reduce the pressure to 100 atm or 1/50 of the former value. Then the supply of explosives can be increased proportionately to 1-2/3. Even this supply is not enough. Any further reduction in pressure is inadvisable in view of the pressure of the atmosphere and the low utilization of chemical energy. It is much more expedient to store the explosive materials separately, without pressure, and pump them separately into an explosion tube, i.e., a special chamber in which the chemical combination (combustion) of the elements occurs. Then ordinary tanks or even the flaming rocket itself can serve for storing them. The problem is how to pump the materials into the explosion chamber, so as to overcome the pressure created by the explosion. But if the pressure is not greater than 100 atm. this work is not very considerable.

I have presented Table 24, which gives this work for different cosmic velocities and explosions of different intensity. I assume that the weight of the rocket is one ton, and the pressure 100 atm.

It is clear from the table that for j = 1 (least intense explosion) and the lowest cosmic velocity (8 km/sec) the work done in pumping is limited to 50 kg-m or 0.5 metric horsepower. At the greatest cosmic velocity and ten times the intensity ($j = 10$), on the other hand, the work is 17 metric horsepower.

All this is easily surmountable and may even be further minimized by means of an intermittent explosion, which we have already discussed. Naturally, for a rocket of greater mass the work will be proportionately greater.

The figures given are average and approximate. The density of the explosives is assumed equal to unity.

It can also be seen from the table that the pumping work will not be onerous even when the pressure of the explosives soars to 1000 atm. But for rockets of large mass and at high pressures it is economical to employ intermittent pressure and pumping, thus greatly reducing the work.

Rocket Components

Explosion tube. Shape. Pressure. Weight. Cooling

The chief engine of the rocket is the explosion tube, which operates like a cannon with a blank charge. The extent to which this tube is lighter than the tank sustaining its pressure is evident from the following. Table 24 shows that when the supply of explosives is 4 tons, the rate of consumption is 0.5 kg per second. The same amount leaves the explosion tube per second. This means that the explosion tube is a vessel containing 0.5 kg of explosives which, moreover, are under a pressure generally smaller than that in the storage tank (where it is maximal and uniform). As for the storage tank itself, it contains 8000 times as much explosive. Therefore, its weight must be at least as many times greater. In comparison, the following savings are provided by my rocket. A cylindrical tube is too long. A conical shape will reduce this length, the more so the greater the expansion of the cone. But the wider the cone angle, the higher the energy loss, since then the flow of gases diverges laterally. Still, at an angle of 10° the loss is almost insignificant. But such a large angle is not necessary either. The cone must be truncated. Liquid explosives are pumped in at the smaller base. Inside the tube they get mixed, explode, and rush out along the tube toward the open, flaring, broader base of the cone, whence they spread out into space, much rarefied and cooled, at a velocity of up to 5 km/sec. In a cylindrical pipe the useful pressure acts only on the round base of the cylinder, while in a conical pipe the useful pressure acts on the entire internal surface of the cone.

TABLE 25

Angle, deg	1	2	3	4	5	6	8	10
$F_{max}:F_{min}$	28.8	95.1	199	342	524	740	1296	2000
Diameter ratio	5.37	9.75	14.1	18.5	22.9	27.2	36.0	44.7
Diameter of opening, m	0.22	0.39	0.56	0.74	0.92	1.08	1.44	1.8

Therefore, the base of the conical pipe is much smaller than that of the cylindrical pipe.

We can easily derive the formula for the ratio of the areas of the cone bases:

$$F_{max}:F_{min} = \left(1 + \frac{l}{r} \text{ tg } \alpha\right)^2, \qquad (187)$$

where, from left to right, we have: areas of large and small bases, length of tube, radius of small base, and tangent of apertural angle of cone.

If the rocket weighs 1 ton or, together with explosives, 5 tons, and its acceleration j = 10, the pressure of the gases on the tube must be 5 tons. Given a maximum gas pressure of 100 atm and a cylindrical tube, the area of the base of the tube will be 50 cm^2, and the diameter and radius of the tube will be 8 and 4 cm, respectively. Assuming further that the tube is 10 m long and assuming different angles in formula (187), I compiled Table 25 for the apertural angle of the tube.

Hence it is evident that an apertural angle of as little as 1° is sufficient, and an angle of more than 3-5° would be excessive. The attendant energy loss would be nugatory. Despite the conical shape of the tube, the efficient utilization of the force of the explosion requires as long a tube as possible, so that the gases can convert nearly all their random motion (heat) into translational motion. The length of the tube could be increased by making bends in it.

Pump Motor

The pump motor, in view of its low horsepower, may be of the airplane engine type; it will consume stored oxygen only in the rarefied layers and (necessarily) in a vacuum. Its combustion products should be released into the common explosion tube or into a special, parallel pipe. The low utilization of the energy of the hot combustion products in the engines should also not be ignored. We could utilize the entire store of explosives in conventional (gasoline, gas) engines in order to obtain tremendous mechanical energy. How huge this can be is shown by Table 24. The minimum consumption of explosives, according to the table, is 1/2 kg/sec. This amount contains $1.37 \cdot 10^6$ kg-m of energy (see Table 1). If 30% of this energy is utilized, we obtain a mechanical energy of 411,000 kg-m/sec. This corresponds to continuous work equivalent to more than 4000 metric horsepower. Having extracted this amount of mechanical work, we can utilize the combustion products as reaction material in the explosion tube. This would be particularly convenient in rarefied air or in a vacuum. But we do not need such tremendous mechanical energy. Pumping the explosives requires very little work (Table 24) -- from 1 to 100 horsepower. Moreover, it would not be feasible, since a 4000-metric-HP aircraft engine weighs at least 4 tons. Its weight would absorb the entire lifting force developed by the rocket. What I mean to say is that the mechanical work, which we could then obtain almost without loss, is thousands of times greater than we need.

Some problem is presented by the extremely high temperature of the explosion in the starting section of the tube. This may reach 2000-3000°C. With increasing distance from the starting section, the temperature of the flowing and expanding gases falls. At the outlet of the tube itself this temperature may be less than zero and even, in the ideal case, reach -273°.

The tube should be made of a tough, high-melting material that is a good heat conductor. Then the incandescent part of the tube will transmit its heat to the neighboring cold parts. But this is not enough. Continuous cooling of the incandescent sections of the tube during the explosion is required. They may be surrounded with liquid oxygen, which is needed anyway for respiration, for combustion in the engines, and for cooling the crew's quarters in the rocket. Therefore, the gas forming as a result of the heating of the tube should be channeled mainly to the heat engine. Nevertheless, a certain initial section of the tube will be damaged during the explosion, no matter how short.

Therefore, the incandescent part of the explosion tube must be made thicker than is needed to resist the gas pressure. It should be made thinner with increasing distance from the inlet, as rarefaction and cooling proceeds. The tube walls should be at their thinnest at the tube outlet. The weight of the tube is very insignificant, even in the event of maximum and uniform pressure throughout its length. Thus, assuming a pressure of 100 atm. a safety factor of 4, the optimal material, and a tube 10 m long, 8 cm in diameter, and cylindrical in shape, we readily find the weight of the tube to be 32.5 kg. But this figure was obtained on the assumption that the entire tube is uniformly strong, although the pressure acting at the inlet is many times higher than that elsewhere. Briefly, this is the maximum weight.

The pump motor will weigh from 5 to 100 kg (see Table 24).*

Rocket Steering Elements

The steering elements are distinguished by their ability to function not only in air but also in a vacuum. There are three control surfaces, all installed close to the flared outlet of the explosion tube. Since a rocket descending to Earth must glide with the power shut off, like an airplane, these surfaces cannot be inside the tube. The rocket must have: 1) an horizontal elevator; 2) a rudder; and 3) lateral stabilizers. The first two need no description, being identical with the corresponding aircraft control surfaces. But they also work in a vacuum thanks to the rapid flow of gases emerging from the explosion tube. The pressure of the stream of combustion products on the deflected rudder causes the projectile to turn correspondingly. This rudder could be very small in area in view of the high velocity of the gas stream, but the rocket must also be able to glide through the air like an airplane, and therefore the rudder must have the same area as in an airplane. The same could be said concerning the lateral stabilizers. If mounted on the sides of the rocket, they would function only in the atmosphere. Therefore, in addition to ordinary ailerons, another stabilizing element, functioning in a vacuum, is needed. This is a small vane mounted in front of the explosion tube outlet and capable of rotating about an axis parallel to the axis of the tube or rocket. As the vane rotates, the exhaust stream from the tube is whirled, generating vortical motion, which in turn causes the projectile to spin about its longitudinal axis in one direction or the other.

If this is mounted outside the tube, it will also operate in air, like aircraft ailerons, independently of the explosion rate; but alone it would be too feeble, and therefore ordinary ailerons will also have to be used. Any bends in the explosion tube may also be regarded as a steering element.

The rocket should have transparent quartz portholes providing

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*Assuming each kg of engine weight corresponds to 1 horsepower. Editor's note in Selected Works of K. E. Tsiolkovskiy, Moscow, ONTI, 1934.

an all-around view, and protected against the effects of heating and vibration. On the inside they should be covered with a layer of some other transparent material offering protection against the noxious effects of direct sunshine undiluted by the Earth's atmosphere. A compass could hardly serve as a guide for determining direction. The Sun's rays are best for this purpose, but if portholes are lacking or covered up, small rotating disks will do. They will work admirably during the short period of the explosion and sojourn in the atmosphere.

A Plan for the Conquest of Interplanetary Space

Master Plan

We can conquer the solar system by quite accessible tactics. First, let us solve the easiest problem: the establishment of a human settlement in the form of an Earth satellite in the ether, outside the atmosphere, at a distance of one or two thousand km from the Earth's surface. The relative supply of explosives required is definitely feasible, since it does not exceed 4-10 times the weight of the rocket. If, moreover, use is made of the preliminary velocity gained on the Earth's surface itself, the supply of explosives actually needed will be quite small (more on this later).

Once we have thoroughly settled down in our satellite base, made it safe and reliable, and become accustomed to living in the ether (in a material vacuum), we will find it easier to modify our velocity, escape from the Earth and the Sun and, in general, depart on voyages in any desired direction. The point is that, once we are a satellite of the Earth or Sun, the application of very small forces will suffice to increase, reduce or otherwise modify our velocity, and hence our position in space. As for energy, it is superabundantly available all around us in the form of the perpetual, unflagging, primeval radiation of the Sun. The necessary thrust could be obtained from negative and, particularly, positive (helium atoms) electrons, taken from the solar radiation. This supply of energy is inexhaustible, and it could easily be trapped by conductors extended far out from the rocket or by some other still unknown means. We could also utilize the pressure of light, directing the light as needed by means of reflectors. In fact, a kilogram of matter with a surface area of one square meter is given by sunlight an annual velocity increment of more than 200 m/sec. Owing to the lack of gravity (apparent or relative, of course), outer space is an ideal place for constructing vast light-weight mirrors that provide much greater additional velocity, thus enabling us to travel "gratis" throughout the solar system.

Eventually, then, we may reach the asteroids, tiny planets, descent onto which presents no difficulty in view of their low gravity. Having reached these minuscule celestial bodies (from 400 to 10 km and less in diameter), we shall obtain an abundance of structural material for space travel and the maintenance of bases in the ether. This will open to us the road not only to all the planets of our solar system but also to other suns.

I have already mentioned that descent to Earth is possible without loss of matter or energy. The construction of the first base in the vicinity of the Earth will require continual support from the Earth, since such a base cannot be established immediately. Therefore, regular traffic between the base and the planet will be needed. Earth will have to provide the machinery, materials, structures, foodstuffs, and manpower. Further, in view of the unusual nature of the extraterrestrial environment, the frequent exchange of personnel will be inevitable.

Return to Earth will not require a reverse explosion and the expenditure of large supplies of matter and energy. If we are in the neighborhood of the atmosphere, a slight retro-explosion will bring us closer, until finally we reach the boundary of the atmosphere, where, owing to air resistance, we shall gradually lose velocity and descend to Earth in a spiral. At first, the velocity will increase, but later, when we enter the denser part of the atmosphere, it will begin to diminish. Once it is no longer sufficient for the centrifugal force alone to balance gravity, we incline the longitudinal axis of the projectile and begin to glide. At this moment the velocity could also be increased by increasing the downward inclination of the rocket, causing it to dive. In a word, we begin to handle the rocket like an airplane with the engine shut off. In both cases the moment of losing the greater part of the craft's velocity must be synchronized with the moment of landing on ground or water. Losing the tremendous velocity of the rocket in the upper atmosphere is completely safe in view of the extraordinary rarefaction of the air there. It is even possible to lose nearly all velocity by circling the Earth repeatedly, retaining only a velocity of 200-300 m/sec (depending on the density of the ambient medium) and then proceeding as with an airplane. Even so, unless the rocket has auxiliary wings, it will land at a much greater velocity than an aircraft, and therefore more dangerously. It should preferably come down on water rather than on land.

From the foregoing we see that the spaceship must also have some of the features of an airplane.

Since it is best to steer the rocket with a small acceleration j, no special precautions need be taken against intensified gravity, as the intensification is very slight, and a normal individual could withstand it even in a standing position. Moreover, it lasts only a few [dozen] minutes or at most 2-3 hours. Respiration products can be absorbed by alkalies and other substances, as chemists are well aware. Likewise, all solid and liquid human excreta must be disposed of. I have written a great deal about obtaining food and oxygen in the ether. This is definitely feasible.

Conditions for Living in the Ether

1. Prolonged existence in a rocket is not possible: the supplies of oxygen for breathing and food are bound to be quickly exhausted, while the products of respiration and digestion will pollute the air. Special accommodation is needed -- safe, bright, at the desired temperature, with self-renewing oxygen, a steady supply of food, and living and working amenities.

Such accommodation, together with all the appurtenances, should be delivered by rocket from Earth in collapsed (compact) form, and unfolded and assembled in the ether on arrival. The walls should be impermeable to gases and vapors, but not to light.

The following materials should be used: nickel-plated steel, regular and quartz glass. The habitation should consist of many compartments separated by bulkheads and communicating only by air-tight doors. Should any compartment become punctured or prove to be permeable to gases, the inhabitants could immediately save themselves by moving into another compartment, and the damaged compartment could be repaired. The least leak would reveal itself in a drop in pressure or the reading of a sensitive manometer. Steps to repair the leak could then immediately be taken. In this way, the safety of living in a vacuum could be raised to 100%.

About one-third of the surface of the habitation should be open to the sunshine, which would permeate all the compartments owing to the transparency of the bulkheads.

The entire surface of the habitation should be covered with a double layer of thin, movable shutters, arranged like a tiled roof or fish scales. If the opaque part of the structure is covered with shiny shutters, while the transparent part is left exposed, we obtain the maximum temperature, which may reach 150°C. If, on the other hand, the opaque part is covered with a black layer, while the transparent part is covered with a shiny silvery surface, we obtain the lowest temperature which, far from Earth, may reach -250°C. In the vicinity of the Earth, however, the temperature cannot drop to more than -100° to -150°, owing to the heat radiated by the Earth. By combining the shiny scales with the black surface in various proportions, we obtain any degree of heat desired: for adults, children, gardens, baths, laundry room, clinic, workshops, and so on.

The following is an example of a heat control system that would insure varied temperatures, though not the extremes of heat and cold actually possible. The outside of the nontransparent part of the habitation is black. At a small distance from it is an outer skin, scaly and shiny on both sides. Its component parts can be turned through an angle until they stand normal to the black surface, like the needles of a porcupine. Then the lower temperature is obtained. When, on the other hand, these scales cover the black surface completely, the maximum temperature is obtained. The same scales may also be made to cover the transparent part of the habitation, in order to obtain a lower temperature. Depending on their function, the different compartments may be differently treated. Thus, for example, the shiny scales may slide over each other in one or more layers and uncover the black surface underneath in varying amounts, so as to provide the desired degree of heat.

At first, the habitations will be of the most elementary kind, suitable for both humans and plants. They will be filled with oxygen, having a density of one-fifth of an atmosphere, and with small amounts of carbon dioxide, nitrogen, and water vapor. They will also contain fertile and moist soil which, on being seeded and exposed to the sunshine, will provide nutritious vegetables and other crops. The human passengers will consume the vegetables and foul the air with their breathing, while the plants will purify the air and produce food. What is taken from the plants will be recovered in full, in the form of fertilizer for the soil and air. Here the work of all sorts of bacteria will be indispensable.

This is exactly the cycle linking animals and plants that exists on Earth, a planet just as isolated from other celestial bodies as our own rocket habitation.

Food will supply 3000 large calories per day. The same heat is provided by half a kilogram of coal or flour, or 3 kg of potatoes, or 2 kg of meat. One square meter of surface illuminated by normal sunlight in the void of space, at a distance from the Sun the same as that of Earth, receives 43,000 calories per day, which corresponds to 10 kg of flour or 43 kg of potatoes (also bananas), or 30 kg of meat.

This means that, in theory, a window measuring 1 m^2, illuminated by the rays of the Sun incident normal to it, would provide 14 times more energy than is needed to live in a severe climate. Some plants utilize as much as 10% of the solar energy (for example, Burbank's cactus), and others up to 5% (bananas and root crops). Therefore, in order to exist, i.e., in order to obtain the oxygen and food he requires, a man could manage with one square meter of sunshine, provided that 1/14 or 7% of the solar energy could be utilized. Accordingly, the vital needs of a single individual could be satisfied by a habitation with a window one square meter in area and a supply of suitable plants. But plants can also be bred by selection and artificial pollination. It is possible that, with time and under ideal conditions of life in the ether, they would produce not 5% or 10%, but 50% and more. Even our present low-efficiency plants, however, if properly selected, would be satisfactory for our purposes.

The plants in our habitations would be provided with excellent conditions. Thus, the temperature would be optimal, and the amount of carbon dioxide could be raised to 1% without ill effects on human health, i.e., 30 times more than on Earth, and the humidity could be adjusted as desired, while fertilizer would be abundant and suitable. Further, the light could be of the desired intensity and composition (which can be accomplished by using glasses of different colors and properties), and any pests, weeds and unwanted growth could be totally eliminated by first sterilizing the soil.

However, the needs of different plants and of man are far from the same. Everything should have its own optimum environment. This will be true in the ether, as time goes on: the different plant species would be provided with an environment offering different soil, atmosphere, humidity, light, and temperature. And man, of course, would also be provided with distinct accommodation, which, moreover, would be differentiated to suit the different races, ages, and temperaments.

But initially plants and men would have to share the same conditions (symbiosis).

There would be no gravity, for the plants or for the men. And for both this might be very convenient. Plants would no longer need thick stalks and branches, which not infrequently break under the burden of the fruit and which constitute useless ballast for trees, shrubs, and even grasses. Gravity, moreover, hinders the rise of the sap. Still, a little gravity may be useful to the plants: to hold the soil and water in place. It could easily be produced by slowly spinning the habitation or greenhouse. It would hardly be noticeable to the plants or the people: the stalks would not bend, and the humans would be able, as before, to float freely in all directions, carried by inertia. The intensity of the artificial gravity would depend on the angular velocity and radius of spin. It might be roughly 1000 times less than terrestrial gravity, although it would be equally possible to make it 1000 times greater than on Earth. No effort need be expended in rotating the greenhouse or habitation. They would rotate of themselves, by inertia, once they were brought into motion, and thereafter they would spin perpetually like planets.

Controlling the temperature would make it possible to dispense with clothing and footwear. Plentiful heat would also reduce the need for food.

Disinfection would destroy all infectious diseases and all pests and enemies of plants and man. The lack of gravity would mean freedom from beds, chairs, tables, vehicles, and the need to expend effort on locomotion. In fact, a single push would enable one to travel forever by inertia.

Every kind of work would be less trouble than on Earth. First, because structures could be any size and made of the weakest material -- there would be no gravity to make them fall. Second, it would be possible to work in any position, so long as the position of the legs or some other part of the body was fixed -- there would be no vertical or horizontal lines, no top or bottom, and no "falling." No object, no matter how massive, could crush a workman, since it could not fall, even if completely unsupported. The parts of a body, no matter how large, would not exert pressure on each other. Any object could be displaced with the slightest push, whatever its mass and size; only an instantaneous application of force proportional to the mass of the object and the square of its velocity would be required. Once this were done, the object would travel continually without halting. Halting, on the other hand, could restore the work originally expended on motion. Thus, transport literally would cost nothing.

But it should not be forgotten that the phenomena of inertia would apply here just as well as on Earth; impact and shock would be just as intense as on a planet, in a gravitational environment. Forging would be possible. On finding oneself between two solids moving differently (or non-synchronously) with respect to one another, one would be in danger of being crushed, if their size or velocity were considerable. Similarly, all sorts of presses, jacks, crushers, hammers, and other machinery, the action of which is not based on gravity or does not depend on it, would function just as effectively in the ether.

We would not have to struggle with the weather, with slush, cold, fog, rain, wind, hurricanes, mist, heat, etc. We would not have to struggle with animals and plants. When working outside the artificial environment, i.e., outside the habitation in the ether, nakedness would be inadvisable. In the ether, in the void, workers would put on special protective clothing resembling a diving suit. Such suits, like the enclosed habitations, would provide oxygen and absorb human exhalation. They would constitute a form of miniature habitation, tightly fitting the inhabitant's body. The only difference is that oxygen would be provided not by plants but by a special tank, which would release it at a fixed rate, as in improved diving suits. Special face-plates would protect against the dangerous action of the Sun's rays. These suits would be impermeable to gases, sufficiently strong to withstand the gas pressure, and flexible enough not to hamper the movements of the limbs. Organic exhalations would be absorbed, and the humidity inside the suit regulated. The coloring of the suit should correspond to the desired temperature. In some suits it would be cold and in others hot. One could be roasted in one suit and frozen in another. The surface of the suit could be a scaly armor, as in the habitations described above; then the inside temperature could be adjusted as desired.

Within the habitations various activities could be carried out as on Earth but much more comfortably, since they would not be hampered by gravity nor by clothing, footwear, cold, heat, or the fact that clothing gets soiled.

All the structures, "diving suits," weapons, greenhouses, and habitations would first be constructed and tested out on Earth. Initially, work in the ether would be confined to assembling prefabricated components. The first colonies would be established with resources drawn from our planet, the more so as there are probably no materials available in the neighborhood of the Earth (at best, the constituents of the rarefied atmosphere might be exploited, but this would not be enough). It would be useful if, from the first, the colonies were independent of a continuous supply of oxygen and food. Even less assistance would be required by colonies established in the asteroid belt, between Mars and Jupiter, where there need be no shortage of raw materials. In this event, the settlers would have at their disposal a myriad of miniature planets, providing as much material as desired and being relatively free of gravity, i.e., no hindrance. There they would obtain not only solid footholds but also vast amounts of solar energy two thousand million times greater than that now received by our own planet. As for the temperature in the asteroid belt, it could be raised to 20°C and higher by a simple technique (described long ago in my writings). By complex methods and the use of reflectors it could be raised to the temperature of the Sun, and through electricity, even higher. But there is also no reason why we should not migrate nearer to the Sun, to a distance where its light is dozens and hundreds of times stronger than on Earth. We could control the temperature. As for matter, masses of it would also be found in between the orbits of the planets nearer the Sun.

We have said that there would be virtually no struggle with nature. But it would be necessary to struggle against the gas pressure, the murderous rays of the Sun, the imperfect nature of man and plants. One has to struggle for comfort, knowledge, the improvement of human nature, etc.

Development of Industry in the Ether, in the Broadest Sense

The first terrestrial animals evolved in water. Water eliminates gravity, that destructive force which was particularly harmful to the first, primitive and vulnerable organisms. When offset by a liquid, gravity ceases to interfere with the unrestricted development of marine organisms (both plants and animals). Thus, marine organisms may reach considerable size and their brain, too, can be quite large. Therefore, logically they should have become masters of the planet. Why has this not happened? Why was mastery seized by land organisms instead? The chief reason lies in the impossibility of maintaining in a liquid environment the high temperatures needed for industrial purposes. Marine organisms, which left the sea to become land organisms, have little by little won mastery of the globe, although, at first, they were very feeble. But they met with no competition on land, and therefore, struggling only with each other, they were able to achieve higher development. One of the reasons for their hegemony is that they were able to discover the secret of fire and to establish industry. Another reason for the backwardness of marine organisms is the absorption of solar energy by water. Thus they could not use this energy to the same extent as land organisms. Further, they lacked a solid footing, since the bottom of most oceans is inaccessibly deep and plunged in the blackest gloom. The third reason for their backwardness is the insufficiency of oxygen in water and their inability to maintain within themselves the temperature most favorable to vital processes, in view of the oxygen shortage and the cooling effect of a dense, heat-absorbing medium, a medium which, moreover, hinders free movement, because of the massiveness of water. It also lacks materials for industry, if we disregard the shore and the limited expanses of shallow water and semi-liquid sediments.

Emergence into the air and the start of the struggle against gravity may have occurred after the organisms had already developed their musculature under water. This struggle was difficult, but victory was ultimately won. In the same way, we shall ultimately succeed in passing from the air to the ether. Transition to land required muscular strength, while the transition from air to a vacuum requires the development of industry, particularly the engineering industry. On Earth, in a gravity environment, things move slowly, even though air is better for this purpose than water. The ether, or outer space, is even more suitable to the growth of civilization, particularly as it is free of the destructive and restrictive effect of gravity.

Accordingly, extra-planetary settlements or tiny asteroids best satisfy the condition for the growth of civilization. They provide everything: superabundance of materials, insignificant gravity, virginal sunlight, limitless and accessible space, solar energy in an amount two billion times greater than that available on Earth, and freedom of movement in all six directions -- even to other solar systems.

Here direct solar energy can be utilized, with the aid of mirrors and reflectors, to produce furnaces of any size, and temperatures ranging from -273° to +6000°C. Conversion of solar into mechanical energy and then into electrical energy could provide as much as 20,000° or more.

The strongest absorber of heat from heated bodies is water, but air also interferes with intense heating or cooling. Moreover, it oxidizes the surface of objects, burns them, or interferes with their preservation or fusion (welding) into a single whole. In a vacuum, industry would be free of this burden.

Gravity is also a tremendous obstacle to construction, technological progress, the operation of machinery, transportation, and social intercourse.

Thus, it is evident why in the belt of tiny planets (where gravity can be easily overcome by the most languorous gesture), in the ether, in the realm of perpetual light and six-directional space, industry and the evolution of intelligent beings with brains of unrestricted capacity should make fabulous advances.

The only problem will be the lack of air, and hence the pressure it exerts on the body, so vitally necessary to animals. With time, animate being will become adapted to this, but at first an artificial atmosphere for plants and men will be needed. A vacuum and pure sunlight kill. The "antidote" will be well-insulated multicompartmented habitations, "diving suits," and artificial selection. As for the necessary oxygen, water, metals, and other substances, they are contained in nearly all rocks. All that needs to be done is to extract them. In general, the function of industry in the ether will be the same as on Earth but more extensive.

Plan of Activities, Starting with the Immediate Future

Now let us consider how we may begin, without delay, the task of conquering the cosmos. Normally, we proceed from the known to the unknown: from the needle to the sewing machine, from the knife to the meat slicer, from the flail to the threshing machine, from the horse-drawn carriage to the motor car, and from the rowboat to the steamship.

It is thus that we expect to proceed from the airplane to the reaction machine -- in order to conquer the solar system. We have already mentioned that a rocket, since at first it must fly through air, should have some of the features of an airplane. But we have also shown that it cannot be fitted with wheels, propellers, airplane engines, permeable gas tanks, and wings. All these would prevent it from achieving velocities exceeding 200 m/sec or 720 km/hr. The airplane will cease to be suitable for the purposes of air transport, but it will gradually become suitable for space travel. Even now, airplanes can fly at altitudes of 12 km, thus surmounting as much as 70-80% of the atmosphere and approaching the sphere of pure ether that surrounds the Earth! Let us assist it to reach that sphere. The following is a rough schedule of the development and transformation of aircraft with the object of attaining these higher goals.

1. A winged rocket plane with a conventional steering system will be designed. The gasoline engine will be replaced by an explosion tube into which explosives are pumped by a small motor. There will be no propeller. There will be tanks for the explosives and a pilot's compartment, the latter covered with some transparent material to serve as protection against the wind, since the speed will be greater than that of an ordinary airplane. This machine will slide on runners along lubricated rails (in view of the limited velocity, the wheels may be retained) until it takes off, reaches its velocity maximum, consumes its entire supply of explosives, and, lightened, begins to glide to a safe landing, like a conventional airplane or a glider.

The amount of explosives and the force of the explosion must be gradually increased, as must be the maximum velocity and flight range and, most important, the flight altitude. Since the pilot's compartment in the rocket plane will be permeable to air, the altitude, of course, cannot exceed the known record. Five kilometers will be sufficient. The aim of these experiments will be to gain skill in operating the plane (at a considerable speeds), controlling the explosion tube, and gliding to a landing.

2. The wings of subsequent models must be reduced somewhat in size, while the engine power and speed must be increased. It will still be necessary to attain the preliminary, pre-explosion speed with the aid of the measures described above.

3. The fuselage of the later models must be impervious to gases and filled with oxygen, as well as equipped to absorb carbon dioxide, ammonia, and other human exhalations. The aim will be to insure survival during flight in extremely rarefied layers. The altitude may greatly exceed 12 km. In view of the great speed, for

safety's sake the landing should be on water. Impermeability of the hull will prevent the rocket from sinking.

4. The control surfaces described above will be used; I mean control surfaces that function well in a vacuum and in the very rarefied air which the rocket will reach. A double or triple-skinned wingless airplane, filled with oxygen, absolutely airtight, and designed for good gliding, will be launched. To take off, it will require a considerable preliminary velocity and hence improved acceleration devices. This gain in velocity will enable it to ascend higher and higher. By then centrifugal force may manifest itself and reduce the work of motion.

5. The velocity reaches 8 km/sec, the centrifugal force annihilates gravity completely, and the rocket first bursts through the confines of the atmosphere, flies on, until its supplies of oxygen and food give out, and then, returns to Earth in a spiral, braked by the air, and coasts down to land.

6. After this, a simple, single fuselage can be used. Extra-atmospheric flights will be repeated. The reaction machine will fly farther and farther beyond the Earth's atmospheric envelope and spend longer and longer in the ether. Nevertheless, all these machines must return, since their stores of food and oxygen are limited.

7. Attempts will be made to dispose of the carbon dioxide and other human exhalations by means of selected small plants, which at the same time will also provide food. A great deal of time and work will be expended on this task, but eventually it will be crowned with success.

8. Ether "diving suits" (protective clothing) for safe emergence from the rocket into the ether will be designed.

9. To obtain oxygen and food and to purify the air in the rocket, special structures for plants will be designed. These will be carried into the ether in collapsed form by rockets, and then unfolded and assembled. Man will make himself largely independent of the Earth, procuring his own means of survival.

10. Populous settlements will be established around the Earth.

11. Solar energy will be utilized not only for nutrition and living amenities but also for travel throughout the solar system.

12. Colonies will be founded in the asteroid belt and else-

where in the solar system, wherever small celestial bodies are found.

13. Industry will develop and the number of colonies will grow.

14. Human nature, both individual and collective, will be successfully improved.

15. The population of the solar system will become one hundred billion times greater than the present population of the Earth. This is the limit beyond which migration throughout the Milky Way will become inevitable.

16. Extinction of the Sun will commence. The remaining population of the solar system will depart for other suns, to join the earlier migrants.

THE SPACE ROCKET. EXPERIMENTAL PREPARATIONS*

Organization of the Experiments

The first experiments should be static ones, i.e., the rocket should not move appreciably. The aim should be to develop a suitable design and means of controlling the rate of explosion and the orientation and stability of the rocket, etc.

Fig. 1 shows the proposed preliminary design. The drawing is schematic (variable scale), i.e., it does not show the parts in strict proportion. Later, I shall attempt to specify the approximate true dimensions.

I shall begin by describing the drawing, working from right to left.

1. On the extreme right is a gasoline motor for pumping liquid air, oxygen or its endogenic compounds. The silencer must be eliminated and the combustion products expelled backward in a direction opposite to the assumed direction of motion. This will contribute at least something to the reaction effect of the rocket. However, this is of no importance to the experiments.

2. O. P. and H. P. -- two pumps, driven by a common motor. The first delivers oxygen compounds to the explosion tube, and the second, hydrogen compounds. Their capacities should correspond to complete combination of the explosives. The volume of the oxygen cylinder will generally be larger than that of the hydrogen cylinder.

Final adjustment may lead to a change in the stroke of one of the pistons. This adjustment is highly important: if there is more oxygen than needed, the explosion tube may start to burn, while if there is not enough oxygen, fuel will be wasted.

Let us determine the ratio of the volumes of the pump cylinders

*First printed privately by the author in the form of a brochure bearing the same title (Kosmicheskaya raketa. Opytnaya podgotovka). Kaluga, 1927. See Appendices, Note 33 (Editor's note).

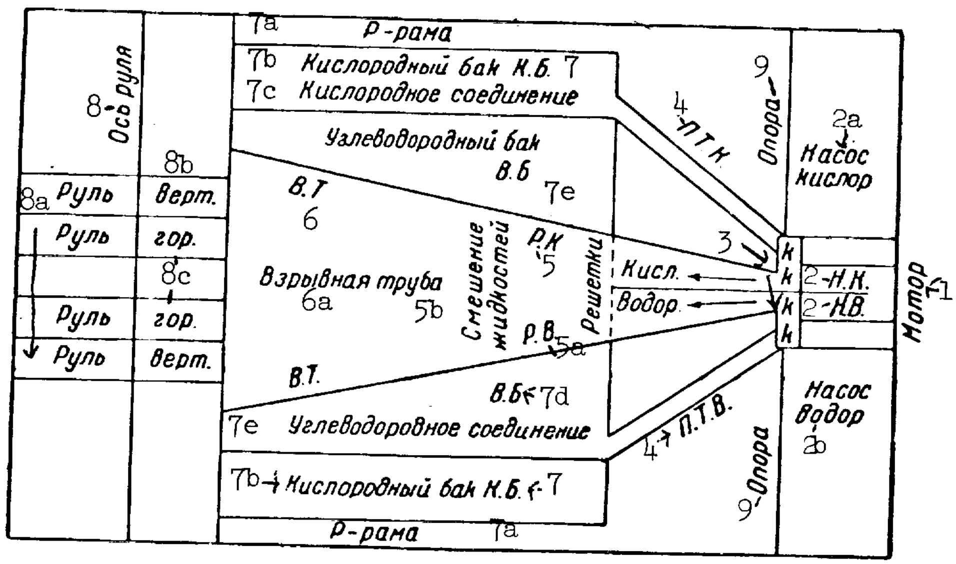

Fig. 1.

1. Motor; 2. H.K. = O.P., H.B. = H. P., 2a. Oxygen pump; 2b. Hydrogen pump , 3. kk, kk = valves; 4 П.T.K. = O. L. (Oxygen line); П. T. B. = H. L. (Hydrogen line); 5. P. K.= Oxygen grating; P. B. = Hydrogen grating; 5a. gratings, 5b. Mixing of liquids; 6. B. T. = E. T. (Explosion tube); 6a. Explosion tube; 7. K. Б. =). T. (Oxygen tank); 7a. Frame; 7b. Oxygen tank; 7c. Oxygen compound; 7d. B. Б. = H. T. (Hydrogen tank); 7e. Hydrocarbon compound; 8. control surface axis; 8b. Vertical; 8c. Horizontal; 9. Supporting member.

in the event that benzene C_6H_6 and liquid oxygen O_2 are used. Their combustion yields water H_2O and carbon dioxide CO_2. For C_6 and to obtain CO_2 we need O_{12}, i.e., 192 parts by weight of oxygen, while for

H_6 we need O_3, or 48 parts. Altogether, 240 parts by weight of oxygen. Now, benzene has 78 parts. This means that we need 3.1 times as much oxygen by weight. For approximately equal densities, the volume of oxygen will also be three times as great as that of benzene. If we use compounds that contain more hydrogen, for example, liquefied ethylene C_2H_4 or turpentine $C_{10}H_{16}$, the ratio will be rather greater. Thus, for ethylene C_2H_4 it will be 3.4. For turpentine (oil) it is close to 3.2 (assuming identical densities). But if we use liquid air, which contains much nitrogen, the volume of oxygen may increase fivefold, and the cylinder volume ratio will thus reach 15. At the same time, some of the nitrogen is usually removed and therefore this ratio will actually be much lower, as low as 4 or 5. Endogenic compounds of oxygen (e.g. nitrogen pentoxide N_2O_5) also increase the volume ratio, but very slightly. Thus, the latter raises the ratio of oxygen compound to hydrogen compound (gasoline) to 4.2.

If we somehow ram pulverized coal into the explosion tube, i.e., if we use pure carbon (C = 12), the amount of oxygen O_2 will be only $2^3/_4$ times greater than the amount of coal. If, however, the carbon is as dense as diamonds, the volume of oxygen required will be even smaller than that of carbon.

3. KK, KK -- pump valves. One pump has two oxygen valves and the other two hydrogen valves (i.e., valves admitting the hydrogen compound). The valves are some distance from the ignition point (oxygen and hydrogen grates) and therefore cannot be damaged by the heat. Moreover, the oxygen mixture is very cold and strongly cools the hydrogen compound; therefore the heat of the explosion cannot harm the pumps and valves. The valves leading to the explosion tube close with enormous strength at the moment of the explosion. Only when the pressure in the tube decreases and the explosion products partly escape and partly undergo rarefaction, do the valves open again and the pistons move so as to feed into the tube another charge of explosives (or, more accurately, explosion elements, since, unlike, say, gunpowder or nitroglycerine, they do not explode independently and are therefore absolutely safe). Hence it is clear that the number of revolutions (or piston strokes) per second may not exceed the limit determined by experiment. Hence also the need for a variable feed. If, for example, the number of revolutions has to be reduced to one-fifth, so that the engine may perform economically, this should be done by reduction. But the same thing can also be achieved by reducing the volume of each pump to one-fifth, or by reducing the piston

stroke correspondingly. The former alternative is preferable. A variable feed or variable piston stroke may be found necessary in the future, however, to modify the force of the explosion.

4. The oxygen and hydrogen lines. These connect the tanks to the pumps. Like the tanks, they are also shielded from the explosion pressure and therefore may be constructed from light materials.

5. Oxygen and hydrogen gratings. These gratings have slanting holes to improve the mixing of the hydrocarbon and the oxygen compound. The inlet section of the explosion tube is divided into two halves: the oxygen compound flows in through one half, and the hydrocarbon through the other. At this point they are cold and cannot mix. Mixing and explosion occur farther on, beyond the gratings, where the numerous different jets meet and mingle. This section of the pipe, which is preheated, stimulates them to combine chemically or explode. (In the initial experiments electrical or some other form of ignition will be needed.) The object of the partition in the tube inlet is to shield the valves from excessive heat, to help to cool the explosion tube, and to reduce (equalize) the force of the explosion and the pressure it exerts on the base of the tube.

If the holes in the gratings are very small and numerous, the explosion will be too rapid and the shock enormous, so that the tube may suffer. The number and size of the apertures must be determined by experiment, beginning with large apertures and reducing their size as much as possible, while at the same time increasing their number. Their direction or mutual inclination should also be varied until the best result is obtained.

6. The conical explosion tube. This shape, expanding toward the outlet, reduces the length of the tube. Experiments will determine the optimal angle of divergence. A very broad angle would reduce the tube length considerably but, since it would also cause the explosives to disperse, their utilization would be reduced.

The explosion tube must be made of strong (even at high temperatures), high-melting and incombustible material, which at the same time must be an excellent heat conductor. It is best to make the tube with a double shell: one, the inner, extremely strong and refractory, and the other, the outer shell, less refractory but just as strong and a good heat conductor. Thus, the heat generated by the powerful heating of the tube in the grating area would be more rapidly dissipated by the outer shell in both directions -- it would be useful in either direction: on the right it would warm up the cold, still unmixed liquids, and on the left, the expanding, and therefore cooling, gas flow. Heating causes this gas flow to accelerate, which is just what is needed. In addition, the tube will be cooled by liquids. Oil (a hydrocarbon compound) cools the tube and is itself cooled by the liquid oxygen.

The results of the experiments will help us to select the best materials, explosives, and explosion-tube design.

7. Oxygen and hydrogen tanks: the inner hydrogen or oil tank, surrounding the hot part of the explosion tube, and the outer, liquid oxygen tank, surrounding and cooling the hydrogen tank. The tanks should not be welded to the explosion tube, since it is subject to explosion shocks and therefore might rupture the tanks, if these were rigidly attached to it. An hermetic joint is possible if the tank walls are corrugated.

8. Vertical and horizontal control surfaces. These are mounted opposite the outlet of the explosion tube. Since future spacecraft will fly through both air and a vacuum and will glide back to Earth (after consuming all the explosives or after deliberately shutting down the explosion), the control surfaces should function equally well in air and in a vacuum, and also while the craft is tied down during the initial experiments. Before the experiments the craft should be suspended from a cable attached to its center of gravity, so as to insure neutral equilibrium. It will not be able to tilt much, as this will be prevented by the nearness of the ground (or floor or a raised platform). During the initial indoor (or outdoor) experiments only the average reaction, produced by a series of nearly continuous explosions, will be measured. This reaction represents the thrust of the vehicle, its forward drive. Of course, during these experiments the vehicle will be restrained from spinning and will only pull on a cable connected to a dynamometer. This will be followed by guidance exercises. The vehicle will be allowed to spin freely and, by manipulating the control surfaces, attempts will be made to orient -- and hold -- it in some definite direction. At first, the exercises will be confined to the vertical control surface. Although the projectile will be slightly tilted, we shall be able to alter at will its direction in the horizontal plane. Subsequently, the horizontal control surface will be manipulated also; this consists of two planes (somewhat like the forked tails of certain birds) and a double bar for manual control. In this way we can attempt to orient the longitudinal axis of the rocket independently of the floor. Suppose, for example, we orient the rocket in perfectly horizontal direction. Lateral stability is insured by adjusting the inclination of the parts of the horizontal control surface, which is accomplished by separating the levers of the double-bar control stick. This is nothing new: it is just the same as in an airplane.

The same control surfaces (they may project beyond the explosion tube) serve both in a vacuum during the explosion and in the air, as the projectile glides swiftly back to Earth.

9, 10. Frame F and supporting member. At its narrow inlet the explosion tube must be particularly massive. Here it ends in a projection which rests on the cross member of the frame. This support must withstand a rapid series of formidable shocks merging into a continuous heavy pressure, which it transmits to the frame. Therefore, the number of free vibrations of the cross member must not be a multiple of the number of engine revolutions or the merging into a continuous heavy pressure, which it transmits to the frame. Therefore, the number of free vibrations of the cross member must not be a multiple of the number of engine revolutions or the number of explosions. Otherwise, even this extremely strong strut might begin to vibrate and eventually rupture.

The explosion cannot be entirely uniform, but in view of the massiveness of the entire system and the large number of explosions per second (as many as 25), we shall get some average pressure that can be determined with a dynamometer. It will be to our advantage to maximize the force of the explosion (or thrust) per unit mass of explosives consumed per second. By means of numerous experiments we could optimize the operating economy, strength, and lightness of the entire rocket. Strength is achieved by using materials of the proper quality, a rocket of the proper shape (or design), good cooling, a big explosion section (the explosion chamber near the gratings), and reduced amounts of explosives and explosive power. The explosion chamber should be gradually reduced, while at the same time the individual charges pumped into it are gradually increased.

Pump and Nozzle Dimensions. Amount of Fuel, Flow Rate and Efficiency

Assuming the weight of the entire projectile, including the supply of explosives and the pilot, to be just one ton, we can achieve practical results, i.e., flight will be feasible, even if we expend only 0.3 kg of explosives per second.*

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*Issledovaniye mirovykh prostranstv reaktivnymi priborami, 1926. This volume, pp. /77 and /82 (Editor).

The pumping work will be less than one metric horsepower. Hence it is clear that the motor will consume hundreds of times less fuel than the explosion tube, and therefore the thrust of the motor (backward expulsion of gases) is almost negligible compared with that of the explosion tube.

Let us base our calculations on 1 kg rather than 0.3 kg. In this case, we know the volume of the two pump cylinders (taken together), assuming the density of the explosives to be unity, which is not very far from the truth.

If the motor makes 25 revolutions per second, each revolution should deliver 40 cc. This means that both pumps taken together have the volume of a cube each edge of which measures 3.4 cm. Obviously, they are tiny pumps. But it is more reasonable to start with a smaller amount of explosives, e.g., 0.1 kg. The corresponding volume would equal a cube with edges of 1.6 cm (16 mm) long. Clearly, we can now completely disregard the weight of the pumps, the more so as they are not exposed to any great pressure.

Experience will show whether a small pressure will be capable of driving this, or a greater, amount of material into the tube. In my notebook I calculated 100 atm of continuous pressure, although for rapid mixing and a small explosion chamber this figure may increase to as much as 3000 to 5000 atm. But when the presure reaches these levels, the valves close, the pumps stop, and the piston merely compresses the liquid or the spring connecting rod is slightly compressed by the motion of the crank shaft. However, this moment is so brief as to have almost no effect on the pump. The gases explode rapidly, so that the pressure in the tube and on the valves decreases, and the pump can resume normal operation.

It is difficult to determine theoretically the optimal diameter of the explosion tube inlet, but it should not be smaller than the approximate size of the pumps, i.e., in the above case the tube diameter would not be less than 2-5 cm. This means that the inlet section will be from 4 to 16 cm^2 in area. The maximum pressure on the tube base, assuming 3000 atm, will not exceed 12-48 tons. But this will last only for a brief instant (impact). An average pressure of one ton will suffice for us.

Even so, flight remains feasible. For a cone-shaped tube there is also a longitudinal pressure component due to the inclination of the tube walls. This means that the average pressure on the base may be less than one ton.

But momentary high pressures and impact are not desirable, since they necessitate making the explosion tube and valves more massive, which adds to the weight of the rocket. Therefore, mixing should not be too thorough. Experiments should start with fairly coarse gratings, so as to avoid instantaneous explosions and very high pressures, even though, in view of the presence of external atmospheric pressure, rapid explosions and high pressures are expedient. In order to moderate the destructive impact on the tube, it may initially be made more spacious and stronger than theoretically necessary.

The motor, which pumps fuel and oxygen, will nearly idle, and the massiveness of the pipe will be necessary only during the brief moments of impact. But at first weight economies may be ignored. Later on, an effort should be made to prolong the period of pressure, so that it occupies at least half the time or the same time as the period of reduced or zero pressure; the former is preferable, as it results in a more uniform pressure. Then the utilization of the massiveness of the tube will be greater, since the average pressure will increase commensurately. As for the work done by the motor, it will not increase as sharply, since pumping must coincide with the minimum pressure in the tube following the explosion. Only the piston strokes will be more intermittent, and the resilience of the connecting rod or crankshaft must be increased.

Here the strength of the tube is utilized by intensifying its action or achieving a greater average pressure for a tube of the same length. It is possible, however, to reduce the mass of the tube without increasing the pressure -- by increasing the number of pump strokes while at the same time reducing their volume.

But let us return to the initial experiments and the first few modest figures. The flow rate in pumps with a cross-sectional area of from 2 to 8 cm^2 will be from 50 to 125 cm/sec (pump volume from 4 to 40 cc). Number of revolutions: 25 per second.

On emerging from the tube the gases cannot have a pressure of less than 1 atm. Assuming a rarefaction of 1300, the absolute temperature of the gases emerging from the explosion tube will be 625°K or 352°C.* This means that the exhaust gases in the atmosphere will still be very hot, and the utilization of heat (its conversion into motion) will never be more than 95%, and actually much less, since the temperature of the exhaust gases will probably be much higher. Their velocity** will not exceed 3-4 km/sec. Maximum velocity must be the aim, and this is possible only for a tube of definite dimensions. A broad-based tube is safer, but it cannot insure maximum velocities.

In rarefied air or in a vacuum, the rarefaction may be very high and will depend on the size and shape of the tube. The temperature

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*See article "Issledovaniye mirovykh prostranstv reaktivnymi priborami."
**Ibid.

of the exhaust gases will be very low, the utilization of heat will be greatest, and the velocity maximal. But we shall have to start the flight in the atmosphere, and therefore we may expect to enjoy the advantages of the vacuum of outer space only after we have conquered the air. In a vacuum, for example, the maximum gas pressure in the explosion tube may be very small, yet we do not lose anything by it. This shows that, with time, after ascending to the more rarefied layers of the atmosphere with the aid of a massive explosion tube, we may jettison it and continue our flight with a lighter tube and lower pressures. But low pressure (compression) would require a redesigned tube: above the atmosphere the tube must be broader and longer, while weighing the same; thus its walls would have to be made thinner. Such alterations in mid-flight are not feasible, and therefore the tube designed for air pressure must remain unchanged in a vacuum. It would be worthwhile to extend it, i.e., to fit an extra section on the end, a more likely solution which may eventually be adopted in the rarefied layers and outside the atmosphere.

There is also another method of utilizing the explosion energy more efficiently: reduction of the rate of consumption of explosives after vacuum conditions are reached. But this is only a limited possibility, depending on the magnitude of the explosion in the atmosphere. This may be so small as to preclude any further reduction. Still, as the rocket's velocity increases, the intensity of the explosion in a vacuum may be reduced to nearly zero.

Gas pressure (per cm^2) falls rapidly with increasing distance from the tube inlet, owing to the rarefaction of the gases and the corresponding cooling. The distribution of densities and temperatures in the explosion tube resembles their distribution in a vertical column of the atmosphere, though not in every respect. In fact, although at first (i.e., over a certain distance from the tube inlet) the gases do indeed expand, their temperature does not fall but equals the dissociation temperature of the combustion products. This is because initially only part of the elements combines chemically, the other part being in a state of decomposition, since complete chemical combination is prevented by the high temperature (3000-4000°C). When, however, the chemical combination is complete, the gases expand and cool just as in a column of the atmosphere.

Hence it is clear that only the initial section (inlet) of the explosion tube is subject to an intense pressure. Let us consider the weight of the tube and the thickness of its walls in relation to a tube one meter long and a constant pressure of 3000 atm, although the average pressure, particularly during the initial experiments, will be much lower.

If the diameter of the tube is several times the thickness of its walls, it may be assumed (for ordinary material) that the weight of the vessel is more than 6 times the weight of the compressed air (or a gas with the density and pressure of the air) it contains. But here this rule does not apply, since the wall thickness will account for a substantial part of the tube diameter. On the other hand, my calculations show that for adequate transverse strength the longitudinal strength is excessive (i.e., much greater than needed).

Here are the calculations:

$$\delta = R - r. \qquad (1)$$

This formula gives the wall thickness and the outer and inner radii of the tube.

Furthermore,

$$q = 2\ (R - r)\ \frac{K_z}{S}. \qquad (2)$$

This gives: the resistance of the tube material per unit length, the ultimate strength of the metal, and the required safety factor. The gas pressure over the same length will be:

$$q_1 = 10^3 p 2r, \qquad (3)$$

where p is the pressure in atm. Equating q and q_1, we obtain from (1), (2) and (3):

$$\frac{R - r}{r} = \frac{\delta}{r} = 10^3 \cdot p \cdot \frac{S}{K_z}. \qquad (4)$$

Let us assume that $p = 3000$; $S = 6$; $K_z = 60\ kg/mm^2 = 6 \cdot 10^6\ g/cm^2$.

We now find $\delta : r = 3$. This means that the wall thickness is three times the inside diameter. But there are materials twice as strong, and, in view of the lower pressure in the tube, the safety factor may also be cut in half. Then the wall thickness will be only 3/4 of the radius or 3/8 of the diameter.

The weight of the tube will be

$$G = \pi \, (R^2 - r^2) \cdot \gamma \cdot 100, \tag{5}$$

over a length of 100 cm; here γ is the density of the material. We assumed $2R = 2$-4 cm.

From (5) and (4) we find

$$G = \pi p \gamma r^2 \left(10^3 \cdot p \cdot \frac{S}{K_z} + 2\right) 10^5 \cdot \frac{S}{K_z}. \tag{6}$$

For an assumed inside diameter of from 2 to 4 cm, i.e., a radius of 1 to 2 cm, formula (6) shows the weight of the tube to be from 37.7 to 150.7 kg for ordinary material and a high safety factor. For very strong material and a lower safety factor, on the other hand, the tube will weigh from 5.2 to 20.7 kg. But formula (6) may be dispensed with. In fact, r is from 1 to 2 cm; δ from 3 to 6 cm; and R from 4 to 8 cm. This means that the weight of the tube according to formula (5) will be $2512 \cdot (R^2 - r^2)$ or from 37.7 to 150.7 kg. The same procedure can be used to determine the weight of a tube the wall thickness of which is 3/8 of the inside radius.

What then is the result? The maximum weight of the tube does not exceed 151 kg -- and that for a consumption of 1 kg of explosives per second. This is more than sufficient for extra-atmospheric flights by a rocket with a total weight of one ton. The other equipment weighs very little. The motor together with pumps and feed lines weighs not more than 10 kg. The frame, tanks, control surfaces, pilot, etc., should weigh altogether 140 kg; a total of approximately

300 kg. For the explosives there remains approximately 700 kg, i.e., [about] twice as much.

For the first experiments and even for flights into the stratosphere and the vacuum of space, this may be enough; 700 kg of hydrogen and oxygen compounds will suffice for an explosion time of from 700 to 7000 sec, or from 11.7 min to 1 hr 57 min.

In the ground experiments, both explosion tube and projectile may be made still lighter: up to 100 kg.

The Endogenic Oxygen Compound or Mixture

In the beginning liquid air may be used. Adding nitrogen will moderate the explosion and reduce the maximum temperature. Later, the amount of nitrogen should be gradually reduced. As a result the temperature will rise somewhat, owing to dissociation effects. The cold liquid entering the explosion chamber will be extremely useful in cooling it. Liquid air is very inexpensive and will probably become even more so.

Its density is close to unity and its heat of vaporization negligible (65), its temperature is -194°C and its heat capacity low. Heating and evaporating liquid air requires little energy, the more so as it is taken from the overheated sections of the tube, the cooling of which is absolutely essential.

Nitrogen pentoxide N_2O_5 would be better than liquid air, were it not for its high cost, chemical action, instability, and toxicity. It contains three times as much oxygen as nitrogen. Moreover, it is an endogenic compound and therefore it releases heat on decomposing. It would have to be heated, since it is a solid at normal temperatures. Let the famous physicists recommend more suitable endogenic compounds of oxygen! As time goes on, liquid air might be supplanted by oxygen recovered from air, which is superior in all respects to N_2O_5. Its temperature in an open vessel is -182°C. Liquid oxygen derived from air is nearly 100% pure.

Hydrogen Compounds

On the whole, liquid hydrogen would be impractical, particularly at first. The reasons: high cost, low temperature, heat of vaporization, storage difficulties. It is more convenient to employ hydrocarbons with the highest possible relative amount of hydrogen. Their combustion energy is nearly the same as that of hydrogen and carbon taken separately. Their combustion products are in the form of vapors or gases. The addition of carbon, however, increases the combustion temperature, since its dissociation is more difficult.

But the hydrocarbons with the highest percentage content of hydrogen are gaseous, for example, methane CH_4 or marsh gas. The latter is difficult to liquefy and, at first, will not be suitable, although its hydrogen content is only three times (by weight) less than its carbon content. More suitable is benzene C_6H_6, although it contains 12 times as much carbon as hydrogen. Even more accessible is petroleum, containing as much hydrogen as possible. It is even cheaper than liquid air. Petroleum is a mixture of hydrocarbons. The saturated hydrocarbon C_nH_{2n+2} contains at least 1/6 hydrogen (by weight) and at most 1/3. I repeat: with regard to chemical energy, any hydrocarbon may be roughly considered as a mixture of hydrogen and carbon. Most have a density of less than one. They all release volatile products and therefore are suitable for rockets.

The maximum velocity of the combustion products decreases somewhat on replacing hydrogen with hydrocarbons: approximately from 5 to 4 km/sec* -- in the presence of an oxygen containing a little nitrogen.

Combustion Temperature; Cooling of Rocket Exhaust and Gas Temperature in the Exhaust

At first, the lower the temperature the better, since this makes it easier to find materials suitable for the explosion tube. Adding nitrogen to the oxygen is therefore useful. The low tempera-

*See "Issledovaniye mirovykh prostranstv reaktivnymi priborami," note 48. Editor's note in "Izbrannyye trudy K. E. Tsiolkovskogo," Moscow, ONTI, 1934.

ture of the liquid air, and of the petroleum it cools, is also useful, although this cooling requires some expenditure of energy. But the hydrogen* of the petroleum increases the combustion temperature. Accordingly, pure hydrogen would be more advantageous and eventually this may be found feasible. It may be that more useful compounds of hydrogen will be developed. Monatomic hydrogen H would be extremely advantageous; according to the available data, it releases 50,000 calories in forming 1 g of diatomic hydrogen H_2; this is nearly 16 times more than 1 g of detonating gas. This shows that there exist practical energy sources dozens of times more energetic than the most powerful used at present (such as detonating gas, oxides of calcium, etc.).

In general, were it not for the artificial and natural cooling of the explosion tube, its highest temperature might reach 3000°C. But the gases, after mixing, exploding, and reaching their maximum temperature, are expelled toward the mouth of the tube, expanding and hence cooling as they go: owing to the guiding effect of the tube, the random thermal motion is transformed into ordered, mechanical motion. In a vacuum the temperature of the exhaust gases should fall to absolute zero, since expansion in a vacuum is not restricted by external pressure. In the atmosphere, on the other hand, for a sufficiently long conical explosion tube, the temperature will drop to 300-600°C. The mean temperature of the explosion tube cannot, therefore, be very high, since the heat from its overheated sections rapidly escapes to the cold ones. Moreover, the tube is continuously cooled externally and internally. In fact, its divided inlet section is flooded by a continuous stream of two extremely cold liquids: liquid air and the petroleum, which it cools. In addition, the outer walls of the tube are cooled by the cold petroleum, which, in its turn, is cooled by the liquid air surrounding it. Hence it is clear that only the central part of the gas column in the explosion tube can have a very high temperature; the parts adjoining the tube walls have a moderate temperature, being cooled by the cold (or rather, not very hot) tube.

*Tsiolkovskiy erroneously assumed that the combustion temperature of carbon exceeds that of hydrogen. I have replaced the word "carbon" by the word "hydrogen" and omitted a sentence. Editor's note in "Izbrannyye trudy K. E. Tsiolkovskogo," Moscow, ONTI, 1934.

Materials of the Explosion Tube

Under these conditions, might not the tube melt or burn? At any rate, the part exposed to extremely high temperatures? The burning of the metal, i.e., its combination with oxygen or other substances, at the tube inlet is prevented by the low temperature of the liquids and the cold walls of the tube. The partition interferes with the chemical process and hence the release (production) of heat. Just beyond the partition, mixing and combustion take place. There the temperature reaches a maximum. But the oxygen is rapidly consumed by the hydrogen and carbon and thus prevented from affecting the cooled metal of the tube and combining with it chemically. When there is a surplus of hydrogen, the mixture even has a reducing effect, i.e., it deoxidizes the metal. The comparatively low temperature of the tube walls even prevents their melting. Overmixing of petroleum is not unhelpful.

The safety of the explosion tube can be ascertained by considering the technique of welding iron with an oxyacetylene flame. The temperature of this flame exceeds the combustion temperature of our explosives, since pure oxygen is used and acetylene C_2H_2 contains much carbon. In the presence of an excess of hydrogen (i.e., of its compound -- acetylene) the iron not only does not burn but even its oxide is reduced. Neither does it melt, if cooled with water, at least from the back, since it cannot reach its melting point. Large masses of metal are difficult to melt, since they must first be intensely heated.

Still, we should strive for a tube material that is not only tough and high-melting but also a good heat conductor and has a low chemical affinity with oxygen and the other elements constituting the explosives.

Many materials have a high melting point. For example, tungsten melts at 3200°C. But these metals are not cheap or plentiful, and working them on a large scale is not easy, precisely because they are so hard to melt. For the time being, they must be forgotten. We shall have to start with simple iron. In its pure form, it has a melting point of 1700°C; that of steel is less (approximately 1200-1300°). But it is precisely steel that we shall have to use, in view of its toughness. To increase its toughness, it may be alloyed with tungsten, chromium, nickel, manganese, cobalt, etc. Here advice from experts is needed.

It would be expedient to sheathe the steel tube in a jacket made of a good heat-conducting metal such as red copper, aluminum, etc. (for better cooling). But these substances are usually either low-melting or weak. Therefore, this approach would not be economical from the standpoint of weight. Perhaps metallurgists will provide us with a material suitable for this purpose. Meanwhile, we shall have to get along without such jackets and be satisfied with high-grade steel, which has a heat conductivity that appears to be adequate for the initial experiments.

Even if the explosion tube were to burn slightly at the point where the temperature is highest, the damage would not be catastrophic. After all, it is exactly at this point that the tube is thickest.

Performance of the Machine as a Whole

Let us examine the performance of the machine as a whole, so as to gain a better idea of the qualities of its different component materials.

We turn on the gasoline motor and let it idle. Note that, in order to reduce the mass of the flywheel, the motor should best have several cylinders, for example, be one of the two-cylinder double-acting type.

We connect the motor to the dual pump, which then begins to suck the intensely cold liquids from the tanks and force them into the divided inlet of the explosion tube. The explosions will begin (like a volley of blank shots). The section of the tube beyond the partition will heat up, and this heat will spread through the tube in both directions, i.e., to the inlet also. Therefore, even before they pass beyond the partition, the liquids will begin to heat up and turn into gases and vapors.

These gaseous substances of variable density will rush through the gratings. This will facilitate mixing, so that the gratings may even become superfluous. But the inlet of the explosion tube and the valves and pumps have a low temperature and therefore cannot suffer. They can be made of ordinary materials.

Every stroke of the pump results in an explosion. The compressed shock wave, having delivered a mighty blow to the tube and the connecting rocket frame, is propagated along the length of the tube in the form of an expanding, and therefore cooling mass of gas. By the time these gases reach the tube outlet, they are no longer very hot, having a temperature of 300-600°C. At any rate, the temperature can easily be withstood by the metal control surfaces. In the vacuum of outer space, on the other hand, the temperature will be quite low, depending on the expansion and the length of the tube. The explosions are so frequent (as many as 25 per second) that they coalesce into a single sustained explosion producing the thrust which drives the vehicle.

To be successful, the (static) ground experiments must develop as follows:

1. The machine should remain intact, and the explosion tube should not disintegrate after the explosives have all been consumed.

2. The dimensions of the machine should be reduced to a minimum.

3. The thrust should be a maximum, depending on the rate of explosion and the quality of the explosives.

4. Therefore combustion should be as complete as possible.

5. The temperature of the gases emerging from the explosion tube should be a minimum.

6. The machine should rotate in response to the controls and hold any desired position.

7. The pumps should not have to work too hard.

Following these ground experiments, if they succeed, the projectile could be mounted on four wheels and propelled by the reaction effect over the airfield. At first, it can be of normal size, but it should then be gradually enlarged as the velocity increases. It may be found necessary, in calm weather, to perform the experiments on a lake, after removing the wheels, using the projectile like a hydroplane.

With four wheels only a vertical control surface will be needed; with two wheels one behind the other both a vertical control surface and lateral stabilizers; and lastly, with one wheel -- all three control surfaces.

Subsequently, launchings from an airfield or lake could be tried, up to the boundary of the troposphere. To facilitate this, the vehicle should be fitted with special airplane wings and the control surfaces should be enlarged to assist in gliding and coasting.

Safety Precautions

All the experiments should be carried out with the proper advance planning and every precaution. The supply of explosion elements should be very small: enough for about ten piston strokes or ten individual explosions. The pumps should be as small as possible, or the piston stroke should be reduced, and they should be driven manually. After each experiment, i.e., after a few explosions, the condition of the explosion tube, the valves, the frame, and the entire machine should be inspected. The number and force of the explosions must be increased only very gradually.

At first a short cylindrical explosion tube with a constant wall thickness may be used, and later on, the same tube, but longer and with the walls tapering toward the outlet, and, eventually, a conical tube with rapidly tapering walls. The tube of minimum calculated weight should be enclosed in another tube to safeguard against the consequences of rupture.

At first, the machine should be cooled with water (in the same way as cannon are cooled), and the supplies of explosives should be kept separate and at some distance, even though only rapid mixing of these supplies could result in a dangerous explosion. I would keep them in different containers, since by themselves they are harmless. The container with liquid air should have holes in the top for free evaporation. To restrict this evaporation, the containers should be thermally insulated. In a vacuum this is easy, but in air something like a Dewar vessel is needed. However, the duration of the explosion in a spacecraft is so short that these precautions are superfluous, since even when ordinary tanks are used the losses are negligible.

By increasing the number of explosions and the size of the charge, we shall ultimately determine which pump and which type of projectile best approximate our sketch.

Essentially, we shall be dealing with a rapid volley of weak explosions. Therefore, if the explosion tube is sufficiently strong or well-protected, our experiments will be quite safe. But we should direct them personally, and we should not give complete credence to any theoretical conclusion that has not been verified experimentally.

WORK ON SPACE ROCKETS, 1903-1927*

The principal value of my work consists in the computations and in the conclusions ensuing therefrom. As for the engineering aspects of the problem, I have done hardly anything about them. A long series of experiments and a great deal of design and development work will be necessary. It is this path that will lead us to the technical solution of the problem. Arduous experimentation is inevitable. In the meantime, one can only describe schemes of limited significance and provide clues based on numerous formulas and calculations.

The very name "rocket" itself implies the true nature of the spaceship. The continuous thrust developed by the rocket is much feebler than that of artillery fire. The explosion exerts pressure on the base of the rocket, imparting acceleration to it. The acceleration generates an additional apparent gravity. Like the acceleration, the apparent gravity may be small, not much greater than terrestrial gravity. Since the flight is nearly horizontal, the apparent gravity is at most one and one-half times normal (taking into account the air resistance).

High acceleration is advantageous from the standpoint of economy in the consumption of explosives. On the other hand, it has the disadvantage of increasing the pressure on the vehicle and its passengers. Intensified gravity requires a projectile with high strength or considerable mass and is dangerous to living organisms, which require protection from it. This also adds to the overall weight of the projectile; moreover, high acceleration increases the work done by the rocket in moving through the air and the frictional heating of the rocket.

The passenger is protected by immersion in a liquid, if the acceleration per second exceeds 20 m. The liquid must be of a density equal to the mean density of the organism. The amount of the liquid is unimportant, and may be very small, provided the protective vessel is adapted to the human form. But the vessel itself must be sufficiently strong. When immersed in liquid, a man loses weight, no matter how heavy he may be. Therefore, he is capable of enduring enormous acceleration. Only the differences in the density of the different parts of the body (bones, blood) limit the safe acceleration

*First published in the "Sbornik TTs Osoaviakhima," Moscow, ONTI, pp. 7-12, 1936. Dated by the author 1908-1927. See Appendix, note 37 (Editor).

of the rocket and the resulting apparent gravity.*

Briefly, if the acceleration is to be optimal, it should be close to the terrestrial value, i.e., approximately 10 m/sec^2. At such low accelerations the inclined path of the rocket should be close to the horizontal. The advantages of a shallow trajectory are tremendous compared to its disadvantages. The latter depend on the length of the path in the atmosphere and the resulting increased expenditure of energy. But since, in general, atmospheric drag is small compared with the pressure on the rocket and the total energy required,** we choose a slightly inclined path as the best. Its advantages are as follows: low acceleration or small explosion; immersion vessels for passengers unnecessary; energy expended in overcoming air resistance diminishes when the velocity is small; and the rocket may be made lighter in view of the low apparent gravity.***

There is an economically optimum angle of inclination; it is no greater than 10-20°.

An important part is played by the exhaust velocity of the gases emerging from the explosion tube (nozzle): the higher this is, the more considerable the final velocity of the rocket. These gases may result, for example, from the combustion of a mixture of liquid oxygen and petroleum in the explosion tube. They expand freely, and thereby cool, part of the heat being converted into mechanical velocity. But the external pressure of the atmosphere restricts the free expansion and cooling of the gases. Were this process to occur in a vacuum, outside the atmosphere, and were we dealing with an infinitely long nozzle, the expanding gases would be cooled to absolute zero, and the entire thermal energy would be converted into motion. Then the velocity of the gases emerging from the tube would reach a maximum. Calculations show that this would be 4-5 km/sec. The velocity of artillery shells, and hence of the gases emerging from the muzzle, is at most 1-2 km. This low velocity stems from four causes: the barrel is insufficiently long, the atmosphere prevents the free expansion of the gases, the explosives used release little energy, and, lastly, part of the energy is absorbed by the motion of the heavy shell.

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*According to modern views, it is precisely the nonuniform density of the human body that precludes applying this method of antigravity protection to living organisms. Editor's note in "Izbrannyye trudy K. E. Tsiolkovskogo," Moscow, ONTI, 1934.

**This is correct only for space rockets. For stratospheric rockets, atmospheric drag is a major factor. Editor's note in "Izbrannyye trudy."

***Here the rocket is to be regarded as a winged rocket that flies in the atmosphere like an airplane. Editor's note in "Izbrannyye trudy."

Of course, the explosion in a rocket cannot be conveniently realized without an explosion tube, since the reaction of the gases would otherwise be randomly oriented and the motion of the rocket negligible. The explosion tube channels the stream of gases in a single direction, so that the gases cannot disperse in all directions until they emerge from the tube, where they are no longer useful to the rocket. It is clear that this tube must be tremendously long.

However, a long cylindrical tube can be replaced with a short conical tube (nozzle) with an apertural angle of at most 30°. This reduces the tube length to a fraction, while at the same time insuring excellent utilization of the heat.

For most of the time, the explosion-propelled rocket races through rarefied air or a vacuum. The exploding materials mix in the explosion tube and may be selected to give the maximum heat of combustion. Lastly, a rocket does not require a heavy shell, it merely ejects gases. This is why the rocket ejects them at a velocity of 4-5 km/sec in a vacuum. Rockets must be launched from high mountains; this shortens their path through the dense layer of the atmosphere; furthermore, with the aid of an external force, a considerable initial velocity may be imparted to the rocket before the explosion begins, if the rocket is launched from a mountain.

I shall prove that a rocket may acquire any velocity.

Imagine, to simplify the conclusions, that gravity is absent. We shall assign a value of unity to the mass of the rocket minus the explosives, and the same value to the mass of the explosives. These two equal masses, repelling one another, acquire approximately equal velocities. This means that the rocket will be given a velocity of close to 5 km per second.

If the rocket carries three times this mass of explosives, the velocity will be doubled. In effect, by first expelling two-thirds of the explosives, we impart a velocity of 5 km/sec to the remaining one-third plus the rocket itself. If we next expel the remaining one-third, we get a velocity gain of 5 km/sec, or a total rocket velocity of 10 km/sec. Thus, if we provide the following supplies of explosives: $2 - 1 = 1$; $4 - 1 = 3$; $8 - 1 = 7$; $16 - 1 = 15$; $32 - 1 = 31$, we obtain the following rocket velocities: 5, 10, 15, 20, 25 km/sec, and so on. Clearly, the rocket velocity can be increased indefinitely. Ten kilometers per second is nearly enough to escape the Earth and follow in its annual orbit, while 15 km/sec is nearly enough to approach any of the planets and even to wander among the suns of the Milky Way -- assuming, of course, that the rocket is fired in the direction of the Earth's annual motion.

Is it then feasible to carry a supply of explosives that is three, seven or more times greater than the mass of the entire vehicle, including its passengers and equipment?

Ordinary explosion techniques will not be suitable. In fact, in this case the shock of the explosion, i.e., the pressure, is transmitted to the entire container in which the explosives are stored. This will require a container with a mass several times greater than the mass of the explosives themselves, as otherwise it would not be sufficiently strong and would collapse. Thus, in the ordinary rocket the supply of explosives can never be more than 10 or 20% of the rocket's mass, whereas it needs to be many times greater than this mass.

The relative amount of explosives could be huge, if they could be pumped at some controllable rate, i.e., little by little, say, at 100 or 200 or 1000 g/sec. The explosive elements themselves, if isolated from one another, cannot explode. This means that the containers need not be much heavier than standard gasoline or kerosene tanks.

Under these conditions and in view of the low acceleration of the rocket, the mass of the explosives may be dozens of times greater than the mass of the rocket itself with all its other contents.*

The mass of the explosion tube and inlet chamber will also not be large, since the amount of explosives pumped in per second is so small. The narrow tube inlet can be adequately cooled by the petroleum, the petroleum itself being cooled by the oxygen.

The rocket enters the rarefied layers of the atmosphere and subsequently airless space. If its path is inclined at 12° to the horizontal and its acceleration is 10 m/sec^2, within as little as roughly 200 sec the rocket will have penetrated to a layer where the air is one-third as dense as at ground level (at the expense of 20% of the total explosion energy). Within 300 sec the rocket will have overcome nearly all the resistance of the atmosphere, as by then it will have reached a layer with a relative rarefaction of 14. The rocket emerges from the atmosphere and acquires a velocity sufficient to follow the orbit of the Earth and become an independent planet, a satellite of the Sun. After 19 min, the explosion can be stopped. The rocket will rush through a vacuum, losing velocity solely owing to the gravitational attraction of the Earth or other celestial bodies which, however, can no longer halt it.

When the explosion ceases, the rocket and all its passengers lose gravity, as it were. Such, at least, is the impression of the passengers. The Earth continues to attract the rocket and all its

*In actual rocket designs the weight ratio of propellant to rocket structure is less than 10 (Editor).

contents, a phenomenon expressed in the continual retardation of their motion. But this gravity has the same effect on the rocket and on its passengers. Therefore, the relative position of the rocket and its passengers remains unchanged. They move at the same velocity like an object carried along by a river current alone. There is no relative fall, and hence no gravity.

The intensified gravity during the first 19 min, the period of the explosion, will not harm the organism: owing either to its low value or to protective measures such as immersion in a tank. But might not the lack of gravity prove harmful? The effect of gravity is manifested in an increase in the pressure of the blood column and an increased load on the internal organs. Clearly, the absence of this pressure and state of stress brings no more risk than resting in a horizontal position or bathing, when gravity is also annihilated, as it were. Lastly, if even standing on one's head is not fatal, why should the absence of gravity be any worse? The flow of blood to the brain doubtless increases, and, similarly, the lack of gravity may be as harmful as lying in a bed. But one can lie in bed for years and still remain alive. A young organism is adaptable to anything. The only bad consequence of lack of gravity may be the ensuing debilitation, as in the case of a long period in bed. However, spinning the rocket and the resulting centrifugal force could restore gravity, with any desired intensity.

Let us now consider breathing. The interior of the rocket must be tightly sealed, as otherwise gas would rapidly seep through even the smallest crack, i.e., leak from the rocket and dissipate itself in outer space. Moreover, a steady supply of oxygen is required, since man, in the act of breathing, converts it to carbon dioxide. But we have a supply of liquid oxygen. Moreover, there are many substances that release oxygen freely when heated or for other reasons. Carbon dioxide and other human exhalations could also be absorbed by alkalis and neutralized by different substances. But it would be best to purify our little atmosphere by means of vegetation, just as on Earth. As a byproduct, we would then obtain food, i.e., the fruits of the plants.

In the course of time, mankind will settle circumsolar space. But this will not occur all at once, and it will mean a great deal of work and many sacrifices. The total solar energy is 2 billion times greater than that received by the Earth. Men will avail themselves of this wealth, though acquiring it will not be easy. But mankind has already started on this path. Experiments with reaction-drive motor cars are currently under way (at the Opel Works near Frankfurt-on-Main). They will teach us how to control explosions and steer with a single rudder. That will be all. Reaction engines are unsuitable for motor cars, since they will give uneconomical results. Therefore, we may expect progress in reaction machines to proceed by the following stages:

1. Development of a two-wheel (single-axle) reaction-drive motor car and the means of manipulating two control surfaces.

2. Development of a single-wheel reaction-drive motor car and the means of controlling its lateral stability as well.

3. Development of a similar motor car but fitted with wings enabling it to rise into the air and make a gliding descent. The motor car will be transformed into a reaction [jet] airplane. But it should be kept in mind that it will be too uneconomical to replace conventional aircraft.

4. Development of a similar airplane with an air-tight cabin and apparatus for enabling a man to breathe inside the cabin.

5. Launchings to altitudes exceeding 12 km and even beyond the confines of the atmosphere, with a subsequent gliding, coasting descent to Earth.

6. Prolonged sojourn outside the atmosphere, in a circular orbit (like a moonlet), and safe return to Earth by gliding without consuming explosives.

7. Introduction of plants into the rocket, to purify the air and provide food.

8. Birth of extra-atmospheric industry.

9. Utilization of solar energy and light pressure for travel throughout the ether. Exact calculations show that a mirror with a mass of one kilogram and an area of 10 m^2, at the distance of the Earth, acquires a velocity increment of 2 km/sec annually thanks to the pressure of light. But where gravity is absent, the area of the mirror may be even larger without any increase in mass. Thus, interplanetary voyages are perfectly possible, so long as light pressure is available.

10. Migration to the region of the ether between the orbits of the Earth and Mars or other, more suitable orbits.

11. Colossal development of industry in the ether. Extraordinary increase and [eugenic] improvement in the population.

12. Gradual occupation and colonization of minor bodies of the planetary system, beginning with the smallest asteroids and satellites.

13. Travel to another sun as our Sun becomes fainter and dies.

It is difficult to foresee how many millenia all this will take.

THE NEW AIRPLANE*

A New Type of Airplane

1. Imagine a spindle-shaped surface of revolution highly inflated with air or oxygen. The diameter of the cross section is at least 2 m and the length at least 20 m.

A parallel series of such spindles, with their sides in contact, forms an undulating square plate with triangular notches at both ends (see Fig. 1).

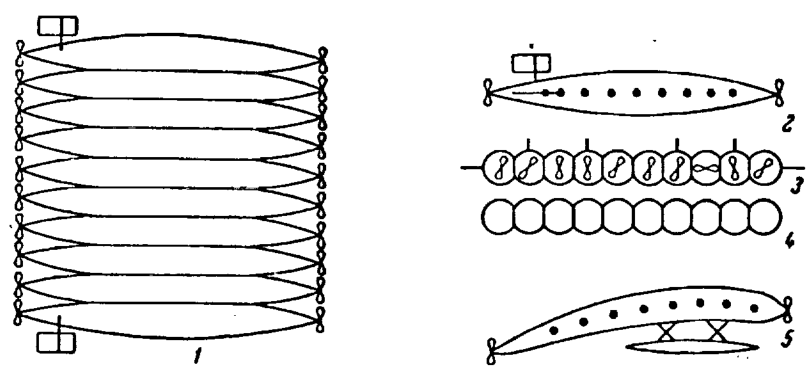

Fig. 1

The area of the plate is at least 400 m^2 (20 × 20). In front and back, at every sharp end, a propeller is mounted. The propeller

*First printed privately by the author in Kaluga in 1929 in the form of a 40-page brochure. Cf. Appendix, note 40 (Editor).

diameter is at least 1 m, and the number of propellers is not less than 10-20.

At the rear two large elevators, which also serve as lateral stabilizers, rudders, are mounted, one on each side. Atop the vessel, also at the rear, one or more rudders are installed.

The propellers are driven by engines.

2. To take off from water, the airplane is placed on special, slightly inclined floats. Once it reaches flying speed, it jettisons these floats. Thanks to the watertightness of its shell, the airplane can land on water directly (i.e., without floats). Takeoff from an airfield follows the same pattern, except that the floats are replaced by a wheeled undercarriage which is also jettisoned as the airplane gains height. But here, too, landing requires an extensive body of water. However, it is also possible to land on a level field or a flat snow surface. Dragging along a heavy undercarriage or floats is a nuisance, and these are quickly left behind.

3. Such is the general design of my new fuselageless airplane. Its advantages can be illustrated only by calculations. Already, however, the most important benefits can be enumerated.

4. Since the airplane shell is sealed, the pressure inside is constant and therefore safe flight in the rarefied layers of the atmosphere is ensured. In this case, air must be pumped into the chambers in order to ensure combustion in the engines. But after all, this measure is also required in conventional aircraft when they fly in the upper air.

5. The strength of the entire machine is conditioned by the internal overpressure; hence its weight can be minimized.

6. Minimum weight and maximum strength are also achieved by the uniform distribution of passengers and cargo.

7. The low air resistance owing to the absence of a fuselage, wheel struts, floats, wings, ties, braces, etc. results in greater speeds.

7_1. For the same reason we can economize on weight.

8. The design is simple; hence the low cost of the entire structure.

9. The possibility of building large, powerful aircraft capable of transporting 100 and more passengers.

10. Efficient distribution of numerous propellers and engines, and hence complete safety. The simultaneous breakdown of even as many as five engines would result in absolutely no danger and would hardly even slow down the flight. Feasibility of using small-diameter propellers and high-speed, high-powered engines.

11. The projectile may be lengthened and broadened without increasing its height. By broadening the work is reduced (transverse aspect ratio), and by narrowing increased (longitudinal aspect ratio). Henceforth I shall base my calculations on a square wing.

12. Low horsepower per engine, and therefore minimum weight, standardization, low cost, and simplicity.

13. Spaciousness and comfort.

14. Possibility of flying at high altitudes where the air is rarefied, and therefore of achieving high speeds.

15. Gradual transition to the reaction-propelled spaceship. The other advantages will become apparent from the calculations, which will also confirm what has been said above.

16. The continuous pumping of air into the airplane is a nuisance, but in general it is indispensable for uniform engine performance in a rarefied atmosphere, and is now being employed in aircraft designed for high-altitude flight.

Determining Flying Speed and Other Characteristics

17. I shall now present the calculations. Let me caution the reader that they are only approximate.

Unless otherwise stated, the principal units of measurement will be: the meter and its derivatives -- the ton, the meter-ton, etc.

Imagine a compartment bounded by two transverse parallel sections of a single spindle spaced one meter apart. Assume it to be circular and cylindrical with a diameter D (mean cross section).

18. The perimeter U of this cross section, and the surface area F, will be

$$U = F = \pi D.$$

19. The weight of the shell G_1 may be expressed as

$$G_1 = \pi D\delta\gamma,$$

where δ and γ are the thickness of the shell and the density of the shell material.

20. Area of horizontal projection $F_h = D$.

21. The load q_1 of the shell alone per unit of projected area can be found from (19) and (20):

$$q_1 = G_1 : F_h = \pi\delta\gamma.$$

22. But this load is incomplete. It only represents the load due to the weight of the shell. To this we must add the weight of the engines and control surfaces q_2, of the fuel and the fuel tanks q_3, of the passengers and cargo q_4, and of the emergency supplies q_5. Thus, the total load q will be

$$q = q_1 + q_2 + q_3 + q_4 + q_5.$$

23. Assuming, for simplicity's sake, that all these loads are identical, we find from (21) and (22)

$$q = 5q_1 = 5\pi\delta\gamma.$$

24. The permissible tensile strength Q of the shell should equal the overpressure P of the gas inside the shell. Therefore, we may write

$$Q = \delta \cdot 2K_z : S = P \cdot F_h = PD,$$

where K_z is the ultimate tensile strength; S is the safety factor, and P is the gas overpressure per unit area.

25. Formula (24) enables us to determine the shell thickness and hence the weight and load of the shell. The total load can also be determined. Thus, from (23) and (24) we obtain

$$\delta = PDS : 2K_z$$

and

$$q = 5q_1 = 5\pi\gamma P \frac{DS}{2K_z}.$$

We assumed that the partial loads per m^2 of projected area were 1/5 of the total load (22).

26. In general, the surface of the airplane resembles one large flat wing. We shall assume the worst conditions. We could have made this wing slightly cambered, thus doubling the lift force. But we shall base our calculations on a flat wing.

27. Thus, we shall assume that the pressure exerted on a plane surface P_n by a normal flow is given by the formula

$$P_n = (c^2 : 2g)d,$$

where c is the flow velocity, g is the acceleration due to gravity, and d is the air density. The formula adopted yields a pressure one and one-half times lower than is actually the case. This is also unfavorable.

28. As regards the pressure on a plane surface inclined to the flow, we shall take Langley's formula, since it is close to mine and is fully confirmed by my experiments. According to Langley, the pressure on an inclined plane can be determined by multiplying the pressure of the normal flow by $2 \sin y : (1 + \sin^2 y)$.

During normal flight, however, the angle of inclination to the horizontal y is very small, and therefore we can simply multiply the normal pressure by twice the sine of that angle. The error will be insignificant.

29. We now obtain the pressure, which actually will be much higher, especially if the airplane is given a slight curvature; in accordance with (26) and (28), this pressure or the lift force P_v per square meter on a plane surface slightly inclined to the horizontal will be:

$$P_v = (c^2 : g)\ d \sin y.$$

The error will be small. Thus, for an angle of 10° it will be at most 3%. It is insignificant compared with the decrease in the lift force following from conditions (26) and (27).

30. Uniform horizontal flight requires that the total load q be equal to the lift force P_v. Therefore, from (25) and (29) we obtain

$$c = \sqrt{5\pi \cdot g \cdot \gamma PSD : 2d \sin \cdot yK_z}.$$

This gives the velocity regardless of the weight of the shell and, in general, the weight of the airplane and its parts. It is merely understood that this weight must equal the total lift force due to the pressure exerted by the counterflow of air on the wing. If this lift force is very small, the weight of the airplane should also be small, which is impractical; conversely, it may be very large, which is also impractical. Therefore, this velocity is of little interest to us. From the formula we see that it should increase with increase in the overpressure, the safety factor, and the dimension D, and decrease with increase in the air density, the angle of inclination of the wing, and the strength of the material.

31. Now we must determine the energy (or engine power) and the air resistance due to friction and inertia.

Imagine our airplane to have a length l, a width b, and a height D. Let us determine the total drag during motion through the air, and the specific drag, i.e., the drag per square meter of horizontal projection.

I refer here to my work "Soprotivleniye vozdukha i skoryy poyezd" (Air Resistance and the Express Train), 1927, where formula (31) gives the total drag of the surface of an ellipsoid of revolution. I shall not analyze the significance of the constants in this formula, but merely replace them by numbers. In addition, I shall divide the total drag by the area of the horizontal projection. We may assume this area to be $l \cdot D \cdot 0.75$, where D and l are the diameter and length of the ellipsoid, respectively.

32. Then, instead of formula (31) for the total drag, we obtain the specific drag, i.e., the drag per square meter of projected area:

$$P_{h_1} = d\xi c^2 \,(A : X^2 + B : XD), \qquad (33)$$

where A = 0.0212; B = 0.00134; X is the aspect ratio of the shape, i.e., the ratio of length to height; and ξ is the special coefficient of friction (formula (20), "Soprotivleniye," 1927), which depends on the ratio $l : c$. It is determined by working out formula (20) and using the tables given in the same publication.

34. In determining A and B I assumed $\pi = 3.14$; $g = 9.8$; the drag coefficient of a sphere $K_s = 0.4$; the coefficient of the shape $K_{sh} = 1$; the coefficient of a flat plate $K_{fl} = 1$; the coefficient of

contraction of the surface toward the ends $K_c = 0.75$; and the thickness of the surface layer $T_{sl} = 0.0084$. The significance of these constants is fully explained in my work "Soprotivleniye vozdukha," 1927.

35. To simplify the calculations, I shall also assume in formula (33) that

$$A : X^2 + B : X \cdot D = C.$$

Then

$$P_{h_1} = d\xi \cdot c^2 C.$$

36. This is the specific drag due to friction and inertia when the airplane is flying an absolutely horizontal path. To create lift, an inclination is required. Therefore we also have a horizontal drag P_{h_2} due to the inclination of the airplane. This is the horizontal component of the lift force P_v or the normal pressure on the wing. It may be written (see 29):

$$P_{h_2} = P_v \cdot \sin y = (c^2 : g) \cdot d \sin^2 y.$$

37. Now, in order to determine the work that must be done by the airplane, we multiply the total horizontal drag (35 and 36) by the rate of motion. Thanks to the use of propellers, however, the work done by the airplane will be a times more ideal.

38. Thus, we obtain the following equation for the work done by the airplane per second (from 35, 36, and 37):

$$(P_{h_1} + P_{h_2})\ ac = adc^3\ (\xi \cdot C + \sin^2 y : g) = L_1.$$

The last symbol stands for the specific engine power, i.e., the work done per second per square meter of horizontal projection of the airplane.

39. On the other hand, the power L_1 is conditioned by the lift force; the greater that force, the more weight we may assign to the engines, and hence the greater the power will be. In (23) we assumed that the masses of the five components of the load were the same and equal to the mass of the shell. Thus, the engine weight can be expressed as the weight of the shell or as one-fifth of the total load (see 25). Knowing the weight of the engines and their energy E or the work done per second per unit of weight (specific work), it is not difficult to determine the total engine power as well. Thus, with the aid of (25), we find

$$L_1 = 0.5\pi \cdot E \cdot P \cdot \gamma DS : K_z.$$

40. The principal equations are as follows: formula (25) expresses the total load per m^2 of projected area as a function of the weight of the shell. Formula (29) likewise expresses the lift force as a function of the rate of translational motion; formula (38) expresses the specific power as a function of the rate of horizontal motion and the angle of inclination; and formula (39) expresses the power per m^2 of projected area as a function of the weight of the engines, which is assumed equal to the weight of the shell, or 0.2 of the total lift force. Equations (32), (33), and (36) are auxiliary. All seven formulas relate to 1 m^2 of the horizontal projection of the airplane. Equation (25) is indispensable, since the shell must have a certain weight for high-altitude flight, as well as for the sake of strength.

For horizontal flight, the total load q must equal the lift force P_v. This makes it possible to eliminate from equations (25) and (29) the unit load or specific lift force.

Similarly, the specific power L_1 is a function of the drag (38) and also depends on the specific weight of the engines (39), which enables us to eliminate the specific power too. Thus, we obtain

41. $$2.5\pi\gamma \cdot PD \frac{S}{K_z} = \frac{c^2}{g} \cdot d \sin y$$

and

42. $$adc^3 \left(\xi \cdot C + \frac{\sin^2 y}{g} \right) = 0.5 \cdot \pi \cdot E \cdot \gamma \cdot PD \frac{S}{K_z}.$$

Eliminating the air density d by means of (41), we obtain

43. $$c = E \sin y : \left[5ag \left(\xi \cdot C + \frac{\sin^2 y}{g} \right) \right].$$

Hence it is clear that the speed of the airplane is proportional to the specific energy of its engines. Thus, if their weight were to decrease 10 times with no change in power, the independent horizontal velocity would increase by the same factor.

44. Let us not forget, however, that the density of the medium is determined by equation (41). Therefore, we have

$$d = 2.5 \cdot \pi \cdot \gamma \cdot PDSg : (K_z \sin y \cdot c^2).$$

Consequently, this density should decrease, as the square of the velocity increases. If, for example, the velocity is to increase 10 times, the airplane must rise to an altitude where the density of the medium is 100 times less than at the lower altitude, where it flew with 10 times less energy. But at high altitudes engine power is more difficult to develop, unless the rarefied air is condensed, or stored liquid oxygen is utilized. It is remarkable that the velocity is independent of the weight and properties of the shell.

45. Let me recall that ξ itself is dependent on the ratio of the velocity to the length of the airplane (formula (20), "Soprotivleniye"). Therefore, we determine the velocity approximately. However, ξ varies little. Thus, from formula (20) or from the tables given in "Soprotivleniye," we find, assuming the length l of the airplane to be 20 m,

velocity....	100	200	300	400
ξ....	2.5	3.4	3.7	4.2.

Therefore, corrections are easy in view of the approximate nature of the calculations.

Note also the factor C. Formula (35) expresses the dependence of C on the dimension D and the aspect ratio X of the airplane. Therefore, the velocity also depends on the aspect ratio of the airplane.

But let us now determine the velocity c itself. Suppose $l = 20$, $D = 2$, $\pi = 3.14$, $E = 100$ (metric horsepower per kg of engine weight), $a = 1.5$, $\sin y = 0.1$ (6° inclination to the horizontal), $g = 10$, and $X = 10$. From these data we find $\xi = 2.5$ (see 45). Assuming a velocity of 100 m/sec, $C = 0.000088$ and $c = 109$ m/sec (393 km/hr).

This is a first approximation. But we assumed a velocity of 100 m/sec, whereas it proved to be approximately 109. Therefore ξ will not be 2.5 but a little more, which will not affect the determined velocity significantly.

46. Let us calculate the corresponding air density from formula (44). We assume: $\gamma = 8$, $P = 10$ (overpressure in atm), $D = 2$, $S = 10$, $g = 10$, $K_z = 10^5$ (100 kg per mm^2 of cross-sectional area), and

c = 109. Then we find the density of the medium to be a little less than 0.0011. This means that the airplane may not ascend higher than 2 km.

47. On the basis of formula (44) I have compiled the table:

Velocities, m/sec	109	545	1090	2180
Ratio of densities of medium	1	1 : 25	1 : 100	1 : 400

48. The dependence of the velocity on the inclination sin y is not quite clear. But the function

$$\sin y : (\xi \cdot C + \sin^2 y : g)$$

has a maximum, at which the greatest velocity is obtained. Taking the derivative, equating it to zero, and determining from the equation obtained the inclination sin y corresponding to this maximum, we have

$$\sin y = \sqrt{\xi C g}.$$

49. Substituting this inclination sin y in formula (43), we find

$$C = \frac{E}{10 \cdot a \sqrt{\xi C \cdot g}} = \frac{E}{10a \cdot \sin y}.$$

50. Let us assume that C = 0.000088, ξ = 2.5, and g = 10. Now from (48) we obtain sin y = 0.047 (inclination 2°40').

51. Assuming further that E = 100 (ordinary aircraft engine) and a = 1.5, we calculate c = 141.8 m/sec or 511 km/hr. This is the maximum velocity, which is obtained when the angle of inclination of the aircraft is nearly 3° to the horizontal. No greater or smaller angle will give a higher velocity.

52. If we always adhere to the optimal inclination, then, for the density of the medium obtained from (44) and (49), we have

$$d = 250 \cdot \pi \cdot \gamma \cdot PD \frac{a^2}{E^2} \cdot \frac{S}{K_z} \cdot \sqrt{\xi \cdot C \cdot g^3}.$$

Hence it is clear that if we are to extract more energy from the engines, flight in very rarefied layers of the atmosphere will be required, since the formula implies that the density of the medium must rapidly decrease with increasing engine power.

53. Let us determine sin y from equation (41). We find

$$\sin y = A \cdot D : (c^2 \cdot d),$$

where

$$A = 2.5 \cdot \pi \cdot \gamma \cdot P \cdot g\ (S : K_z).$$

54. Now, eliminating sin y from equation (42) and solving it with respect to the density of the medium d, we obtain

$$d = \frac{AED}{10 \cdot \xi Cac^2} \cdot \left(1 \pm \sqrt{1 - \frac{100g \cdot \xi Ca^2 c^2}{E^2}}\right).$$

55. Hence it is clear that

$$c \leqq E : (10 \cdot a \sqrt{\xi Cg}),$$

i.e., the velocity may not exceed a certain specified limit. Proceeding from our previous premises, we find

$$c \leqq 141.8.$$

We shall obtain the same maximum velocity as that found previously (49).

55_1. Thus, the speed of conventional aircraft cannot be increased in the rarefied layers of the atmosphere, unless the specific energy of the engines is increased. Therefore, conventional aircraft engines are apparently unsuitable for attaining higher speeds.

55_2. The required rarefaction for this maximum speed may be expressed, in accordance with formula (54), as follows:

$$d = AED : (10 \cdot g \cdot \xi Cac^3).$$

If we eliminate the velocity c and A by means of equations (54) and (55), we obtain formula (52).

56. What then is the work done by the airplane? The specific work is expressed by formula (38) or (39). Under conditions (45) and (46) I calculate L_1 to be 2.5 meter-tons, i.e., 25 metric horsepower per square meter of horizontal projection. For the entire projected area (20 × 20), I obtain 10,000 metric horsepower.

57. The total load is given by the formula (25)

$$g = 5q_1 = 0.125 \text{ ton} = 125 \text{ kg}.$$

Each type of load (0.2) will account for 0.025 ton or 25 kg.

58. A person weighing 75 kg will require 3 m^2 of projected area, i.e., 75 metric horsepower. And since the entire projected area is approximately 400 m^2, the airplane can carry 133 persons.

59. The volume corresponding to 1 m^2 of projected area will be $0.75 \cdot 2 = 1.5$ m^3. Therefore, we shall have about 4.5 m^3 per person. Actually, a floor area of 3 m^2 may even be more than necessary.

61. The specific work done by the engine per person, which we calculated as 75 metric horsepower, is excessively high and therefore wasteful (although a velocity of 511 km/hr completely justifies the expenditure of energy). Could it not be reduced? For this purpose we must first express the work done by the engine not in terms of a unit of projected area but in terms of unit lift force and unit rate of translational motion. In fact, if we can move at 10 times the speed and carry 10 times the load, why not do 100 times the work? The saving in time due to the higher velocity is an additional advantage which we shall not consider here (in view of its indeterminacy).

62. From formulas (39), (55) and (25) we obtain

$$L_1 : (c \cdot q) = 2a \sqrt{\xi C g}.$$

Here we divide the power (39) by the maximum velocity (55) and the total load (25).

63. This shows clearly that the power required to move unit load through unit distance depends neither on the energy of the engine nor on the velocity but only on the shape and size of the airplane and is a nearly constant factor.

64. Formula (62) gives the work per second (in meter-tons) required to move one ton of airplane through one meter of the flight path. But the passengers account for only one-fifth of total weight or 200 kg. This means that we can thus determine the work required to move two passengers (with luggage) through one meter.

65. Let us assume conditions (46). Then from (62) we find 0.047 meter-tons or 47 kg-m per ton of airplane and per meter of flight path. This is for two passengers; for one passenger (100 kg) we obtain 24. Usually, a conventional airplane flying at a speed of 40 m/sec (144 km/hr) does work equal to 40 metric horsepower per passenger, or one metric horsepower per meter of flight path. Our results, on the other hand, are 4 times lower, not to mention saving in time!

66. How far, then, can our airplane fly without landing under conditions (46)? We see that the speed is 551 km/hr. The total load is 125 kg, and the partial load (engines, for example) 25 kg (1 m^2 of horizontal projection). The corresponding power will be 25 metric horsepower (56). Twenty-five metric horsepower will consume 0.1 × × 25 = 5 kg of fuel. This means that our gasoline will suffice for 5 hours of flight -- during which time the airplane will have flown 2555 km. But we have shown that the lift force will actually be twice as great, i.e., an additional 75 kg of fuel may be added. This will enable the airplane to make a nonstop flight of 30 hours or 15,338 km, enough to fly across the ocean.

67. The speed of an airplane depends on the tip speed of its propeller (not on the number of propeller revolutions per minute, which is the greater the smaller the propeller), which in no way depends on the propeller size (diameter) but only on the strength of the material and its distribution in the propeller. It is best to have a propeller with a more massive base. At any rate, this tip speed can be at most 500 m/sec, as otherwise the material could not withstand

the centrifugal force, and the propeller would burst into pieces. The speed of the airplane at the least angle (45°) of the propeller blades relative to the air stream will in practice be not more than 250 m/sec, or 900 km/hr, which is well below the escape velocity.

68. Therefore, if we wish to reach the escape velocity while flying in the rarefied layers of the atmosphere, a propeller will not be suitable (not to mention the low power of our present engines).

In addition to these obstacles, there is another no less serious. This is the oxygen problem. Air can be compressed, i.e., pumped into the chamber. But when air is compressed six times, its absolute temperature is doubled (see table):

Compression factor:					
1	6	36	216	1296	7776
Absolute temperature of compressed air:					
200	400	800	1600	3200	6400
Temperature in °C:					
-73	127	527	1327	2927	6127

69. The temperature of the compressed air may reach 6000°C. Enormous work is done, which is partly recovered if the compressed air is forced into the engines without reducing this high temperature.

A compression factor of 36 is the permissible limit (under greater compression, the chemical reaction and heat release will be inhibited). The accompanying temperature will then be 527°C.

70. This is also good for the airplane, i.e., 3066 km/hr. But such a degree of compression has still not been attained in prac-

tice and perhaps will never be attained.

71. But what about later? How can we achieve still greater velocities, for which neither propellers nor engine compression will be suitable? Conventional engines and propellers will have to be abandoned.

We may take along a store of oxygen in liquid form, use it to explode fuel, expel the explosion products through an explosion tube, and utilize the reaction as an "engine."

But, on the one hand, it is extremely uneconomical to burden the airplane with the weight of the oxygen, which previously was taken direct from the atmosphere. On the other hand, the speed of the airplane is not so considerable as to make utilization of the reaction effect worthwhile.

Unit weight of a fuel consisting of pure carbon will require 2.7 times as much oxygen by weight (32:12). Thus a supply equivalent in energy would have to be 3.7 times greater in mass. Were the utilization of the fuel proportionately greater, this disadvantage would be tolerable, the more so as we would then gain a good deal in velocity as well.

72. In rarefied air the utilization of heat may be raised to 50-100% (in moving the exhaust gases). As for the rocket utilization (in moving the rocket) at a velocity of 1-2 km/sec it will hardly be greater than in conventional airplane engines.

For the rocket utilization to be complete, the exhaust velocity (at any given moment) must be equal to the speed of the airplane.*

73. Hence the need for a high-velocity vehicle of complex design. At first, it will be driven by conventional engines and a propeller. Subsequently, the propeller will be eliminated or idled, while the engines pump air into an insulated aft compartment, from which it is ejected at a velocity equal to the speed of the vehicle. Since, at first, the speed of the aircraft increases, the velocity of the exhaust air should also increase. When it reaches 1 km/sec or more, the same engines will pump explosive elements into the explosion tube. These will rush out into the rarefied air at the rate of 3-5 km/sec.

*"Issledovaniye mirovykh prostranstv reaktivnymi priborami." This volume, [Russian] p. /195. (Editor).

74. This is where the centrifugal force due to the motion of the airplane around the Earth becomes extremely important and greatly reduces the weight of the airplane and the work that must be done to move it. When the airplane attains the first escape velocity and emerges beyond the atmosphere, this work approaches zero.

75. A propeller can impart more speed to an airplane than might be thought. Its tip speed, of course, can not exceed 500 m/sec, but the blades can be oriented almost parallel to the air stream or direction of motion of the airplane (with an angle of attack of 20-40°). At first, this work will be nearly useless. But once the airplane acquires a great velocity, then, at a certain ratio, the propeller will begin to function more economically. All propellers perform uneconomically at the start, before the airplane acquires a constant speed. It would be desirable for the angle of attack of the propeller blades to be gradually reduced, automatically or manually, as the airplane's speed increases.

Although the performance at a low angle of attack is extremely uneconomical, there is no other solution. However, I do not recommend this design or the low angle of attack.

76. It is simplest to find some way of imparting a high velocity to the airplane from the very outset and then to activate air pumps which, with the aid of conventional motors, would compress the air and deliver it to a special chamber. From the chamber, air would rush out through special pipes in the tail of the machine. The exhaust could easily be regulated according to the speed obtained.

77. The velocity of the gas rushing out into the rarefied atmosphere is fairly uniform and depends little on the degree of compression. But this is true only if its temperature is constant. If the temperature is not constant, on the other hand, it may reach many thousand degrees (however rarefied and cold the compressible gas may be at first). If a low exhaust velocity (and a low flying speed projectile) is required, we compress and pump the air moderately. Then the outlet velocity may even be less than 500 m/sec. But if a high exhaust velocity is needed, the pumping is accelerated, the air is compressed and heated more intensively, and the velocity rises. The velocity of strongly compressed air heated to many thousand degrees may reach 2 km/sec and more (proportional to the square root of the gas pressure or the absolute temperature of the gas).

Do not forget that the air being compressed is extremely rarefied, say, 1000 times, and its compression will yield a pressure of roughly only 1 atm, and that at first it is cold, but the compression causes it to grow hot and rush out at a commensurately rapid rate.

78. Engines can perform at a constant horsepower, and the flow of compressed air can be regulated by valves. The smaller the outlet, the more air will accumulate in the tank and the more it will be compressed and heated, hence the faster its exhaust velocity.

79. All that is needed is to insulate the air chamber against loss of heat. If the compressed air cools, it is difficult to increase the exhaust velocity, and, moreover, energy will be wasted (by being dissipated in space after being converted into heat).

80. At still greater speeds it becomes convenient to burn the fuel directly in the store of oxygen.

81. Any heat engine is at the same time a reaction device, if the exhaust gases are channeled into conical pipes and ejected in a direction opposite to that of the motion of the vehicle or ship. But since the amount of gases ejected is small and the velocity of the ship is small, the utilization of this additional energy will be extremely small and, for example, in a motor car or an ordinary airplane, it is not utilized, the gases being simply ejected into space, without any special attachments being installed.

In our high-speed airplane traveling at high altitudes this feature should not be ignored. But, of course, the force of the reaction will not suffice in view of the small amount of material exploded in the engines.

The engines may pump in air and produce an air reaction. But the exhaust gases, too, will produce a gas reaction.

The air reaction will utilize approximately 20% of the heat of combustion. The other 80% will be utilized by the exhaust gases. Considering the low speed of the airplane, however, only 10 to 20% of this energy will be utilized in moving it.

The net result, nevertheless, is that the utilization of the exhaust gases in a rarefied atmosphere can double the work done by the engines.

82. Note, by the way, that the air for pumping must be extracted by the pumps from in front of the nose of the craft and expelled at the tail. Thus, the air in front of the machine will be rarefied and that behind condensed. This will result in further acceleration.

83. The complex design of the airplane engines adds to its weight and detracts from its suitability. Therefore, I propose several

different types, all with a high passenger-carrying capability -- at least 133 persons, in a cabin at least 20 m long and wide and at least 2 m high. The engine power is at least 10,000 metric horsepower (however, the airplane can be made half as wide, whereupon the specific work will increase 1.4 times).

The only reservation to be borne in mind is that the true total lift force or the load per m^2, is at least twice as high as calculated in formulas (26) and (27).

This surplus could be utilized in various ways: the number of passengers could be increased sixfold, or the fuel supply could be enlarged to enable the airplane, together with all its passengers, to fly nonstop over one-fourth of the Earth's perimeter. Or part of this surplus lift force could be utilized to increase the safety factor of the airplane (25). Other uses are also possible.

Airplane Types Suitable for Different Speeds

But let us return to our different types of airplane.

84. A. An airplane for flights in the troposphere up to 3-4 km. An overpressure of 1/2 atm will be needed simply to give the shell strength and rigidity. Engines and propellers of the ordinary type; speed 500 km/hr; trans-Atlantic flight would take not more than 12-15 hr. Number of passengers, for the smallest model (20 X 20): from 133 to 798. From 75 to 12 metric horsepower will be needed per passenger.

85. B. An airplane for flight at altitudes where the rarefaction of the air begins to cause the passengers discomfort and where the speed can be much greater. Conventional engines, but the propeller blades have a small angle of attack. Part of the work done by the engines goes into compressing air for their own use, and the rest into the air reaction. Here propeller operation is uneconomical, while the speed is doubled.

86. C. Propeller eliminated. Engines occupied exclusively with compressing the air for the purpose of the air reaction. Exhaust gases also utilized. Speed and altitude greater than for type B.

87. D. Even greater speed and altitude. Low-power engines

occupied exclusively with pumping petroleum and oxygen compounds into conical explosion tubes.

88. E. Speed still higher. Considerable altitude eliminates air resistance, while the great velocity and centrifugal force eliminate gravity. As a result, the machine can set off on a perpetual voyage, for which no expenditure of energy is required.

89. The last three types require a high initial velocity, which could be provided by auxiliary "trains" launched from mountains.*

90. As new engine systems are developed, it will become possible to attain high altitudes, rarefied layers of the atmosphere, and considerable velocities. The cost per kilometer will be quite high, but the savings in time will be tremendous. Such are the advantages of these airplanes. Later on they will serve for the transition to interstellar travel.

91. There is no need to make the horizontal projection of the airplane square. It could also be narrow, consisting of 3-5 inflated surfaces of revolution. But then the specific work done by the engines would increase, owing to the longitudinal slenderness. Thus, with a reversed aspect ratio equal to 2, the work would increase by some 30% (see "Soprotivleniye," 1903).

92. When the airplane travels at a speed of 300-400 m/sec along the equator in the direction of the Earth's rotation about its axis, the centrifugal force will reduce the weight of the airplane by approximately 1%.

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*"Raketnyye kosmicheskiye poyezda" (Space Rocket Trains). This volume, pp. /298-326 (Editor).

THE REACTION ENGINE*

I have been preoccupied with reaction engines since 1895. But it is only now, after 34 years of work, that I have arrived at a very simple conclusion about them. The problem, as will be seen, proved to be quite straightforward: these engines have long been invented and require only slight modification. (I do not disown the devices I proposed earlier, but they have still to be built and tested.)

Explosion (internal combustion or heat) engines are at the same time reaction engines. However, at present the reaction of the ejected gases is not being utilized: they are expelled uselessly in different directions and without the use of conical exhaust pipes.

The explanations are plausible: the effect is fairly feeble in view of the small amount of fuel burned and the low speeds; moreover, the pressure of the atmosphere prevents the free expansion of the combustion products and the full utilization of their heat.

All this changes once the airplane rises into the rarefied layers of the atmosphere, traveling at high speeds, and once the gases are expelled through conical pipes oriented in a single direction -- aft.

Let us consider how large this exhaust will be. Suppose we have an engine of 1000 metric horsepower (each equivalent to 100 kg-m). Suppose it consumes 0.5 kg of fuel per horsepower per hour. Then its 1000 HP will consume 500 kg of fuel. If the fuel is hydrogen, the amount of atmospheric oxygen consumed will be 8 times greater, i.e., 4000 kg. But oxygen accounts for only one-fifth of the atmosphere, so that the mass of air taken in will be 20,000 kg. We shall disregard the hydrogen. More than 20,000 kg are ejected per hour, and 5.6 kg of vapors and gases are expelled per second. This is a large amount. It cannot be ignored, and it is sufficient to attain tremendous speeds.

My "Issledovaniye," 1926, contains Table 24 for a space rocket weighing one ton.** This rocket attains its first escape velocity of 8 km/sec when the fuel (including oxygen) supply is 4 tons. The fuel alone will weigh from one-half to one ton (if a supply of

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*First published in the form of an article in the brochure "Novyy aeroplan" (The Airplane), printed privately by the author. Kaluga, 1929. See Appendix, note 40 (Editor).

**Cf. "Issledovaniye mirovykh prostranstv reaktivnymi priborami" (Editor).

oxygen is not taken along). The escape velocity is acquired after 800 seconds, the acceleration per second is 10 m, the amount of combustion products ejected per second is 5 kg, i.e., even less than in our engine.

True, owing to the presence of a large amount of nitrogen in the combustion mixture, the rate of ejection of combustion products is actually less than 3 kg per second. This means that we shall not attain the escape velocity, though we shall come close to it.

But let us proceed. The rocket weighs a ton. Could this mass accommodate a 1000-HP engine? Nowadays engines weigh half as much as they used to, so that a 1000-HP engine would weigh only 500 kg. The prospects are further improved by the fact that the engine could be very inefficient, it could produce not 1000 but only 200 or even fewer horsepower, so long as it burned as much material as possible. The more material it burns, the better, because we need not so much engine power as explosions and ejectable gases.

Let us again assume that we are taking along a supply of four tons of fuel. If, however, we could succeed in utilizing even part of the oxygen present in the air, one ton of fuel would suffice. This means that we would save three tons in weight. This saving would serve the most varied purposes. For example, we could increase the supply of hydrogen compounds (and thus attain escape velocities), increase the number of passengers, improve and strengthen the equipment, etc.

What then is the problem? How to extend our capabilities and reach out beyond the atmosphere.

Visualize an airplane such as I have described, but of the minimum possible size. At first, its engines operate mainly with propellers and only secondarily with the reaction of ejected gases. But as higher altitudes are attained and the speed increases, the work done by the propellers diminishes, while the work done by burning the fuel grows. This is possible because any engine is capable of idling. Thus, the work done by the propeller is gradually converted to reaction work. Ultimately, the propeller is eliminated or spins without producing thrust or stops with the blades parallel to the flow.

Thus, we use the work of the engines, first, to pump air, and, second, in the highly rarefied layers of the atmosphere or in a vacuum (where this is feasible), to pump explosives into explosion tubes and acquire escape velocity.

If we have 10 engines, each with 10 cylinders and each working at 30 revolutions per second, we obtain 3000 explosions per second and a reaction of from 1 to 5 tons. This is for 100 explosion tubes each with a mean reaction of from 10 to 50 kg.

SPACE ROCKET TRAINS*

From the Author

I am already 72 years old. I long ago ceased working with my hands and doing experiments.

Practical research on reaction machines has been carried out in the West since the publication of my first work on the subject in 1903.

At first, the military implications were explored (Unge in Sweden and Krupp in Germany).

Later on, after the publication of my second study in 1911-1912, general theoretical and experimental research began (Birkeland, Goddard). It was then, moreover, that Esnault-Pelterie announced his theories.

But starting in 1913 interest in the problems of extra-atmospheric flight began to develop in our own country too, particularly after we learned of the serious attitude taken toward it in the West.

Following the publication in a popular journal ("Priroda i lyudi," 1918) of my story "Vne zemli" (Beyond the Earth) (reprinted separately in 1920), Oberth became interested in astronautics. His work gave powerful impetus to German scientists and thinkers, thus leading to many new studies. Two of these scientists (especially Lademann) have been sedulously translating and popularizing my theories.

Rocket-driven automobiles, gliders and sleds, and even a rocket plane (developed by Stammer) have appeared. They have all been very imperfect, but they caused a great sensation and were useful from the experimental standpoint as well as in attracting the interest of the public and scientists and designers.

These ideas also began to spread in the USSR, where Vetchinkin (lectures) and Tsander and Rynin started working on them. The last-named, with his superb accomplishments, his extensive knowledge of the related literature and his objectivity, has made a special contribution to popularizing the ideas of astronautics.

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*First published in Kaluga by the collective of the Kaluga Section of Scientific Workers in 1929. See Appendix, note 39 (Editor).

Not only abroad but also in our own country there are now being established institutes and societies, the members of which are successfully and cleverly propagating the new ideas. Among them are: L'vov, Perel'man, Vorob'yev, Rodnykh, Vengerov, Kondratyuk, Lutsenko, and others.

I send my greetings to the workers in astronautics both in the USSR and abroad. They will have to labor more than one decade. As yet their's is an unrewarding, hazardous and immeasurably difficult task. It requires not only an extraordinary effort and a great deal of talent but also many sacrifices.

Most people consider astronautics a heretical idea and refuse to entertain it at all. Others are skeptical, regarding it as an absolute impossibility, while others are too credulous, considering it a simple matter easily accomplished. But the first, inevitable failures will discourage and repel the faint-hearted and destroy the confidence of the public.

Astronautics just is not comparable with flight in the atmosphere. The latter is child's play by comparison.

Doubtless, success will be achieved, but I simply cannot predict how long this will take.

Any notion that the solution will be easy is a delusion. Of course, it may be useful in the sense of stimulating boldness and energy.

Were they aware of the difficulties involved, many who are now working with enthusiasm would be appalled and repelled.

On the other hand, success would be so splendid. The conquest of the solar system will yield not only energy and life 2 billion times more abundant than terrestrial energy and life, but even more abundant expanses of space. Earthbound man is, so to speak, master of only two dimensions, having only limited control of the third -- i.e., motion upward and downward is still restricted. Once this problem is solved, man will be master of three dimensions.

And what of the absence of gravity, the virginal sunlight of outer space, the absolute control of temperature by means of solar radiation, the means of transportation in any direction at no cost, the exploration of the universe? We can scarcely appreciate all the blessings and benefits of a conquest of the solar system. I have given an inkling of some of them in my story "Vne zemli" (see above).

What is a Rocket Train?

1. By a rocket train I mean a series of interlinking identical

reaction machines, which start by moving along a track, then travel through the air, then through the extra-atmospheric void, and ultimately somewhere between the planets or suns.

2. But only part of this train will fly off into outer space; the other parts, lacking sufficient velocity, will return to Earth.

3. A single rocket must be provided with a large supply of fuel, if it is to attain escape velocity. Thus, to attain the first escape velocity, i.e., 8 km/sec, the weight of the fuel must be at least 4 times the weight of the rocket plus all its other contents. This complicates the design of reaction machines.

A rocket train, on the other hand, makes it possible either to attain high escape velocities or to carry a comparatively small supply of fuel.

4. I shall first solve the problem in its most elementary form. Let us assume that all the rockets in the train are identical in design, carry identical supplies of fuel, and have an identical thrust. In reality, some deviations are inevitable. Thus, the rockets operating on the track should be simpler, while those that operate only in the atmosphere do not have to be equipped with biological facilities for a prolonged sojourn in the ether.

Design and Performance of the Rocket Train

5. The explosion starts in the front rocket, so that the train as a whole undergoes not compression but tension, which is easier to resist. Moreover, this also contributes to the stability of the train during the explosion. Thus, a longer train can be made up and a higher speed attained with the same supply of fuel in each rocket car.

6. The shorter the cars, the more numerous they may be for the same safety factor and the greater their number, the greater the final velocity of the rearmost car. This is an inducement to make the individual machines as short as possible. But the diameter of the rocket machine can not be less than 1 m. This means that the length of a rocket car can not be less than 10 m. If the aspect ratio is any smaller, the air resistance will be too overwhelming. For the rockets that return to Earth this may suffice, but the rocket car

that reaches outer space must be at least 3 m in diameter and 30 m in length. Hence the conclusion: the last (outer-space) car must be made larger.

7. The design of the space rocket is very intricate and will continually increase in complexity. I do not intend to enter into all the details. My aim is rather to demonstrate the advantages of the rocket train with respect to the final velocity, as compared with a single reaction machine. It may be that a small rocket can be transformed into a large one after reaching outer space. But I shall leave all this to the future and assume the rocket's dimensions to be 3 and 30 m.

8. Thus, the diameter of the rocket is 3 m and its length 30 m. The wall thickness is 2 mm (thicker toward the ends). The density of the wall material is 8. The cross-sectional area is 7 m^2; the surface area, 180 m^2; and the cubic capacity 105 m^3. The rocket can accommodate 105 tons of water. A one-meter section of the shell weighs the same throughout (0.15) ton), since toward the ends, where the diameter is reduced, the shell is thicker. I shall assign another 0.15 ton for the passengers, fuel tanks, explosion tubes, machinery, and other equipment: or a total of 0.3 ton per meter. This means that the entire shell of the rocket will weigh 4-1/2 tons. Its contents will weigh the same. Thus, the total will be 9 tons. Of this total, an allocation of one ton should suffice for the passengers.

9. I shall assume the supply of explosives to be 0.9 ton per meter or 27 tons for the entire rocket, i.e., three times the weight of the rocket with all its other contents. (The corresponding velocity for a single petroleum-burning rocket will be 5520 m/sec). In a single rocket this supply (assuming a density of 1) would occupy 27 m^3, i.e., about one-fourth the entire cubic capacity of the rocket. For the passengers and machinery there would remain 78 m^3. If 10 persons were carried, there would be approximately 8 m^3 of space for each. This volume of oxygen, at a pressure of 2 atm., would enable 160 persons to breathe for 24 hr or 10 persons for 16 days, assuming, of course, that the products of respiration are eliminated.

I wish to show that even such a voluminous store of fuel will not overburden the rocket.

10. The explosion pulls the train along -- that is why the

wall thickness is greater at the ends of the rocket; the tensile strength at every section of the rocket must be the same.

11. Given a safety factor of 5, the rocket shell will withstand an excess pressure of 4 atm. But since the excess pressure even in a vacuum is no more than 2 atm, the safety factor will actually be 10.

12. Since all the rockets -- even the last, outer-space stage -- must ultimately glide back to Earth, every rocket is equipped with the necessary gliding apparatus.

A single inflated envelope resembling, if necessary, a workpiece turned on a lathe (solid of revolution) would not glide well. But three such envelopes could be interconnected. On being inflated with air or oxygen up to approximately 2 atm, they would form an extremely strong beam.

13. I cannot suggest wings, in view of their considerable weight.

14. Each rocket must be fitted with surfaces for controlling direction, height, and spin. They should function not only in the air but also in a vacuum.

15. The control surfaces are located at the tail of the rocket. There are two pairs of control surfaces directly adjacent to the explosion tubes. The latter are bent slightly to one side. Otherwise the exhaust gases might exert pressure on the following rocket car.

The number of explosion tubes is at least four. Their outlets are equally spaced around the perimeter of the rocket. The explosion occurs in spurts, like a series of rifle shots. The intermittent impact might harm the rocket. Therefore it is advantageous to make the number of explosion tubes much greater than 4. The explosions will then be more frequent and can be distributed so that the pressure they exert on the rocket is fairly uniform.

Each pair of control surfaces lies in a single plane (parallel to the longitudinal axis of the rocket), but their inclination to this axis may be different: in this case the rocket will begin to spin. It is clear that in this case any pair will serve to prevent the rocket from spinning. In addition, each pair serves to control the direction of the rocket in a given plane. In general, any desired orientation in space and the elimination of spin can both be achieved. The stream of exhaust gases is directed against these control surfaces; this explains how they can function not only in air but also in a vacuum.

16. Small quartz portholes admit the sunlight necessary for piloting. Other larger portholes are covered with outside shutters. Later, when a more rarefied atmosphere or the vacuum of space is reached, they are opened.

17. The nose of the rocket is occupied by the passengers. Amidships is the machine room (pumps and their motors), while the tail is occupied by the explosion tubes surrounded by tanks of petroleum. These tanks, in turn, are surrounded by tanks of freely evaporating cold liquid oxygen.

18. The flight unfolds more or less as follows. A train of, say, five rockets, slides along a track several hundred kilometers long, rising 4-8 km above sea level.* When the leading rocket has burned nearly all its fuel, it detaches itself from the other four, which continue to move by inertia, while the leading rocket leaves them behind thanks to the continuing, though reduced explosion. Its pilot turns it to one side, and then gradually brings it down without interfering with the forward motion of the remaining train of four rockets.

Once the track is clear, the second (now the leading) rocket starts to fire. It suffers the same fate as the first: it is detached from the other three, at first speeding away from them but later, lacking sufficient velocity, returns willy-nilly to the ground.

The same thing happens to all the rockets save the last, which not only emerges above the atmosphere but also acquires escape velocity. As a result, it may either circle the Earth like a satellite or fly away -- toward other planets and even other suns.

Determining the Velocity and Other Characteristics of the Train

19. For a single rocket we employ the following formula (see my "Issledovaniye mirovykh prostranstv reaktivnymi priborami," formula

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*I worked out the question of this track "Soprotivleniye vozdukha i skoryy poyezd" (Air Resistance and the Express Train), 1927.

(38))*

$$\frac{c_1}{W} = \ln\left(1 + \frac{M'_1}{M_0}\right),$$

which gives the ratio of the final velocity c_1 of the rocket to the exhaust velocity W as a function of the ratio of the total mass of the exhaust gases M'_1 or fuel to the mass of the rocket together with all its contents other than the fuel elements; ln means natural logarithm.

20. This formula can also be applied to a multiple rocket, i.e., a train of reaction machines; c_1 will denote the gain in velocity V by the train due to the explosion of the material carried by a single rocket car. The relative exhaust velocity W always remains the same, like the mass M'_1. But the rocket mass M_0 is not the mass of a single rocket car but that of the entire train minus the mass of explosives M'_1 in the leading rocket, which propels the entire rocket train together with the untouched rese ves of fuel in the other cars.

21. Therefore, in formula (19) we should replace the rocket mass M_0 by the train mass M_{tr}, in accordance with the expression:

*Cf. "Soprotivleniye vozdukha i skoryy poyezd," 1927, p. 88.

$$M_{tr} = (M_0 + M'_1)\, n - M'_1,$$

where n is the number of rocket cars. It is clear that this expression applies not only to the complete train, consisting of a given number n of rockets, but also to any other partial train consisting (after the first few rocket cars have been detached) of a smaller number n' of cars.

22. Now instead of formula (19) we have

$$\frac{V}{W} = \ln\left[1 + \frac{M'_1}{(M_0 + M'_1)\, n - M_1}\right].$$

23. For the first train, consisting of the greatest number n_1 of rockets, we obtain

$$\frac{V_1}{W} = \ln\left[1 + \frac{1}{[(M_0 : M'_1) + 1] \cdot n_1 - 1}\right].$$

24. For the second train, which has one rocket car less, we find that

$$\frac{V_2}{W} = \ln\left[1 + \frac{1}{[(M_0 : M'_1) + 1] \cdot (n - 1) - 1}\right].$$

25. And so on for the others. In general, for a train of order x we have

$$\frac{V_x}{W} = \ln\left[1 + \frac{1}{[(M_0 : M'_1) + 1] \cdot (n_1 - x + 1) - 1}\right].$$

26. For example, for the final train $x = n_1$. On substituting, we obtain formula (19) for a single rocket.

27. The velocity of the first train is expressed by formula (23), and the total velocity of the second train by the sum of velocity of the first train plus the velocity gain of the second. In general, the total velocity of a train of order x is expressed by the sum of the velocity gains (25) of the first x trains. The total velocity of the last, rearmost rocket car will be equal to the sum of the velocity gains of all the trains, from the longest to the shortest consisting of only a single rocket car (of order n_1).

28. From the general formula (25) we see that the velocity gain is the greater the fewer the number of remaining cars. The least velocity gain corresponds to the complete train, and the greatest to the final train with $x = n_1$, i.e., when only one rocket car still remains. The velocity gains increase extremely slowly, and therefore a large number of rocket cars would not be very advantageous, i.e., it would not greatly increase the total velocity of the last car.

Nevertheless, the increase in escape velocity would be infinite, were it not for the limited strength of the rocket materials.

29. The calculations can be simplified by counting the trains from the back, in reverse order, i.e., by considering the final, single-rocket train as the first, the penultimate train as the second, and so on. Then the ordinal number will be y and we obtain

$$y + x = n_1 + 1.$$

30. Using this equation to eliminate x from equation (25), we obtain

$$\frac{V}{W} = \ln\left[1 + \frac{1}{[(M_0 : M_1') + 1] \cdot y - 1}\right].$$

Thus we have proved that when the trains are counted from the back, the velocity gain depend only on the reverse order y and not on the total number of rocket cars n_1 in the train.

31. We can now compile a table, from which we can easily find the total velocity of each particular train and the maximum total velocity of the last, single-rocket train.

32. If, for example, we have a four-rocket train, the final relative velocity will be 2.325, i.e., that number of times greater than the exhaust velocity.

The velocities of the individual trains (assuming four rockets) in the normal order can be found from the second row of the table. Starting with the original, complete train, they will be successively

Order y from end of train									
1	2	3	4	5	6	7	8	9	10
Order x from beginning of train									
10	9	8	7	6	5	4	3	2	1
Relative velocity gain if $M_0 : M'_1 = 1/3$									
1.386	0.470	0.262	0.207	0.166	0.131	0.113	0.100	0.09	0.08
Final relative velocity of last (single-rocket) train initially consisting of several rockets									
1.386	1.856	2.118	2.325	2.491	2.622	2.735	2.835	2.925	3.005

as follows:

$$0.207;\ 0.207 + 0.262 = 0.469;\ 0.469 + 0.470 = 0.939;$$

$$0.939 + 1.386 = 2.325.$$

For a ten-rocket train the total velocity of the last rocket is 3.005.

The velocities of the individual trains of this ten-rocket system in the order x can also be found from the second row by adding the figures beginning from the right.

33. The true velocities can be determined if we know the velocity V and the exhaust velocity, i.e., the velocity of the combustion products rushing out of the explosion tube. We obtain the table following.

Even if the fuel is petroleum and 50 % of the combustion energy is utilized (W = 3 km/sec), given a train of 7-8 rockets, the escape velocity is attainable. If the energy utilization is higher, the escape velocity can be attained even with a train of 2 or 3 rockets. Launched from the Earth, a ten-rocket train would suffice to reach the planets and asteroids.

34. If in formula (30) the rocket mass M_0 is large compared to the exhaust mass M'_1, or if a particular train contains many rockets, i.e., if y is large, the second term in formula (30) will represent a small proper fraction Z.

Then we can put, approximately:

$$\ln (1 + Z) = Z - \frac{Z^2}{2} + \frac{Z^3}{3} - \frac{Z^4}{4} .$$

Number of rockets in train									
1	2	3	4	5	6	7	8	9	10
Final velocity of last train in km/sec, if $M_0 : M_1' = 1/3$ and W = 3 km/sec									
4.17	5.58	6.36	6.96	7.47	7.86	8.19	8.49	8.76	9.00
The same, for W = 4 km/sec									
5.56	7.49	8.49	9.28	9.96	10.48	10.92	11.32	11.68	12.00
The same, for W = 5 km/sec									
6.95	9.30	10.60	11.60	12.45	13.10	13.65	14.15	14.60	15.00

The smaller the fraction Z, the fewer terms we can take.

35. For example, let us assume as before that

$$M_0 : M'_1 = 1/3 \text{ and } y = 6.$$

As a first approximation (34) we get 1/7 or 0.143. This is somewhat higher than the value given in Table 31 (0.131). The second approximation will be 0.133, which is closer to the truth. If we take a nine-rocket train, Z = 1/11 and the first approximation gives Z = 0.91, which virtually coincides with the tabulated value.

36. Thus, beginning with the eleventh train, we may boldly assume

$$\frac{V_y}{W} = Z = 1 \left[\left(\frac{M_0}{M_1} + 1\right) \cdot y - 1\right].$$

37. The sum of the velocity gains of trains beyond the 11th train, counting from the end, may be approximately found by integrating expression (36). We obtain

$$\frac{M'_1}{M_0 + M'_1} \cdot \ln\left[\left(\frac{M_0}{M'_1} + 1\right) \cdot y - 1\right] + \text{const.}$$

If const = 10, the sum of the velocity gains will be zero. Therefore,

$$\text{const} = -\frac{M'_1}{M_0 + M'_1} \cdot \ln\left[\left(\frac{M_0}{M'_1} + 1\right) \cdot 10 - 1\right].$$

This means, that for the sum of the velocity gains we obtain

$$\frac{M'_1}{M_0 + M'_1} \cdot \ln \frac{\left(\frac{M_0}{M'_1} + 1\right) \cdot y - 1}{\left(\frac{M_0}{M'_1} + 1\right) \cdot 10 - 1}$$

38. Putting y = 11 (an eleventh train, i.e., adding one more rocket to the ten), we find the relative velocity gain to be 0.77 (Table 31).

If we add 10 trains, y = 20, the resulting velocity gain will be 0.55. For an exhaust velocity of 4 km/sec this velocity gain will be 2.2 km/sec in absolute figures.

Suppose we add 90 rockets: y = 100, and the velocity gain will be 1.78 or, in absolute terms (W = 4 km/sec), 7.12 km/sec. According to Table 33, under the same conditions, ten trains yield 12 km/sec. This means that 100 trains will yield a velocity of 19.12 km/sec or more than that needed to travel to other suns.

Assuming 50 % utilization of the fuel (Table 33), we find that the velocity due to 100 rockets will be 9 + 5.34 = 14.34 km/sec.

39. When there are more than 100 rockets in the train, we may express the total velocity gain as follows (from 37):

$$\frac{M_1'}{M_0 + M_1'} \cdot \ln\left(\frac{y}{10}\right).$$

40. For example, for a 1000-rocket train, the maximum relative velocity will be 3.454. If W = 4, in absolute terms the velocity gain from 990 rockets will be 13.82 or, for all 1000 rockets, 25.82 km/sec.

41. First, let us suppose that all the rockets move in the horizontal direction. The last rocket will have the greatest acceleration per second (velocity gain per second). In practice, it is desirable to have a constant rate of explosion. Then the acceleration of the individual rocket will at first be weaker, because the mass will be large, the fuel not yet being expended. Later, as more fuel is burned, the acceleration will increase. Thus, for our three-to-one supply of explosives, the acceleration will at first be only one-fourth as great as at the end, when all the explosives have been expended.

42. If the explosion is normal to the direction of gravity, it is not expedient to employ a high acceleration (whether on a solid track, in the air, or in a vacuum). First, this would require special means of protecting the passenger against intensified gravity; second, the rocket itself would have to be made stronger and therefore more massive; and third, the explosion tubes and other machinery would also have to be stronger and heavier.

43. Let us assume that the maximum acceleration of the train is 10 m/sec^2. The same acceleration is imparted by the Earth to freely falling objects. Clearly, this acceleration will characterize the last, single-rocket train, at the end of a uniform series of explosions. Suppose that the force of the explosion decreases in proportion to the diminution of the total mass of the rocket, so that the acceleration is constant and equal to 10 m/sec^2 throughout.

44. The mass of trains consisting of two or more rockets changes little, and therefore in this case the force of the explosion may be assumed constant and the acceleration unchanging. The latter will be

the smaller the greater the number of rockets in the train, so that the slight irregularity actually present will be of no consequence.

45. The acceleration of the second train (counting from the end) will be half as great, since its mass is twice as large; the acceleration of the tenth train, one-tenth as great, since it consists of 10 rockets of identical mass, and so on.

Thus, the pull of the horizontal train, or its relative weight, is independent of the number of rockets. In other words, even if the train consists of 1000 rockets, its pull will be, on the one hand, 1000 times greater owing to the increased mass, but, on the other, it will be 1000 times smaller owing to the low acceleration. Obviously, a train consisting of any number of rockets will have the same pull as a single-rocket train.

46. If, in fact, the pull of a very long train is actually somewhat greater, this is solely owing to friction and drag. For the time being, we may disregard these.

47. The inclination of the track to the horizontal also increases the pull of the train in proportion to its length. But if we assume a curving, gradually rising track, the inclination (tangent or sine of the angle of inclination) of which is very small and proportional to the train's acceleration, this, too, may be disregarded.

48. Taking all this into account, let us calculate the times, velocities, trajectories, and altitudes of the trains (Table 49).

It is very convenient to assume that the explosion chamber in each rocket is identical in design and performance. Then the explosion time for the complete expenditure of an identical supply of fuel will be the same for every rocket in the train. Once we attain the first escape velocity of 8000 m/sec, which takes us outside the atmosphere, it will be easy, by means of a light pressure or some other method, to escape from the Earth and travel through the solar system or even beyond it.

49. A 5-rocket train.

Number of train in chronological order					
(1)	1	2	3	4	5
Number of rockets in each train					
(2)	5	4	3	2	1
Mean acceleration in m/sec^2					
(3)	2	2.5	3.33...	5	10
(Constant explosion time) Relative velocity gain for each train					
(4)	0.2	0.25	0.333...	0.5	1.0
Final relative velocity of each train					
(5)	0.2	0.45	0.783	1.283	2.283
Absolute velocity of each train, assuming velocity gain of last rocket to be 5520 m/sec*					
(6)	1104	2484	4322	7082	12602

*See "Issledovaniye mirovykh prostranstv reaktivnymi priborami," 1926, This volume /203-205. (Editor).

[table continued]

(7) Explosion time in seconds: 1104:2 = 552 = 5520:10 = 552, the same for every rocket.

Mean velocity of each train, m/sec

(8)	552	1242	2161	3541	6301

Total distance covered by each train (during explosion), km

(9)	228.14	685.58	1192.87	1954.63	3478.15

Tangent of inclination

(10)	0.02	0.025	0.033 ...	0.05	0.1

Total vertical ascent of each train, km

(11)	5.76	17.1	39.6	97.7	347.8

The same, when the inclination is halved

[Table continued next page]

[table continued]

(12)	2.88	8.5	19.8	48.8	173.9
Final velocity for 50 % utilization of explosives, if the velocity of a single rocket is 3900 m/sec					
(13)	780	1755	3054	4992	8892
Length of trains, m					
(14)	150	120	90	60	30

50. Row 6 shows that the five-rocket train achieves a velocity sufficient for escape from the Earth and even from its orbit. The penultimate, two-rocket train nearly attains the first escape velocity (8000 m/sec). Thus, it could just barely emerge above the atmosphere and circle the Earth together with the last rocket, the explosives of which are still not expended. Obviously, these could be replaced with cargo. This reveals the possibility of turning complete freight trains into Earth satellites, if the total number of elements of the train, i.e., rockets, is sufficiently large.

51. Row 7 shows that the explosion time for every train is 552 sec of 9.2 min. For five trains this will total 46 min. This means that everything will be over within less than an hour, after which the last rocket becomes a body wandering in space.

Our supply of explosives is three times the weight of the rocket with its other contents; therefore it must weigh 27 tons.

Consequently, 48.9 kg of explosives must be exploded per second. A uniform rate of explosion requires a large number of explosion tubes. If each rocket has 40 such tubes and if the speed of the motor is 30 revolutions per second (i.e., if it pumps 30 charges per second), each charge will be 0.041 kg or 41 g. What is this cannonade comparable to? Twelve hundred shots per second, each shot containing 41 g of powerful explosives. And this cannonade must continue, steadily and successively, in one rocket after another, for 46 minutes.

52. We assumed the rocket diameter to be 3 m. For a start, 1 m will suffice. Then this terrible picture will be 27 times (three cubed) less formidable. We mentioned that the last space rocket could possibly be enlarged by some special technique and thus provide spacious accommodation for its passengers, but we shall return to this elsewhere.

53. From row 9 it can be seen that the distances covered by the trains do not exceed the dimensions of the Earth. But the vertical ascent of each train (row 11) is much less. Thus, the first train alone, after sliding for 288 km, will ascend to a height of 5-6 km. The second train should leave the solid track behind much sooner and fly through the air. The last rocket should burst through the top of the atmosphere even before its explosion is finished This happens when the maximum tangent of the angle of ascent (for the last train) is 0.1 and the corresponding angle to the horizon is 6°. For the first train it is slightly more than 1°, for the second about 2°, and so on.

54. When the inclination is half as great (row 12), two trains will consume all their explosives while still on the ground. The altitude of the Earth's mountains would just barely permit this. Then the preliminary distance to be covered will be about 600-700 km.

55. In row 13 I have assumed 50 % utilization of the energy of the explosives. Even then the last train would be given a velocity greatly in excess of the first escape velocity (8 km/sec). In this case the distances would, of course, be shorter.

56. The largest (initial) train is 150 m long. If, however, we at first content ourselves with dimensions one-third as great, we will have a five-rocket train 50 meters long.

57. We have already mentioned that the (tensile) strength of the train is independent of the number of rockets in a horizontal trajectory. But is the strength of the individual rocket sufficient?

The cross-sectional area of the rocket shell is everywhere the same, namely, 18,000 m^2 (for a thickness of 2 mm). The tensile strength, assuming a safety factor of 6, will be at least 180 tons. The total weight (including fuel) of the rocket will be 36 tons. An acceleration of 10 m/sec^2 in conjunction with normal gravity creates a relative gravity 1.4 times greater than the terrestrial. But the horizontal component will be only equal to the latter. Thus, the rocket is subjected to a tensile force of 36 tons. This destructive force is one-fifth the tensile strength of the material. If, however, we assume that the diameter and length of the rockets are three times smaller, the destructive force will be 15 times less than the strength of the material.

58. Inclined motion intensifies this destructive force. But it is the same for all the trains. Thus, the inclination is greatest for a single rocket and increases the stress by only 0.1 The inclination of, say, a five-rocket train is five times less, so that, despite its greater mass, the tensile stress will (on balance) also be increased by 0.1.

59 Hence it is clear that the rockets could be made less massive, were it not for the excess gas pressure, unavoidable in a vacuum. Still, this can be reduced to one-fourth, so that, instead of 4 atm, 1 atm of excess pressure may suffice. For small rockets, however, the shell would then be impractically thin.

60. In view of the high factor of safety in tension, I shall again present tables for trains of 1, 2, 3, 4, and 5 rockets. But this time I shall assume that the force and the rate of explosion of the same mass of explosives are proportional to the mass of the train. Thus, the first train of, say, five rockets, is pulled by a force five times greater than one rocket, and therefore both trains have the same acceleration, as do all the other individual trains derived from this common starting train. The result is that, despite the differences in the number of rockets making up the individual trains, we can deal in every case, as it were, with a single body having a constant acceleration. The explosion time, of course, is inversely proportional to the masses of the individual trains (or, the stronger the explosion, the faster it comes to an end).

61. In all the tables (see 62 and 63) I assume that the final total velocity of the last rocket is equal to the first escape velocity of 8 km/sec. The tables show, inter alia, what velocity

gain is needed from the single rocket. From the fifth row of the table we can see that the maximum velocity gains will be as follows for the different trains:

Number of rockets in train				
1	2	3	4	5
Required velocity gain for single rocket, km/sec				
8	5.3	4.4	3.8	3.5

We observe that the velocity gain required is the smaller the greater the number of rockets in the train. Thus, for a five-rocket train it is only 3.5 km/sec, which is attainable with a relative fuel supply of 1 or 1.5.

From rows 10 and 16 we see that the track on the ground is now much shorter. In fact, the entire process is shorter -- only 800 sec or 3.3 min, since the acceleration does not decrease while the explosion is in progress.

62. The length of each rocket is 30 m.

1 rocket	2 rockets		3 rockets		
Number of train					
1	1	2	1	2	3
Number of rockets in each and relative force of explosion					
1	2	1	3	2	1
Relative explosion time for each train					
1	1	2	1	1.5	3
Relative time of accelerated motion for each train					
1	1	3	1	2.5	5.5
Final velocity of each train, m/sec					
8000	2667	8000	1454	3636	8000

[Table continued next page]

[Table continued]

Velocity gain for each train, m/sec					
8000	2667	5333	1454	2182	4364
Traveling time for each train from above, seconds					
800	266.7	800	145.4	363.6	800.0
Traveling time for each train separately, seconds					
800	266.7	533.3	145.4	218.2	436.4
Mean velocity of each train, m/sec					
4000	1333.3	4000	727.2	1818.2	4000
Distance covered by each train from above, km					
3200	355.5	3200	105.7	661.1	3200

[Table continued next page]

[Table continued]

Flight of each train separately, km					
3200	355.5	2844.5	105.7	555.4	2538.9
Altitude reached sin α = 0.30					
960	106.7	960	31.7	198.3	960
The same, sin α = 0.25					
800	88.9	800	26.4	166.3	800.0
The same, sin α = 0.20					
640	77.1	640	211	132.2	640.0
The same, sin α = 0.15					
480	53.3	480	15.8	99.2	480.0

[Table continued next page]

[Table continued]

The same, sin α = 0.10					
320	35.5	320	10.6	66.1	320.0
Length of complete train, m					
30	60	30	90	60	30

63. The length of each rocket is 30 m.

4 rockets				5 rockets				
Number of trains								
1	2	3	4	1	2	3	4	5
Number of rockets in each train, and relative force of explosion								
4	3	2	1	5	4	3	2	1

[Table continued next page]

[Table continued]

Relative explosion time for each train								
1	1.33	2	4	1	1.25	1.67	2.5	5
Relative time of accelerated motion for each train								
1	2.33	4.33	8.33	1	2.25	3.92	6.42	11.42
Final velocity of each train, m/sec								
960.4	2237.7	4158.8	8000	700.6	1576.3	2746	4497.8	8000
Velocity gain for each train, m/sec								
960.4	1277.3	1920.8	3841.5	701	876	1170	1752	3502
Traveling time for each train from above, seconds								
96.0	223.8	415.8	800.0	70	158	275	450	800
Traveling time for each train separately, seconds								
96.0	127.8	192.0	384.2	70	88	117	175	350

[Table continued next page]

[Table continued]

Mean velocity of each train, m/sec								
480.2	1118.8	2079.2	4000.0	350	788	1373	2249	4000
Distance covered by each train from above, km								
46.08	250.43	864.45	3200	24.50	124.50	377.57	1012.05	3200
Flight of each train separately, km								
46.1	204.03	614.02	2335.6	24.5	100.0	253.1	634.4	2188.0
Altitude reached $\sin \alpha = 0.3$								
13.8	75.1	259.3	960.0	7.35	37.35	112.28	303.61	960
The same, $\sin \alpha = 0.25$								
11.5	62.6	216.1	800.0	6.1	31.1	94.4	253.0	800
The same, $\sin \alpha = 0.20$								
9.6	50.1	172.9	640.0	4.9	24.9	75.5	204.4	640

[Table continued next page]

[Table continued]

The same, sin α = 0.15								
6.9	37.5	129.7	480.0	3.67	18.6	56.7	151.8	480
The same, sin α = 0.10								
4.6	25.0	86.4	320.0	2.45	12.4	37.8	101.2	320
Length of complete train, m								
120	90	60	30	150	120	90	60	30

64. Here again, the inclination of the track to the horizontal should be assumed to be very small, but constant, e.g., 6°, for $\sin \alpha = 0.1$. The path will be straight, but not curved as in the case of a nonuniform rate of acceleration of the individual trains.

65. For trains consisting of 2, 3 and 4 rockets we may assume constancy not only of the acceleration but also of the explosion time. But then the fuel supply of each leading rocket must be proportional to the force of the explosion or the mass of each individual train. This means that the first rockets (trains) burn not only faster, but longer than indicated in Tables 62 and 63, owing to the greater supply of fuel. In this case, moreover, all the individual trains move like a single body at a constant acceleration. This is the basis on which I have compiled the following table.

66. The length of the rocket is 30 m.

	2 rockets		3 rockets			4 rockets			
Number of trains									
(1)	1	2	1	2	3	1	2	3	4
Number of rockets in each train, relative force of explosion, and fuel supply									
(2)	2	1	3	2	1	4	3	2	1
Relative time of accelerated motion of each train									
(3)	1	1	1	1	1	1	1	1	1
Total relative explosion time for each train									
(4)	1	2	1	2	3	1	2	3	4
Final velocity of each train, km/sec									
(5)	4	8	2.7	5.3	8	2	4	6	8
Velocity gain for each train, km/sec									
(6)	4	4	2.7	2.7	2.7	2	2	2	2

[Table continued next page]

[Table continued]

Total traveling time of each train, if the acceleration is always 10 m/sec^2

(7)	400	800	267	533	800	200	400	600	800

Traveling time of each train separately, seconds

(8)	400	400	267	267	267	200	200	200	200

Mean velocity of each train, km/sec

(9)	2	4	1.33	2.67	4.00	1	2	3	4

Total distance covered by each train from above, km

(10)	800	3200	355.5	1422	3200	200	800	1800	3200

Flight of each train separately

(11)	800	2400	355.5	1066.5	1778	200	600	1000	2200

Total altitude reached, km
$\sin \alpha = 0.1$; $\alpha = 6^\circ$

(12)	80	320	35	142	320	20	80	180	3200

[Table continued next page]

[Table continued]

	Length of train, m								
(13)	60	30	90	60	30	120	90	60	30

67. Here the inclination of the track to the horizontal can be constant, e.g., the tangent of the 6° angle of inclination is 0.1.

Even the first train can travel only part of the way over solid earth, the rest, the greater part, being through the atmosphere.

From row 6 it can be seen that the velocity gains are the same for all the trains of a single system and are the smaller the greater the number of rockets in the complete train. For a four-rocket train the velocity gain required is only 2 km/sec, which corresponds to a relative fuel supply of 0.5 to 0.7 (with respect to the mass of the rocket less the explosives).

In the initial experiments, however, the trains may have a larger mass of fuel, since they will carry fewer passengers and simpler equipment and will return to Earth immediately.

68. Nevertheless, the most practical and feasible are trains consisting of identical rockets with a fixed fuel supply and a constant explosion rate (see section 4). These trains may even consist of an enormous number of links (individual rockets), which would increase the final velocity or make possible a small fuel supply (or a low rate of utilization) per rocket. In a word, escape velocities are attainable despite all the imperfections of the reaction machines.

69. Following is a table for a ten-rocket train. The explosion time is the same for each train, as is implied by the identical design of all the links.

Each rocket is 30 m long. The rockets are all of the same design and carry the same fuel supply.

	Number of train									
(1)	1	2	3	4	5	6	7	8	9	10
	Number of rockets in each train									
(2)	10	9	8	7	6	5	4	3	2	1
(3)	Explosion time the same in all cases									
	Acceleration of each train, m/sec^2									
(4)	1	1.111	1.250	1.429	1.667	2	2.5	3.333	5	10

(5) To attain the first escape velocity 8 km/sec, the explosion time must be 8000 m/sec:29.29 m/sec^2 = 273.1 sec (see below, section 70);

[Table continued next page]

[Table continued]

	Velocity gain for each train, m/sec									
(6)	273	301	343	391	456	546	682	1009	1365	2734
	Final velocity of each train, m/sec									
(7)	273	574	917	1308	1764	2310	2992	3901	5266	8000
	Mean velocity of each train, m/sec									
(8)	136	287	458	654	882	1155	1496	1950	2633	4000
	Distance covered by each train separately, km (see rows 3 and 5)									
(9)	37.1	78.3	125.0	178.5	240.8	315.3	408.4	532.3	718.8	1092.4
	Total distance covered from above, km									
(10)	37.1	115.4	240.4	418.9	659.7	975.0	1383.0	1915.7	2634.5	3726.9

[Table continued next page]

[Table continued]

Inclination of path of each partial train. The tangent of the angle (6^{o}) of the last is taken as 0.1										
(11)	0.01	0.0111	0.0125	0.0143	0.0167	0.02	0.025	0.0333	0.05	0.1
Total distance ascended by each train, km										
(12)	0.371	0.870	1.562	2.553	4.021	6.306	10.21	17.22	35.94	109.24
Total altitude reached, km										
(13)	0.371	1.241	2.803	5.356	9.377	15.683	25.89	43.61	79.55	188.79
Altitude-to-distance ratio (from 12 and 10)										
(14)	0.01	0.0302	0.01090	0.0508	0.01179	0.01278	0.0140	0.0161	0.0187	0.0227
Total explosion time for each train, seconds										
(15)	273	546	819	1092	1365	1638	1911	2184	2457	2730

70. If we denote by x the explosion time and require the last rocket (train) to attain the first escape velocity, then, on the basis of row 4, we have

$$1\,x + 1.1\,x\ldots + 1.25\,x\ldots + 2\,x\ldots + 5\,x + 10\,x = 29.39\,x = 8000,$$

whence x = 273.1 sec.

71. The maximum velocity gain required of the last, single rocket will be only 2.7 km/sec, which corresponds to a relative fuel supply of 0.8-1. If, however, this supply is greater, the final velocity will be greater. But, at first, this will not be necessary.

72. The first four trains could travel on solid earth, the altitude reduced being 6 km and the length of the track 419 km (see rows 10 and 13). These figures are permissible for the Earth. The fifth train will complete its journey in the atmosphere, where the remaining five will begin their powered flight. In view of the spherical shape of Earth the altitude reached by the last few trains will be much greater than specified in row 12.

The total distance covered during the explosion will exceed 3000 km.

73. The earthbound section of the trajectory is curved (row 14). Exact calculations of this curvature yield excessively complex formulas (with second derivatives), which I shall refrain from reproducing here, so as not to obscure the essentials. But let us assume that this curvature is constant for each train. A well-known elementary theorem gives us

$$r = L^2 : 2h,$$

where the letters stand for: radius of curvature, distance covered, and altitude reached, in that order. Rows 10 and 13 make it possible to determine radius of curvature for every section of the trajectory.

Thus, for the first, fifth, and last, i.e., the length, we find, in km

$$r = 1850,\ 23\ 220 \text{ and } 36\ 770$$

Hence it is clear that the radii of curvature increase, whence the centrifugal force diminishes. At the same time, however, it increases with the velocity of the trains (the true radii are greater and therefore the true centrifugal force is smaller).

74. I shall calculate this force for all three cases in units of acceleration (m/sec^2). As is known, it is given by:

$$c_r = v^2 : r,$$

where the letters stand for the centrifugal force,* the velocity, and the radius of curvature of the trajectory, respectively. This formula (row 7 and (73)) yields

$$c_r = 0.04,\ 1.34 \text{ and } 1.74.$$

Relative to terrestrial gravity (10 m/sec^2 acceleration) this gives from 0.04 to 0.17. But let us not forget that only the fourth

*For a mass equal to unity (Editor).

train can travel on the solid track and develop centrifugal force. The remaining trains travel in the atmosphere, and then the centrifugal force may be completely absent: in general, it will depend on ourselves, i.e., on the way we steer the rocket train (operate the control surfaces). For the fourth train r = 16 360 and c = =1.05, i.e., the force pushing the train against the track is not more than one-tenth of the train's weight (and in reality even less).

75. Let us now turn to a general discussion of the relative gravitational force created in the rocket train, while it is in motion. Centrifugal force presses the train against the track, at first imperceptibly, later more strongly, but never by more than one tenth the force of terrestrial gravity. I shall ignore this force. Another force, normal to the latter, depends on the accelerated motion of the train. Its maximum is equal to the Earth's acceleration (10 m/sec^2). A force of this magnitude can not be ignored. Together with the Earth's gravitational attraction, it results in an acceleration of approximately 14 m/sec^2, or 1.4 times the terrestrial value. Inside this train a man normally weighing 75 kg would weigh 105 kg. Such an increase in gravity can be easily endured for a few minutes even in a standing position. Gravity will increase slightly, varying from 1 to 1.4 compared with normal. The inclination of this relative gravity to the vertical will also gradually increase, from 0 to 45°. With increasing acceleration the horizontal surface of the earth will seemingly become more inclined and, at the end of the accelerated motion, it will seem to the passenger as if the train were racing up a mountainside at an angle of 45°. At the start this mountain is nearly horizontal, then it becomes steeper and steeper until, at the end of the track, it seems almost vertical. A stupendous and awesome spectacle. Friction and air resistance will reduce the accelerated motion somewhat and therefore the intensification of gravity itself.

76. When the train leaves solid ground and rushes into the air, matters become more complex.

In the atmosphere the process will be the same, if the resultant of the explosion forces is directed along the slightly inclined longitudinal axis of the rocket. Then, in falling, the rocket will experience air resistance equal to its weight. The air will press against it like the solid track, but since the rocket is flying in an inclined position, nose up, it will not hurtle to the ground, as it will be rising faster than it is falling.

77. Falling due to terrestrial gravity will at first be slow and accelerating, but later will reach a rate at which the air pressure equals the weight of the rocket. Thereupon the vertical rate of fall will become constant and not very considerable compared with the continually increasing rate of ascent of the rocket.

78. As we have seen, at the start of the explosion, a rocket tripled or quadrupled in parallel will weigh about 0.9 ton per 3 m^2 of horizontal projection (for rockets 1 m in diameter -- 9 times less). We shall thus have 0.3 ton per m^2 (see (8)). The air pressure per m^2 of horizontal projection will also be 0.3 ton. This will enable us to formulate an equation and draw the necessary conclusions.

79. Let us assume that the direction of the resultant of the explosion is horizontal. Then the air stream will flow against the rocket (assuming the underside is flat) at an angle, the tangent of which is equal to:

$$c_h : c,$$

where c_h is the constant rate of fall of the rocket due to its weight, and c is the variable translational velocity of the rocket.

80. The pressure exerted by the air stream on a (normal) surface 1 m^2 in area will be at least

$$(d : 2g) \cdot c^2,$$

where d is the air density, g is the acceleration due to gravity, and c is the flow velocity.

Now an air stream acting on an inclined plate exerts a stronger pressure (proportional to twice the tangent of the angle). Therefore, the pressure on one square meter of the underside of the rocket may be expressed as

$$(d : g) \cdot c \cdot c_h .$$

81. This pressure must be equated to the weight G_1 of the rocket per m^2 (0.3 ton or 300 kg). Accordingly,

$$G_1 = (d : g) \cdot c \cdot c_h .$$

whence

$$\frac{c_h}{c} = (g \cdot G_1) : (dc^2).$$

This shows that the relative rate of fall, or angle of fall (tangent), rapidly decreases as the translational velocity of the rocket increases. But it increases with decreasing air density, i.e., as the rocket rises to higher altitudes.

82. I shall calculate the tangent of this angle for different rocket velocities and air densities.

If, for example, $d = 0.0012$, $G_1 = 0.3$ ton, $g = 10$ m/sec^2, $c = 1000$ m/sec, then the inclination will be 0.0025. Even at an altitude of 8-10 km, where the air density is one-fourth as great,

..e inclination will be 0.01. If the rocket velocity is halved (500 m/sec), the inclination will be 0.04, but even then it will still be 2.5 times less than the assumed inclination (0.1) of the longitudinal axis of the rocket with respect to the horizontal (when launched along a track). Thus, under these conditions, too, the rocket will not fall, but climb rapidly, rising further above the Earth thanks to the latter's spherical shape.

83. But the rarefaction of the air increases much more rapidly than the square of the translational velocity of the rocket. Therefore a moment will come when the weight of the rocket is no longer balanced by the resistance of the atmosphere and the relative vertical component of its weight will diminish until, in the void outside the atmosphere, it disappears. Then there will remain only the weight due to the accelerated translational motion of the rocket at 10 m/sec^2. This will create an apparent gravity equal to that on Earth, but acting in a direction nearly perpendicular to the latter. Then the Earth will seem to be a sheer wall with the rocket moving parallel to it (ascending).

But this, too, will continue only for a few minutes: the explosion will cease, and all traces of gravity will appear to vanish.

84. If, in this last equation, we assume the tangent of the angle of inclination to be 0.1 and take $c = 1000$ m/sec, we find that $d = 0.00003$, i.e., it is possible to soar without falling to an altitude where the air density is extremely small (0.00003; 40 times less than at sea level) at a velocity of 1000 m/sec. This velocity will not yet develop a centrifugal force equal to the Earth's gravitational attraction and therefore will not give a circular trajectory, always equidistant from the Earth. Only when a velocity of 8 km/sec is reached will the path be circular and perpetual (provided it lies outside the atmosphere).

Various Train Systems

85. Let us consider a number of different train systems. Four cases are possible.

A. Rockets of nearly identical design. The supply of explosives carried by each is the same, but the explosion is the stronger the greater the mass of the train. Hence, the acceleration will be the same for each particular train, but the explosion time will be inversely proportional to the mass of the train (62) and (63).

B. The supply of explosives and the force of the explosion are the greater the larger the mass of the particular train. Hence the rate of acceleration and the explosion time are the same for all the trains (see (66)).

C. The supply of explosives is proportional to the mass of the particular train, but the force of the explosion is constant. In this case explosion time for each train is the longer the greater the mass of the train. The acceleration, on the other hand, is inversely proportional to the mass of the particular train. I have not examined this case.

D. All the rockets carry the same supply of fuel, which is exploded at the same rate. The greater the mass of the particular train, the smaller the acceleration. The explosion time is the same for all trains (see (49)).

86. System A is not the best, since in the first few rockets the explosion must be stronger and more rapid and this means that the explosion mechanism must be heavier and more intricate. By the same token, the force required to pull the first few, long trains will be enormous. The entire system might easily break apart, and therefore multi-rocket trains could not be employed. The velocity gain per train will be the same as in system D. Advantages: shorter track, and shorter explosion time, but this is not very important (see (62) and (63)).

87. System B, like system A, involves an increase in the mass and volume of the rocket, the more so the greater the number of rockets in the train. This is because space is needed for the fuel and also for more intricate and powerful machinery. In this case, too, a multi-rocket train would be impractical: it would break apart owing to the powerful acceleration. This system has the advantage of a rapid increase in velocity, since the velocity gain is the same for each train. This means that the final velocity will be proportional to the number of rockets in the train. If, for example, the velocity gain for a single rocket is 8 km/sec then a system B train consisting of two rockets will attain a velocity of 16 km/sec, which is nearly sufficient to travel to other suns. If a single rocket gives a velocity gain of 2 km/sec, a four-

rocket train will impart to the final rocket an escape velocity of 8 km/sec (see (66)).

88. System C is more practical, because the acceleration for long trains will be less than for system D, and therefore multi-rocket trains are feasible. The explosion mechanisms and the rockets themselves are nearly identical. But since the amount of fuel is proportional to the mass of the particular train, the leading rockets should be larger, so as to accommodate a larger mass of fuel. This is their disadvantage. But we have seen that our rockets are spacious enough, and therefore a two-or three-rocket train is feasible without enlarging the vehicles. Another advantage is that, unlike system B, velocity gains do not decrease as the number of rockets increases. In fact, although the acceleration of a long, massive train is smaller, the explosion time -- in view of the large supply of fuel -- is proportionately longer. Therefore, in this system, the final velocity gain is the same for each individual train, which is a major advantage. The increase in time and the length of the track (compared with systems A and D), is not important.

89. Although I have not analyzed this case, we can use Table 66 to determine the velocity gain. System C merits the most serious attention. For example, if we could extract a velocity gain of only 1 km/sec per rocket, which requires a relative fuel supply of 0.2 to 0.3, then 17 trains would suffice to attain the maximum escape velocity, adequate not only to reach (but not to land on) all the planets of our solar system but also to wander through the Milky Way. The fuel supply carried by the rockets, beginning with the leading rocket, would be at most

$$5.1 \quad 4.8 \quad 4.5 \quad 4.2 \ldots 1.2 \quad 0.9 \quad 0.6 \quad 0.3.$$

These proportions are quite acceptable. The last rocket, the space rocket, would be nearly empty, i.e., free of fuel.

Such are the great prospects offered by the use of trains of this kind, and this is how they may enable us to attain escape velocities!

90. I have already discussed system D (see (49)) in

sufficient detail. Its advantage lies in the complete uniformity of the train elements (apart from the last rocket -- the space rocket).

In general, once the mission has been accomplished, i.e., once the last rocket has been dispatched on its cosmic voyage, all the remaining rockets, whatever the system, having followed a variable trajectory through the atmosphere, glide down to a landing on land or water, whereupon they may be re-used for the same purpose. Thus, one and the same train, running along the same track, could launch millions of vehicles into space. The only regular requirement would be for fuel, consisting of low-cost petroleum products and endogenic compounds of oxygen.

The shortcoming of system D is the low velocity gain. But if we replace series (89) by equal terms, e.g., make them all equal to 5.1, then system C becomes system D, and the final velocity will increase much further.

91. The problem of the explosion materials and the design of the explosion tubes, shell, and other parts of the rocket cannot as yet be solved. Therefore, for the time being, I propose that the explosion elements be petroleum products and liquid oxygen or its endogenic compounds, while the material used to build the rocket should be one of the known alloy steels: chrome, beryllium, etc.

Of course, it is much more advantageous to use monatomic hydrogen and ozone as the explosion elements. But are these materials sufficiently stable and can they be used in a convenient form? This is a question that must be answered by chemists with a special knowledge of substances of this kind.

If satisfactory results are possible with oxygen, petroleum and steel, they will be even more satisfactory with other, improved materials.

Temperature of the Space Rocket

Even among scientists vague and conflicting ideas are held concerning the temperature of bodies in the ether, for example, the temperature of a rocket.

They speak of the temperature of outer space. This is illogical and nonsensical, since we have no clear idea of the nature of the ether. We can only speak of the temperature of gases, liquids, and solids placed in outer space.

Assuming that a certain body in the ether is not surrounded by other bodies, e.g., suns, planets, comets, and minor bodies, this body would only lose heat without receiving any in exchange from other bodies. It is very probable that the temperature of this body would reach absolute zero, i.e., -273°C; the motion of the molecules might be arrested, but this does not mean that the motion of their parts, and the more so of the protons and electrons, will cease. In fact, the motion of the molecules and atoms will not be completely arrested.

However, I shall not explore this question in detail. What we need is to get an idea of the simple temperature of bodies in outer space. In all likelihood it is close to -273°C. This is the temperature far from any suns, at a distance from which they look as remote as stars, since then solar heat may be disregarded. This is hardly open to doubt (although on this point, too, the scientists hold conflicting opinions). In fact, it has now been confirmed that the temperature of the planets remote from the Sun is extremely low, even though they receive some solar heat. Were their distance from the Sun still greater, so that it seemed like just another star, this temperature would doubtless fall to absolute zero (-273°C).

In addition, the planets have their own internal heat; they resist cooling, they still have a large reserve of heat and heat sources.

Small bodies, on the other hand -- among which we may classify not only articles of everyday use but also asteroids (if remote from warm or incandescent bodies) -- rapidly reach the absolute freezing point.

Therefore a space rocket far from the Sun, among barely twinkling stars, would apparently be in a critical situation. Its temperature would rapidly descend to -273°.

But, first, it would carry its own heat source and, second, it would be insulated by a series of concentric shells against the loss of heat, so that any loss could be easily offset artificially even over a period of thousands of years.

But I shall not discuss this question further for the present. Let us consider a rocket in space, equidistant from the Sun and the Earth. This in no way prevents it from being in orbit around the Earth at a distance of hundreds of millions of kilometers, from which vantage point the Earth would look like a little star, like Venus.

Our rocket will lose heat only through radiation, since it is surrounded neither by air nor by any other material medium. But it will also receive heat from the Sun and therefore its temperature will fall only to a point at which the efflux of heat (due to radiation) equals the influx (due to sunlight).

This means that these opposing flows must be somehow estimated and, on this basis, the question of a stable, constant temperature resolved.

The influx of heat, of course, depends on the energy of the sunlight. I shall assume this energy to be constant. But none at all may be received by the rocket if its sunward side is covered by several layers of shiny material that reflects all the heat. This means that, regardless of the energy of the sunlight, it need not all be received by the rocket, thanks to the structure and properties of its surface.

Conversely, black surfaces would absorb almost all the incident heat of the Sun.

Thus, the heat influx may vary from zero to a certain maximum, which depends on the energy of the warming sunlight. Were there no loss of heat due to radiation, our rocket would become heated to the temperature of the Sun.

Let us now consider the radiative losses.

Every surface of a body loses heat, but to a varying extent. Further, this loss rapidly increases (as the fourth power) with increase in the absolute temperature of the body. Of course, the loss also increases with the area of surface (of the rocket, for example). All these considerations and calculations lead us to the following conclusion.

A structure, one side of which faces the Sun and has a black, heat-absorbing surface, while the opposite side, which lies in the shadow, is insulated against loss of radiant energy by several shiny surfaces, can have a temperature of at most 150°C.

Consider a practical example. Imagine a closed spherical vessel containing a gas. One-third of its surface, facing the Sun, consists of glass, which transmits radiant energy. This radiant energy falls on the dark inside surface of the sphere, which is a good absorber of sunlight. The other two-thirds of the surface are insulated against loss of heat by one or more layers of shiny material. The temperature of the gas inside the vessel reaches 150°C.

If the shiny surface is turned toward the Sun, the same hollow sphere experiences a drop in internal temperature to nearly -273°C. The temperature range thus exceeds 400°C.

If turned sideways to the Sun, so that only part of the transparent surface is exposed to the sunlight, the same sphere will have a temperature halfway between -273° and +150°.

By rotating the sphere, we can arrive at any temperature in between these two extremes, for example, a temperature corresponding to any climate, altitude above sea level, or season on Earth.

If the rocket is spun sufficiently rapidly, so that its transparent side is turned periodically toward the Sun, a mean (calculated) temperature of about 27°C will be established inside it. This is nearly twice as high as the mean temperature of our spinning planet Earth.

But Earth reflects most of the Sun's heat back into space. After all, 50 % of its surface is always covered with clouds, the shiny surface of which makes a splendid reflector of sunlight. This is why the mean temperature on Earth is approximately 15°C.

In general, the question of the temperature of planets is a conditional and very complex one and I do not intend to go into it here. My notes contain many observations and calculations on this subject, but my published works present only the final results....

It would appear that this satisfactorily settles the question of the temperature of space rockets.

However, it may be that in the future certain space rockets will be designed for temperatures expressed in thousands rather than hundreds of degrees. In this event, the heat losses would have to be still further reduced without reducing the influx of heat from the Sun.

Suppose that we reduce the area of the windows in our spherical vessel and increase the area of the shiny surface; then the heat losses would diminish, but the heat influx would also be reduced. This vicious circle can be broken, however. A very small transparent opening could be left in the sphere, so as to admit any desired amount of solar energy by means of a lens or spherical mirror. This opening should coincide with the focal image of the Sun. In this way, the heat loss could be minimized without any reduction in the influx of solar energy.

What will be the result ? The amount of heat inside the sphere will increase until the efflux per second equals the influx per second. This will certainly happen, since the heat efflux increases with rise in temperature. The temperature inside the sphere may reach 1000°C or more.

Even if our rocket reaches the limits of the solar system, where Saturn and its rings, Uranus, and Neptune spin, it can still receive from the Sun the heat needed to support life.

And, conversely, it is possible to produce a low temperature however fierce the sunlight. This would enable our rocket vehicle to travel in the vicinity of the Sun -- where Mercury circles and swelters in the heat of the solar furnace, and even closer.

THE REACTION AIRPLANE*

1. The reaction airplane differs from the conventional airplane in that it has no propeller.

The action of the propeller is replaced by the thrust (reaction) of the combustion products of ordinary aircraft engines.

But these engines require certain modifications and additions, since they burn a great deal of fuel yet do comparatively little work, e.g., 10 times less than the amount of fuel would permit; similarly, they run at high speeds and therefore have expanded valve openings. Moreover, as the table shows, compression of even the very chilly air found at higher altitudes makes it extremely hot.

The last row of the table shows that even icy (-73°C) air from the upper layers of the atmosphere requires cooling if it is to be compressed 36 times.

To this end we can avail ourselves of the intensive expansion of the combustion products in the rarefied atmosphere and the resulting strong cooling effect. Therefore, the compressed air is first fed into a special jacket surrounding the outlets for the expanding combustion products.** This compressed and cooled air serves to cool the working cylinders, before being burned in them.

2. The airplane acquires increased velocity in the rarefied layers of the atmosphere only if the work done by the engine is proportional to the speed of the airplane.

The following table will serve to clarify this point.

This ability (to do work proportional to the velocity of the machine) is inherent only in the reaction engine, and it is into such an engine that I wish to transform the conventional aircraft engine, my object being to achieve higher flying speeds in the rarefied layers of the atmosphere. There is no other solution. We arrive at this conclusion if we disregard the work done in compressing the air needed for combustion of the fuel.

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*First printed privately by the author in the form of a brochure with the same title ("Reaktivnyy aeroplan"), Kaluga, 1930. See Appendix, note 48 (Editor).

**To reduce the work done in cooling the gases, it is best to cool the air between every two compressor stages by leading suitable pipes to the rear part of the nozzles. Editor's note in "Izbrannyye trudy K. E. Tsiolkovskogo," Moscow, ONTI, 1934.

Compression factor for some constant gas or mixture of gases (air)					
1	6	36	216	1296	6800
Relative absolute temperature					
1	2	4	8	16	32
Absolute temperature					
+273	546	1092	2184	4368	8736
The same, in °C					
0	273	819	1911	4095	8463
Absolute temperature					
+200	400	800	1600	3200	6400
The same, in °C					
-73	+127	+527	1327	2927	6127

Relative density of upper air				
1	1:4	1:9	1:16	1:25
Approximate altitude above sea level, km (at °C)				
0	11.1	17.6	22.1	25.7
Relative translational velocity of airplane				
1	2	3	4	5
Required relative engine power				
1	2	3	4	5

But at higher altitudes the rarefied air must be compressed before it can be used in the engines. The ordinary mechanical work done by the engines will be expended mainly on this task. That is why we cannot eliminate them completely.*

The engine, running at tremendous speed, almost idles and does comparatively little work: it is uneconomical. But we do not need more work, since the work done in compressing cold rarefied atmospheric air is relatively small and the engine power is much more than enough for this. The main function of the engine is to create a reaction effect by ejecting the combustion products; as for a propeller, it would be superfluous.

*But air can also be compressed dynamically, by the jet method, in jet aircraft engines. Editor's note in "Izbrannyye trudy K. E. Tsiolkovskogo," Moscow, ONTI, 1934.

Let me illustrate the magnitude of this work. Since the compressed air is cooled by the rear parts of the reaction pipes, I shall assume that its temperature is constant. In this event, we can use the following formula to determine the work done in compression*

$$L = P_1 \cdot V_1 \cdot \ln\left(\frac{V_1}{V}\right).$$

Here P_1 and V_1 are the initial pressure and volume, while V is the final small volume (after compression). Suppose the air is rarefied 1000 times. Then its pressure will be 1000 times smaller. Our object is to compress this huge volume a thousandfold, so as to reduce it to the original small volume, at the expense of a certain amount of work. This shows that the product P_1V_1 remains constant, however rarefied the layer of air we take. In other words, the work done in compression depends solely on the logarithm of the compression $V_1{:}V$. At 0°C the product P_1V_1 equals 10.3 meter-tons. We now use the resulting formula to compile a table of values of the work required to obtain one cubic meter of compressed air of normal density.

Rarefaction of air or required compression	1	6	36	216	1296	7800
Work needed to obtain one cubic meter of air of normal density (0.00129) at 0°C, in meter-tons (approximately)	0	18	36	54	72	90

*The formulas used here are all taken from the article "Davleniye na ploskost' pri yeye normal'nom dvizheniyu v vozdukhe" (Pressure on a Plane in a Normal Airflow). "K. E. Tsiolkovskiy. Sobrannyye sochineniya," Vol. I. AS USSR Press, 1951 (Editor).

About 11 m^3 of normal air will be needed per unit of weight (kg) of fuel (benzene).* Obtaining this amount of air from a volume of air with a rarefaction of 7800 will require $90 \cdot 11 = 990$ meter-tons. One kilogram of benzene will yield at least 4 horsepower per hour. This amounts to $(75 \cdot 3600 \cdot 4)$ or 1,080,000 kilogrammeters or 1080 meter-tons, which is not much greater than that required for compression.

At lower compressions the work will also be smaller, as the table shows. But if the air is not cooled, the work will be much greater. Here we can use formula (39), namely:

$$L = B \cdot P_1 \cdot V_1 \, [1 - (V_1 : V)]^{1:B}.$$

From (44) we know that: $B = 2.48$ and $1 : B = 0.403$. We put $V_1 : V = 7800$. Then we calculate

$$L = P_1 \cdot V = 34.7 = 358 \text{ meter-tons},$$

i.e., more than three times greater than before (90 meter-tons). It is 4 times greater than the work done by the engines. In practice, an average amount of work, 5 times less than that done by the engines, should be taken. The work computed relates to compression in a vacuum. The pressure of the atmosphere contributes to the compression, and therefore the real work is smaller, particularly in the lower layers of the atmosphere and when the compression required is small.

The airplane does not stay long in the lower layers of the atmosphere, but even then the engine work is useful and goes toward the air cooling of the working cylinders and the compression of air with

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*This amounts to $1080:5 = 216$ meter-tons per kg benzene, or $216:11 = 19.6$ meter-tons per m^3 normal air. This amount of work, roughly speaking, is needed for sixfold compression at constant temperature. Without cooling, on the other hand, the attainable compression ratio is even lower. Editor's note in the 1934 edition.

the object of intensifying the combustion of gasoline and increasing the engine power and the force developed by the exploding gases.

In fact, we can also apply the formulas and tables to the compression of normal air (near sea level), for intensifying the engine power (provided the engine walls are reinforced).

From formulas (14_1) and (39) it can be seen that in this case the work of compression will increase proportionately, since P_1 increases. On the other hand, the work done by the engine increases in the same proportion. And since the safety factor of the working cylinders is always excessively high (so as to avoid very thin walls), it is extremely convenient to compress the air even in the lower layers of the atmosphere.

3. In developing the theory of airplanes of this kind, we have to deal with the compression and expansion of gases, with their ability to produce heat, i.e., their heat of combustion, and also with their rate of ejection, their thrust, the resistance of the air, the compressors and their efficiency, and various other matters.

Therefore, I must again refer to my previous publication "Pressure on a Plane," 1930.

4. In my discussion of fuels, for the sake of being specific, I shall choose three types: hydrogen, carbon, and benzene. To burn them we may employ pure oxygen, ordinary air, or nitrogen pentoxide N_2O_5.

This does not mean that I consider these to be the optimal or most suitable engine fuels; it is merely that other materials have not yet been tested and the possibility of their practical application has not yet been demonstrated.

For example, monatomic hydrogen H, upon forming diatomic hydrogen H_2, releases 16 times as much energy as the same mass of detonating gas ("Kosmicheskaya raketa," 1927, see p. /130).

But I cannot propose a still untested fuel. For example, it is not known whether monatomic hydrogen H can be liquefied and, if so, under what conditions the liquid might explode. The same can be said of the other materials suggested as fuels by various investigators, for example, ozone O_3 and light metals (e.g. aluminum, lithium, calcium, etc.).

Similarly, the idea of ejecting parts of the airplane or converting them into fuel is still impractical.

Below is a table giving the relative weight of the materials taking part in the combustion:

Fuel	Hydrogen	Carbon	Benzene
Formula of fuel	H_2	C	C_6H_6
Relative weight of particle (molecule)	2	12	78
Combustion products	Water	Carbon dioxide	Water and carbon dioxide
Formula of combustion products	H_2O	CO_2	H_2O and CO_2
Relative weight of oxygen O_2 needed for combustion	16	32	240
The same, nitrogen pentoxide N_2O_5	21.6	43.2	324
Relative weight of products of combustion in oxygen	18	44	318
The same, in N_2O_5	23.6	55.2	402
If we take the weight of the fuel as unity	1	1	1
Then the weight of the oxygen will be	8	2.67	3.33

[Table cont'd. on next page]

[Table cont'd.]

Fuel	Hydrogen	Carbon	Benzene
Then the weight of the combustion products in oxygen will be	9	3.67	4.33
Then the weight of N_2O_5 will be	10.8	3.6	4.5
Then the weight of the combustion products in N_2O_5 will be	11.8	4.6	5.5

6. If in our airplane we burn air, the quantitative ratio of its constituents must be specified.

I therefore present the following table:

	Air	Oxygen	Others
Composition of air by weight	100	23.6*	76.4
The same, by volume	100	21.3	78.7

*The handbooks specify somewhat lower figures for oxygen: 23.1% by weight, or 20.9% by volume. Editor's note in the 1934 edition.

Hence we find the following weight ratios for the constituents of air: $N_2:O_2 = 3.24$; $O_2:N_2 = 0.309$; $O_2:air = 0.236$; $air:O_2 = 4.24$,

which means that the oxygen is equal to 0.31 of the nitrogen by weight and accounts for 0.236 of all air by weight.

For the volume ratios we obtain: $N_2:O_2 = 3.69$; $O_2:N_2 = 0.271$; $O_2:air = 0.213$; $air:O_2 = 4.70$.

7. Now we can specify the amount of air by weight and volume per unit weight (kg) of fuel (see table on p. /333).

Fuel Formula	H_2	C	H_6C_6
Amount of fuel by weight	1	1	1
Amount of oxygen required	8	2.67	3.33
Weight of combustion products, combustion in oxygen	9	3.67	4.33
Amount of air required	33.9	11.3	14.13
Weight of combustion products, combustion in air	34.9	12.3	15.13
Amount of air required by volume (density 0.0013), m^3	26.1	8.7	10.9

8. But it is also important for us to know the amount of at-

mospheric oxygen and nitrogen pentoxide required per metric horsepower (100 kg-m). Therefore, I present the following table (pp. /334-335).

		H_2	C	C_6H_6
1.	Fuel formula	H_2	C	C_6H_6
2.	Quantity of heat per unit mass of fuel	34 180	8 080	11 500
3.	Heat ratio	2.97	0.709	1
4.	Amount of fuel required per metric horsepower per hour, kg	0.0842	0.353	0.25*
5.	Oxygen required per horsepower (100 kg-m/sec), per hour	0.674	0.942	0.833
6.	Air required per horsepower per hour, kg	2.498	3.994	3.532
6_1.	N_2O_5 required	0.910	1.272	1.125

[Table cont'd. on next page]

*Taking one metric HP as equal to 100 kg-m/sec, we find that the author assumed the efficiency to be about 30%; we thus obtain for H_2 29.4%, for C 29.6%, and for C_6H_6 30.7%. Editor's note in 1934 edition.

[Table cont'd.]

7. Weight of materials ejected per hour for combustion in oxygen, kg	0.758	1.295	1.083
8. The same, for combustion in air, kg	2.584	4.347	3.782
8_1. The same, when N_2O_5 is used	0.994	1.625	1.375
9. Weight of materials ejected for combustion in oxygen per 1000 HP per hour	758	1295	1083
10. The same, per second	0.21	0.36	0.30
11. The same, for combustion in air, kg	0.72	1.21	1.05
12. The same, when N_2O_5 is used	0.275	0.450	0.380
12_1. One-hour supply of fuel per 1000 HP, kg	84	353	250
13. Rate of ejection per second, for combustion in oxygen ("Raketa v kosmicheskom prostranstve") [The Rocket in Outer Space], 1926, m/sec	5650	4290	4450
14. The same, for combustion in air	2743	2082	2160

[Table cont'd. on next page

[Table cont'd.]

14_1. The same, for combustion in nitrogen pentoxide N_2O_5	4900	3840	3900
15. Acceleration of one-ton rocket per second for combustion in oxygen, m/sec^2	1.19	1.54	1.33
16. The same, for combustion in air	1.97	2.52	2.27
16_1. The same, for combustion in N_2O_5	1.35	1.75	1.48
17. Resulting pressure (thrust) on rocket for combustion in oxygen, kg	119	154	133
18. The same, for combustion in air	197	252	227
18_1. The same, for combustion in N_2O_5	135	175	148
19. Velocity of rocket 1 hr after start of flight, in a vacuum, for combustion in oxygen, m/sec	4284	5544	4788
20. The same, when air is used (see 15, 16 and 12)	4092	9072	8172

[Table cont'd. on next page]

[Table cont'd.]

21. Number of seconds needed to attain a velocity of 8000 m/sec, when oxygen is used	6720	5200	6010
22. The same, in hours	1.87	1.44	1.67
23. Corresponding amount of fuel in kg (see 12)	154	508	418
24. Number of seconds needed to attain a velocity of 8000 m/sec when air is used (see 18)	4061	3175	3524
25. The same, in hours	1.13	0.88	0.98
26. Corresponding amount of fuel	94.9	310.6	245.0
27. Volume of air needed per 1000 HP per hr, m^3. Air density 0.0013	1921	3079	2717
28. The same, per second	0.53	0.35	0.75

9. We may draw certain clarifying conclusions from this table. If atmospheric oxygen is used, it is very advantageous to carry a supply of hydrogen. The weight of this fuel, in terms of a given amount of work required, will be three times less than that of benzene (rows 3 and 12_1). It is only a pity that liquid hydrogen is still scarcely available. Liquefied marsh gas, or methane CH_4, is also

suitable. Should the machine carry a supply of liquid oxygen, however, the difference in the fuel load is not so great (row 7). Here replacing benzene with hydrogen will bring no great advantage. More or less the same thing applies when N_2O_5 is used. If the total weight of the equipped and fueled airplane is 1 ton, even a one-hour supply of fuel would not appear excessive (12_1). For hydrogen, in fact, it is quite small.

Rows 13 and 14 specify the rate of ejection per second under the most favorable conditions: complete combustion, no heat loss, long cone-shaped exhaust pipes, and expansion of the combustion products in a vacuum. When air is used, naturally, the mass of the explosion products will be 4 times greater (rows 7 and 8) than when pure hydrogen is used. Therefore the rate of ejection will be half as high. On the other hand, the plane will then be relieved of the burden of having to carry a supply of oxygen. However, oxygen will have to be carried for flights in a vacuum or in the more rarefied layers of the atmosphere. A supply of N_2O_5 affords only a slight advantage compared with a supply of oxygen.

Rows 15 and 16 specify the acceleration of a rocket with a mass of one tone, disregarding the air resistance. It follows that using air is more expedient, as this gives greater acceleration, not to mention the avoidance of the need to carry burdensome liquid oxygen. I obtained these figures by determining the factor by which the weight of the rocket (1000 kg) is greater than the mass ejected per second. I then divided the rate of ejection per second by the result. (According to well-known laws, when a force acts between two masses, the velocity imparted to the larger mass is inversely proportional to the amount by which this mass is greater than the smaller mass.) Naturally, as the combustion of the fuel progresses, the acceleration must increase. I have given the lowest figure.

Rows 17 and 18 express the reaction or thrust, in kg.

Rows 19 and 20 give the velocity of the rocket after the elapse of one hour, without taking into account the drag. This reaches the escape velocity when air is used.

But is a 1000 HP engine possible, considering that the total weight of the machine is 1000 kg? Benzene fuel alone accounts for 250 kg (row 12_1). In view of the current state of the art, a 1000 HP engine would weigh at least 500 kg. But the point is that our engine need be only 100-200 HP (see Section 2), provided that it burns as much fuel as a 1000 HP engine. Here the main thing is not work, but combustion and reaction. Such an engine could weigh much less, e.g., 100 or 200 kg. Then plenty of weight would be left for other equipment.

Row 23 gives the supply of fuel alone required to attain a velocity of 8 km/sec (in a vacuum) when oxygen is used. The supply of fuel is considerable, and when oxygen is also carried, it is too much for a one-ton rocket. But if air is used instead of oxygen, the required supply of fuel becomes practical.

But can an ordinary airplane weighing 1000 kg take off, in view of the magnitude of the thrust required (rows 17 and 18)? Assuming a conventional 100-HP airplane weighing one ton and having a speed of 40 m/sec, we find its thrust to be 125 kg. We assume the propeller efficiency to be 0.67. When oxygen is used, this thrust for the reaction airplane is close to 125 kg (17), so that in this case, too, the airplane will take off and fly without a propeller (at a speed of 40 m/sec). But if air is used (18) the thrust is nearly twice as great. According to my theory* ("Aeroplan," 1894 and 1929), an airplane with 125 kg of thrust can fly twice as fast at an altitude of 12 km, where the air is one-fourth as dense.

10. Let us assume that the motion of the airplane is uniform and horizontal. We shall disregard the work done in climbing to a high altitude and in achieving a constant rate of motion. This may be disregarded only at speeds of not more than 500 m/sec at altitudes of not more than 30 km.

Under these conditions the natural condensation of air in the forward pipe is far from sufficient and thus we can no longer avoid using a compressor of one type or another.

11. Let us assume that we have attained a speed of 100 m/sec at sea level, using our reaction engine. At an altitude of approximately 12 km, where the air is four times less dense, the speed of the airplane, using the same engine, will be twice as great. How is this possible? After all, the engine is the same. The point is that the reaction engine generates power proportional to the rate of motion of the machine. Actually, the thrust or reaction does not change, whatever the speed. For example, if the reaction is 250 kg, what can reduce it when the speed of the airplane rises or falls? And if this is so, the work done per second will be proportional to the speed of the airplane. If the speed is quintupled, then, for the same thrust, the

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*The reference is to the author's "Aeroplan ili ptitsepodobnaya (aviatsionnaya) letatel'naya mashina" (The Airplane or Bird-Like Flying Machine), 1894. "K. E. Tsiolkovskiy. Sobrannyye sochineniya," Vol. I, Moscow, AS USSR Press, 1951 (Editor).

work will also be quintupled. At zero speed the engine power will also be zero, despite the tremendous thrust. I mean, of course, the useful work: the higher the speed the higher the utilization of the energy of combustion.

12. The work required to traverse unit distance at different altitudes remains constant (see "The New Airplane")*. It is independent of the speed of the machine at different altitudes. This means that the power or the work done per unit of time is proportional to the speed of the airplane. But this is true only for conventional propeller-driven airplanes. For a reaction engine the power (or more exactly, the fuel consumption) is one and the same. Therefore, the fuel consumption per unit of distance is the lower the greater the speed.

13. Let us take an example. We found that an airplane weighing one ton should burn at least as much fuel as is needed for 1000 metric HP. At sea level it will have a speed of 100 m/sec. It will then burn five times as much fuel as is needed by a conventional propeller-driven aircraft.

Thus, our reaction engine will burn five times as much fuel as a conventional engine. But, on the other hand, it flies twice as fast where the air is one-fourth the normal density. At such altitudes it will thus be only 2.5 times more costly to operate. At still higher altitudes, where the air is 25 times more rarefied, it will fly five times faster and utilize energy as efficiently as the propeller-driven airplane. At an altitude where the air is 100 times more rarefied, the speed of the reaction airplane will be 10 times greater and it will be twice as efficient as the conventional propeller-driven type.

At very high speeds the phenomenon becomes so much more complicated that our conclusions are no longer completely reliable (since we have made no allowance for the atmospheric origin of the oxygen used in combustion; see "Soprotivleniye vozdukha i skoroy poyezd" (Air Resistance and the Express Train), 1927).

14. What then is our objective, what are we pursuing, if the savings in work are not particularly impressive? The point is that we achieve a speed that is not attainable for a propeller-driven airplane.

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*"K. E. Tsiolkovskiy. Sobrannyye sochineniya." Vol. I, Moscow, AS USSR Press, 1951 (Editor).

At high speeds we inevitably attain higher altitudes. Moreover, we develop an appreciable centrifugal force which reduces the work and raises us higher in proportion to the increase in speed. At a speed of approximately 8 km/sec the work shrinks to zero, and we emerge above the top of the atmosphere.

15. The high speed of the machine also has applications to terrestrial transport, even if no fuel savings are achieved.

We have seen that, under the conditions considered, flight cannot continue for more than one hour. Below are the distances which can be traversed at different altitudes and different flying speeds:

Relative density of rarefied layers of atmosphere					
1	1 : 4	1 : 9	1 : 16	1 : 25	1 : 100
Approximate altitude, km					
0	11.1	17.6	22.1	25.7	36.8
Speed, m/sec					
100	200	300	400	500	1000
Speed, km/hr					
360	720	1080	1440	1800	3600

The last row also shows the distance that can be covered in one hour. Clearly, it is inadequate for practical purposes. But, first, the altitude and speed can be made still greater and, second, the weight and energy of the fuel carried can be still further increased. Then one flight would suffice to cross oceans.

16. I have hardly touched on the calculations relating to the accelerating ascent of the machine and the achievement of the cosmic velocities needed to free it from the resistance of the atmosphere. I have discussed only terrestrial transport, merely hinting at space travel. The era of propeller aircraft must be followed by an era of reaction or stratospheric flight.

TO THE ASTRONAUTS*

(1930)

People with a practical bent are striving to utilize the reaction principle in building: 1) powerful reaction engines for high-speed motion; 2) automobiles; 3) hydroplanes, and 4) sleds.

I shall examine all these.

An explosion engine, like a water turbine, cannot insure a high utilization of the explosion energy, since the peripheral speed of the bladed wheel (turbine) can not exceed 200-400 m/sec. Now, favorable utilization requires a blade speed 1.4 times less than the velocity of the explosion products, and this velocity may reach 5000 m/sec. Therefore, the blade speed would have to be approximately 3500 m/sec, which is unattainable even with the sturdiest materials at present available.

If, however, we rest content with a blade speed of 100 m/sec, we utilize only 3% of the available chemical energy. This is uneconomical.

A complex turbine wheel is needed and, in general, the methods employed in building modern steam turbines. Then the percentage energy utilization may be very high.

But there is still another condition. The explosion products must be released into a vacuum, otherwise they will lack sufficient velocity. This alone is enough to show that the engines concerned could not be very light. Moreover, we would encounter various other practical difficulties, which this is not the place to discuss. There can be no doubt, however, that such engines have a great future.

As for automobiles, the rocket method (or any other method for that matter) cannot give them high speeds in view of the considerable air resistance in the lower layers of the atmosphere. Moreover, their wheels, even if without inner tubes, would burst under the centrifugal force, if the (rim) speed exceeded 200-400 m. To attain a speed greater than 100 m, wheels must be dispensed with and a special track built (cf. my "Skoryy poyezd" (Express Train); moreover, the body shape must be improved and elongated. But even then we would not

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*First printed in 1930 in Kaluga in the form of a 32-page brochure. Private edition. See "Appendix," note 37 (Editor).

attain speeds exceeding 1000 m/sec. Nonetheless, the expenditure of energy in overcoming the air resistance would be staggering.

Compressed gases (for example, carbon dioxide CO_2) cannot conveniently be used for this purpose, since their internal energy of motion (kinetic energy) is negligible. Moreover, they require vessels ten times their own weight. Liquefied, cold, freely evaporating gases do not require strong, massive vessels, but their kinetic energies are smaller than those of compressed gases. In releasing this energy, they borrow heat from surrounding bodies and the air, which cannot be done as quickly as required.

Ready-made explosives (gunpowder, dynamite, etc.) are also unsuitable. In addition to the danger of accidental detonation, they require heavy cannon or containers, since an explosion at one point transmits the resulting pressure to the entire mass. The inevitability of accidental explosions was recently confirmed by the tragic death of Vallier.

As for hydroplanes and sleds, the same thing applies. But they lack wheels, and that is an advantage. On the other hand, in their case the air resistance is compounded by the resistance and friction of water or snow. I am, of course, referring to reaction-propelled (rocket) automobiles and hydroplanes -- those with other types of drive are doomed to lower speeds owing to their propellers or wheels.

So far, two principal approaches to astronautics have been considered: 1) gradual transition from the aeroplane to the astroplane; and 2) the pure reaction machine (rocket).

At first, the aeroplane climbs to a low altitude in the atmosphere and flies horizontally for a short distance. Then it resumes its climb and covers an increasing distance until, finally, it emerges above the atmosphere and "coasts" along (by inertia) as a heavenly body.

From there on the converted aeroplane, like the rocket, can continue to travel by utilizing the pressure of sunlight.

I have checked my calculation repeatedly and they are absolutely reliable.

Thus, I have shown * that in the course of a year one kilogram of matter with a surface area of 1 m^2 would receive from sunlight a velocity increment exceeding 200 m/sec.

In the absence of gravity it is easy to construct vast surfaces of negligible weight. For example, a surface 0.01 mm thick with the

*Cf. "Issledovaniye mirovykh prostranstv reaktivnymi priborami."

density of water and measuring 100 m^2 in area weighs only one kilogram. Spinning this square (each side 10 m long) would give it a certain tension, smoothness, and strength. The pressure of sunlight would give it a velocity of 20 km/sec in the course of a year. This is more than enough to wander throughout the solar system and even escape it completely (i.e., travel through the Milky Way). Thus, a vehicle launched from Earth with a velocity of 30 km would reach a velocity of 50 km. The velocity required to escape the gravitational pull of the Sun is 42 (30 × 1.4) km. Thus, a surplus velocity of 8 km would remain (for wandering through the Milky Way).

Let us assume for the vehicle one ton of matter, and for the surface as much again. Then in 2 years the vehicle will acquire the same velocity gain, i.e., 20 km/sec.

It would be wonderful if the pressure of sunlight could be thus utilized; this would insure the exploration of the universe, since the required velocity could thus be obtained if not in 2, then at least in several years.

Let us first consider the conversion of the aeroplane to the astroplane and then discuss the rocket.

In earlier publications ("Aeroplan," 1895, and "Novyy aeroplan," 1929*), I proved that an aeroplane can fly twice as fast in a medium with one-fourth the normal density (at an altitude of 10 km) by merely doubling the work done by the engine for a given weight. In general, the speed of an aeroplane increases by (n) times if the medium is rarefied by (n^2) times, provided the engine power is (n) times greater.

On the one hand, the power of a conventional engine not only can not be increased but actually decreases precipitously in a rarefied medium. This means that an air compressor is needed, and hence an extra expenditure of energy as well as increased weight. Moreover, when operating at full power, this compressor will overheat dangerously, therefore a cooling system will also be needed.

On the other hand, if the propeller speed is too great, the propeller will burst into small fragments owing to centrifugal force.

For the present, our aim will be limited to merely doubling the speed of the aeroplane. Doubling the engine power means doubling the engine speed. Then the valve ports must be widened and a fuel that mixes rapidly with air must be used. This fuel could be high-grade gasoline or liquid hydrogen, or some other combustible gas.

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*"K. E. Tsiolkovskiy. Sobrannyye sochineniya," Vol. I, Moscow, AS USSR Press, 1951 (Editor).

The tangent of the inclination of the propeller blades to the propeller plane should also be doubled, approximately from 0.3 to 0.6. The corresponding angles will be 17 and 31°. These angles do not detract seriously from the operating economy. As a result, the speed pf the aeroplane can be increased 100% with no change in r.p.m. But the r.p.m. of the engine has already been doubled. What is to be done? A reduction gear (0.5) should be employed, or the propeller diameter could be halved. The former solution (chain transmission) is more economical.

In addition, the rarefied air must be compressed fourfold. Then its absolute temperature increases by a factor of 1.75.* If the temperature is -43° or 230° absolute, at an altitude of 10 km, it will rise on compression to 403°, i.e., the air will be heated to (403-273) = 130°C. This is tolerable and the air need not be cooled. But a compressor is still necessary.

This is not all. The combustion products rush out of the engine very vigorously. We shall not use silencers, since we shall utilize the reaction. The greater the speed of the aeroplane, the more advantageous this is. Likewise, the more rarefied the medium, the less the restraint on the expansion of the combustion products and the greater their exhaust velocity, and hence the reaction.

It is understandable why the combustion products should be expelled through special conical pipes, parallel with the longitudinal axis of the aeroplane, their flaring mouths facing backwards, toward the tail of the vehicle.

It is also possible to triple the speed of the aeroplane at an altitude where the air is rarefied by a factor of 9. The angle of inclination of the propeller with respect to its plane of rotation must then be changed from 17° to 42°, which is still permissible. The reduction ratio will be 3:1 (or the propeller diameter will be reduced to one-third), which will cut by two-thirds the speed of the propeller, i.e., restore its previous speed. (We must not forget the tripled speed of the engine shaft and the unavoidable widening of valve ports.) The absolute temperature will increase by a factor of 2.4. This means that from -73° or 200° absolute the temperature will rise to 480° or (480-273) = 207°C. This is still tolerable without cooling.

But even these doubled and tripled speeds are still far from escape velocities. How are these to be attained? The blade angle

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*Cf. K. E. Tsiolkovskiy's "Pressure on a Plane in a Normal Airflow," Vol. I, p. /233 (Editor).

cannot be increased further. The temperature rise will necessitate cooling -- but how? At high altitudes it is very cold, but not cold enough, since the air is too rarefied and the temperature is still not less than -70°C.

Thus, any further increase in speed is blocked by: 1) the propeller; 2) the need for compression; 3) the resulting intense heating; and 4) the need for cooling. The propeller could be replaced by flapping wings like those of a bird. This is very advantageous, since it increases the lift, but it is complicated from the structural (design) standpoint.

The simplest solution is to discard the propeller. This is feasible if the aeroplane is flying at high speed in rarefied air, since the thrust produced by the combustion products is the more intense, the greater their exhaust velocity and the more rarefied the medium. A rarefied medium permits the gases to expand more vigorously, whereby they attain a high exhaust velocity and a lower temperature, which ultimately (in a vacuum) falls to -273°.

It is this that will serve as a means of cooling the heat generated by the compressor. Thus, the hot compressed air is made to flow around the outlets for the combustion products, which are extremely cold owing to expansion. Then this compressed, but cool air is channeled to the working cylinders of the engine.

Here we kill three birds with one stone: in the exhaust pipes we heat the combustion products cooled by expansion and thereby increase their flow velocity and the corresponding reaction; at the same time, we cool the intensely hot (owing to compression) air destined for the working cylinders; and, lastly, we obtain a magnified thrust, since a propellerless engine can run at higher speeds. As for the mechanical work done by the engine, it will be small, going mainly toward compressing the air.

The extent to which the speed of the aeroplane can be increased by these means is unknown. Whether the escape velocity can be attained and the confines of the atmosphere left behind is a question which we cannot yet answer (certainly not affirmatively). At any rate, the development of high-altitude aeroplanes will teach us a great deal and make the astroplane more feasible. I long ago prepared detailed calculations of the thrust that can be produced by an aeroplane using this device.

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Let us now pass to the pure rocket machine. Here, too, an engine is indispensable, since we have to thrust or pump the explosion elements into the mixing-and-combustion chamber. The rocket has no propellers, since it rapidly attains velocities which a propeller could not withstand. But there is no reason why we should not utilize the reaction of the combustion products, as described above.

This means using the same device as I described in my "Kosmicheskaya raketa" (Space Rocket), 1927.

But once the vehicle reaches an extremely rarefied layer of the atmosphere, it will no longer be possible to supply air to the engines. How then can they be supplied with oxygen? The answer is that the rocket would carry its own supply of oxygen on board, and start feeding it to the engine once the extremely rarefied layers were reached.

I shall now point out the design requirements which a rocket must meet. In general, these are disregarded by the experimenters (the heroic Vallier paid for this with his life).

1. Ready-made explosives are unsuitable. This applies to all kinds of gunpowder, nitroglycerine, lyddite, dynamite, etc.

2. The explosion elements (for example, oxygen and hydrogen) should not be mixed before they enter into combination in the explosion tubes.

3. They should be kept in separate containers or compartments.

4. They should be liquid at room temperature, e.g., in the form of gasoline and nitrogen pentoxide.

5. They should be as compact as possible, so as to occupy minimum space.

6. Their vapors must not exert any considerable pressure on the container walls, so that massive walls will not be required.

7. They should not have a low temperature, like liquid, freely evaporating gases, so as to contain more energy.

8. The pumps should be of the piston type and the liquids should be pumped cold.

9. These liquids should not have a chemical action on the walls of the pumps, the pipes leading to the explosion chamber, or the explosion tubes themselves. Therefore, these parts must be made of or lined with a suitable material.

10. In the explosion chamber the explosion elements should be mixed as thoroughly and rapidly as possible, so as to give an in-

stantaneous explosion similar to that of gunpowder or a firearm.

11. The explosion chamber should be cooled with cold extracted from the expanding explosion products, the temperature of which at the outlet should reach -273°. To this end, the explosion chamber and its continuation, i.e., the tubes through which the combustion products are expelled, should be encased in a jacket within which a thin layer of a light fluid (e.g., oil, gas, etc.) is circulated. This layer will transfer the heat from the explosion chamber and from the intensely heated sections of the expulsion tubes to the cold sections of these tubes. The benefits will be twofold, as I already explained. The pipes themselves could also serve the same purpose, if they are good heat conductors.

12. The explosion must be rapid, as must the rise in pressure in the chambers and tubes. Thus, we have an instantaneous explosion, a pressure of several hundred atmospheres, and the release of the tubes and chambers from this pressure. Thereupon the pumps deliver another charge of explosives. A second explosion occurs, leading to the development of more thrust and the expulsion of the exhaust gases.

13. This intermittent pumping must go at a very fast rate, say, 30 or 50 cycles per second. We will thus get the same number of explosions per second.

14. The mechanical work of pumping will be small, since it coincides with minimum pressure in the explosion chamber.

15. The tubes leading from the chamber, through which the explosion products are ejected, must be conical in shape and flared at the outlet (like a trumpet, horn, an ear trumpet, etc.). This reduces the required length and intensifies the reaction.

16. There should be several such tubes, and the explosions in them should not be simultaneous, but should occur at equal intervals. Thirty to 50 explosions per second in a single tube merge into one; in ten tubes, for example, we would have 300 to 500 explosions per second, which is even more like a continuous explosion. In this way we can protect the vehicle against destructive vibrations. A large number of explosion tubes and chambers is also expedient from the standpoint of savings in materials. Gunners know that the weight of a cannon increases at a much faster rate than the pressure, given the same barrel volume.

Oberth's experiments were most instructive, but they did not satisfy most of these requirements. As for the other astronauts, there is nothing to be said. That is why the results thus far have been so lamentable. Such is the fate of all great undertakings. Nevertheless, they are precious, and no one should be discouraged.

At first, the early attempts to fly, to utilize steam and electricity, and many other inventions also seemed foolhardy and vain to [common] mortals and even to the inventory. But profiting from the lessons of history, we should be courageous and shrug off our failures, determine the causes and then eliminate them.

ASCENDING ACCELERATION OF A ROCKET PLANE*

(1930)

1. This aeroplane resembles an ordinary one, but it has small wings and no external airscrew; instead, there is a special propeller. The aircraft has a very powerful engine, whose combustion products are vented via conical tubes to the rear of the propeller. This gives recoil (repulsion, reaction), and the force from this increases the accelerated rising motion.

2. The speed can rise only to a low value in horizontal motion in air; but the motion is upward, and the air becomes ever less dense, so the resistance falls. The accelerated motion therefore continues while the engine is working.

3. By the time the fuel is exhausted or the engine stops working, the vehicle may reach a height or an atmospheric density such that the speed will enable it to escape from the atmosphere and move solely by inertia in outer space.

4. Then, in accordance with the magnitude and direction of the velocity, it may: a) eventually return to the atmosphere, whose resistance deprives it of its speed, so it descends to earth; b) move for ever in outer space around the Earth as does the Moon or a comet; c) recede from the Earth and move around the Sun, as does a planet; or d) escape entirely from the Sun and travel among the stars (other suns).

5. All of these results can be attained as may be desired if the operation of the engine is sustained by stored oxygen, using the recoil of the combustion products.

6. The principal parts of this stratoplane are as follows: a) a body in the form of two tapered fuselages, which carry the crew,

*Printed from a copy of Tsiolkovskiy's manuscript found in his archive (File 555, mss 1) and bearing corrections and additions in his hand. See Appendix, Paragraph 49 (Editor).

machines, fuel tanks, and so on; b) between the two fuselages and parallel to them, a tube bearing a special propeller; c) small fixed thin flat wings, whose principal purpose is to provide correct flight; d) a suspended rudder (at the rear above the body); e) at the rear, at the sides, two horizontal rudder fins to provide lateral stability, which act together to serve also as height controls; f) a somewhat modified aviation engine, with conical tubes for venting combustion products at the rear, which lies in the propeller tube in a medium at atmospheric pressure; g) an air compressor to supply the motor (it is essential to compress the air at great heights), which is driven in part by the oncoming air and in part by the engine; h) a cooler for the compressed air that is to supply the cylinders; i) a section for the fuel (benzine); and j) absorbers for sweat, carbon dioxide, ammonia, and other human wastes.

The engine lies at the middle of the propeller tube, and the combustion products are vented there via exhaust pipes, where they expand and are cooled, although at height this rarefaction extends both to the propeller tube and after escape from the exhaust pipes. The temperature of the combustion products in a highly rarefied atmosphere may attain 270° of frost, so the propeller tube will contain a cold medium that cools the engine; this is further aided by the rapid motion of the air flow in the tube. The propeller also contains thin pipes to extract pure air from near the screw. The air is cooled, enters the compressor, and then supplies the cylinders. The atmosphere becomes more rarefied the greater the height of the stratoplane, so the compression and heating of the air supplying the motor becomes greater; but the expansion of the combustion products is then also greater, and the initial temperature of the air to be compressed is less.

7. Body. The vehicle is designed to reach heights where a man cannot breathe and would die, so the body (fuselage) must be carefully sealed on all sides to allow not the slightest escape of gas. The pressure inside will remain unchanged; but this is much greater than the external pressure of the rarefied atmosphere at height, so internal excess pressure (distension) is inevitable in such an aeroplane. The same could occur at sea level; it would only be necessary to pump a little air into the body or to release from a store a flow of oxygen within.

8. Excess internal pressure gives rigidity even to a thin shell on the vehicle, as well as a fixed shape and resistance to bending and other deformations.

All the same, the vehicle must have some rigidity without this excess pressure, before air of oxygen is pumped in. It would be useful here to give it a ribbed form in cross-sections with the ribs running along the length. The ribs stretch in response to the excess pressure, but then the (distended) vehicle is reasonably rigid as a result of the distension. All parts of the surface where there are windows and entrances, and certain other parts, must remain smooth.

9. It would be appropriate to make the vehicle of large size, but a start should be made with the smallest possible dimensions. The diameter of each fuselage cannot be less than 2 m; in any other case, this would impede movement within the closed space. The aspect ratio would best be large, but at first only a moderate value (e.g., 10) would do, in which case the length of a fuselage would be 20 m. (At first we might even restrict the height of the vehicle to 1 m, which for the sitting position on cushions is more than sufficient; the length could be 5 m.)

10. The volume W is given by

$$W = 0.5 l \frac{\pi d^2}{4},$$

in which d is the largest diameter and l is the length of the fuselage. Now $l = \lambda d$, in which λ is the elongation (aspect ratio) or ratio of length to diameter; so

$$W = \frac{\pi}{2} d^3 \lambda.$$

11. We put $d = 2$ m, $\lambda = 10$; then $W = 31.4\ m^3$. For two such fuselages we would have 62.8.

12. The surface area F is put as

$$F = 0.75 l \pi d = 0.75 \pi \lambda d^2.$$

13. With $d = 2$ m and $\lambda = 10$, we have $F = 94.2\ m^2$, or 188.4 for two fuselages.

14. The excess pressure will be quite sufficient at 0.5 atmosphere; it can be that low down. It would rise during the ascent, but then part of the air may be let out, to be replaced by pure oxygen, which would give a sufficient supply even for the sick or weak. However, it would be necessary to raise the pressure again during descent, otherwise the shell would collapse under atmospheric pressure.

The thickness of the shell must be considered. The stress will be largest in the middle (wide) parts of the cross-section if the thickness is constant, and the tension around the circle will be greater than that along the length. On this basis we put

$$\delta = \frac{npd}{2k_z},$$

in which p is the excess pressure per unit area, δ is thickness, and k_z is the resistance coefficient of the material, n being the strength coefficient or safety factor.

15. The equation shows that the thickness increases with the diameter, with the safety factor, and with the excess pressure, and also if the resistance decreases.

16. With $p = 0.5$ kg/cm^2, $n = 16$, and $k_z = 10^4$ kg/cm^2 we have $\delta = 0.5$ mm; $n = 20$ implies $\delta = 1$ mm. This is a perfectly practical thickness for a shell of chrome steel; it will retain its shape well in corrugated form without an excess pressure.

17. A square meter of this will weigh about 8 kg, making the total weight of one fuselage 752 kg, or 1504 kg for two.

18. The volume of the body may be distributed as follows. One third will be taken up by the fuel, the same by machines, absorbers for human wastes, and other essentials, leaving one third for people. Each part has a volume of about 20 m^3. This is sufficient space for two or three* travelers if the air is carefully purified.

*Two or three has been altered in the author's hand to 10 in the manuscript (Editor).

19. The volume actually taken up by fuel and machines will not exceed 30 m^3; the remaining 30 m^3 is filled by gaseous oxygen, whose weight will be about 19.5 kg for twofold rarefaction. This is sufficient for the respiration of one man for 10 days, or one day for 10. However, the whole journey may be over in an hour. The shell could be pressurized with air, and this would be quite sufficient, although the useful time would be reduced by a factor 5 (2 days for one man, 5 hr for ten, provided that no air is released at height and waste products are absorbed).

20. The fuel takes up 20 m^3. Even if its density is 0.5 we may take its weight as 10 tons.

21. The engine and its associated plant must be considered; but here we need a special engine, which should burn as much fuel as possible and produce appropriate power. We do not need a large amount of work; most of it goes to compress the air for the cylinders. We need a large amount of exhaust gas or combustion products to increase the thrust of the propeller.

22. How can we increase the fuel consumption? Here we can: a) increase the shaft speed (which involves a loss of fuel economy); b) precompress the air supply to the cylinders.

23. Increased shaft speed would require larger valves and is usually accompanied by uneconomic operation of the engine and far from justified fuel consumption; but here we do not need economy. For instance, 10 times as much fuel could be burned with only an increase in work done of 2 times. This would be sufficient to compress the air for the cylinders. The use of hydrogen instead of benzine facilitates raising the speed; this is also three times lighter than benzine for a given energy.

24. Compression of air, even at sea level, increases the work to be done by the engine and the amount of fuel burned per second, even if the speed is not increased.

The work of compression is not large, as we shall see. The compressor, the increased wall thickness of the cylinders, and the sizes of the other parts will increase the weight but not the volume. The amount of fuel burned is to be increased by a factor 4 (i.e., the amount of fuel could give 40 000 horsepower but gives only 10 000), so the economy is reduced by a factor 4.

25. We can now say roughly how much the vehicle will weigh: body, rudders, and wings (small) 2 tons, propeller with its fuselage

1 ton, fuel 10, motor and machines 10, crew and other trifles 1; total 24 tons.

26. The initial reaction, or thrust, setting the vehicle in motion is 8-10 tons, which is sufficient (see 'Reactive aeroplane') to provide ascending accelerated motion of the aeroplane. The acceleration will be 3.8, but the propeller may further increase this acceleration.

27. The following is based on my papers of 1930: "Pressure on a plane" and "Reactive aeroplane"; also on those of 1895 and 1929: "Aeroplane" and "New aeroplane."

28. Compression of the gas can occur without loss of heat and with absorption from outside; the gas is then the more heated the more it is compressed. The elasticity rises rapidly, so the work of compression increases very rapidly. The degree of heating is not dependent on the rarefaction, on the density of the gas, or on the nature of this (if it is constant).

Table 1* relates to this case.

TABLE 1

Ratio of volumes (compression)									
1	2	3	4	5	6	7	8	9	10
Ratio of absolute temperatures									
1	1.322	1.557	1.748	1.913	2.058	2.190	2.311	2.421	2.529
Centigrade temperature									
0	87.9	152.1	204.2	249.2	288.8	324.9	357.9	387.9	417.4

[Table 1 cont'd. on next page]

*The table corresponds to adiabatic compression (K = 1.4) (Editor).

[Table 1 cont'd.]

Ratio of absolute temperatures									
19.05	21.40	25.19	28.29	30.95	33.30	35.44	37.40	39.22	40.93
Centigrade temperature									
4928	5569	6604	7450	8176	8818	9402	9937	10434	10901

The temperatures relate to the compression of gas at zero temperature. The compression of air at the low temperatures at height causes heating less than in proportion to the initial temperature.

The table shows that compression by a factor 4 raises the temperature to only 204°C; but the air is a thousand times less dense at height, so it must be compressed a thousand times more, which causes a tremendous rise. For instance, compression by a factor 10 000 produces a temperature of 10 901°C, which is hotter than the surface of the Sun.

30. The problem would be insoluble if there were no source of cooling in the vehicle; but the combustion products provide this, for they expand, especially in the rarefied atmosphere, and so acquire a very low temperature, which serves to cool the compressed air.

31. Table 2 illustrates the work to be done by the compressor without this cooling. The work is not very large for small compression ratios; it is greater in a vacuum than in a medium of equal pressure, because the external atmosphere aids the compression in the latter case. This is especially so for low compression ratios. For instance, the work needed to reduce the volume of 1 m^3 of air to half under normal conditions is almost 8 ton-meters in the absence of external pressure, or only 3 t-m at atmospheric pressure (i.e., less by almost a factor 3).

[Table 1 cont'd.]

Ratio of volumes (compression)									
15	20	30	40	50	60	70	80	90	100
Ratio of absolute temperatures									
2.978	3.344	3.937	4.422	4.837	5.206	5.540	5.847	6.130	6.397
Centigrade temperature									
540.0	639.9	801.8	934.2	1047.5	1148.2	1239.4	1323.2	1400.5	1463.4
Ratio of volumes (compression)									
150	200	300	400	500	600	700	800	900	1000
Ratio of absolute temperatures									
7.532	8.459	9.959	11.18	12.24	13.17	14.01	14.79	15.51	16.18
Centigrade temperature									
1783	2036	2444	2779	3068	3322	3552	3765	3961	4144
Ratio of volumes (compression)									
1500	2000	3000	4000	5000	6000	7000	8000	9000	10 000

[Table 1 cont'd. on next page]

TABLE 2

Compression									
1	2	3	4	5	6	7	8	9	10
Work in ton-meters to compress 1 m^3 of air in a vacuum									
0	7.14	11.34	14.25	16.62	18.51	20.11	21.48	22.69	23.79
Work at atmospheric pressure									
0	2.0	4.8	6.5	8.4	10.0	11.3	12.5	13.5	14.5
Compression									
11	12	13	14	15	16	17	18	19	20
Work in ton-meters to compress 1 m^3 of air in a vacuum									
24.70	25.60	26.42	27.18	27.89	28.56	29.18	29.77	30.32	30.86
Work at atmospheric pressure									
15.60	16.43	17.19	17.89	18.56	19.19	19.77	20.33	20.85	21.36
Compression									
22	24	26	28	30	32	34	36	38	40

[Table 2 cont'd. on next page]

[Table 2 cont'd.]

Work in ton-meters to compress 1 m^3 of air in a vacuum									
30.91	31.78	32.58	33.32	32.01	34.66	35.26	35.84	36.38	37.89
Work at atmospheric pressure									
20.91	21.78	22.56	23.32	24.01	24.66	25.26	25.84	26.38	26.89
Compression									
45	50	55	60	65	70	75	80	85	90
Work in ton-meters to compress 1 m^3 of air in a vacuum									
38.07	39.12	40.07	40.94	41.74	42.49	43.18	43.82	44.43	45.00
Work at atmospheric pressure									
28.07	29.12	30.07	30.94	31.74	32.49	33.18	33.82	34.43	35.00
Compression									
100	120	140	160	180	200	220	240	260	280
Work in ton-meters to compress 1 m^3 of air in a vacuum									
46.05	47.88	49.42	50.75	51.93	52.98	53.94	54.81	55.61	56.35

[Table 2 cont'd. on next page]

[Table 2 cont'd.]

Work at atmospheric pressure

36.05	37.88	39.42	40.75	41.93	42.98	43.94	44.81	45.61	46.35

Compression

300	400	500	600	700	800	900	1000	1500	2000

Work in ton-meters to compress 1 m^3 of air in a vacuum

57.04	59.92	62.15	63.97	65.61	66.85	68.02	69.08	73.13	76.01

Work at atmospheric pressure

47.04	49.92	52.15	53.97	55.51	56.85	58.02	59.08	63.13	66.01

Compression

3000	5000	10 000	50 000	100 000	500 000	1 000 000	5 000 000	10.10^6	10^9

Work in ton-meters to compress 1 m^3 of air in a vacuum

92.10	115.13	138.16	207.24

Work at atmospheric pressure

82.10	105.13	128.16	197.24

I do not go into details in this, because the air is compressed while being cooled. The air enters special tubes (the propeller cylinder), where it may be cooled far below atmospheric temperature, since the temperature of the expanding combustion products may attain as limit 273°C of frost.

32. In Table 2 we assume that the air temperature remains unchanged at 0°C; atmospheric pressure has been taken as 10 tons per square meter. The table gives the work of compression for one cubic meter of air for this case. This has application particularly to increasing the power of the engine low down (at sea level), where the pressure of the medium is of assistance and the work of compression is low. For instance, only 2 t-m of work would be needed to double the density, but 14.5 t-m to increase the density tenfold. To produce 1000 metric horsepower needs 1.5 m^3 of air per second; supply of air at twice the density doubles the power of the engine, so we get 2000 metric horsepower, or an excess of 1000.

Does this excess power go to compress the air? We must double the work given in the table for 1 m^3 of air, because we need 1 m^3 of compressed air, not 0.5 m^3, so the work is 4 t-m; 0.75 m^3 requires 3 t-m, or 30 metric horsepower for a second, whereas we have gained 1000 metric horsepower. It is clear that compression of the air is advantageous.

33. High compression is not so favorable, as the following table (Table 3) shows.

TABLE 3

Compression or density ratio								
2	3	4	5	6	7	8	9	10
Work to produce 1 m^3 of compressed air in ton-meters								
4	14.4	26	42.0	60	79.1	100.0	121.5	145

[Table 3 cont'd. on next page]

[Table 3 cont'd.]

The same for 1.5 m^3								
6	21.6	39	63	90	118.6	150	182.2	217.4
The same, in metric horsepower								
60	216	390	630	900	1186	1500	1822	2174
Excess work of motor from compression of air, in metric horsepower								
2000	4000	6000	8000	10 000	12 000	14 000	16 000	18 000
Percent of the excess absorbed by the work of compression								
3	5.4	6.5	7.9	9	9.9	10.7	11.4	12.1

The last line shows that the excess power is much larger than the proportion absorbed by compression; this absorption is 3 to 12%. This is not important for an ordinary aeroplane, but for our purpose it is both necessary and advantageous, because the mechanical work is much more than that required; whereas the recoil increases in proportion to the material burned and is in no way dependent on the fuel economy of an ordinary aeroplane. In addition, the thrust from the propeller is increased. In fact, a larger proportion is absorbed, because the compressor gives not more than 50% efficiency. This means that the percent absorption in the table must be doubled.

34. Now we turn to the rarefied air at height. The assistance received from the pressure of the external medium can be neglected for rarefied layers of the air. Table 2 gives the work needed for the two cases. The difference is the greater the higher the compression ratio.

Let us suppose that the air at height is 100 times less dense; $1\ m^3$ of air of ordinary density must be produced by compressing $100\ m^3$ by a factor of 100. The work is increased on the one hand by a factor of 100, and on the other is reduced by the same factor, because the pressure at height is 100 times less. The work thus remains unaltered.

The values in the table thus relate to the production of $1\ m^3$ of air no matter what the degree of rarefaction provided that the temperature remains the same (0°C). Even compression by a factor of a million needs only 128 t-m to produce $1\ m^3$ of ordinary air, so $0.75\ m^3$ of ordinary air needs 96 t-m, or 960 metric horsepower. But in this case the work of the motor is completely consumed by the compression (for a perfect compressor).

If the front (nose) part of the flying vehicle has a mouth with a tube leading to the motor, the air in the tube is compressed and can serve to supply the cylinders without especial compression; but this is possible only at very high speeds (about 1 km/sec or more), and a compressor must be used at lower speeds. All the same, we should not neglect the compression of the air resulting from the motion of the vehicle (see my "Pressure" of 1930). Of course, here the compression is not performed without work, because the resistance of the medium to the motion of the vehicle is increased. The work is merely transferred to reaction and to the propeller, so it is still to be reckoned as necessary.

The following table gives the densities of air on a plane at various speeds of the vehicle, as well as the heating from compression ("Pressure," point 70).

Speed in kilometers per second							
0	0.4	0.5	1	2	3	4	5
Ratio of densities							
1	1.38	4.31	138	4420	33 530	141 400	431 200
Ratio of pressures							
1	1.46	6.95	890	114 000	$2 \cdot 10^6$	$14 \cdot 10^6$	$69 \cdot 10^6$

Air cooled to zero implies a pressure at 1 kilometer sufficient to compress ordinary air to the density of water (compression ratio of 890).

The advantage of utilizing this pressure is that no compressor is needed.

35. We have defined the initial reaction or thrust from the vented gases as 8-10 tons; the propeller increases this by at least about double, namely to 16-20 tons. (But the thrust becomes proportionately weaker at high speeds.) Is this pressure sufficiently large relative to the resistance of the air at various heights? To solve this problem we must state the density of the air at the various heights (for this controls the resistance) as well as the resistance of our vehicle for a given speed and shape. The solution of the problem of rocket motion is simplified if the resistance is negligible relative to the thrust; also, the motion will be accelerated and will give us the high speeds we need.

36. Reference may be made to my "Resistance of Air" (1927), "Balloon and aeroplane" (1906-8), and "Pressure on a plane" (1930).

37. If the speed is high and the body is not elongated, the air in front of the aircraft is compressed by a factor of hundreds, so the resistance becomes extremely great and the vehicle as it were penetrates a steel wall. Table 4 gives the relation of the elongation to the forward velocity for a vehicle of good shape; here the air in front is almost uncompressed, and the motion is comparatively economical.

TABLE 4

Elongation of flying machine												
1 (sphere)	2	3	4	5	6	7	8	9	10	15	20	25
Maximum economic speed, km/sec												
0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0	4.5	6.0	7.5

It is even better if the elongation (ratio of length of vehicle to diameter of the largest cross-section) is larger than that given in the first line for the same speed. For instance, for a speed of 1.2 kilometers it is better to make the elongation (aspect ratio) 5 or 10 instead of 4. An aspect ratio of 25 is sufficient even if cosmic speeds are to be attained in the atmosphere. This means that a diameter of 2 meters requires a length of 50 meters.

38. The formulas and calculations in the above-cited papers give us the following table (Table 5).

TABLE 5

Aspect ratio		5	10	20	30
Length		10	20	40	60
		Ratio of resistance of body to that of plate, and reciprocal of this			
Speed in m/sec	10	0.0244	0.0211	0.0226	0.0248
		41	47	44	40
	50	0.00927	0.00657	0.00761	0.0106
		108	152	131	94
	100	0.00756	0.00422	0.00489	0.00573
		132	236	204	174
	200	0.00610	0.00372	0.00357	0.00398
		164	269	280	251
	300	0.00561	0.00335	0.00310	0.00336
		178	299	323	298

[Table 5 cont'd. on next page]

[Table 5 cont'd.]

Aspect ratio		5	10	20	30
Length		10	20	40	60
		Ratio of resistance of body to that of plate, and reciprocal of this			
Speed in m/sec	500	0.00488	0.00298	0.00273	0.00283
		205	336	366	353
Speed in m/sec	700	0.00464	0.00260	0.00244	0.00256
		216	385	410	391
Speed in m/sec	1000	0.00439	0.00248	0.00226	0.00230
		228	403	442	435

Table 5 gives the resistance of a vehicle of maximum transverse diameter 2 m (as a ratio to the resistance of a plane) as a function of the speed and aspect ratio. For instance, an aspect ratio of 10 and a length of 20 m give a ratio of resistance to that of a plane reduced by a factor 47 at 10 m/sec and by a factor 403 at 1000 m/sec.

39. The absolute pressure from the head-on flow on the vehicle is to be found from the resistance of the air to the motion of the transverse plane of the vehicle for the same speed, which is then divided by the form factor K (reciprocal of the resistance coefficient). The resistance of the area for a diameter of 2 m and for three identical bodies is given by

$$Q = 0.918 K_{\Phi} \Delta V^2 (\mathrm{kg}),$$

in which Δ is the ratio of the density of the medium to the density at sea level.

If, for example, the form factor, speed, and relative density are all unity, the resistance will be 0.918 kg (for a diameter of 2 m).

40. Column 3 of Table 5 now enables us to calculate the resistance of our vehicle at sea level at various speeds:

TABLE 6

Speed of vehicle in m/sec							
10	50	100	200	300	500	700	1000
Form factor							
47	152	236	269	299	336	385	403
Resistance of air in kg							
1.938	15.09	38.7	135.9	277	684	1170	2277
The same, as a ratio to a reactive force of 10 000 kg							
0.019	0.151	0.387	1.36	2.77	6.84	11.7	22.8

Table 6 shows that even a speed of 1000 m/sec and an air density equal to that at sea level give a resistance of only 23% of the reactive force; but before the vehicle attains a speed of 1000 m/sec it will have reached a height at which the resistance of the medium will have become nearly zero, on account of the rarefaction. (We have so far neglected the resistance of the comparatively small and flat wings.)

41. This is further confirmed by a table for the densities of air at various heights above sea level. The density is also affected by the fall of temperature with height. Taking this fall as 5°C per kilometer upwards, the sea-level temperature as 0°C, and the atmospheric pressure at sea level as 10.33 tons per m^2, we have* the following table.

This gives the density up to a height of 18 km, but the fall in temperature can be taken only up to a height of 15 km. There is no further fall in a temperature, and the densities become less than those calculated here. A systematic and fairly uniform fall in temperature can be assumed only for the troposphere.

42. Another table is given for heights above 15 km (for the stratosphere). This has been compiled on the basis of a constant temperature of -75°.

43. We now see that the density and resistance have fallen by a factor of 6 at a height of 15 km, by a factor 80 at 30 km, and by 135 at 33 km; past this point they become almost inappreciable. For instance, the factor for the density is 10 000 at 58 km**.

Thus we see that the resistance of the air can be neglected for the ascending motion of a reactive aeroplane burning a large quantity of fuel and developing a thrust of 8-10 tons. This greatly facilitates preliminary calculations on the motion of the aeroplane: inclination of path, speed, vertical and horizontal distances covered, appropriate density of medium, resistance, work required, and so on.

44. At first the vehicle moves uphill with a definite gradient under its own thrust or by the action of an external force. Then,

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*Tsiolkovskiy here calculated on the basis of these quantities two tables for the variation of density with height. Other initial values are used in the international standard atmosphere, so these two tables have been omitted as of no particular interest (Editor).

**See previous footnote p. /358

when its speed has become sufficient, it takes off from the hill and moves in the air without its support. The inclination of the body may remain the same. The vehicle will move forward and upwards; but it also falls on account of gravity: the inclined position and the speed cause it to rise, whereas the weight causes it to fall. But the fall is impeded by the resistance of the air*, and the more so the greater the speed of the body, but the less the lower the density of the medium. Before a fixed path can be set up the speed must be such that the fall is less than the rise, otherwise the vehicle may fall on land or sea. The best situation is a fall very small relative to the rise; then the vehicle will move in air as on rails, but at great heights the motion, in spite of the inclination, will approximate to horizontal.

45. The conditions for such motion are now found. Langley's results give the pressure on a plane slightly inclined to a flow as the pressure from a flow normal to the plane multiplied by 2 sin α**. I have shown theoretically ("Pressure of a fluid," 1891) that this pressure is proportional to $(a/b)^{1/2}$, in which a is the side of the rectangle placed normal to the flow and b is the other side. The diameter d plays the part of a in our case; it is less than b (i.e., the length l). Further, we do not have a plane but an elongated body of rotation (fuselage). The rounding causes the lateral pressure of the medium to be reduced, as for a circular cylinder, whose resistance coefficient we may take as $K_2 = 0.6$ (from various experiments). The narrowing of the body (fuselage or bird) towards the ends implies a fall in $\frac{b}{a}$, but we take this as equal to the aspect ratio $\frac{l}{a}$ and so obtain a resistance less than the true value, so the fall will be more rapid than that calculated.

Then the resistance coefficient of the vehicle in its inclined motion (or rather, position) at a small angle to the horizontal is:

46. $K_1 = 2 \sin \alpha \left(\frac{d}{l}\right)^{1/2} K_2$. Here sin α is the sine of the angle of the flow to the long axis of the body.

*I.e., by the lift (Editor).

**α is the angle of attack; this formula is inaccurate (Editor).

This slightly inclined body may move under the influence of a thrust (directed along the length) with a speed v_1 and may fall in the same air under its own weight with a speed v_2; then

47. $\sin \alpha = \frac{v_2}{v_1}$, and the resistance coefficient will be

48. $K_1 = 2K_2 \left(\frac{v_1}{v_2}\right) \left(\frac{d}{l}\right)^{1/2}$.

The area S of the lengthwise section of the machine may be taken as

49. $S = 0.75dl$. The pressure Q from the normal flow on the plane may be put as

50. $Q = K_3 S_\gamma \left(\frac{v_1^2}{2g}\right)$.

Here K_3 is a correction factor close to 1.5 and γ is the specific gravity of air; this Q must be multiplied by K_1. The supporting (upward) pressure on the vehicle is

51. $$p = \frac{0.75}{g} \gamma K_3 K_2 v_1 v_2 d^2 \sqrt{\frac{l}{d}}.$$

52. Here we put $\gamma = 0.0013$ t/m^3, d = 2 m, l = 20 m, which gives $p = 0.0111 v_1 v_2$; this is the pressure on the vehicle as a function of the speed of fall v_2.

For uniform fall we must have that the force arising from the resistance of the medium is equal to the weight G: $0.0111 v_1 v_2 = G$, so

53. $$v_2 = 901 \frac{G}{v_1}.$$

54. If the vehicle were not falling under gravity, it would rise as a result of its inclined motion (nose upwards). The rate of rise would be $v_1 \sin \alpha$. The motion would be horizontal if the two speeds (of fall and rise) were equal; this occurs if

$$v_1 \sin \alpha = 901 \frac{G}{v_1}.$$

Then we have

55. $$v_1 = \sqrt{\frac{901\, G}{\sin \alpha}}.$$

56. We have seen that G = 12 tons.
Here we take $\sin \alpha = 0.1$ as an example; then v_1 = 329 m/sec. The vehicle after leaving the hill will fly horizontally once it has reached this speed.

57. Now we consider the length and height of the hill. A thrust of 4 tons gives the vehicle an acceleration j of

$$j = g \frac{4}{12} = \frac{g}{3}.$$

The distance L traveled before attaining a speed of 329 m/sec is L = $= \frac{v_1^2}{2j}$ = 5412 m (i.e., about 5 km). The height is found by multiplying the inclined path covered by $\sin \alpha$ and is 541 m or about 0.5 km. This is quite feasible.

58. At this speed the vehicle will not fall when it leaves the solid road; at higher speeds it will start to rise, and an ascending motion is desirable. This requires that the ratio of v_2 (rate of fall) to $v_1 \sin\alpha$ (rate of rise) should be very small. But this ratio, which we denote by m, is

$$m = \frac{v_2}{v_1 \sin\alpha} = \frac{901\ G}{v_1^2 \sin\alpha}.$$

Then

59. $$v_1 = \sqrt{\frac{901\ G}{m \sin\alpha}}.$$

60. We put here G = 12 tons and $\sin\alpha = 0.1$ to get

m	1	$\frac{1}{4}$	$\frac{1}{9}$	$\frac{1}{16}$	$\frac{1}{25}$
v_1 m/sec	329	658	987	1316	1645

The fall will be almost inappreciable at a speed of 1 km/sec; but these speeds are quite high, and the heights of the hills needed to support the inclined ways will be large, namely

H, km	0.54	2.16	4.95	8.80	13.75

61. The rate of fall and the length of the solid way may be

reduced by the use of thin, narrow, and almost flat wings, which we mentioned above but whose effect we neglected.

But, in any case, a hill of height 5 km is quite sufficient to attain a speed at which the vehicle would move without support.

FROM AIRCRAFT TO ASTROPLANE*

Long ago man observed the stars and turned his eyes to the sky. What is there? May there not be there riches exceeding those of the Earth? What lies beyond that inaccessible blue vault?

Our ideas on the sky and the air were very confused until quite recently. Even the educated thought that one could reach the Moon, planets, and stars through the air; and accordingly, attempts were made to fly. Until very recently flying was considered the same as celestial travel.

The atmosphere does not extend far and belongs to the Earth; the one carries the other along with it in the vacuum of stellar space, and the atmosphere is merely the Earth's air ocean, which is deeper than the water one, for it covers the tops of the highest mountains. Its depth is 200-300 km, and its density is 800 times less than that of water (or thousands and billions of times less at high altitudes). The density is reduced by the following factors for successive ascents of 5 km: 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, and so on. The air at a height of 50 km is 1000 times less dense than at sea level.

To attain the celestial bodies we must therefore find a means of moving in a vacuum; then celestial travel will be accessible.

What means do men have for this? Clearly, airplanes and dirigibles are unsuitable, for they need support from the air. In general, motion is impossible without support; but what support can there be in the empty bottomless celestial spaces?

But meteorites, the planets large and small, and even great suns, all are eternally carried in the empty expanses of the cosmos. They not only eternally move, but even need not the least consumption of power for their rapid motion. They never wear out, never stop, and never rest. This is a great advantage for celestial voyages in a vacuum. There is none of this on Earth, in the air.

This shows that one of the means of celestial travel is rapid motion at speeds comparable with those of heavenly bodies.

These speeds are very varied, being dependent on the masses and distances. For instance, the speed of the Moon is about one kilometer a second, while the planets move with speeds of the order

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*First printed in Iskry Nauki (Moscow), 1931, No. 2, pp. 57-57; see Appendix, Paragraph 52 (Editor).

of ten kilometers a second or more.

This means that a high speed can free us from the yoke of terrestrial gravity and make us celestial wanderers in the same way as the Moon and planets; but such speeds are extremely high and inaccessible for various technical reasons. We set aside this mode of flying for the time being.

Another means is the rocket, in which the support consists of gunpowder; of course, this support is mobile and not so convenient as the earth, but water and air are also mobile, yet this does not prevent them from acting as supports for steamships and aircraft.

Imagine a reactive vehicle or (for brevity) a rocket, by which is meant a flying or otherwise moving device having its support within itself in the form of some mass or explosive material. The mass is ejected from the rocket by means of some energy also stored in the vehicle.

The vehicle may also be supported by the surrounding medium, in which case it is semireactive; it may be so while it flies in air or any other material medium, but it cannot be so in the vacuum of universal space, and there it must be purely reactive.

Any motor that carries a store of material support that it ejects may be called reactive.

The support for a reactive vehicle may, in general, be a liquid, a solid, a vapor, a compressed gas, or an explosive; accordingly, many devices have been invented, and at different times foreigners and Russians have taken out many patents for the propulsion of aeroplanes and dirigibles with reactive motors. The rocket itself was known to the Chinese some thousand years before our time.

But ordinary motors with airscrews (i.e., with external support) have proved victorious for airplanes and dirigibles; reactive vehicles appeared impracticable or uneconomical for terrestrial transport. The error here was that rocket apparatus was applied to propulsion on solid ground or in a medium in which it would be much more advantageous to use the abundant external support, which is already there and which does not need to be carried in the vehicle. The reactive principle is advantageous only in a vacuum, where it is essential and where there is as yet no other means of producing a propulsive force or drive.

The history of space travel began when reactive vehicles became applied only in this field, when it had become understood that they are unsuitable for terrestrial transport.

It would be redundant to list here the many who have written on the possibility of voyages outside the atmosphere; I mention only two universally known authorities, namely Gauss and Newton. The latter said that a craft may fly in outer space by the aid of a reactive motor. Gauss predicted that the rocket should have a great future. In general, as we have seen, the reactive method has been repeatedly proposed for flights in celestial space.

In 1896 I first developed the theory of reactive devices for use in flights outside the atmosphere; I also showed that explosives can give speeds not merely sufficient to overcome the attraction of the Earth but also that of the Sun. The vehicle I proposed is the astroplane (zvezdolet).

The support must be carried in the vehicle for a journey in ethereal space, for there is no other support; this means that the purely reactive principle is inevitable.

What type of support should be ejected?

Solids, liquids, gases, vapors, or particles from radioactive bodies?

Compressed air requires vessels whose weight is 10 times that of the gas (i.e., the support); other gases such as hydrogen, even for use with air, also require heavy tanks. This applies also to vapors. Highly heated water and other liquids also require heavy vessels, but they contain more energy than compressed gases; they are thus more favorable but are still unsuitable. Liquefied, very cold, and freely evaporating gases do not require strong and massive vessels, but they contain very little energy, because the speed of their particles is very small on account of the low temperature (close to absolute zero).

There remain explosives, which are exploded little by little; they contain much energy, but one cannot use ready-made explosives in a reactive craft on account of the danger of simultaneous explosion of the whole mass. Then what would remain of our vehicle? Theory demands amounts of the strongest explosives greatly in excess of the weight of the vehicle itself in order to reach cosmic speeds. The danger of explosion is clear from the death of the brave Vallier, who was killed by the explosion of a rocket. Hanswindt proposed the use of separate dynamite cartridges, but these do not really alter the position, and they can explode almost simultaneously.

This means that we must take not ready-made explosives but their components, such as liquid (freely evaporating) hydrogen and oxygen in the same state, which are separated by a barrier impermeable to them. But the cold of the liquids would reduce their stored chemical energy, so cold liquids should be avoided if possible. Hydrogen could well be replaced by one of its endothermic compounds (some hydrocarbon, for example) and oxygen by one of its compounds (e.g., with nitrogen). The energy arising from the chemical reaction of a unit mass of such substances is somewhat lower, but it is still sufficient to produce cosmic speeds.

The two carefully isolated liquids are pumped by two separate pumps into a special vessel (the combustion chamber) where, after thorough mixing, they give an explosion resembling that in a firearm. The resulting vapors and gases leave the combustion chamber via a conical tube, in which they expand more and more to finally escape from the rear of the vehicle. They press on the walls of the tube and chamber, and so drive the vehicle in the opposite direction.

The first blank firing is followed by a second. The number per second must be as large as is reasonable, but it must not be excessive, for then the gases would not have time to escape from the tube, and so the pumps would have to provide too large a force.

The explosion chamber and the front end of the tube will become extremely hot; they may melt or burn away if they are not cooled. But how can they be cooled? And whence can one obtain a source of cold? Such a source there is, at the wide end of the tube, near the exit. The gases and vapors expand in the tube and thereby become colder and colder; a properly constructed tube should give a gas temperature near the exit that is close to absolute zero (273° of frost on the centigrade scale). This is the cold that should be used for cooling.

To this end the tube is covered by a thin and light jacket, in which a gas (water or other liquid being ruled out on account of its excessive weight) circulates as rapidly as possible. This flows around the chamber and narrow part of the tube to rapidly transport their heat to the exhaust pipe, where it is cooled by yielding up its heat to the cold gases and so increasing their exit speed and useful effect. This is a circular motion: from the hot parts of the tube to the cold ones and back again.

The astroplane thus demands a special engine. The gasoline engine is the most economical and convenient, and its exhaust can escape via the same conical tubes or via special ones. The backward escape of used gases increases the force on the rear part of the craft and accelerates its motion.

It is extremely inconvenient to carry oxygen in the vehicle, for this increases its mass and so retards the attainment of the speed. This difficulty does not occur in automobiles, trains, steamships, aeroplanes, and dirigibles, because they all use atmospheric oxygen taken in little by little as required.

However, the astroplane will fly part of its time in the atmosphere, so it can also use air in this period. Only after leaving the atmosphere or entering highly rarefied layers will it need to draw on its stores of oxygen.

In this way the astroplane is converted from being purely reactive to semireactive.

All this will come about gradually; we are still far from the astroplane. First we must reach the rarefied layers of the atmosphere (the stratosphere). We may so far restrict ourselves to the principal part of the astroplane (combustion chamber and oxygen store), which greatly simplifies the problem and prepares us for the construction of an astroplane. So far we need a stratoplane (high-altitude aeroplane) in order to reach heights of 20-30 km or more.

We may try the conversion of an ordinary aeroplane into a stratoplane (high-level aeroplane). The screw propeller must be discarded as liable to break at high rotational speeds.

But the reaction from the gases of the aeroplane is far from sufficient to enable it to fly; calculations show that the recoil must be increased by at least a factor 10 in order for the vehicle to rise in the air. How can this be done with the same engine weight?

As an example we assume that the stratoplane with all its equipment weighs 1000 kg; the usual engine output required is 100 metric horsepower, and the weight of this will be about 100 kg.

Sufficient recoil requires that the consumption of fuel be increased by a factor 10; the power of the engine may increase or may remain as before. Of course, the engine could work on no load, whereupon its speed would increase, and so would the amount of fuel consumed; but some amount of work, although small, is needed at height in order to compress the rarefied air. In addition, the speed on no load will even so increase by a factor 10, which means that we must increase not only the amount of fuel consumed but also the work output (with the object of greater consumption of fuel).

If we were to use air compressed by a substantial factor even at the start of the flight (at sea level), together with larger valves and pipes, it might be possible to increase the work output by a substantial factor and the fuel consumption even by a factor 10. The latter is the more important to us. It may be that we must then assign 200-300 kg to the engines instead of 100 kg. The use as the fuel of liquid hydrogen, which mixes very rapidly with air, may also facilitate increased speed and also greater fuel consumption. This problem is not excessively difficult given careful thought.

A tenfold increase in the rate of combustion will give an exhaust action of the gases so considerable that the stratoplane first starts to move and then rises in the air to race with a speed increasing to 50-100 meters per second.

But where are the cosmic speeds, and where in general is the increase in speed? This increase will be observed in the higher layers of the atmosphere as the air becomes more rarefied, especially when the rocket has overcome terrestrial gravity and moves in airless space.

If the fuel consumption is constant at all heights, on account of the compressor, then the reaction (thrust) will also be constant. The work available to the aeroplane will thus be proportional to the speed of its forward motion; the speed will increase in direct proportion to the work, and conversely.

My calculations show that constant thrust at the height where the air is four times less dense (12 km) will give twice the speed to the aeroplane; where the air is 9 times less dense, 3 times the speed, and so on. The following table gives the relation between these quantities:

Rarefaction of air						
1	4	9	16	25	36	49
Speed, m/sec						
100	200	300	400	500	600	700
Speed, km/hr						
360	720	1080	1440	1800	2160	2520

At the height where the rarefaction factor is 100, the speed will rise to 3600 km per hour (1 km a second); the equator will then be reached from our latitude (say 45°) in 1.4 hr, or from the pole in 2.8 hr. Pole to pole will take 5.6 hr, and a circuit of the Earth 11.1 hr. This is twice the speed of the Earth at the equator or the apparent (diurnal) speed of the Sun. One can imagine what views of the sunrise and sunset and of the daily movement of the Sun across the sky will thus be obtained.

ATTAINMENT OF THE STRATOSPHERE. FUEL FOR A ROCKET*

Explosives and Fuels

There is essentially no sharp distinction between explosion and simple burning; both are more or less rapid chemical reactions, burning being slow combination and explosion being rapid burning.

The same may be said of smoldering, rusting, and slow oxidation, or in general of any slow chemical reaction. In fact, the differences between these phenomena are purely quantitative.

The energy per unit mass of an explosive may even be much less than the energy produced per unit mass of a fuel. Fuels are also economically more favorable than explosives, for the latter are far dearer and vastly more difficult to use.

Consideration has scarcely been given yet to doing this economically**. All experiments with rocket automobiles, seaplanes, sledges, and gliders are of major value only as training and preparation for the stratoplane and astroplane.

What then are the advantages of explosives? There are major ones, though these are not economic ones.

An explosive releases a vast amount of energy in a short time, for the chemical combination of the mixed combustion elements occurs almost instantaneously.

Let us assume that one kilogram of carbon is burned in a second (although several tons of explosive could burn in this second). If, as is usual, the products are volatile, the speed of these can be several kilometers a second; their energy of motion could be used by a turbine, although no practical solution to this problem is yet at hand. But we believe that rocket engines

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*Manuscript received 9 March, 1934, by the Central Council of the Society for Collaboration between Aviation and Chemical Defense.

**Reliable reactive engines are now available, which use alcohol as fuel and liquid oxygen as oxidizer (Editor).

have an outstanding future.

We have as basis that the volatile explosion products convert all their energy to motion by expansion in an artificial or natural vacuum (outside the atmosphere), so the proportion of the heat used can be high. In addition, there is the rapidity of burning and the considerable production of work (energy) per second.

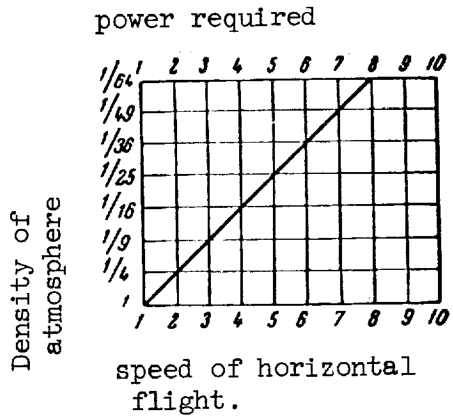

Fig. 1.

The energy of explosives is already utilized in firearms and to disrupt solids (e.g., granite crags); in a small fraction of a second they give a great speed to the projectile and develop (on average) several million horsepower. In the same small fraction of a second they can perform the powerful work of disintegrating stony masses.

Direct-action rocket vehicles (rockets) can also give high performance to missiles and vehicles at speeds of several kilometers a second. But such speeds are impossible in the lower layers of the atmosphere, for here the resistance of the air is an obstacle. Such speeds and favorable uses for them are possible only in extremely rarefied layers of the atmosphere.

Here we must reject a very common error, namely that a cosmic speed is possible in the highly rarefied layers of the atmosphere with the usual energy of engines. As long ago as

1895 I showed* that the power required of the engine at constant weight is proportional to the speed of the aircraft in the most favorable rarefied layer.

Figure 1 shows the speed of horizontal flight at ground level as unity, the power of the engine then also being taken as unity. This power is proportional to the curve of the speed for air of unaltered density, so the power increases in the ratio of the numbers 1, 8, 27, 64, and so on. This was confirmed 35 years later by the American scientist Corwin-Krukowsky.

The difficulties of flight in the stratosphere are greater, but they can be overcome by the use of the stupendous power of combustible substances.

Engines and Explosion

Continuous burning (explosion) occurs in any furnace, especially if forced feed is used; but this explosion process is not used directly in an ordinary steam engine or turbine. Instead, only the heat is used. This is very economical if a cheap fuel (such as peat or poor coal) is available and if the weight of the machine is unimportant; but the fuel for a locomotive is purer and more costly, so here the economy is less. This explains the trend towards explosion motors (benzine and diesel) or electrical ones.

The second case occurs in internal-combustion engines, in which use is made of the force of the explosion, so these engines are more correctly termed explosion ones. Their advantages are enormous energy, economical use of fuel, and hence only a small store of fuel. Their disadvantage is that the fuel is purer and more costly. In both cases use is made of oxygen that costs nothing (from the air).

Reactive automobiles, seaplanes, sledges, aeroplanes, strato-

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*See K. E. Tsiolkovskiy. The aeroplane, or birdline (aviation) flying machine. Collected Works, vol. 1, Izd. Akad. Nauk SSSR, pp. 40-73.

planes, and astroplanes use stored oxygen or some other element needed for combustion, with the object of obtaining vast energy in a short time. There are two methods here.

1. The oxygen supply or its substitute may be previously mixed with the fuel (e.g., as in gunpowder). Only finished explosives have so far been used in motion or flight by men.

This method has the following advantages: the energy is produced rapidly and the engine is of simple design. The disadvantages are much greater: danger of simultaneous explosion of the entire store (death of Tilling and others), burdening of machine by the weight of the oxygen compound or liquid oxygen, burdening by the weight of the tubes surrounding the explosive, which have to withstand the enormous pressure of the compressed explosion products (the tubes must be strong and heavy to do this) at the low speeds reached in the lower atmosphere, the low proportion of the chemical energy used, and the costliness of explosives.

2. In the second method the oxygen compound is separated from the fuel; the elements combine gradually, as in an aviation engine, but the oxygen is not taken directly from the air. There is no danger of complete explosion, or encumbrance by the heavy tubes; but the other disadvantages remain.

What forces us to resort to stored oxygen? We need a store of an oxygen compound at great heights in the extremely rarefied atmosphere or even higher (outside the atmosphere) in the vacuum, because it is practically impossible to extract the oxygen from the atmosphere, and there is none in a vacuum. High speeds can be reached there, and a large fraction of the chemical energy may be used. The following disadvantages remain: burdening by the weight of the oxygen and costliness of the latter or its compounds. However, the explosion elements can be cheap petroleum (fuel) and liquid oxygen or a liquid compound of this, e.g. N_2O_3, which is not so dear. The explosion elements have already been separated in small flying machines (unmanned). Progress will undoubtedly be made, but these devices have other disadvantages, which I have dealt with in my "Reactive motion and its successes," which was printed in 'Samolet' (The Airplane) No. 6 (1932). They also therefore will give poor results.

Choice of Explosion Elements

Here we envisage attainment of very rarefied layers of the air, from which it is difficult to extract oxygen.

The elements of any explosive for reactive motion must have the following properties:

1. They should yield the maximum work per unit mass on combustion.

2. They should combine to give gases or volatile liquids, which give vapors on account of heating.

3. They should develop as low a temperature as possible on combustion in order not to burn out or melt the combustion chamber.

4. They should occupy a small volume, i.e., should be of high density.

5. They should be liquid and readily mixed. It is complicated to use powders.

6. They may also be gaseous but have a high critical temperature and low critical pressure, in order to make them convenient to use in liquefied form. Liquefied gases are generally unsuitable on account of their low temperature, for they absorb heat to evaporate. Use of these involves evaporation losses and the danger of explosion. Costly compounds that are chemically unstable or difficult to obtain are also unsuitable.

The following are some examples. Hydrogen and oxygen, for example, satisfy all conditions except 4 and 6; liquid hydrogen is 14 times lighter than water (density 0.07) and so is inconvenient, because it takes up a large volume. The critical temperature of hydrogen is equivalent to 234° of frost, and that of oxygen 119°. Carbon in isolation is unsuitable, on account of its solid state. Silicon, aluminum, calcium, and other substances are unsuitable not only because of their solid state but also because they give nonvolatile products with oxygen. Ozone is unsuitable, because it is costly and chemically unstable; its boiling point is 106° (centigrade) below zero. Most simple and composite bodies are unsuitable because they produce little energy per unit mass on combination.

The following are the substances that are suitable.

1. Simple or composite ones, provided that they are liquid at ordinary or very low temperatures and have densities not far from the density of water. This means that we can allow liquefied gases that do not have low critical temperatures.

2. Ones that produce the most work per unit product, such as certain slightly exothermic and (especially) endothermic compounds (the latter do not absorb heat on decomposition but produce it, and so are particularly suitable).

3. Ones that are cheap and chemically stable.

4. Ones that give volatile products (gases and vapors) on combustion.

The most energetic parts for an explosion, and ones that give volatile products, are hydrogen and oxygen.

The formation of one gram of water vapor produces 3200-3300 cal, while the burning of light metals (lithium, aluminum, magnesium; also silicon and boron) gives 3400 to 5100 cal (rather more); but the latter are unsuitable, since they give nonvolatile products.

Hydrogen and oxygen in isolated form are also inconvenient; they are best replaced by weak compounds with other elements. The hydrogen is replaced by hydrogen compounds, and similarly for the oxygen. Hydrocarbons are the most suitable for burning in oxygen; hydrogen and carbon both combine with oxygen to give volatile products. Hydrogen produces more energy per unit mass on combination with oxygen than carbon does; it gives from 3233 cal (as steam) to 3833 cal (as water), whereas carbon gives 2136 cal. All of these values are in small calories per gram, not per mole, so hydrocarbons produce on combustion the more energy the greater the proportion of hydrogen.

The saturated hydrocarbons satisfy this requirement; the simplest is methane CH_4 (marsh gas), which contains only 25 % hydrogen. However, we must bear in mind that most of these compounds are exothermic (heat is produced when they are formed); when they burn in oxygen, they must first decompose to H_2 and carbon, which absorbs heat. In addition, liquid methane boils at -82°C and so is inconvenient.

However, we may calculate its explosion energy (Fig. 2). One part of C requires two parts of O, and this produces 94 000 cal per gram-molecule (mole). Four parts of H require two parts of O, and the 36 g produce 36 000 cal, so in all we have 310 000 cal from 80 g.

But the preliminary decomposition of CH_4 takes up 18 500 cal for 16 g (a mole), so there remains 191 500 cal for 80 g, or 2394 cal per g of products.

The hydrocarbons include one with a lower proportion of hydrogen (12.2 %) but which absorbs heat on formation (endothermic compound); this is ethylene, C_2H_4. This is more suitable, for the two parts of C require four parts of O, and 88 g produce 188 000 cal; four parts of H require two of O, and 76 g produce 116, 000 cal (as steam), so 124 g produce 304 000 cal. But the decomposition of C_2H_4 yields up 15 400 cal per 28 g (one mole) previously absorbed, so we obtain a total of 319 400 cal for 124 g, or 2576 cal per g, which is slightly more than for methane. Ethylene is readily liquefied, for its critical temperature is 10° and its critical pressure is 52 atm. Ethylene is readily made from ethyl alcohol or ether by passage over clay balls heated to 300-400°C. The result is that ethylene is more suitable than marsh gas (methane).

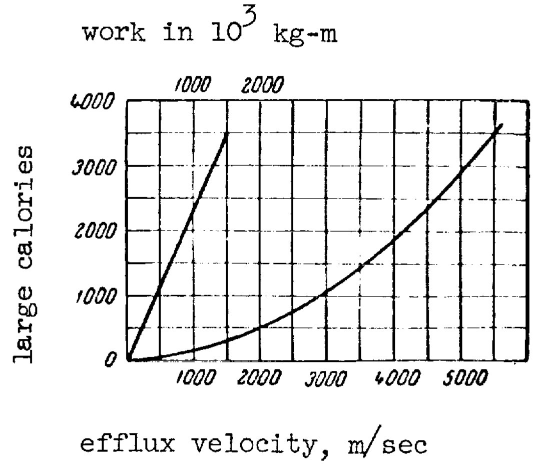


Fig. 2.

Consider now benzene, C_6H_6. This is a fairly dense liquid and so is most suitable for rockets; but it contains only 8 % hydrogen. The energy per unit mass of the products from combustion with oxygen is as follows. On formation it releases only 102 000 cal per mole (78 g); C_6 requires O_{12}, H_6 needs O_3, which means that 318 g of products yield 738 000 cal. Subtracting the heat of formation of C_6H_6, we have 727 800 cal for 318 g, or 2289 cal per g of products. This is slightly less than that from ethylene, but here we have a substance liquid at ordinary temperatures and having a low vapor pressure.

Acetylene C_2H_2 has the same elemental composition as benzene but, being a gas, is inconvenient; and this exothermic compound produces 18 times as much heat on formation as does benzene, which means that it absorbs more on burning. In addition, the dissociation temperature of a hydrocarbon increases with the proportion of carbon, and hence so does the combustion temperature. Liquefied hydrogen is best of all, but it is difficult to make and store, and it takes up a very large volume.

The following are the heats of combustion of alcohols, ether, and turpentine:

Methanol CH_4O	2123 cal
Ethanol C_2H_6O	2327 cal
Ether $C_4H_{10}O$	2512 cal
Turpentine $C_{10}H_{16}$	2527 cal

The figures are calories per unit product; clearly, these fuels cannot be neglected.

In my calculations I have assumed liquid oxygen, which is very inconvenient; ozone is chemically unstable and largely inaccessible, so we must consider oxygen compounds.

The oxygen compounds of nitrogen are of interest; the following are the most suitable. Nitrous oxide N_2O is an endothermic gaseous compound and is unsuitable on account of its high proportion of nitrogen. The same may be said of the endothermic nitric oxide NO. NO_2 is a brown fairly stable liquid, whose synthesis releases a negligible amount of heat. It is stable up to 500°C and very dense (1.49), which makes it very favorable. It is a strong oxidizing agent, but the machine can be protected from corrosion by coating the vessels, pipes, valves, and so on with gold, platinum, iridium, or resistant alloys or other substances.

Another compound, N_2O_5, contains slightly less nitrogen, but it is inconvenient on account of its chemical instability.

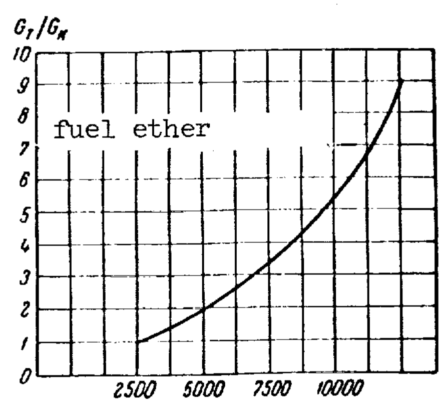
We settle for NO_2. This compound completely replaces oxygen, but it is loaded by the nitrogen, which reduces the exhaust velocity of the gaseous combustion products, because it increases the mass. We have settled on benzene, whose molecular weight (pure) is 78. This needs O_{15}, or 240 g of oxygen, for complete combustion, and the weight of the combustion products with pure oxygen is 318 g. But we have NO_2, and the O_{15} is accompanied by 105 g of nitrogen, so the products will weigh 423 g, which is larger by a factor 423:318 = 1.331. The increase in mass reduces the exhaust velocity by a factor 1.15, or to 87 %. For instance, instead of 5000 m/sec we would have 5220 m/sec. The energy of explosion per g of products is 1721 cal.

One might be led to enquire after nitroglycerine, pyroxyline, and so on, which might give more energy; but no, it is much less, as the following table shows by reference to the heat of formation of various compounds from the elements per g of products in small calories. I have chosen here the most powerful explosives.

Aluminum with ammonium nitrate	1480 cal
Powder, smokeless or otherwise	720 to 960 cal

Nitroglycerine powder	1195 cal
Nitroglycerine	1475 cal
Dinitrobenzene + nitric acid	1480 cal
Picric acid	750 cal
Pyrobenzene nitrate	1330 cal
Mercury fulminate	350 cal

These finished explosives cannot be used, on account of the danger of unexpected explosion of the whole mass, apart from the low energies.



maximum speed of rocket, m/sec

Fig. 3.

To sum up, we have as follows.

1. Hydrogen is unsuitable on account of its low density and of the difficulty of storage in liquid form.

2. Liquefied methane, CH_4, gives 2394 cal with liquid oxygen but is inconvenient on account of its low boiling point.

3. Ethylene, C_2H_4, gives 2576 cal with O_2. This mixture is more suitable, because the critical temperature of ethylene is about $10^{\circ}C$.

4. Benzene, C_6H_6, gives 2289 cal with oxygen; this is less energy, but benzene is liquid at ordinary temperatures, which is convenient. Mixtures of liquid hydrocarbons of high boiling point (kerosene and so on) are convenient, the more so since they are cheap (petroleum).

5. Liquid oxygen represents a certain inconvenience, on account of the storage difficulty.

6. The best course is to replace oxygen by NO_2, which is a brown chemically stable liquid denser than water. This produces 1721 cal per unit product on reaction with benzene.

These two liquids are the most suitable for the rocket of (1) (Fig. 3), but the parts of the machine must be protected from the oxidative action of the NO_2. The energy (1721 cal) is not large, but it is more than that of the best gunpowder or of the most powerful explosives (nitroglycerine).

Further, the latter are dear and cannot be stored in large quantities.

8. Alcohol and sulfuric (ordinary) ether are also suitable.

The following table gives the relation of heat of combustion to speed of combustion products under ideal conditions (escape into vacuum from very long tubes):

Heat of combustion, kcal/kg					
700	1000	1200	1500	1700	2000
Ideal mechanical work, kg-m x 1000					
300	428	513	642	727	856
Speed of products, m/sec					
2450	2920	3200	3580	3810	4130
Heat of combustion					
2200	2500	2700	3000	3200	3500
Work in kg-m x 1000					
941	1070	1155	1284	1369	1498
Speed, m/sec					
4340	4630	4800	5060	5230	5470

Ether gives a speed of 4630 meters per second.

In this last case we obtain the final speeds of the vehicle given in the following table for various values of the ratio of mass of explosive to all-up weight of vehicle (apart from fuel and oxygen) for horizontal motion on rails or in the absence of gravity, when there is no resistance from the medium:

Relative store of fuel									
1	2	3	4	5	6	7	8	9	10

Taking the exhaust velocity for ether as 4630 m per second, we obtain the maximum speed of the vehicle as:

3200	5094	6400	7465	8314	9026	9646	10194	10685	11126

A ratic of 5 is sufficient to provide a satellite of the Earth; one of 10, a satellite of the Sun, since the vehicle escapes from the Earth and enters the orbit of our planet.

THEORY OF REACTIVE MOTION*

Reactive motion is the motion produced in the recoil of firearms.

It may seem strange that one should hope to use the force that causes a gun to recoil during firing not only for the purposes of rapid movement in the rarefied layers of the atmosphere (stratosphere) but also for travel at lightning speeds between planets and stars.

First we shall show that an explosive (provided, of course, that a sufficient amount is used) can impart to the device in which it is burned any desired speed.

To simplify the treatment, we assume that the air exerts no resistance or friction. This condition could be approached if we consider the device to move in a long tube from which the air has been removed.

Let the weight of the device with man and all machinery (but without explosives) be always one ton; let the weight together with explosives be (in tons) a series of multiples (a geometric progression): 2, 4, 8, 16, 32, 64, 128, ...

Subtracting the weight of the device (one ton), the weights of explosive become 1, 3, 7, 15, 31, 63, 127, ...

If the mass of the rocket and that of the explosive are the same (one ton), it is clear that the speed of the exploding gases and the speed of the vehicle will be approximately equal, for the same force (Fig. 1) acts in this case between equal masses.

On the other hand, why should one mass move more rapidly or slowly than the other?

Let the speed (per second) be unity, e.g., one kilometer.

Now consider firing in accordance with the second term of the series (4 and 3). First we explode two tons, the residual two tons acquiring a speed of 1 kilometer. Then we explode the last ton; the residual ton acquires an additional speed of one kilometer. The final speed of the device is thus two kilometers

Now we fire explosive in accordance with the third term in the series (8 and 7). First we explode 4 tons, which gives the residual four tons unit velocity. Then we explode 2 tons, and the remaining

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*First published in: V boy za tekhniku (Struggle for Technology), Moscow, 1932, No. 15-16 (August). (Editor) two tons acquire an additional unit velocity, total two. Finally, we explode the remaining ton. The residual ton acquires a further unit of velocity, total three.

Continuing the above series, we find for the various degrees of charge in the same rocket (nominal term) the following relative velocities: 1, 2, 3, 4, 5, 6, 7 ....

Then, increase in initial weight in geometrical progression causes the speed to increase also without limit, but in arithmetic progression.

What will be the true final second speed of the device? It will depend on the speed of the gases escaping from the fixed tube and on the reserves (e.g., of gunpowder).

Tests by Goddard and others have shown that the speed of the gases energing from the barrel in blank firing can be 3 km/sec or more; it has been shown theoretically that in a vacuum and with a fairly long conical tube (rocket) the most powerful explosives could give speeds of 5-6 km/sec.

We assume a value of 5 km/sec; then we obtain speeds (in km/sec) of 5, 10, 15, 20, 25, 30, 35, ...

Even the more modest value of 4 km/sec gives us 4, 8, 12, 16, 20, 24, 28 ....

But even a speed of 8 km is sufficient to carry the vehicle eternally above the atmosphere in a circle around the Earth as a satellite (as for the moon). A speed of 12 km would be sufficient

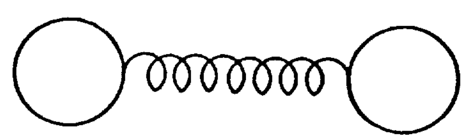

Fig. 1.

to put it in the path (orbit) of the Earth and thereby make it a minute planet*. Finally, a speed of 16 km would enable it to overcome the

*More exact values for the speeds are 7.9 and 11.2 km/sec respectively (Editor).

attraction of all the planets and the Sun. A vehicle given that speed would externally recede from our solar system and would wander in the Milky Way (Galaxy) among other suns and planets. And for this the load of explosive need exceed the weight of the rocket by only a factor 15. I shall not here speak of higher speeds. But are such loads possible?

The mass of explosive material does not exceed the weight of the vehicle even in record-beating aeroplanes. The same is true for steamships. Economic factors intervene in the latter case: as much space as possible must be left for freight. In aircraft, especially large ones, the main mass of material lies in the engines, body, and wings. The store of fuel is inevitably small.

The following conditions must be complied with in order to ensure that the weight of the fuel plus oxygen should be 15 times that of the rocket.

The elements of the explosive (petroleum and oxygen) should not exert high pressures on the containing vessels (otherwise the latter would have to be massive).

They should be dense, in order not to take up much space. In this respect even liquid hydrogen is unsuitable, as it is 14 times lighter than water.

The increase in speed (acceleration) of the vehicle should not be more than 10 m/sec, otherwise the relative increase in the weight of the elements of the explosive and in all parts of the vehicle would force one to make the latter stronger, and hence more massive and heavier. It would be better to give the vehicle an inclined motion.

Safety, lightness, and good performance in the rocket require also the following:

1. Separation of the elements of the explosive, whose gradual combination gives the reactive pressure.

2. Use of a conical pipe, the materials mixing and exploding in the narrow part.

3. Piston pumps to handle the elements of the explosive.

4. Periodic pumping. This would give the effect of a series of blank firings at the rate of about 50-100 a second.

After each firing the barrel (blast pipe) clears of gases, and then only a small force is needed to inject the components of the explosive. Without this the pumps and motors would have to supply an unreasonably large power*.

Flight in a rarefied medium (stratosphere) and later in the vacuum of cosmic space would require special equipment for keeping the pilot and passengers alive. This includes:

1. A sealed body impermeable to gases, as in Professor Picard's flights (he reached heights of 16-17 km, where the air was 6 times less dense than at sea level).

2. Supply of the interior with oxygen. The daily requirement per man does not exceed one kilogram.

3. Alkalis and other substances to absorb the products expired and excreted.

4. A store of food. Specially chosen plants that provide abundant oxygen and food may prove useful for long flights outside the atmosphere. This obviously demands transparent windows and sunlight (plants absorb carbonic acid and produce oxygen only in response to light). There will be no lack of sunlight, because clouds, air, and mists do not occur outside the atmosphere.

5. Control of the temperature of the rocket by adjustment of surfaces that reflect and absorb sunlight. This system would be constructed as follows: in addition to the strong and gas-tight shell of the device, there would be mounted on the latter another resembling the scales would be moved apart to make the surface of the rocket shiny, while by bringing them together and folding them (scale under scale) the black gas-tight body would be exposed.

The adjustable skin would serve also for protective cooling of the body during flight through the atmosphere.

These cosmic speeds (8-16 km) are impossible in the lower layers of the atmosphere, for there they would be rapidly lost, on account of the enormous resistance of the atmosphere.

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*There are now pulsed jet engines having explosion rates of about 50 per second as well as liquid-fueled jet engines in which the fuel components are fed into the engine either by means of high-pressure gas or by special pumps (Editor).

But the reaction machine accumulates its cosmic speed gradually and attains it finally only outside the atmosphere.

It would be best for the early part of the path to be that of inclined rising accelerated flight; flat wings are useful there, and the speed in the lower layers of the atmosphere is low. It would rise gradually to one or two km/sec in the rarefied air, but there this speed would not give high resistance, as the air is highly rarefied. The surface of the vehicle would also not be greatly heated, because the air in the upper layers is not only rarefied but cold*. A single insulating layer (e.g., of powder or cork) would probably suffice to prevent excessive heating of the rocket. The most suitable for this purpose (on grounds of weightlessness) would be a vacuum between the first and second shells of the device (for which purpose the air there must be pumped out).

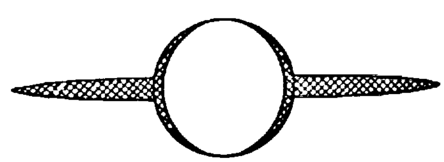

Fig. 2.

Figures 2 and 3 show schematically the device in its simplest form.

1. The wings resemble tailplanes. They would not be heavy, on account of the small size, and on account of their great length (along the vehicle) they would not be very thick. Their effect at low speeds would be slight, but at high speeds it would be greater. The wings should be almost flat.

*Current evidence indicates that high positive temperatures occur at heights above 80 km (Editor).

2. The adjustable polished skin (only part is shown in the figure) covers the black surface of the body the better the more nearly normal it is to the surface of the rocket, which produces a fall in temperature. Conversely, the more nearly parallel it is to the body, the less the loss of heat and the higher the temperature. The windows facing the sunlight should not be covered by the scales when a high temperature is attained. During flight in the atmosphere, the scales should join up to form a single surface, so no temperature control is possible there. This makes adjustable lengthwise scales best.

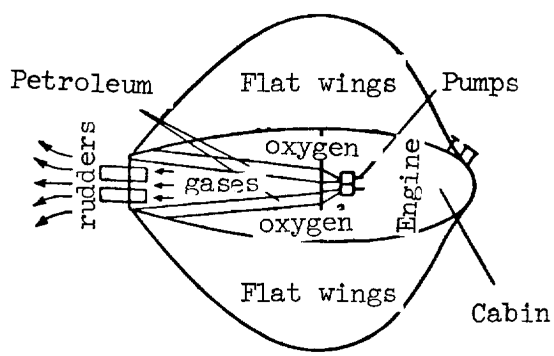

Fig. 3.

3. Cabin for humans.

4. A gas-tight strong shell that can sustain a pressure of one atmosphere at least.

5. Adjustable scales (as in a fan).

6. Low-power motor.

7. Pumps for oxygen and petroleum.

8. Mixer for explosion elements.

9. Conical pipe. The expanded and cold gases escape from the wide end with a relative speed of 3-6 km/sec. This speed is always the same for a given vehicle.

10. Two each of vertical and horizontal rudders; these work even in a vacuum on account of the directional flow of the combustion products (the gases act as the bearing medium of the rudder blades.

11. Liquid oxygen.

12. Petroleum.

(See Tsiolkovskiy, "The Cosmic Rocket", 1927, for details.)

The design and operation of reactive systems similar to that described is relatively very simple. The liquid oxygen and petroleum mix in the combustion chamber, explode, and are ejected as expanding gases via the conical pipe; in doing so they impel the walls of this forward, and hence the vehicle as a whole. The impermeable and very elongated surface controls the temperature during flight; it is cooled by the petroleum, and the latter is cooled by the oxygen. Even special tanks for the fuel are absent (only partitions are used). The design always envisages two separate pumps and a low-power motor. Two rudder systems are used to control the vehicle and to prevent spin.

Simplicity and lightness are the advantages of this system, whose main defect is the need to carry oxygen. The amount required is over three times the amount of benzine, for example, which causes a 4-fold increase in weight (see: The Reactive Aeroplane, 1930).

Experimental flights with a device of this type must be performed gradually. At first the rocket may be restricted to flights in the lower layers of the air (troposphere), then to ones in the upper layers (stratosphere), next it may fly to the vacuum beyond the atmosphere, and finally to space flights.

Hohmann and I have shown that return need not involve the consumption of explosive material: first there is required a rapid spiral motion in the highly rarefied layers of the air, then a gradual loss of the cosmic speed in the more dense ones, and finally straight gliding and descent to earth or water as for an ordinary aeroplane.

It might seem that these purely reactive devices are very unpromising, for which reason little work has so far been done on them in Europe and America. For instance, the most successful rocket flight (Ridel's of 1931 near Berlin) reached a height of only 1.5 km. The greatest height reached was that by Dr. Lion's Italian rocket (9.5 km).

Other practical results are even less notable.

Goddard's and Swan's rockets with wings have not proved justified. For instance, Swan's planer (weight 80 kg) reached a height of only 60 m.

The causes of this poor performance lie in part in the deficiencies of equipment and in part in the errors of the experiments. I have pointed out these errors in my pamphlet "To Astronauts" (Zvezdoplavatelyam); there is not space here to go into these details.

After all, the first attempts to make aeroplanes were no less disappointing.

* * *

Now I turn to high-flying aeroplanes (stratoplanes). These are ordinary aeroplanes equipped with extremely light and powerful engines, with air compressors, with airscrews having blades of large angle of attack (ones lying near to the direction of flight), and with numerous coolers.

Such a stratoplane can fly only in air. Its design is very complicated, and its mass is necessarily high.

My calculations, which have been confirmed by recent workers (Corwin-Krukowskiy; see Professor Rynin's Superaviatsiya i superartilleriya (Superaviation and Superartillery), 1929, pp. 51-53), show that the speed of a stratoplane (other things being equal) is proportional to the square root of the rarefaction of the medium, while the power must be proportional to the flight speed.

The following table is derived from these relations:

Relative rarefaction (lightness) of air in which aeroplane flies	1	4	9	16	25	36
Corresponding speed of horizontal flight	1	2	3	4	5	6
Relative power required of engine	1	2	3	4	5	6

This means that the engine power must be doubled in order to double the speed (which increases the weight of the aeroplane); alternatively, the engine must be made twice as light for the same power. The latter is the sole deduction. It may be that time will witness great increases in lightness; let us say that it will increase 5-fold (200 g per horsepower). Then the forward speed will increase fivefold. This speed has reached 200 m/sec (720 km/hr) with engines of ordinary weight, so with the lighter ones it would rise to 1000 m/sec (3600 km/hr).

Such aeroplanes could cross the Atlantic in 2-3 hr; this crossing would be made at relatively small heights, where, however, the air is 25 times more rarefied than at sea level.

Newspaper evidence indicates that the famous constructor Farman is very much concerned with high-level aircraft; he hopes that the speed of a stratoplane will be doubled at a height of 6 km, and quadrupled at 12 km. The atmosphere is rarefied by a factor two at 6 km, and by four at 12 km, so in the latter case the speed could only be doubled relative to the record value, and that on condition either that the specific weight of the engine is halved or that the power and weight are doubled. This doubling of speed is hardly to be expected, for the complexity of a high-flying aeroplane will lead to a corresponding increase in weight.

The English press declares that it has been proposed to fly across the Atlantic in 1932 at a height of 16 km with a speed of 1250 km/hr (347 m/sec). The air is 6-fold rarefied at a height of 16 km, which means that the speed could be increased by a factor 2.5; but this would require 2.5 times the energy from an engine of the same weight. If the record speed for long distances stood at 100 m/ sec (360 km/hr), it would be possible to attain a maximum of 250 m/sec, not 347. This also is at present only a hope*. We have not even considered the increase in weight of the aeroplane consequent on the compressors and other complicated equipment associated with the rarefaction of the air.

We must assume that all of this will come about in the future, but conditions appropriate to it are not yet in existence. Of course, the results achieved in high-altitude flights are magnificent, but how can the engines be lightened 5-fold? So far the basic speed (200 m/sec or 720 km/hr) has not been attained in the lower layers of

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*Current experimental aeroplanes have speeds exceeding that of sound, that is, over 340 m/sec (Editor).

the atmosphere, and at height a great hindrance is presented by the extremely complicated design of the stratoplane.

A publication of mine to appear shortly, "Stratoplan polureaktivnyy" (The Semicreative Stratoplane) deals with my proposal for semireactive stratoplanes. These are also complicated, but they should sooner provide the desired advance, although they will not give cosmic speeds.

* * *

Interstellar flight is only a hope and is very far off. It will have come very much closer when we have discovered how to use the Sun's energy, only one two-billionth part of which reaches our planet.

But several stages have to be passed through before this goal can be approached. The first stage is that of improvement of the ordinary aeroplane and attainment of a doubled or trebled speed of flight at heights of 12-18 km, where the air is 4-9 times less dense. We shall then have available speeds of 200-300 m/sec (720-1080 km/hr), and trans-Atlantic flights will have shortened to 8-10 hr (see my "New Aeroplane" of 1929).

Then the semireactive stratoplane will make its appearance; its speed may be vastly greater, say up to 1000 m/sec or 3600 km/hr. This will fly at heights of 23-24 km, where the atmosphere is 100 times less dense than at sea level*.

There will be no economy in the consumption of fuel; theory shows that the same mass of fuel is consumed per unit path or over any given path. Moreover, the semireactive stratoplane will be very complex and costly, which cannot but be reflected in the cost of flights.

But even this will not provide complete victory over the stratosphere. In the next stage the purely reactive vehicle will enable us to penetrate even further, on account of its great simplicity and large store of oxygen.

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*The International Standard Atmosphere gives the density of air at a height of 24 km as 26 times less than that at the surface of the Earth (Editor).

Practical experience will decide its maximum speed, but we should not forget that centrifugal force becomes appreciable at speeds above one kilometer per second, and thus reduces the weight of the rocket. All weight is lost at 8 km/sec, and the vehicle is carried outside the atmosphere. That is when we shall attain victory over the air ocean and shall overcome terrestrial gravity.

The rocket in its spiral ascent will then fly in a vacuum in the manner of a small moon close to us.

However, we can hardly reckon on attaining this first cosmic speed without the use of accessories.

These accessories are as follows:

1. A specially equipped solid rising path must be used to provide preliminary acceleration. No fuel is consumed by the rocket in this time, but energy is drawn from equipment at the sides of the way (as in a streetcar).

2. A multirocket train flying in the atmosphere must be built up. One of the component rockets then acquires the greatest speed and flies out of the atmosphere, while the others return to the Earth (see: Cosmic Rocket Trains, 1929)*.

3. The flying vehicle must at first be powered by terrestrial energy via material or immaterial drives (e.g., gunpowder or radiant energy).

Having reached the highest possible speed, the rocket continues its flight with its own energy by burning its load of explosion elements.

My book "The Aims of Interstellar Flight" (1929) deals with the benefits and powers that man will gain by overcoming gravity and conquering the solar system.

Mastering the Sun's energy, which at present is dissipated in space, is not yet conquest of the Moon and planets. Even a landing on the Moon represents a complex and difficult task for many reasons. It is early even to think of this as regards the major planets

The minor planets (asteroids) are very accessible, as these are 10 to 400 km in diameter; celestial bodies of smaller size are even more accessible. These will be the first attained by cosmonauts and

*This method has come to be fully accepted in recent scientific-technical studies (Editor).

the first to be conquered by man. There also we shall find the first material for building in the bottomless pits of the ether.

When will all this happen?

No one has the power toforesee this, even if he allows for the rapid progress of science and technology at the present time. It will probably require decades, if not centuries.

On the other hand, it is all possible. The rate of progress is the unknown quantity.

THE ASTROPLANE*

An astroplane is an aeroplane without an airscrew; the wings have a scarcely appreciable concavity, in view of the extreme rapidity of its motion. The explosive elements (i.e., fuel and oxygen) are separated, as in Fig. 1. They are injected into the combustion chamber

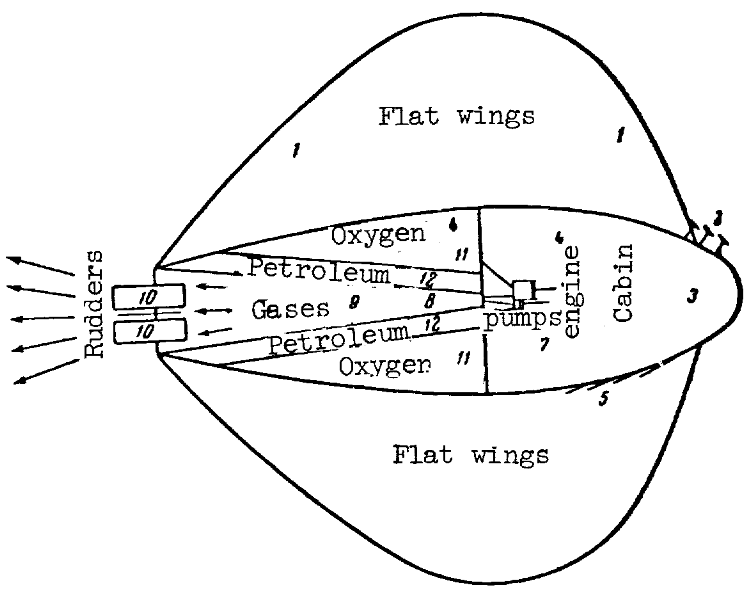

Fig. 1.

*This article was especially written by K. E. Tsiolkovskiy for this journal (note from editor of "Znaniye-sila", No. 23-24, December, 1922).

by two piston pumps, where they encounter a special mixing lattice and are detonated in the various standard ways. From the combustion chamber they pass to a conical pipe, from which they escape to the exterior from the rear of the vehicle after cooling by expansion and rarefaction. The recoil from these gases produces the continuously accelerated motion of the rocket. The wide outer part of the pipe (nozzle) is fitted with rudders for direction, height, and lateral stability. The directional flow of the exhaust gases allows these to work in a vacuum without effect from any surrounding medium.

The combustion chamber performs a series of explosions as in a Browning automatic or machine gun. The only differences are that in this reactive astroplane the barrel is conical and the firing is blank (without projectile), and that the components of the explosive are separated and are mixed only in the combustion chamber. A further difference is that a special motor is used to pump them. The latter could be eliminated by the use of the recoil (reaction), as in a machine gun. This would further simplify the vehicle, which then would differ only a little from a machine gun.

Such a gun performs ten or so explosions a second; the number in an astroplane could be larger, because the gases escape more rapidly from the pipe (nozzle) in blank firings. Aviation engine give 20 or more explosions per second in the cylinders Engines of speeds of about a hundred revolutions per second (50 explosions per second) are known.

If each stroke of the pump delivers 100 grams of explosive, then 40 strokes per second lead to the combustion of 4 kg of explosive material. This is quite sufficient for the flight of an astroplane of weight one ton and would produce continuously accelerated motion.

But the explosion chamber and conical pipe (nozzle) would become very hot if measures were not taken to cool them, so they are surrounded by the liquid fuel, while the latter is surrounded by the liquid oxygen, which evaporates freely. It is desirable to keep these liquids continuously stirred.

A metal pipe is also a good conductor of heat The wide part is strongly cooled by the expanding gases, so by conduction it can convey its cold to the narrow hot part and thereby reduce its heat. It would be more correct to say that the heat of the narrow part is transferred to the cold end of the tube.

It is difficult to use the heat of combustion efficiently in machine guns and other firearms, so the tube (barrel) has to be cylindrical and very long. An astroplane has a conical tube that widens rapidly, and so it can be made the shorter the larger the angle of the cone or the rate of widening (though the angle should not be more than 30 degrees).

If we can make a machine gun, we can make an astroplane. We only need to replace part of the recoil mechanism to dispense with the special motor.

Assuming a consumption of 4 kg/sec for the explosive and a total loaded weight of a ton for the astroplane, we find that a store of 0.8 ton (800 kg) of explosive would be exhausted in 200 seconds. During this time an astroplane climbing at about 30 degrees to the horizontal would rapidly reach the rarefied layers of the air and would acquire a speed such as to carry it outside the atmosphere.

THE SEMIREACTIVE STRATOPLANE*

Introduction

An aircraft cannot attain high speeds in the lower layers of the atmosphere; if we wish to raise the speed by factors of 2, 3, or 4 we would have to increase the all-up weight of the aeroplane by factors of 8, 27, or 64 for a given engine horsepower. There are many reasons why this is very difficult. For instance, the engines might be weak, the airscrew might break from the rapid rotation, the aircraft itself might not withstand the pressure of the head-on flow, and so on.

At great heights the air is rarefied and it is easier to attain increased speeds. Exact calculations show that when the rarefaction** becomes 4, 9, 16, or 25 the speed of the aircraft can increase by factors of 2, 3, 4, or 5 provided that the power of the engines is increased by factors of 2, 3, 4, or 5; these values replace the factors of 8, 27, 64, and 125 required lower down, when the air density does not change.

The rarefied air is cold, but its rarefaction means that it does not cool the engines sufficiently.

The shortage of oxygen at great heights and the low peressure of the atmosphere make it necessary to employ a sealed body (cabin) that will not allow the oxygen to escape. Then the pressure on the human body will not lessen and man will not weaken or be unable to breathe.

In addition, it is much more difficult to increase the engine

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*First published in "Khochu vse znat'". Zhurgazob" yedineniye, 1932, No. 29, October; see Appendix, Note 62 (Editor).

**Tsiolkovskiy has in mind ρ_0/ρ_n, the ratio of the density of the air at the surface of the Earth (h = 0) under normal conditions to the density at height h (Editor).

power at height than it is lower down, because it becomes necessary to compress the air supplied to the cylinders. This increases the weight of the engine and so that of the whole aircraft. On the other hand, the increase in weight may be balanced in part by the use of the recoil (reaction) of the exhaust gases.

My speculations and calculations have now led me to consider the following type of high-flying aircraft as the most feasible.

Brief Description

1. Figure 1 shows in plan three almost identical bodies of good shape; one contains the pilot and is heremtically sealed, so in it one can breathe as easily at height as lower down. The second contains the fuel. The middle one contains the airscrew (propeller), engine, compressor, cooler, and so on. (The middle one is described further by reference to Figs. 2 and 3.) On top of the bodies there is a large wing, which serves to bind them together. At the rear there are two wings, which serve as height and lateral controls. Finally there is the rudder, which is placed at the rear of and above the middle body.

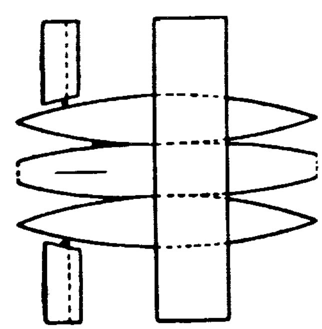

Fig. 1.

2. Figure 2 shows a lengthwise section of the middle body. The front part 1 may be more or less open (see also Fig. 3); it is never completely closed. The rear part 9 has the same construction. The airstream enters the body while the aircraft is moving, and this is facilitated by the airscrew 2, which is driven by the petroleum or gasoline engine 3. This is cooled by the general flow of air in the middle body (fuselage). Flows of pure air are indicated by single arrows. The combustion products from the engine flow along the numerous pipes 3 and come together in the annular space between the cylinders, which gradually expands.

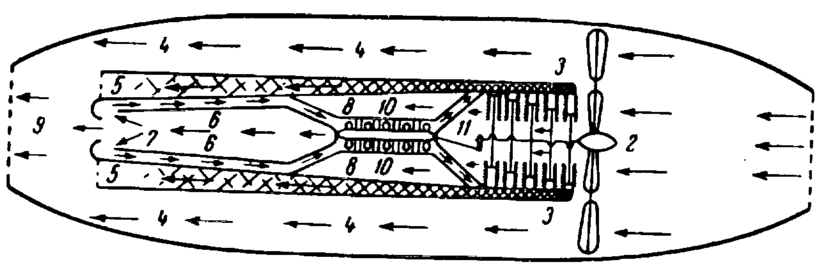

Fig. 2.

In this space the gases expand greatly, so their heat is transformed to motion and they acquire a high speed and a low temperature (up to 250^{o} of cold)*. This gives us the good cooler 5. The pipes containing the combustion products are hatched in the drawing.

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* A temperature as low as this would be obtained with an initial temperature of 2400^{o}K (that of the combustion of gasoline in air) if the combustion products undergo an adiabatic expansion sufficient to reduce the pressure by roughly a factor 17 x 10^{6}. This implies extremely low final pressures even if the initial pressures are

The double arrows show the motion of the combustion products.

The aircraft is driven by the force of the airscrew and by the recoil of the combustion products; the entire mass of gases escapes at high speed through the rear adjustable aperture in the middle body.

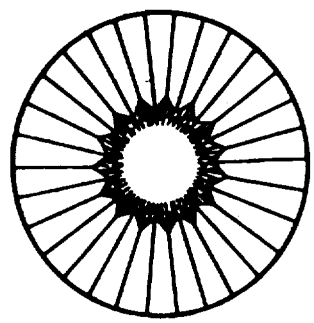

Fig. 3.

The annular space 5 of the cooler adjoins another such space, also between two cylinders. The annular aperture 7 allows a flow of air to enter this space and reverses its direction. This

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high. In fact, the resistance arising from friction within the gas and with the walls results in the production of heat and in a loss of pressure. The gases at the end of the exhaust pipe will therefore be much warmer, and their exit speed will be reduced; there may be a secondary rise of pressure within the pipe and then an ultimate fall in the pressure at a lower efflux speed. The best over-all length of the pipe can be determined for a given angle of the cone. The temperature will thus be higher than -250°C. (Note by the editor of Selected Works of K. E. Tsiolkovskiy, Moscow, ONTI, 1934.)

is strongly cooled by the cooler 5 and passes via pipe 8 to the compressor 10, which is driven by the motor 3 via gears and the universal joint 11. The compressor supplies fresh air, heated as a result of the compression, via several pipes to the motor to feed the cylinders along with the gasoline*.

The holes to front and rear in the middle body are gradually narrowed as the speed of the aircraft increases; Fig. 3 illustrates the device for doing this by reference to the front or rear hole. The surface at the end of the body consists of rectangular plates that form a diaphragm or star at the hole. Other such devices could be used.

The following is a list of the facilities provided by this.

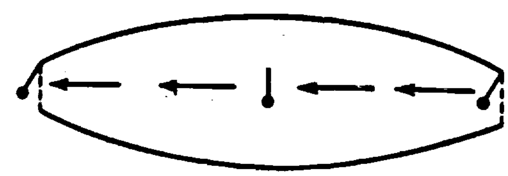

Fig. 4.

3. A sealed body for pilot and passengers, which allows of flight in highly rarefied layers of the air.

4. The airscrew always turns at a fixed safe speed (150-300 m/sec at its circumference), in spite of the high speed of the aircraft. The area of the holes to front and rear is reduced in proportion to the increase in speed. Suppose, for example, that

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*It is best to cool the air between stages in the compressor and to supply the cylinders with comparatively cool air; this increases the cylinder filling factor (i.e., the power of an engine of a given size) and reduces the work needed to compress the air. Ibid.

the speed is 100 m/sec with the throat fully open; a 9-fold increase in speed (to 900 m/sec) involves a 9-fold reduction in the area, or a threefold reduction in the diameter*. This keeps the quantity of air entering the middle body always the same, so the flow speed in the wide part of the fuselage is constant, as is the speed of the screw, in spite of the great range of speeds of the aircraft and of the air entering the throat. This is explained below.

5. The thrust of the aircraft is generated not only in the usual way (by the airscrew) but also by the recoil of the combustion products.

6. The greater the height at which the stratoplane flies the more rarefied the atmosphere and the greater the expansion of the gaseous combustion products, so the lower the temperature of these, the greater the cooling of the air supplying the engine, and the greater the effect of the compressor, since this operates correctly in dense and rarefied atmospheres.

The theory of the gas compressor is to be found described in a separate publication of mine**.

7. At first the stratoplane runs on rails, snow, or water (it is also a stable hydroplane). On reaching a speed of 100 m/sec it ascends and flies obliquely upward faster and faster. It would attain a limiting speed of about 200 m/sec in the lower layers of the air, but as it rises steeply it encounters ever more rarefied layers, so its speed continues to rise, at first slowly and then (at great heights) more rapidly.

8. The engine not only does not operate less efficiently but actually more so, on account of the low temperature of the cooler and the strong cooling (even, perhaps, liquefaction) of the air entering the compressor.

9. The drawings are schematic. All minor details have been omitted to make the design and performance of the vehicle better and more easily understood; the fastening fixtures and the mechanisms for adjusting the air inlet and outlet have not been shown, for example.

10. If the speed of the stratoplane is to exceed that

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*The effects at the inlet become complicated on account of shock waves as the speed of sound is approached.

**Szhimatel' gazov (The Gas Compressor). Kaluga, 1931, 36 pp.(Editor).

permissible for an ordinary airscrew without fuselage by a specified factor, it would be more practical to make this fuselage smooth and of good shape, but with equal holes at front and rear.

If, for example, the speed of the vehicle is to be 9 times the ordinary speed, the holes are reduced 9-fold in area or 3-fold in diameter.

Stratoplanes may thus be designed for doubled, trebled, and so on speeds.

The fuselage could have special lengthwise holes that are closed gradually (at the top at the front, underneath at the rear) in order to avoid expenditure of excessive work during the start of the flight at low speeds. The lift is thereby increased.

The Air Compressor

11. The ordinary airscrew is inapplicable at the high speeds of a high-flying aircraft because it breaks at a certain peripheral speed no matter what its size. For the same reason the blades of the blower must not exceed a certain limiting speed at the periphery. The angular speed increases as the diameter of the screw is reduced, but the speed at the circumference cannot exceed a limit dependent on the strength of the material used.

12. Figure 2 shows the compressor fan, except that at the rear (where the flow emerges) there must be added a conical surface narrowing towards a vertex. The aperture at the vertex can be narrowed or widened as desired; the surface can be transformed from a cone with a scarcely visible hole to a cylinder.

13. The compressor (Figs. 2 and 3) consists of a circular cylindrical tube within which rotates another closed cylinder bearing airscrews arranged around it (these resemble aircraft ones or take the form of an archimedean spiral). A flat fixed blade is placed between each pair of screw circles parallel to the axes of the cylinders This may be located eccentrically in the large cylinder and fixed to it. The object of these blades is to suppress rotation of the air in the compressor. The diameter of the inner rotating cylinder is about half of that of the outer fixed one.

14. When the shaft rotates with the end cone (cylinder) fully open, there is scarcely any resistance to the flow of the air, which moves almost without compression, as from the action of a single screw. But as the exit hole is closed (Fig. 3) the gas becomes more strongly compressed.

The action is most readily understood if we imagine the exit to be completely closed; there is no flow, but the air becomes more highly compressed the nearer it comes to the end of the tube.

15. In this case each pair of blades compresses the gas by a certain amount. Let us assume that the first screw increases the pressure of the air by a factor 1.1: then the second screw together with the first increases the pressure by a factor $(1.1)^2$, the third together with the first and second by $(1.1)^3$, the tenth by $(1.1)^{10}$, and so on.

The maximum pressure (compression) clearly increases with the number of screws; it is represented by the series (1.1), ..., $(1.1)^3$, ... $(1.1)^{10}$ in a single tube. The last number here represents the pressure in the tube after the tenth airscrew.

The compression also raises the temperature, which alters the above deductions by tending to reduce the pressure, since the density of air is reduced by heating.

16. If the aperture is opened a little, a flow is obtained; but the pressure is then somewhat reduced from the above. The larger the aperture in the cone (Fig. 3) the faster the flow, but the less the pressure and compression (the actual effect is much more complicated).

17. There is an average external resistance for which the performance is best.

18. We assume that the shaft is covered by a cylinder whose diameter is half of that of the tube. The screw blades are arranged in a circle on the small cylinder and the air flows in the annular space between the two cylinders. This annulus constitutes 0.75 of the cross-sectional area of the large cylinder. The small cylinder ends in smooth surfaces, which close it at both ends.

19. Figure 2 shows a lengthwise section of the compressor 10, with the baffles, which are fixed to the large cylinder but which do not touch the small one. The baffles have the function of suppressing rotating flows in the tube, which would eliminate or reduce the stress on and forward motion of the gas.

20. It is best if baffles of least resistance also have the least weight; for this purpose both ends of each baffle are attached to the large cylinder.

Calculation of the Compressor

21. First we determine the maximum peripheral speed u of a rotating body. Let this body be a cylindrical rod or a cylinder generally placed perpendicular to the axis of rotation (as a spoke in a wheel).

The largest speed at the periphery is obtained if the largest stress in the cylinder (at the axis) produced by the centrifugal force is equal to the resistance of the material. On this basis we get the equation

$$\frac{u^2 l}{l g} \cdot \gamma \cdot 0.5 = \frac{K_z}{S} ,$$

in which l is the length of the cylinder, g is the acceleration due to gravity, γ is the density of the material, K_z is the tensile strength of the material, and S is the safety factor. The factor 0.5 arises from a simple integration. Then

$$u = \sqrt{\frac{2g \cdot K_z}{\gamma S}} .$$

This shows that the maximum peripheral speed of a cylinder is not dependent on the thickness or length; the number of revolutions per second is naturally the larger the smaller l, but u is proportional to the square root of the strength of the material and inversely to S and γ as the formula shows.

22. The rod may taper toward its ends (as a wedge or cone, or as a body of constant resistance); this increases the peripheral speed. But we have in view the blades of an airscrew, so it is

hardly convenient to reduce the cross-sectional area towards the ends. In any case, the blade becomes thinner away from the cylinder.

23. Now we consider the compression of the air by a blade of the fan.

The blade has the shape of part of an archimedean spiral. We use only the top half of the rod.

Let tan α indicate the inclination of the top element of the blade to the circle of rotation; then the inclination of the lower element is 2tan α. The maximum flow speed of the air normal to the circle in the cylindrical tube is $v = u \tan \alpha$; this speed is the same for the whole of the blade for a given cross-section of the tube, by virtue of the properties of an archimedean spiral.

24. The maximum pressure P produced by this flow of air along the tube is not less than

$$P = \frac{(u \text{ tg } \alpha)^2 d}{2 \cdot g}.$$

25. We can eliminate u by means of formula (21) to get

$$P = \text{tg}^2 \alpha \, [K_z : (\gamma S)] \cdot d.$$

The maximum pressure is the value of interest to us; it increases with $K_z : S$, with the density d of the medium, and with the square of the tangent of the angle of inclination of the blades.

Large safety factors S are unsuitable.

26. The tangent of the angle of the upper part cannot be taken as larger than 1; then the angle between blade and circle is 45°, the angle for the lower part being 64.5°. Further, we put $K_z = 2 \times 10^6$ kg/cm^2 of cross section in (25), which applies only to selected and tested grades of chrome steel or other such steel; $\gamma = 8$, $S = 4$ (not less), and $d = 0.0012$ kg/dm^3. Then from

formula (25) we have P = 75 kg/dm^2 or 0.75 atm. Formula (21) gives the corresponding peripheral speed of the blades as u = 353.5 m/sec.

27. A more realistic value is tan α = 0.5; then P = 19 kg/dm^2 or 0.19 atm and u = 353.5 (unchanged).

28. A cylindrical tube having several airscrews on one shaft gives the following maximum pressures. We can take the pressure increase as being by a factor 1.2 on the assumption of constant temperature or of artificial cooling of tube and air.

No. of airscrews	1	2	3	4	5	6	7	8
Compression ratio	1.2	1.44	1.73	2.07	2.48	2.99	3.59	4.28
No. of airscrews	10	12	14	16	18	20	22	24
Compression ratio, approximately	6.75	8.94	12.9	18.3	26.3	37.8	54.44	79.9

29. Values even closer to the practical case for use in formula (25) are

$$\tan \alpha = 0.5; \quad K_z = 10^6; \quad \gamma = 8; \quad S = 5; \quad d = 0.0012.$$

Then P = 75 kg/dm^2 or 0.075 atm. From formula (21) we have u = 223.6 m/sec.

30. On this basis we get the table:

No. of screws	2	4	6	8	10	14	18	20
Pressure, atm, approx.	1.15	1.32	1.52	1.74	2.00	2.64	3.48	4
No. of screws	30	40	50	60	70	80	90	100
Pressure, atm.	8	16	32	64	128	256	512	1024

31. Large compression ratios are needed for a stratoplane flying at great heights in highly rarefied layers of the air; this demands a small number of screws and a vast volume intake of air for combustion.

On the basis of (26), namely u = 353.5 m/sec, for a compression of 1.75 (one screw) we have

No. of screws	1	2	3	4	5	6	7	8	9	10
Compression ratio	1.7	2.9	4.9	8.4	14.3	24.0	40.8	70.5	117.6	204.5
No. of screws	12	14	16	18	20	22	24		26	
Compression ratio	591	1714	4960	14 380	41 470	120 000	348.10^3		10^6	

Of course, all these tables give the maximum (limiting) pressure. High degrees of compression are applicable only for corresponding rarefaction of the air in the higher layers of the atmosphere.

Use of the Compressor

32. This compressor can give any desired pressure (until the gas is liquefied or a very high temperature is reached) and any desired amount of air. The efficiency with which the engine power is used will depend on the design of the compressor and on the pressure and flow speed.

The low efficiency is offset by the simple design, the lack of need for lubrication, the compactness, the possibility of using high temperatures, the lightness, and the low cost. This system is used in fans, in houses, in blast furnaces, and in devices which need a great deal of air at high pressures and high temperatures. It is also applicable to stratoplanes, reaction-drive vessels, road vehicles, and fast trains (see, for example, "Zeppelin on rails" and my wheelless train). It converts mechanical work to heat and conversely; it can also serve to raise liquids and as a turbine.

The Propeller

33. This differs from the above compressor in that it has in front a cone resembling the rear one (Fig. 4). The number of airscrews can be varied indefinitely and may even be only one (Fig. 2).

When the propeller with the holes fully open to form a cylinder moves with the vehicle, the speed of the flow (relative to the tube) is c + w, i.e., the speed c of the vehicle plus the slipstream speed w relative to the screw resulting from the section of the latter. But c can be very high, so the relative speed of the flow in the propeller tube is also high; but the latter cannot exceed the limit set by formula (21), which gives

$$v = \sqrt{\frac{2g \cdot K_z}{\gamma S}} .$$

This is a closely defined speed; its maximum we have found as 353 m/sec. It means that the vehicle cannot have a higher speed, for the airscrews (blades in the tube) would break from centrifugal force.

34. How can this be remedied? Cannot the vehicle have a higher speed? There is a way out of this impasse.

We start with an experiment (Fig. 4). I constructed the outer part (fuselage) of my propeller without the blades (without the screw).

The plates (bobs) in this tube were very wide in the middle and were placed at four points: in the middle, at the entrance, at the exit, and to the side at the entrance (outside the tube). The two holes were of the same size and the bobs were identical.

With this device I moved uniformly or stood at the half-open door of a warm room; in the latter case there was a very regular flow from the warm room into the cold one at the top of the door.

All the vanes were identical, so the observed equal deviation of the extreme ones pointed to identical forces or flow speeds; but the middle vane was deflected only a very little. This indicated a low air speed in the central part of the tube.

35. What we see is as follows. Let such a tube move together with the vehicle along its long axis. The head-on flow enters the front hole with the speed of the vehicle*, but the speed becomes very much less in the wide part of the tube; the air leaves the exit with the speed with which it entered, though. My experiment confirms this.

36. If we reduce the area of the end holes in proportion to the increase in the speed of the aeroplane, the relative speed in the wide part of the tube will remain unchanged in spite of the increased speed of the vehicle. In fact, a speed increased (say) by a factor 10, if accompanied by a reduction in the areas of the holes by the same factor, will leave the volume of air entering the propeller unaltered. The cross-sectional area of the tube at the center is unvarying, so the flow speed in this cross-section cannot alter.

37. The airscrews will thus work safely at any speed of the aircraft, since their peripheral speed will not increase, in spite of the increase in the speed of the aircraft.

The relative speed of the air at intake and exit in the absence of the screws will be roughly equal to the speed of the

*See footnote on p 392 (Editor).

aircraft (a slight reduction arises from friction and from the changes in temperature associated with compression and expansion). But the action of the propeller will increase the speed to a certain extent, on account of the energy power.

This means that the flow at the exit has a speed somewhat in excess of that of the stratoplane.

38. The holes must be closed down as the motion accelerates. For instance, if the speed of the stratoplane increases by a factor of 25, the areas of the holes must be reduced by a factor of 25, and the diameters by factors of 5.

39. The adjustment must be effected by reference to the accelerometer in the vehicle; the holes must be adjusted to maximize the acceleration. The accelerometer is a simple instrument having the special purpose of indicating precisely the acceleration of any body. This device enables one to use the airscrew at any speed of the aircraft, since the screw always rotates at the same speed, no matter what the speed of the vehicle.

The highest flow speed in the middle part of the tube has been shown to be 353 m/sec; a lower speed (say, 210 m/sec) would be safer. At first this speed is not obtained, but the speed of the vehicle rises gradually and eventually attains (say) 200 m/sec. The speed of the slipstream (relative to the screw) we take as 10 m/sec. The flow speed and angular speed of the blades should not increase further while the tube is of cylindrical form (completely open at the ends), so the holes are gradually narrowed in proportion to the increase in the speed of the motion as that speed continues to increase.

The following table illustrates this:

Vehicle speed, m/sec	100	200	400	900	1600	2500
Relative area of end sections of tube	1	1	1/2	2/9	2/16	2/25
Relative diameter of holes	1	1	0.707	0.471	0.354	0.284

The flow speed in the wide part of the tube will always be 10 m/sec, but the speeds of the intake and exit flows (which are roughly equal) will be

110	210	420	945	1680	2625

Of course, the holes may be narrowed more than the values given (though this is unfavorable), but they cannot be enlarged beyond their norms, as the airscrew would fracture.

The propeller tube can therefore move with the holes fully open only up to a speed of 100 m/sec; past this point it is essential to narrow the holes. Greater narrowing than necessary leaves the airscrew intact, but it breaks if narrowing values lower than those given in the table are used.

This stratoplane needs at least 100 metric horsepower for an all-up weight of 1 ton even in order to reach moderate heights, so the engine must be lighter than an ordinary aviation one. It needs to give about 2-4 metric horsepower per kg of its weight. Practical values are approaching this, and there are already (1930) engines giving up to 2 HP per kg of weight.

A STEAM-GAS TURBINE ENGINE*

Foreword

Very heavy engines can be used in ships; lighter ones are used on railroads. Automobiles, seaplanes, speedboats, and dirigibles must have even lighter engines; while high-flying machines need engines of quite unusual power with small weight and volume, which do not exist yet.

The specific weight of an engine is the weight per metric horsepower (the metric horsepower is 100 kg-m/sec, or 4/3 of the British horsepower).

For instance, a locomotive engine weighs 100 kg, an automobile engine 4 kg, and an aeroplane engine 1 kg.

We would like to have an engine with a specific weight of 0.2 kg or less. This lightness would enable one to use in the flying machine an engine of extremely high power, which is necessary for high flights.

The same or even greater lightness is required for high-altitude aeroplanes or stratoplanes.

The specific volume of the engine is also important; this is the volume per unit power. Space is restricted in a flying machine, so small size in the engine is very necessary. Such a motor cannot have boilers and coolers, of course. Piston engines are also unsuitable as being heavy and being damaged by the high temperatures inevitable in a light and powerful engine. The use of compression cylinders and lubrication is to be avoided. Complexity must be eliminated with a view to economy of material and cheapness of the engine.

Lightweight engines must breathe atmospheric oxygen, because carrying liquid oxygen, and especially nitrogen compounds of oxygen, would heavily load the machine. Also, pure oxygen gives temperatures too high for constructional materials to resist (iron alloyed with small amounts of other metals.) The fuel must give as much heat as possible and must be of the highest density. Liquid hydrogen satisfies the first condition, and dense petroleum products satisfy the second. Initially, petroleum is to be preferred, it being necessary to transfer to hydrogen afterwards. The great disacvantage of the

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*Printed from the original of 1934 (Editor).

latter is its low density, even in liquid form (0.07 of that of water).

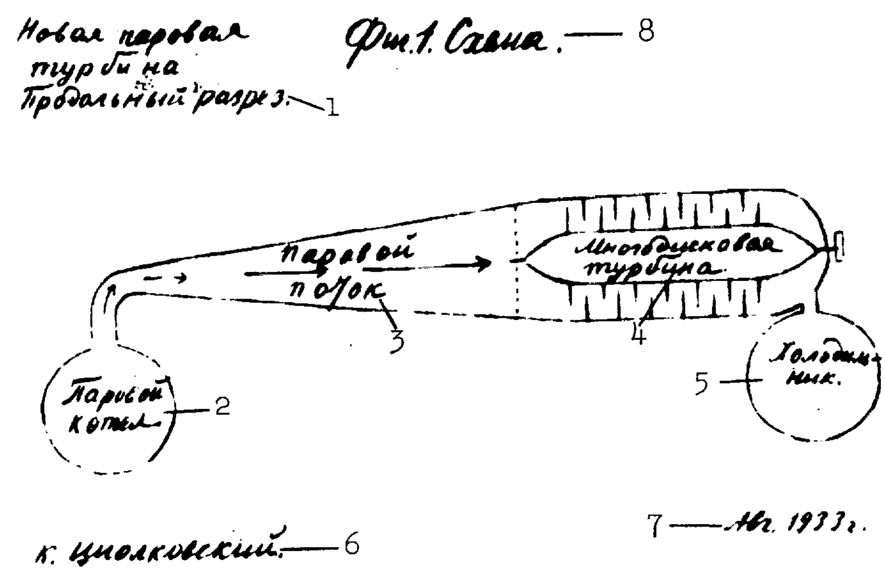

Fig. 1

1. New steam turbine, longitudinal section; 2. Steam boiler; 3. Steam flow; 4 - Multidisc turbine; 5. Cooler; 6. K. Tsiolkovskiy; 7. April 1933; 8. Fig. 1: diagram.

My engine has 4 main parts (Fig. 4): air compressor 1, small boiler or carburetor 2, turbine 3, and a pump (not shown) for delivering the fuel to the boiler. The compressor forces air into boiler 3 at the highest possible pressure; the higher this pressure relative to that of the surrounding atmosphere, the better the use made of the heat of the fuel. In addition, the higher the absolute pressure the less the specific volume and specific weight of the engine. The best machine will thus be one working with compressed air at sea level.

However, very high compression of the air is a disadvantage not only on account of the large amount of work needed but also (particularly) on account of the high temperature. For instance, compression to 10 atm raises the temperature to 418°C. This is not altogether excessive, as the compressed air can be cooled somewhat. The work of compression is recovered when the combustion products expand.

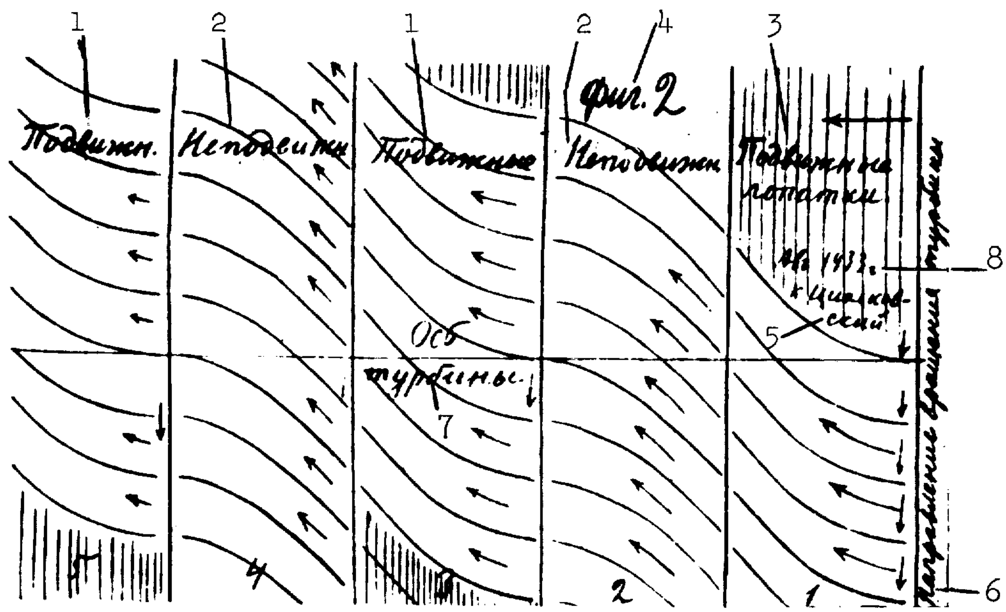

Fig. 2

1. Moving; 2. Fixed; 3. Moving blades; 4. Fig. 2; 5. K. Tsiolkovskiy; 6. Direction of rotation of turbine; 7. Axis of turbine; 8. April 1933.

A compression ratio of 10 (say) always gives the same rise in temperature no matter what the rarefaction or density of the atmosphere, namely from 0 to 418°C (absolute temperature increased by a factor 2.53).

The combustion chamber receives oil in the form of a fine spray at the same time as the air; the combustion here is incomplete, and it continues in the conical tube between the combustion chamber and the turbine, where the combustion products expand and so cool, thereby acquiring a high speed and completing their combustion.

The cooling of the combustion products from the expansion is the larger the more rarefied the surrounding atmosphere.

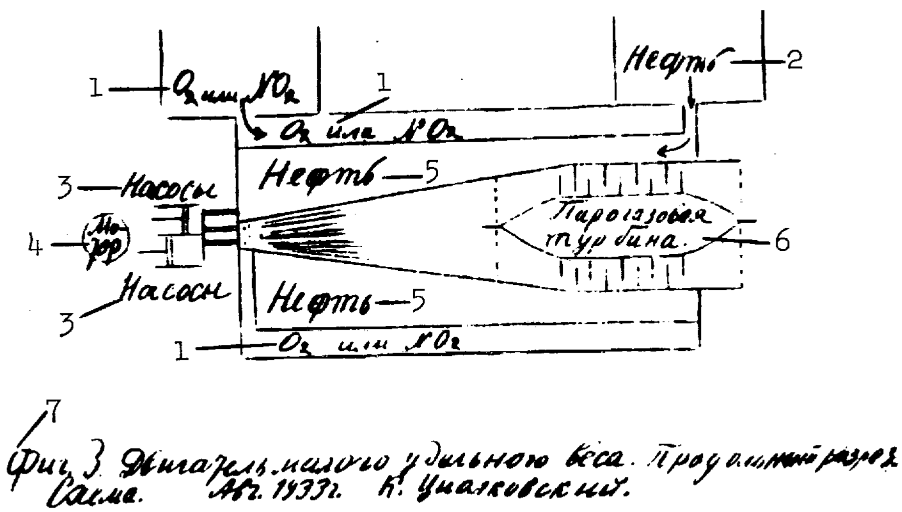

Fig. 3

1. O_2 or NO_2; 2. Oil; 3. Pumps; 4. Engine;

5. Oil; 6. Steam-gas turbine; 7. Fig. 3. Engine of low specific weight, lengthwise section, schematic. April 1933, K. Tsiolkovskiy.

These highly cooled products drive a multidisc turbine.

The gas exerts a force simultaneously on almost the entire surface of the discs.

Dirigibles use exhaust gases to heat the hydrogen and so adjust the lift; water then condenses in the heating tube, and the liquid flows to a store. There is no vacuum in the heating tube, and the gases escape into the atmosphere. Stratoplanes use exhaust gases much more extensively cooled than in the previous case in order to obtain recoil (reaction).

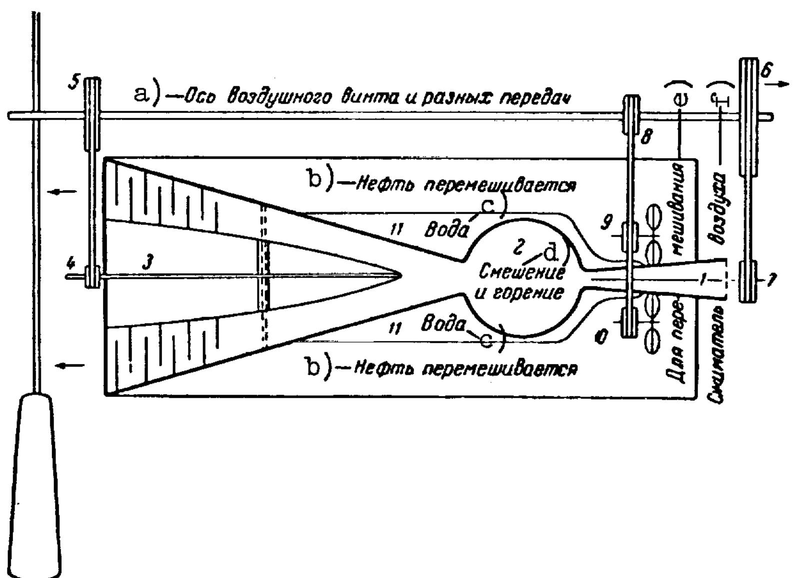

Fig. 4

a) Shaft of airscrew and of various gears; b) oil mixed; c) water; d) mixing and combustion; e) for mixing; f) air compressor.

The high temperature of the tiny boiler-carburetor makes cooling necessary; the surrounding oil provides this, and the oil is continuously stirred to carry the heat from the strongly heated boiler to cooled parts of the machine, where the turbine is and where the relatively cool gases emerge. A special cooling jacket filled with water could be fitted around the combustion chamber and the nearby very hot parts of the conical tube. When the water in this jacket becomes heated to 179°C and the pressure rises to 10 atm, the steam generated rushes into the combustion chamber and serves to strengthen the steam-gas flow and thereby increases the power of the turbine.

The jacket (11 in Fig. 4) is also surrounded by the oil 9 and 10, which is circulated by a special drive and rotating blades. The water cools the combustion chamber and is cooled by the oil; the oil is cooled by the walls of its tank, and the walls are cooled by the atmosphere. Tests might be made of operation without water. The oil might be cooled by spraying it in the air flow and then collecting it. This is simpler than cooling with air bubbles or air pipes.

The engine is set in action as follows. First, a special accessory motor starts the air compressor 1 and the oil pump; combustion chamber 2 and turbine 3 start to work. Then this motor (not shown in drawing) is switched off. The air compressor and pump are driven via the transmission 4, 5, 6, and 7 from the turbine.

If the water jacket 11 is discarded, the oil (i.e., the fuel) will surround the combustion chamber 2 directly, and also the compressor 1 and turbine 3. The latter two must be cooled, because the compressor is strongly heated by the compressed air, and the combustion chamber is even more strongly heated. The front part of the conical tube is also heated, because the sprayed oil is burned there. The wide part of the conical tube is only slightly heated, and it may even be strongly cooled if the engine operates at high altitudes, on account of the great expansion of the escaping gases. The heated walls of the combustion chamber and front end of the conical tube pass their heat to their colder parts, since the metal conducts heat well. The oil tank is kept at a uniform temperature by the forced stirring of the oil 8 and 9. The outer air can also be used to cool the oil in the lower layers of the atmosphere. The most economical method here is to spray the oil in a cold air flow, though the air will then carry off part of the fuel; but it is necessary to choose a fuel that will not give a vapor at a moderate temperature. This cooling air carrying oil vapor could be directed to the compressor; then the oil would not be lost. All that is necessary is that the boiling point of the oil should be high, so that much vapor would not be carried off, which would eliminate explosion in the compressor. Fins on the tanks represent surplus weight and are not permissible for engines that must be both powerful and light. Pipes passing through the oil tank and carrying air are not so heavy and so are better as coolers.

Such is the general outline of the engines, whose object is to provide extreme lightness, great power, simple design, and hence cheapness. Such engines would be especially advantageous at high altitudes, where the reaction of the escaping gas can be utilized.

Atmospheric oxygen can be used only up to a certain height, where the air is not excessively rarefied; difficulty in compression will be encountered in other cases. For instance, if extremely rarefied air were compressed by factor of 1,000 its temperature would rise to 4 thousand degrees; such air could scarcely be cooled sufficiently by oil, so the body of the compressor would have to have thin fins. Of course, diaphragms welded to the shell of the compressor could perform this function*. Such diaphragms must be made of the very best heat conductor.

The essence of the operation of my engine is as follows.

Let us suppose that we force into the boiler during one second one cubic meter of air. The pressure in the boiler would rise continuously if there were no exit hole** through which the gas could escape to the tubine. The smaller this hole, the higher is the pressure in the boiler. We assume a hole such that the pressure in the boiler is always 10 atm. The inflow of air must equal the outflow in mass; but 1 m^3 of air enters per second, and the products from combustion have almost the same mass but a temperature of about 1638°C. This increases the volume of the air (at the same pressure) by a factor 7. The addition of the hydrogen in the fuel and the cleavage of the oxygen increase the volume of the products even more, so the volume of the air will not be 7 but 10 times greater. Then 10 m^3 of gas must escape each second from the exit hole (at a pressure of 10 atm and a temperature of 1638°C).

Thus the heat is transformed to rapid mechanical motion of the gas molecules; but this is far from complete, as is the combustion. Both processes continue in cone 3; the gas compressed to 10 atm may expand by a factor 10. Greater expansion is prevented by the resistance of the atmosphere.

The expansion is accompanied by a fall in temperature and by after-burning; if the latter did not occur, the temperature would fall by a factor 2.53 (i.e., to 487°C), but the continuing burning causes it to remain much higher (about 1000°C).

This shows that best utilization of the energy requires much higher compression ratios, e.g., 100.

The object of the compressor is clear; without it the engine could not work. The compressor is especially necessary at high altitudes.

It is preferable to use a turbine (rotary) compressor, because this can give a vast volume of air, requires no lubrication, and so can give a very high degree of compression, which is especially

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*See Tsiolkovskiy's "Gas compressor" (Editor).

**Critical junction of nozzle (Editor).

advantageous when the surrounding atmosphere is dense, as for dirigibles.

A narrow exit hole in the boiler is necessary, otherwise there could be no excess pressure in the gas; and this is needed to convert the heat energy into rapid mechanical motion of the combustion products.

But combustion and expansion do not end at the exit hole; the gas emerges still hot and compressed. This further increases the flow speed and the conversion of heat to motion. A conical exhaust pipe is necessary to shorten the length of the entire machine.

In the limit, when there is no external pressure and the tube is sufficiently long, the combustion products cool almost to absolute zero; all the heat is transformed to forward motion of the gas, which is utilized via the multidisc turbine 3. The exhaust pipe is useful also for simultaneous utilization of all the turbine blades, which reduces the weight.

The parts of the engine vary in temperature from zero to two or three thousand degrees. This means that the average temperature of the machine can not be very high and such as the materials can withstand: the surrounding fuel is mixed to cool the heated parts of the motor and to heat the cold ones.

The advantages of this engine over the lightest aviation ones are as follows: Simple design, absence of pistons, small specific volume, high energy, and low-cost materials and fuel. Unfortunately, a power less than 1000 horsepower can scarcely be advantageous; such engines are unsuitable for low powers, and in such cases preference should be given to aviation engines. (It is assumed that the engine operates at sea level.)

Operation with low compression at atmospheric pressure is very advantageous, but then the output falls. For instance, the work of compression for a compression ratio of 5 for a 1000-hp engine is about 292 horsepower. Twofold compression requires 80 metric horsepower for an output of 500 metric horsepower.

The volumes of the boiler-carburetor and other parts are given approximately below, starting with the compressor. The carburetor receives 2 m^3 of compressed air per second to produce 1000 metric horsepower, so a volume of 0.5 m^3 will be sufficient for it. We allow three times as much for the rest, so the volume of the main parts of the motor is 2 m^3. If we assume that all the vessels have to sustain an excess pressure of 10 atm on average, their weight subject to an adequate safety factor would be about 30 kg. Taking into account the other parts, we have a weight of 100 kg for 1000 metric horsepower, or 0.1 kg per horsepower, which is the specific weight of the engine. This is 10 times less than the specific weight of an aviation engine.

Speed in m/sec	200	300	400	500	600
Necessary rarefaction (ratio)	4	9	16	25	36
Height, km	12	17	21	23	25
Natural compression of air	1.37	2.19	4.41	8.1	25
Necessary compression ratio	4	9	16	25	36
Less by a factor of	2.9	4.1	4.7	3.1	2.24
Speed in m/sec	700	800	846	1000	2000
Necessary rarefaction (ratio)	49	64	71.6	100	400
Height, km	27	29	29	31	39
Natural compression of air	51.5	99	138	316	9330
Necessary compression ratio	49	64	71.6	100	400
Larger by a factor of	1.05	1.56	1.9	3.16	23.3

The engine becomes more advantageous the larger it is, because the undesirable heating of the walls is reduced, since the very hot gases are far from them.

I have repeatedly shown that the speed in the rarefied layers of the atmosphere will be proportional to the square root of the rarefaction, provided that the power of the engine for the same weight is proportional to the forward speed of the flying vehicle.

Compliance with this condition requires compression of the rarefied air to densities higher than those at sea level.

The first line in the above table gives the speed of a stratoplane; the second, the rarefaction of the air needed to attain this speed; the third, the corresponding height above sea level; the fourth, the natural compression of the air in the head-on flow; the fifth, the compression ratio needed to bring the density of the air to that at sea level; and the sixth shows that the natural compression is insufficient to do this, and by what factor it is too small. This is so up to a speed of 700 m/sec; but above this the compression of the flow is greater than that giving the density at sea level. Only the rise in temperature impairs this, and this rise is too great to be sustained if measures are not taken to reduce it.

Here we thus encounter three difficulties. The first lies in increasing the power of the engine in proportion to the speed of the stratoplane. Of course, the power can be increased at the expense of increased weight in the engine and thus of the stratoplane as a whole. For instance, let the all-up weight be 1000 kg; the power needed for ordinary speeds is 50-100 horsepower, and the weight of the engine is not less than 50 kg. Let 500 kg be devoted to it; then the speed can be increased by a factor 10. The second lies in the need for a compressor to operate on rarefied air; this can be dispensed with at very high speeds (above 700 m/sec). The third lies in the very great rise in temperature of the air consequent on compression.

These are the difficulties that at present prevent the construction of a high-flying aeroplane. To these we must add the need for a sealed cabin or special clothing to protect the crew from the rarefied air.

All these calculations and arguments are only approximate. Experiment and research will give more exact conclusions, and perhaps more modest ones.

VEHICLES THAT REACH COSMIC SPEEDS ON LAND OR WATER*

1. Such vehicles have the following notable advantages over those that must reach these speeds at height without communication with ground structures, namely:

a) they can use electrical energy supplied from outside (i.e., from fixed ground installations, as streetcars);

b) the elasticity of electrically heated gases can be used in horizontal gun barrels;

c) the structures can be used continuously for launching many vehicles beyond the atmosphere;

d) a tube can be evacuated to allow the vehicle to move in it, the long path of the vehicle being horizontal or slightly inclined and adjacent to the ground, not rising to a height as in a tower; and

e) vehicles are launched without large stores of explosive components.

The principal advantage, however, is that the vehicle can receive any form of energy and can attain a cosmic speed.

2. Such devices also have many disadvantages relative to reactive ones. The latter represent the first stage, and the former a later one.

These disadvantages are as follows:

a) a special track (roadway, tube) of length up to 100 km is needed, which of course would be very costly;

b) auxiliary fixed energy sources are required, such as generators, compressors, and so on;

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*Printed from manuscript completed December 3, 1933 (Editor).

c) the vehicle must be 40 to 400 meters (or more) long, and also of good shape, otherwise cosmic speeds cannot be attained; and

d) the vehicle reaches cosmic speed in dense layers of the air and so is subject to high resistance.

A general obstacle is the complexity, size, and cost of these structures; but they are possible, and it is only necessary that men should be convinced that cosmic speeds can be attained.

3. High speeds are possible only if the vehicle flying or moving over the earth is elongated. I refer here to my 'Pressure on a Plane' of 1930, the following being part of one of the tables:

Speed, km/sec						
1.2	1.5	1.8	2.4	3	4.5	6
Minimum elongation of vehicle						
4	5	6	8	10	15	20

We assume that a speed of only 1 km/sec can be reached with an aspect ratio of four. This gives us a modified table:

Speed in km/sec											
1	2	3	4	5	6	7	8	9	10	11	12
Elongation											
4	8	12	16	20	24	28	32	36	40	44	48

If now we double the elongation we get nearly the same friction, and the inertial resistance may then be neglected as comparatively small.

In that case the resistance Q_q from friction per unit volume of the vehicle is given by formula (56) from my 'Resistance of Air' of 1927:

$$\frac{Q_q}{v} = a\,\frac{F\gamma v^2}{xD^2}\,.$$

in which x is the elongation, D is the diameter of the largest cross-section, γ is the density of air, and v is the speed.

5. F is a variable and is given by

$$F = 1 : \left[1 + \ln\left(\frac{v}{l}\right)\right]$$

in which l (or xD) is the length of the vehicle [see (19) of 'Resistance'].

7. $a = 0.00225.$

8. We assume that v = 1000 m/sec, D = 4, $\gamma = 0.013$, and x = 0.013, and x = 100; then l = xD = 400 and F = 0.5211 ('Resistance', Table 21). Then we have

$$\frac{Q_q}{v} = 0.000093\ T.$$

Then the resistance per m^3 of vehicle is less than 0.1 kg at 1 km/sec in the densest layers of the atmosphere.

9. The following table for the specific resistance (resistance per m^3) derives from the above formulas; the values are in kg for the various speeds in km/sec:

v	1	2	3	4	5	6	7	8	9	10	11
F	0.52	0.383	0.331	0.303	0.283	0.270	0.254	0.250	0.243	0.237	0.231
$\frac{Q_q}{v}$	0.1	0.296	0.576	0.928	1.35	1.87	2.45	3.07	3.77	4.56	5.37

10. The work done per second is found by multiplying the specific resistance by the speed:

$$L_s = \frac{Q_q}{V} v.$$

The result is in metric horsepower, if divided by 100.

11. The all-up power of the vehicle is enormous, for it is proportional to the volume:

$$N = \left(\frac{Q_q}{V}\right) vV = Q_q v.$$

12. From formula (33) of 'Resistance' we have

$$N = a_1 FDv^3.$$

14. $$a_1 = 0.00000156.$$

Then this gives the total power in second terms (subject to the condition of 8).

16. The following table gives the speed in km/sec, the resistance per m^3 of vehicle in kg, the work per second in metric horsepower,

v	1	2	3	4	5
$\frac{Q_q}{v}$	0.1	0.296	0.576	0.928	1.35
L_s	1	5.95	17.28	37.12	67.5
N	251.2	15060	42670	92870	170680
v	7	8	9	10	11
$\frac{Q_q}{v}$	2.45	3.07	3.77	4.56	5.37
L_s	171.5	245.6	339.3	456.0	590.7
N	430	615	848	1140	1478

the resistance Q_q of the whole vehicle in tons, and total power N of the entire vehicle in metric horsepower.

The power is in metric horsepower except for speeds over 6 km/sec, in which case it is in thousands of metric horsepower. For instance, the power is nearly 12 million metric horsepower at 12 km/sec, and the resistance is nearly 16 tons.

17. This power can be reduced if the dimensions of the vehicle are diminished. We assume that the mean density of the vehicle is 0.2, the volume being 2680 m^3; the mass is then 5216 tons, which means that the resistance of the medium is 326 times smaller even at 12 km/sec.

18. It is of interest to determine how many ton-meters of work are consumed by the resistance of the air. The work needed to overcome the inertia and produce the speed is not considered.

19. Taking friction alone, we have

$$Q_q = A_1 F D_v^2 .$$

20. Or $Q_q = A_2 v^2$, in which $A_2 = A_1 FD$.

21. The differential of the work consumed by friction is $dL = A_2 v^2 dx$, x being path length.

22. But dx = vdt, in which t is the time from the start of the motion, and v = jt. We assume that the acceleration j of the vehicle is constant.

23. Then $dL = A_2 v^3 dt = A_2 j^3 t^3 dt$.

24. The integral is

$$L = \frac{A_2}{4} j^3 t^4 ,$$

or, from (22)

$$L = \frac{A_2 v^4}{4j} .$$

25. From this we see that high j are best for the attainment of a given speed; but there is a limit to the acceleration that objects as well as fliers can withstand without damage. A low acceleration is unsuitable, because the path would be excessively long and costly. A man in a lying position can withstand an acceleration of 100 m/sec^2, or ten times the acceleration due to gravity.

26. The conditions of section 8 and a speed of 12 km/sec are assumed; the calculations are facilitated by putting (24) in the form

$$L = A_2 v^3 \frac{v}{4j} .$$

But from (12) and (20) we have

$$L = N \frac{v}{4j}$$

27. But N is given by the table of (16); this gives for $v = 12$ km/sec and an acceleration of 100 m/sec^2 that $L = 5\ 775\ 000$ ton-meters.

28. A power of 1 metric horsepower (second basis) gives 86 400 hp-sec (metric) in a day, or 8640 ton-meters.

The work found in section 27 is equivalent to a power of one metric horsepower acting for 670 days, or to a machine of 670 horsepower acting for one day, or to one of 1000 horsepower acting for 16 hours.

29. It is best to compare this work with the inertial energy of the vehicle, which is

$$L_i = \frac{v^2}{2g} G.$$

30. The weight is governed by the volume and mean density.

32. We compare this inertial energy with the work done against the resistance found in 12 to get

$$\frac{L_i}{N} = \frac{G}{2ga_1 FDv}.$$

33. Section 9 gives a table for F for various speeds for a vehicle 400 meters long.

34. The ratio of section 32 is found as 8440 for the conditions of section 8 with a speed of 1 km/sec and a vehicle of density 0.2; the work of resistance is thus quite negligible.

Even a speed of 12 km/sec implies a resistance energy less than the inertial energy by a factor 703. The figure will be even lower for large Dx and vehicle densities.

Why then do we dread the resistance of the atmosphere? It is troublesome and relatively large only for relatively unelongated bodies such as aeroplanes, dirigibles, and (especially) automobiles and ordinary railroad trains.

But this is not all. We are to propel a long body of smooth shape with a speed of 8-12 km/sec, and this speed may perhaps generate further resistance when the vehicle flies through the atmosphere. This we now consider.

I shall prove this theorem: the work of penetrating the entire atmosphere in vertical motion of the vehicle at a constant speed is the same as if the whole atmosphere having the same mass had a constant density, such as that at sea level.

This density is 0.00129; the known mass of the atmosphere at this constant density is equivalent to a height of about 7800 m.

In fact, the work needed to penetrate any part of the atmosphere is the same, no matter whether that part is rarefied or dense. Let the atmosphere somewhere be 100 times less dense, for example; then the resistance will be 100 times weaker, and this would tend to reduce the work by a factor of 100, but the time is thereby increased by a factor of 100, for the path in the rarefied part will be 100 times longer. The work thus remains unchanged.

35. We can assume a practically constant flight speed in the atmosphere, for the resistance is completely negligible relative to the stored vis viva of the rocket (or to the kinetic energy). The Earth's gravity reduces the speed a great deal more; but even this is unimportant, on account of the cosmic speed of the vehicle, within the thin dense layer of the atmosphere (20-40 km).

36. The motion of the rocket along the solid road is only slightly inclined to the horizontal, so the path is not that of free fall; it rests on the hills, whose over-all inclination is small. The rocket thus has an inclined motion. Taking the Earth as horizontal over a small part of the rocket's path, we have a second theorem: the work of penetrating the atmosphere for an inclined motion of the vehicle is inversely proportional to the sine of the angle of inclination of the path to the horizontal.

37. These two theorems readily give us the work absorbed by the atmosphere. We will obtain rather large value on account of the fall in speed as the vehicle rises; the true work of overcoming the atmosphere will be less.

For this purpose it is sufficient to multiply the resistance as given by the table of 16 by 7800 m; for instance, for a speed of 12 km/sec we get 124 800 ton-meters.

This 7800 is the result of dividing the pressure of the atmosphere at sea level by the density of air at that level.

38. A general formula for the resistance of the entire atmosphere [see formula (33) of "Resistance"] is

$$L_a = \frac{\pi A_1 F v^2 D}{4 \sin y} 7800.$$

39. The ratio to the resistance of the air along a solid track as of (24) is

$$\frac{L_a}{L} = \frac{7800\pi j}{v^2 \sin}$$

This means that the relative resistance of the entire atmosphere is the less the higher the initial speed v at which the vehicle leaves the road and the greater the inclination y to the horizontal. This ratio increases with the acceleration j along the track.

40. For instance, we put $j = 100 \text{ m/sec}^2$, $v = 12\ 000$ m/sec, $\sin y = 0.1$; then the ratio is 0.1717, or 1:5.8, which means that the work of penetrating the atmosphere is almost 6 times less than the work of friction in traveling along the track.

41. Of course, this work is still more negligible not only relative to the kinetic energy but also to the work of lifting the rocket. This last is the product of the weight and the height H

of the atmosphere, which in this case can be taken as 30 kilometers. The work of lifting is then

$$L_1 = GH.$$

Comparison with (38) gives

$$\frac{L_1}{L_a} = \frac{GH^4 \sin y}{\pi A_1 F_v{}^2 D 7800} .$$

42. But H = 7800, so we have

$$\frac{L_1}{L_a} = \frac{G \sin y}{\pi A_1 F v^2 D} .$$

This means that the relative importance of the gravitational work increases with the inclination and size of the vehicle and as the velocity decreases.

43. We use the table of (9) in conjunction with the conditions of (8), putting the density of the vehicle as 0.2, sin y = 0.1, and

$v = 12\ 000$ m/sec. The formula then shows that the gravitational work is still 45.16 times the work of penetrating the atmosphere in free motion, in spite of the small inclination and high speed.

44. The elongation of the vehicle can be reduced by a factor 2, in view of the comparatively small air resistance and hence low work; the dimensions can be reduced correspondingly, and then $D = 2$ m, $x = 50$, and $l = 100$ m.

This is far more feasible as regards energy consumption and cost; and it is even more so for the attainment of a maximum speed of 8 km/sec. Then the elongation and dimensions can be reduced by a further factor two, so $D = 1$ m, $x = 25$, and $l = 50$ m. Here the diameter has been made rather small, but this is significant in moving the mass and in flight through the atmosphere. Outside it one may construct a space station of any desired size, where the dimensions are of no importance, for there is no resistance from the medium.

45. Now we consider the length of the solid track. A high acceleration for the vehicle is impossible, in view of the effects on human beings. It is unimportant that the solid track will be long and that there is not space for it on land.

46. Taking the acceleration j of the vehicle as constant, the path length is found as $x = \frac{v^2}{2j}$. The length is thus the less the lower the speed and the higher the acceleration. We may neglect the resistance of the air from what we have seen above, but the work needed to attain a given speed is the same no matter what the acceleration.

We do not know what is the greatest acceleration a man can withstand in a lying position immersed in water; but we may take it as not less than 100 m/sec^2, or 10 times the acceleration due to gravity. The path length in kilometers is then given for various speeds by the following table:

v, km/sec.........	5	6	7	8	9	10	11	12
x, km	125	180	245	320	405	500	605	720

Double the acceleration ($j = 200\ m/sec^2$)

x, km...........	62.5	90	122.5	160	202.5	225	302.5	360

The lengths are 320 or 160 km for a maximum speed of 8 km/sec, the inclination of the smooth hill being then 1:64 or 1:32, the sines being 0.0156 or 0.0313, the angle being one or two degrees.

47. We need not consider the resistance of the medium, but the relatively large forces require a strength proportional to j for the vehicle. It would be better to make the path longer from this point of view.

Electricity provides the best means of transmitting energy, but there is no difficulty in converting the electrical energy to mechanical work. No known electric motor is suitable, on account of its weight. High temperatures and chemical decomposition of materials are readily produced by electric current, and this can be utilized in heat engines, but the motors themselves are heavy. Reactive motors might be used, with the electricity employed to heat gases cooled by expansion; but the advantage of this is not very great. The heating temperature cannot be very high, because it would melt the pipes bearing the gas. The primary need is for refractory materials and methods of working these.

IS IT ONLY A PHANTASY?*

(Director V. N. Zhuravlev recorded at the Mosfilm Studios the science-fiction film "A Cosmic Voyage," whose content we have already given. Tsiolkovskiy gave advice on the staging of the film, and he here today shares his thoughts on it with our readers.)

About 10 years ago I was approached with a request to prepare my tale "Beyond the Earth" for presentation as a film, but the matter was not taken up. Only now has Mosfilm, in the person of the talented V. N. Zhuravlev, firmly decided to make a film called "A Cosmic Voyage."

I began to dream of possible voyages away from our planet when I was 17. In 1895 I wrote a book "Speculations on Earth and Sky," which was published by a nephew of the celebrated Goncharov and then was twice republished by Gosizdat under the title "Gravity Has Vanished," I spent much time on this topic in the early years after the revolution, and the science fiction tale "Beyond the Earth" (1918) was a reflection of this.

The mathematically developed theory of reactive vehicles appeared as long ago as 1903, first in the Filippov's "Nauchnoye Obozreniye" (Science Review), a philosophical journal with small circulation, and some years later (1911-12) in "Vestnik Vozdukhoplavaniya" (Bulletin of Air Flight). Then there were several papers published separately and in journals. From 1914 onwards my work also began to become known abroad.

Nothing occupied me so much as the problem of overcoming terrestrial gravity and of cosmic flights. Half of my time and energy seem to have gone on this topic. I am now 78, but I still continue to calculate and invent an imaginary reactive machine. So much I have thought on it, so many thoughts have passed through my head. These are not fantasies, but exact knowledge based on the laws of nature; they prepare new discoveries and new accomplishments. But

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fantasy has also attracted me; many times I have mused on the theme of "Cosmic Voyages" but have ended by taking up detailed considerations and passing to serious work.

Fantastic tales on themes of interplanetary voyages stir the imagination of the masses; he who does this does something useful: arouses interest, stimulates the brain to activity, generates in current and future workers great aspirations.

What grandeur could be greater than to harness the total energy of the Sun, which is 2 billion times greater than that reaching the Earth!

Films have a wider influence than literature; they are more direct and closer to nature than a description. This is the highest form of art, especially when the cinema has encompassed sound. It seems to me that Mosfilm and Comrade Zhuravlev have shown great strength of purpose in making "A Cosmic Voyage;" and it must be said that the work is highly satisfactory.

What do I myself think about cosmic voyages; do I believe in them? Will they ever be an achievement of man's?

The more I have worked the greater the various difficulties and obstacles I have found. Until recently I considered that it would need centuries in order to perform flights with astronomical speeds (8-17 km per second), and this was supported by the poor results obtained here and abroad. But continuing work recently has cast doubt on these pessimistic views of mine; ways have been found that will give outstanding results even within decades.

These hopes of mine I believe will be confirmed and justified by the attention our Soviet government is devoting to the development of the industry of the USSR and to every type of scientific research.

THE MAXIMUM SPEED OF A ROCKET*

A. Relation of Rocket Speed to Mass of Explosion Elements

1. I use here the simple formulas of my "Studies" of 1926 (gravity and resistance absent). The results are approximate and apply in the following cases:

a) motion in a vacuum away from gravitational fields;

b) vehicle moving on a horizontal path and having a highly elongated and good shape; and

c) nearly horizontal flight in the atmosphere, with little deviation from the horizontal on account of the rapid motion and the use of flat wings.

These formulas will also be applied to motion of the vehicle at a small angle to the horizontal (flight in air).

2. We have $v = v_1 \ln\left(\frac{M_1 + M_2}{M_1 + M}\right)$, in which v is the speed and M_1 is the mass of all parts of the rocket apart from the explosives; v_1 is the relative speed of the exhaust (constant), M_2 is the total mass of the explosives, and M is the mass as yet unused. Of course, v and M are variables.

3. We put M = 0 (all explosive exhausted) to get the maximum speed as

$$v_0 = v_1 \ln\left(1 + \frac{M_2}{M_1}\right).$$

*Chapter VII of "Osnovy postroeniya gazovykh mashin" (Principles of Construction of Gas Machines). See Appendix, Note 74 (Editor).

4. From this formula we derive Table 4* for the maximum speed in relation to total mass of explosive consumed and to relative exhaust speed. The first column gives the mass of all explosive consumed as a ratio to the mass of the rocket apart from the explosive; the subsequent six give the speed of the rocket (km/sec) for relative exhaust speeds of 1, 2, 3, 4, 5, and 6 km/sec. (Theory shows that the energies of explosives presently available to man are such that the velocity of the explosion products cannot be more than 6 km/sec.) The last column gives (as %) the proportion of the explosion energy retained as motion of the rocket. This proportion is at first very low, but it increases as the relative amount of explosive consumed grows; it becomes maximal (about 65%) when the amount is close to 4, and then starts to fall towards zero. It is reasonably large (greater than 40%) between mass ratios of 0.7 and 30.

The absolute speeds reached by the rocket are of cosmic order, being sufficient not merely for escape from the Earth but also for eternal recession from our Sun and for a voyage among the suns of the Milky Way.

5. But so far the exhaust velocity has not yet reached 5-6 km/sec, and the stores of explosives cannot be made as large as those needed to attain cosmic speeds (at any rate, those needed to overcome the Sun's gravity and to take the vehicle among the stars of the Milky Way).

What speeds are attainable under the most exiguous conditions, and how, with such speeds available, should we seek to reach cosmic ones?

6. The thermal energy of an explosion cannot be fully utilized; the escaping products cannot be cooled (by expansion) to absolute zero, which would enable us to convert all the heat into kinetic energy of the gases. The restricted dimensions of the tube** also hinder the ideal use of the chemical energy. For this reason the exhaust velocity will be less than that given in Table 4.

7. The following table expresses this:

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*The tables are numbered in accordance with the paragraphs (Editor).

**Nozzle (Editor).

50%	60%	70%	80%	90%	100%
0.707	0.775	0.837	0.894	0.949	1.000

The first line shows the percent of the heat of combustion used (proportion converted to kinetic energy, exhaust motion); the second, the reduction factor for the rocket's speed, which is proportional to the reduction in exhaust speed. For instance, the speed is reduced by a factor 3 if the thermal or mechanical work is reduced by a factor 9. The numbers in Table 4 must be multiplied by one of the factors in the second line to get the true maximum speed of the rocket corresponding to a given percent utilization of the heat of explosion.

8. For this purpose I have compiled a new table on the assumptions that 70% of the heat is used and that the relative speed of the products is 4 km/sec. This last figure is, naturally, dependent on the nature of the explosive.

TABLE 4

Speed of the Rocket

Exhaust speed, km/sec	Rocket speed for complete conversion of thermal energy into motion of gases, m/sec						% used
	1	2	3	4	5	6	
Ratio of exhaust mass to mass of rocket 0.1	94.5	189	283.5	378	472.5	567	8.9
0.2	182.0	364	546	728	910	1092	16.5
0.3	262	524	786	1048	1310	1572	22.9
0.4	336	672	1008	1344	1680	2016	28.2

[Table 4 cont'd. on next page]

[Table 4 cont'd.]

	Exhaust speed, km/sec	Rocket speed for complete conversion of thermal energy into motion of gases, m/sec						% used
		1	2	3	4	5	6	
Ratio of exhaust mass to mass of rocket	0.5	405	810	1215	1620	2025	2430	32.8
	0.6	469	938	1407	1876	2345	2814	36.7
	0.7	529	1058	1587	2116	2645	3174	40.0
	0.8	586	1172	1758	2344	2930	3516	42.9
	0.9	642	1284	1926	2508	3210	3852	45.8
	1.0	693	1386	2079	2772	3465	4158	48.0
	1.2	788	1576	2364	3152	3940	4728	51.8
	1.5	915	1830	2745	3660	4575	5490	55.8
	2.0	1098	2186	3294	4392	5490	6588	60.3
	2.5	1253	2506	3759	5012	6265	7518	62.0
	3	1380	2760	4140	5520	6900	8280	63.5
	4	1609	3218	4827	6436	8045	9654	64.7
	5	1792	3584	5376	7168	8960	10752	64.1
	6	1946	3892	5838	7784	9730	11676	63.0
	7	2079	4158	6237	8316	10395	12474	61.7
	8	2197	4394	6591	8788	10985	13182	60.5

[Table 4 cont'd. on next page]

[Table 4 cont'd.]

Ratio of exhaust mass to mass of rocket	Rocket speed for complete conversion of thermal energy into motion of gases, m/sec						% used
Exhaust speed, km/sec	1	2	3	4	5	6	
9	2303	4606	6909	9212	11515	13818	58.9
10	2398	4796	7194	9592	11990	14388	57.6
15	2773	5546	8319	11092	13865	16638	51.2
20	3044	6088	9132	12176	15220	18264	46.3
30	3434	6848	10302	13736	17170	20604	39.3
40	3714	7428	11142	15856	18570	22284	34.4
50	4480	8960	13440	17920	22400	26880	31.6
100	5256	10512	15768	21040	26280	31536	21.0
193	6007.6	12015.2	18022.8	24032	30038	36045.0	14.4
	Infinity			Infinity			Zero

9. The first line of Table 9 gives the speed of the explosion products (2 to 4 km/sec); the second, the % utilization of the heat; and the third, the final speed of the rocket after all explosives have been consumed. The first column gives the store of explosive material as a ratio to the mass of the rocket. It is clear that the practical speed is scarcely sufficient for a satellite moving near the Earth.

But we have to hand other methods of obtaining vastly greater rocket speeds, which consist in the use of several identical rockets of low speed. These, apart from the last, use up only half their stores of explosive, the other half being used to feed other rockets.

Only the last rocket reaches the maximum speed; the other vehicles after discharging their stores glide down to earth.

B. Speed of Rocket with Incomplete Fuel Consumption

10. The mass of explosive burned in relation to the total amount is

11. $$\frac{M_2 - M}{M_2} = y.$$

12. Then $M = M_2 (1 - y)$.

13. With $\frac{M_2}{M_1} = x$ we have

$$v = v_1 \ln \frac{1 + x}{1 + x (1 - y)}.$$

14. Let $y = 0.5$; then we have

$$v = v_1 \ln \left(\frac{1 + x}{1 + 0.5 x} \right).$$

The formula shows that the speed does not increase without limit with the store x but has a definite limit; $x = \infty$ gives $v = v_1 \ln 2 = 0.693 v_1$. For instance, the speed will be 2079 m/sec if $v_1 = 3000$, even though x is infinite. There is clearly no great advantage in burning half of the store when this is large.

TABLE 9

Speeds for Complete Consumption of Explosive but Various Degrees of Use of the Heat of Combustion

Relative store of explosive	Speed of products 2000 m/sec			Speed of products 3000 m/sec			Speed of products 4000 m/sec		
	% of heat used			% of heat used			% of heat used		
	50	60	70	50	60	70	50	60	70
	Final speed of rocket, m/sec								
0.3	370	406	439	556	609	658	741	812	872
0.5	573	628	678	859	942	1017	1145	1255	1356
0.7	748	820	885	1122	1230	1328	1496	1640	1771
1	980	1074	1160	1450	1611	1740	1946	2156	2320
2	1545	1694	1830	2329	2553	2744	3105	3404	3676
3	1951	2139	2310	2927	3208	3465	3903	4278	4620

[Table 9 cont'd. on next page]

[Table 9 cont'd.]

Relative store of explosive	Speed of products 2000 m/sec			Speed of products 3000 m/sec			Speed of products 4000 m/sec		
	% of heat used			% of heat used			% of heat used		
	50	60	70	50	60	70	50	60	70
	Final speed of rocket, m/sec								
4	2275	2494	2693	3414	3741	4040	4550	4988	5387
5	2534	2778	3000	3801	4166	4500	5068	5555	6000
6	2752	3016	3258	4127	4524	4886	5503	6033	6524
7	2940	3222	3480	4410	4834	5220	5879	6445	5960
8	3107	3405	3678	4660	5108	5517	6213	6811	7355
9	3256	3570	3855	4885	5354	5783	6513	7139	7710
10	3391	3717	4014	5086	5575	6021	6781	7434	8028

15. This formula has been used to compile Table 15, which confirms this conclusion. This gives the speed of the rocket (m/sec) when only half of the explosive has been used, x being the total store. It is assumed that the heat is ideally converted into motion of exhaust and rocket.

The first line gives the total relative store of explosive; the first column, the relative exhaust speed. Even a value of 2000 m/sec gives, for a total store of 4 and half consumption, a speed of 1023 m/sec. A total store of 2 and half consumption gives the rocket a speed of 1215 m/sec if the relative exhaust speed is 3000 m/sec.

C. Speed Reached by One Rocket with the Aid of Others

16. We shall now see the role of restricted consumption of explosive in attaining cosmic speeds.

17. Consider a large number of completely identical rockets each with x = 1. Let each rocket use up half its store, the exhaust speed being 4000 m/sec for all.

Squadrons of these rockets enable one to obtain speeds not accessible to one rocket by transfer of fuel. Fuel transfer, as of benzine from one aeroplane to another, is not only possible but has been performed.

18. We assume that one rocket flies. Table 4 gives its maximum speed as 2772 m/sec.

19. Now consider two such rockets flying simultaneously and close together; let both at first use up half their fuel, which will give them a speed of 1150 m/sec (Table 15). Then one transfers to the other its unconsumed (0.5) store and descends to Earth. The second now has a full store of 1 and gains an additional speed of 2772 m/sec, the result being 1150 + 2772 = 3922 m/sec.

20. Now we assume that four rockets fly. Each uses up half its store, so all flying in sequence have a speed of 1150 m/sec. But two of them fill up the stores of the other two and descend empty; the two remaining flying then use up half their store again, which gives them a speed of 2300 m/sec. One of them then fills up the store of the other and descends. This last uses up its full store and so gains an additional speed of 2772 m/sec, the total being 5072 m/sec. After this it too has to glide down to ground.

TABLE 15

v_1, m/sec	x (store)												
	0.1	0.3	0.5	1	2	3	4	5	6	7	8	9	10
1000	46	122	182	287	405	470	511	539	567	573	588	598	606
2000	93	245	365	575	810	940	1023	1078	1134	1146	1176	1196	1212
3000	139	368	547	863	1215	1410	1534	1617	1701	1719	1764	1794	1818
4000	186	490	729	1150	1620	1880	2046	2156	2268	2292	2352	2392	2424
5000	232	613	911	1438	2024	2350	2557	2695	2835	2865	2940	2990	3030
6000	279	736	1094	1726	2429	2820	3068	3234	3402	3438	3528	3588	3636

21. Table 21 gives the speed of the last remaining flying in the air as a function of the number of rockets, on the basis $v_1 = 4000$ m/sec and x = 1.

TABLE 21

Number of rockets	1	2	4	5
Speed of last in m/sec	2772	3922	5072	6222
Number of rockets	16	32	64	128
Speed of last in m/sec	7372	8522	9672	10822
Number of rockets	256	512	1024	2048
Speed of last in m/sec	11972	13122	14272	15422
Number of rockets	4096	8192	16384	-
Speed of last in m/sec	16572	17722	18872	-

22. The first line in Table 21 gives the number of identical rockets taking part in the production of a very high speed in one; the second line gives the speed of this last.

23. The first cosmic speed (orbital velocity) is attained with 32 rockets; entry into the Earth's orbit requires 256, and escape from

the Sun and planets requires 4096.

24. The hardest part is to fly out of the Earth's atmosphere, remaining attached to the Earth as a satellite. Further increase in speed can be produced in other ways, and much more easily than on the ground. All the same, the number of rockets is very large.

25. But we can take a larger store of explosive, e.g., 4; then even the modest exhaust speed of 3000 m/sec gives the rocket a speed of 1534 m/sec for half consumption (Table 15) and a final speed of 4827 m/sec (Table 4). This gives us a new table.

TABLE 25

Number of rockets	1	2	4	8	16
Speed of last in m/sec	4827	6361	7895	9429	10 962
Number of rockets	32	64	128	256	512
Speed of last in m/sec	12 497	14 031	15 565	17 099	18 633

Then 256 rockets would suffice to wander among the suns of the Milky Way; an earth satellite is attained by four rockets, and a satellite of the Sun by 16.

26. The exhaust speed can be more than 3 km/sec, so smaller numbers of rockets would suffice to reach cosmic speeds.

27. There is a general formula for the speed of the last rocket as a function of the number, the exhaust speed, and the relative store of explosive. The speed of one rocket will be, from formula (3),

$$v_0 = v_1 \ln (1 + x),$$

in which x is the total relative store of explosive. The number of rockets is 2^n, where n is the number of fuel transfers, whereupon the speed of the last is

$$v = nv_1 \ln \frac{1 + x}{1 + 0.5\,x} + v_1 \ln (1 + x) =$$

$$= v_1 \left[(n + 1) \ln (1 + x) - n \ln (1 + 0.5\,x)\right].$$

28. The first term in the first part tends to a limit no matter how large x may be (see section 14), the limit being $0.693v_1$; but it can still increase without limit with n or with the number of rockets (2^n). However, the second term increases without limit as the relative store of explosive increases, so we must increase x and n as far as possible.

29. Although x and v_1 (relative exhaust velocity of combustion products) cannot be increased greatly, we yet can increase the number of rockets (2^n) at our disposal and hence the speed of the last of the group.

30. Experience has shown that it is quite possible to have a material connection between two aeroplanes moving at the same speed; fuel has been transferred from one to the other. All that is needed is the most convenient method of doing this. The work is rather more complicated in our case, because two separate elements have to be transferred individually: hydrocarbons (fuel) and oxygen compound. Various methods are possible, such as:

a) transfer via a pipe joining the two flying vehicles;

b) transfer of tanks containing the explosion elements;

c) direction of a jet of the element into the rear part of the vehicle flying in front (syringe, fire hose).

Experience will show which of these methods is the best.

D. Practical Approach

31. We shall have to start with very imperfect low-power aeroplanes; first we must become accustomed to flying one only. The exhaust velocity must be made very low, e.g., 2000 m/sec, with an explosive reserve of unity. Table 4 then gives the low speed of 1386 m/sec. Such a rocket plane could fly horizontally or at an angle; neglecting air resistance, it could rise to a height of 96 km at this speed. But there is some resistance, and some speed must be retained, so it would rise to about 50 km. From there, lacking explosive elements, it would glide down to the solid or liquid surface of the planet.

The greatest speed of this modest rocket plane will not exceed 1 km/sec, so its elongation need not be very great.

32. The following is the necessary elongation of a rocket plane as a function of the given greatest speed (see my "Pressure" of 1930):

v, km/sec		1	2	3	4	5	6	7	8
λ		4	8	12	16	20	24	28	32
v, km/sec	9	10	11	12	13	14	15	16	17
λ	36	40	44	48	52	56	60	64	68

The first line gives the speed in km/sec; the second, the minimum necessary elongation (for good shape, of course). We see that our first modest rocket may be restricted to an elongation of 4. An elongation less than that given in the table would lead to the air in front of the nose becoming compressed so far as to resemble a steel wall, no matter how rarefied it might be.

33. Speed higher than about 5 km/sec will be attained outside the atmosphere, so the elongation in general will not exceed 20 (see table).

34. When we have attained good control over a single rocket plane with an elongation of 4, we can go over to the construction of two identical rockets of greater elongation. Then we start trials on the transfer of explosion elements from one rocket plane to another. Next we go to a group of four rockets of yet greater elongation, then to a group of eight, and so on. At the same time the vehicles will be improved, e.g., by increasing the relative store of explosion elements and the exhaust velocity of the products.

35. We now have a table of the speed of the rocket planes as a function of the number, on the assumption of unit store of explosive giving an exhaust velocity of 2000 m/sec. The table also gives the necessary minimum elongation of the group of equal rocket planes. This table has been compiled on the basis of Tables 4 and 15.

Number of rockets	1	2	4	8	16	32	64	128	256	512
v, km/sec	1386	1961	2536	3111	3586	4271	4846	5421	5996	6571
λ	5	8	10	12	14	16	20	22	24	26
Height reached, in km, for constant gravity	95	192	320	484	680	910	1170	1470	1800	2160

The first line gives the number of rockets in a group; the second, the maximum speed; the third, the elongation of each member of the group; and the fourth, the maximum height reached (speed fallen to zero).

In fact, of course, only half these values are attained. A group of 8 or 16 rocket planes would possibly escape from the atmosphere, where the elongation is unimportant, so this need not exceed 12-14, which means that a vehicle of maximum diameter 2 m would be not more than 24-24 m long.

36. But we would hope to attain during these trials or earlier an exhaust velocity exceeding 2 km/sec, since the extreme limit is 6 km/sec. The store may also rise from unity to 5 or more. Cosmic speeds would then be attained by small groups of not very elongated rocket planes.

37. As our limits to progress we will assume an exhaust velocity of 6 km/sec and a store of 10. On this basis we obtain the following from Tables 4 and 15:

No. of rockets	1	2	4	8	16
v, km/sec	14388	18024	21660	25296	28932

Here we do not need to mention either height or elongation, for one rocket or a group will rapidly fly out of the atmosphere without attaining 2 km/sec in it, so an elongation of 8 is quite sufficient for all rockets, however advanced.

E. Object of the New Method

The object of the above is to indicate methods of attaining cosmic speeds sufficient not only to capture solar energy but also for a voyage between other suns within our Milky Way, and this although a single rocket plane is highly imperfect. The method here is to use a group of rocket planes with transfer of fuel elements in mid-air to maintain the strength of one final rocket plane, which will attain a very high cosmic speed.

39. I have already proposed artificial ground roads and rocket tracks for this purpose; this may be correct, but at present it is impracticable for reasons of cost, amongst others.

40. Even less practicable are gun barrels lying on the ground (i.e., especially constructed tracks), which are even more costly. These tracks and "guns" may find application in the remote future, when the importance of interplanetary travel will increase and mankind will give more attention to it; then it will command belief and real hopes, though it will involve expenditure and sacrifices even greater than those required for all other human needs.

41. The use of a group of early low-power machines with explosive transfer is far more comprehensible to the mind of man at present. A single rocket plane alone will soon lead to the next experiment with two identical but imperfect vehicles.

These alone are valuable; even singly they may serve the people. Trials with several will be performed as interesting experiments, quite apart from anything else. But these experiments will inevitably lead on to the production of cosmic speeds.

The basis of this progress will be the production of the first rocket plane, although of poor performance. Construction of identical vehicles of this type will advance the matter of producing higher speeds, to which there is no limit.

Previous chapters have provided the basis for making individual rocket planes; of course, the better the resulting rocket plane, the greater the results from trials with groups for a given number of vehicles in a group.

F. Exhaust Velocity of Explosion Products

43. Consider once more a single rocket plane. The escape velocity of the explosion products is of great importance, but what does this depend on? In the chapter "Energy of a Chemical Compound" I give tables for the ideal maximal escape velocities of explosion products, which derive almost entirely from the following conditions:

a) the combustion products are gaseous or very volatile;

TABLE 38

Speed of Rocket after Consuming 0.5 of the Store of Explosive for Heat Utilization Factors of 50, 60, and 70%

Total relative store of explosive	Store utilized	Ideal speed of explosion products, km/sec								
		2			3			4		
% of heat used		50	60	70	50	60	70	50	60	70
Speed of combustion products, m/sec		1414	1550	1674	2121	2325	2511	2828	3100	3348
0.3	0.15	173	190	205	260	285	308	347	380	410
0.5	0.25	258	290	305	387	424	458	515	565	610
0.7	0.35	326	357	386	489	536	579	652	715	772
1	0.5	407	446	481	610	669	722	813	892	963
2	1.0	571	620	678	850	942	1017	1145	1255	1355
3	1.5	665	729	787	996	1093	1180	1329	1457	1574

[Table 38 cont'd. on next page]

[Table 38 cont'd.]

Total relative store of explosive	Store utilized	Ideal speed of explosion products, km/sec								
		2			3			4		
% of heat used		50	60	70	50	60	70	50	60	70
Speed of combustion products, m/sec		1414	1550	1674	2121	2325	2511	2828	3100	3348
4	2.0	723	733	856	1084	1189	1284	1446	1585	1712
5	2.5	762	835	902	1143	1253	1353	1525	1671	1805
6	3.0	800	877	947	1199	1315	1420	1600	1753	1894
7	3.5	815	892	963	1225	1338	1446	1627	1783	1926
8	4.0	831	911	984	1246	1367	1476	1663	1822	1968
9	4.5	846	927	1001	1268	1390	1497	1691	1853	2002
10	5.0	858	940	1015	1285	1409	1522	1714	1879	2029

b) there is no external pressure to prevent the gaseous products from expanding;

c) the tube for the exhaust is very long;

d) this tube is not very broad at the exit, i.e., does not deviate greatly from cylindrical (a conical shape reduces the length);

e) there is no loss of heat by conduction or radiation; and

f) the diameter of the tube is so large that friction of the gases on the internal walls can be neglected.

44. These conditions cannot be complied with exactly in practice; the following are some deviations.

A vehicle is usually of small size, so the tube is short; the tube must be made conical in order to make good use of the expansion and hence of the conversion of heat to motion.

The external pressure is absent only in a vacuum (outside the atmosphere) or at speeds greater than 300-500 m/sec, when a vacuum arises behind the blunt end of the vehicle on account of the rapidity of the motion. The rear of the rocket will, in general, be tapered; but the part where the exhaust pipe emerges is inevitably blunt, so here there will be a volume of rarefied air (but this will be filled with explosion products, of course).

The escaping gases cannot cool to absolute zero, on account of the restricted size of the tube and the residual external pressure, so they retain some part of the energy, the degree of expansion being the decisive factor. Not all the heat energy from the combustion is converted to the motion of gas jets. This incomplete utilization of the heat causes the speed of the products to be somewhat less than that shown in the tables.

This is incorporated in the above table.

The first line gives the ideal speed of the products, which is governed solely by the chemical energy released by combination of the components. Here I give speeds from 2 to 4 km/sec, although values up to 6 km/sec are attainable. The second line gives the proportion of the heat of combustion utilized (as %), which clearly is governed by the temperature of the escaping gases.

The first column gives the total relative store of explosive (0.3 to 10).

The second column gives half of this, which produces the speed.

The numbers in the body of the tube are the speeds in m/sec produced by consumption of half the store of explosive.

All the above conditions are very moderate and feasible.

APPENDIX

PRINTED WORKS AND MANUSCRIPTS ON REACTIVE FLYING MACHINES AND INTERPLANETARY TRAVEL*

(Compiled by B. N. Vorob'yev)

1. Tsiolkovskiy's earliest writings on interplanetary travel in his Archive are notes he made in July 1878 on nine separate sheets (ac 1, f 1/2 s). One of these has a very careful drawing of Saturn with its rings, together with a little planet or asteroid. On this is shown a man finding himself in "a world without gravity"; around him suspended in space are the objects of his environment (tables, chairs) and the note "July 8, 1878, Sunday. Ryazan'. At this time began to make astronomical drawings". With this are the earliest manuscripts in his Archive.

2. The next in time of Tsiolkovskiy's surviving manuscripts on interplanetary travel is an exercise book (1/4 s, schoolbook) consisting of 18 pages plus cover, which he wrote in Ryazan', where he lived from the summer of 1878 to January 1880 (before transferring to Borovsk to take up his duties as a school instructor). There he continued to examine aspects of interplanetary travel. To study the effects of gravitational acceleration he made experiments with small animals and insects in a rotating machine he made. Sketches of the wheel are preserved on one of the nine sheets of 1878 described above. This notebook (dated "April 30 1879. Monday" on the penultimate page) he used to sketch devices and schemes for further experiments, calculations, and short notes. He retained it for nearly 43 years up to February 1923, when he sent it to the Leningrad journalist Ya. I. Perel'man. On the cover he wrote:

"Relates to 1879 (the author was 21 years old). K. Tsiolkovskiy".

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*Abbreviations used: f= formal, s = sheet (written), i = ink, p = pencil, bs = writing on both sides, os = writing on one side, ac = archive catalog, no = new orthography, oo = old orthography, cc = carbon copy, pop = popularization.

Below: "Juvenile work" (illustrations for 'Dreams')* ll.

"Sent to Ya. I. Perel'man from Tsiolkovskiy in 1923, 31 Jan."

On the back of the front cover "(Very dirty, because it was in the flood of 1908)" ll.

The manuscripts are supplemented by a special commentary (pencil, both sides) on three sheets headed: "Explanation of K. E. Tsiolkovskiy's 'Juvenile drawings' compiled in February 1923 (rudiments of present ideas)"**.

1. Attraction of a cone for a pyramid at its vertex is proportional to the length (or height) of the cone. There is no gravity in a homogeneous sphere of equal thickness. Gravity is balanced out also in a similar (infinite) cylinder. One one side of a homogeneous infinite plate of constant thickness there is a field of equal and parallel forces. Gravity is eliminated between two such equal and parallel plates.

1. Uniform rectilinear motion of a body has no effect on the phenomena on it (example: the solar system).

3. Accelerated rectilinear motion generates gravity in a medium free from gravity. Example: in a gun.

A sphere moving in this way generates gravity in one direction (in accordance with the conception of the ancients). A downward-moving accelerated body (acc. > 10 m) generates gravity the reverse of the Earth's.

4. There is no gravity in a body falling freely (rocket after firing). A body in accelerated downward motion (acc. < 10) has gravity less than the Earth's (load in Atwood's machine). Gravity is greater than the Earth's in a body with upward acceleration (Atwood's machine).

*This refers to Tsiolkovskiy's "Grezy o zemle i nebe" (Dreams of Earth and Sky), Moscow, Izd. Goncharova, 1895 (B. V.).

**The author's numbering has been retained (Editor).

5. Increased gravity in a gun projectile.

Artificial production of all these effects (Atwood's machine).

6. There is no gravity in an ejected or falling missile.

Horizontal gravity is produced in a carriage that is starting or ending its motion; this combines with the Earth's gravity to give an inclined relative gravity. The same occurs in the projectile in a horizontal gun.

8. Man takes a position normal to a hill while descending; friction is neglected. In the particular case of a vertical hill, gravity is eliminated. The apparent gravity in the projectile in a short gun is tremendous.

9. Quite inappreciable traces of gravity remain in a falling body subject to newtonian attraction (water and atmospheric tides, fracture or stressing of crust facilitating earth tremors).

A body falling in a hole along a diameter of the Earth reaches the center in 20 minutes; relative gravity vanishes in the body.

10. Carriage in a chordal channel in a planet. Gravity in carriage constant in magnitude and direction.

11. Rotating body produces relative gravity on it, which could not be there previously.

12. Effects in a rotating chamber, no gravity before rotation.

14 and 13. Surprising effects. One object sinks, falls, in general experiences gravity, while another, moving does not feel gravity; it travels, for example, without becoming submerged in water. Strange curve of motion from a kick.

15. The same. Two men standing one perpendicular to the other in a room.

16. The same. Liquid takes the form [of a body] of rotation.

17. The same. Effects on a pendulum, on a swing, and on spokes of a wheel.

20.* Effects on a rotating planet. Gravity balanced by centrifugal force at a certain height, afterwards reversed.

Tower in the form of a fan suspended without support above the planet and not falling on account of centrifugal force (effect possible on small planets).

19. Carriage moving uniformly along equator of planet. Gravity reduced, gravity eliminated and reversed. Rotation of planet does this (possible on asteroids).

21. No gravity on rings of Saturn.

[Omission. 26. Effects on American mountains.]

28, 29, and 30. Effects on a rotating planet. Possibility of moving in all directions from an artificial ring similar to one of Saturn's.

31. Rings surrounding a planet without an atmosphere, from which it is possible to rise easily into the heavens or descend from them, and also to set out on a cosmic voyage.

22. Motion on one of Saturn's rings causes gravity of different magnitudes, forward and reverse, in accordance with the speed and direction relative to the motion on the ring.

23. Effects in accelerated rotation.

24. Effects in a projectile in a curved gun; on swings.

25. Centrifugal mountains. In one particular case there is no gravity, then strengthened gravity in lower part.

Curvilinear motion in a space free from gravity produces relative gravity proportional to the curvature of the path and to the square of the speed of the carriage.

K. Tsiolkovskiy

Kaluga, Prospekt Jaures, house No. 3.

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*As in the original (Editor).

The figures given here have been reproduced facsimile from pages of this manuscript, which was sent to the Archives of the Academy of Sciences of the USSR in 1950 to the Tsiolkovskiy section, together with the commentary. They are published here for the first time.

3. Manuscript "Free Space," 1883 (f 1/2 s, ink on both sides); consists of 12 sets each of 3 pages sewn together, without pagination (rare for Tsiolkovskiy's manuscripts), but the sets are numbered. In all 142 pages of text. Begun February 20, 1883, completed April 13 of the same year. The first part to go with them would appear to be the notebook of 1879. On the first page of the manuscript there is a later note by the author (in the old orthography):

"Foreword.

Early work. Significance of concepts on phenomena that we will encounter on constructing habitations outside the atmosphere. This is part of mechanics, the mechanics of the simplest conditions, when imposed gravity is removed (I was then 25 years old)."

Many figures and sketches in the text and margins. Some of these are reproduced in this volume.

This manuscript is Tsiolkovskiy's first completed monograph on interplanetary travel, in which he not only indicates for the first time the reaction principle for motion in cosmic spaces but also gives sketches and a theoretical scheme for a reactive interplanetary vessel, which also shows two gyroscopes for rotating the whole system*.

Tsiolkovskiy mentions this work in his (unfinished) "Survey of My Works from 1881 to 1911 (30 years)," which was evidently written in the early years of Soviet power.

At the start of this review he lists his unprinted works and writes:

"Effects absolute and relative.

This work ... is not finished, but it was very broadly conceived.

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*This scheme was first published (facsimile) in B. Vorob'yev's "K. E. Tsiolkovskiy," Moscow, Molodaya Gvardiya, 1940, p. 45.

Absolute phenomena are more or less known, but relative phenomena (apparent ones), or those occurring on a body in nonuniform motion or deviating from rectilinear, are in no way comparable with absolute ones and are extremely interesting. They are inaccessible and strange to those unfamiliar with this. I mention this work, which has never been published, because I retain my regard for it and see no errors in it."*

4. Paper: "How to Preserve Frail and Brittle Things from Knocks and Blows," which appeared in Trudy Fizicheskogo otdeleniya Moskovskogo obshchestva lyubiteley yestestvoznaniya, antropologii i etnografii pri imperatorskom Moskovskom universitete (Transactions of the Physics Section, Society of Natural Philosophy, Anthropology, and Ethnography at the Imperial University of Moscow), 1891, vol. IV.

This deals with the protection of brittle or fragile objects from harm by gravitational forces. The author proposes placing the objects in a vessel filled with liquid (e.g., a raw egg in a tank containing water). Under these conditions even very sharp blows on the vessel will not damage the stored object.

The author, however, overlooks the fact that parts differing in weight will differ also in acceleration.

This, together with "Pressure of a Liquid on a Plane Moving in it," which was printed in the same issue of the above journal, was published as a separate pamphlet (with the title "Pressure of a Liquid", Moscow, 1891, 18 pp.). These are Tsiolkovskiy's first printed works.

5. "On the Moon." A science-fiction tale in the journal "Vokrug sveta" (Around the World), 1893.

It describes the dream of a youth who sees himself as a traveler on the Moon together with his companion. The surface of the Moon is described, as are various natural phenomena observed by the travelers, and their adventures in the unusual environment.

6. Book "On the Moon," a separate publication of the science-fiction tale printed in "Vokrug sveta" (1893); Moscow, 1893 (48 pp.,

*This work of Tsiolkovskiy's will appear in volume V of the present series (Editor).

4 figs.). "On the Moon" has been reissued 5 times during the Soviet period, including once in Ukrainian.

In his list "Published Works of K. E. Tsiolkovskiy," which he published in Kaluga in 1927, he writes in the third person of his published papers and comments on them; of his "On the Moon" he makes the following remark: "Only now have we confirmation of what the author said in his description of the temperature of various parts of our satellite. Previously Langley, for example, has indicated that the surface of the Moon is icy and has a very low temperature."

7. Manuscript "Change in Relative Gravity on the Earth," 1894, 191 pp., f 1/4 s. In ink, 2 figs.

This was found in 1937 in the attic of Tsiolkovskiy's former house, which is now a museum. At that time I made an exact type-written copy of it with all later corrections in Tsiolkovskiy's own hand.

On the first page of the manuscript there was a note in his hand: "Examined and corrected in pencil at the end of December 1916. K. Ts.". In this examination he inserted at the top of the first page another heading: "Fantasy and reality about the sky." In the top left-hand corner he had noted "Written in '94. K. Ts.".

The titles of the unnumbered chapters of this manuscript are as follows:

Strangeness of relative gravity. Horizontal carrousel with vertical axis. Man walking on a wall as on a floor. How to represent a horizontal place in the form of a steep hill. Apparently complete absence of gravity in a falling chamber. An equatorial train. Hypothetical travels in celestial space. The Milky Way. Interstellar house in the Milky Way. Mechanical phenomena, subjective and objective. Picture of artificial life in a medium without gravity. The planetary system of our Sun. To the Moon and on it. Mercury. Mars. Vesta. Cerera and Pallada. On the rings of Pallada.

This work of Tsiolkovskiy's of 1894 anticipates the book of his printed in the following year, "Speculations on Earth and Sky," although it differs considerably from the latter in manner of writing and in its treatment of the question. In 1908 this manuscript was under water for 3 days during the flood, as Tsiolkovskiy records in a note on it; but it was well preserved and was exhibited up to the war in 1941 in the Tsiolkovskiy Museum in Kaluga. In 1942 the Germans occupied Kaluga for 2 months, during which they destroyed the exhibits in the museum, the manuscript being torn. Some of the pages were destroyed altogether.

8. Book "Speculations on Earth and Sky," Effects of universal gravitation. Goncharov Publ. Ho., 1895, 143 pp (without figures).

This is described as extending Tsiolkovskiy's previous writings on interplanetary travel, which in part it repeats; it includes the following chapters:

I. External structure of the universe. II. Universal gravitation. III. Description of various phenomena occurring without the participation of gravity. IV. One independent of gravity. V. Is it possible to produce on Earth a medium with gravity differing from the Earth's. VI. Thoughts of an eccentric on the danger of air and of the possibilities of life in a vacuum; his dreams of a special type of intelligent beings living without an atmosphere. VII. In the asteroid belt. VIII. The energy of the Sun's rays. IX. Gravity as the cause of the speeds of the heavenly bodies and of radiation from these.

In his explanation of this book in his list of 1927 he writes that "it examines the possibility of sentient and intelligent beings who can live in a vacuum on the energy of the Sun's radiation without requiring food, somewhat as do plants and zoophytes. Indicates the possibility of immortality in higher organisms."

A review of this book was printed in the journal Nauchnoye Obozreniye (Science Review), 1895, No. 21, pp. 665-666, in which comment was made on the extreme phantasy of Tsiolkovskiy's statements.

9. Article "Can the Earth notify the inhabitants of the planets that there are intelligent beings on it?" which appeared in the newspaper Kaluzkskiy Vestnik (Kaluga News), 1896, No. 68. On the assumption that intelligent beings live on other planets in our solar system, it is proposed to transmit signals to them by means of mirrors that reflect the Sun's light.

In the margin of the first page of the text:

"All corrections in accordance with the manuscript remaining never able to recover and publish it. This deplorable occurrence led him to decide thenceforth to write "under copy," although this required more force than ordinary writing with pen or pencil on a desk. Only with the coming of Soviet power, from about 1922, was Tsiolkovskiy able to have his manuscripts typed; but he still continued to write as before on a board resting on his knees.

14. Article "The Reactive Vehicle as a Means of Flight in a Vacuum and in the Atmosphere" in Vozdukhoplavatel (The Aeronaut) of St. Petersburg, 1910, No. 2, pp. 110-113 (see earlier part of this volume).

The date on the above carbon copy (item 13), namely August 1908, would indicate that this paper was then sent to the editor of the above journal, but remained there awaiting publication until 1910.

15. Manuscript "The Reactive Vehicle -- the Rocket" (192 pp., f 1/2 s, oo). This is a form of the paper printed in Vestnik Vozduzkhoplavaniya in 1911 under the same title under the title of the first part, which was published in 1903 in Nauchnoye Obozreniye (No. 5): "Exploration of the Universe with Reactive Machines." The first part had appeared 8 years previously, so he included in this second part a summary of the first. The form of the article he sent to the journal was somewhat different, but the changes were only minor stylistic ones.

16. The article "Exploration of the Universe with Reactive Machines" was printed in Vestnik Vozdukhoplavaniya (St. Petersburg), 1911, Nos. 19, 20, 21, and 22, and 1912, Nos. 2, 3, 5, 6, 7, and 9; it contains the following sections:

Foreword. Summary of the 1903 paper. Gravitational work in escape from a planet. Speed needed by a body to escape from a planet. Time of flight. Resistance of the atmosphere. Curves for motion and speed of the vehicle. Life supports during flight. Fatigue from increased gravity. Problem of abwence of gravity. Speculations. The future of reactive vehicles. The reactive vehicle eliminates the obstacles imposed by the Earth (1 fig.).

The publication of this work saw the start of the popularization of Tsiolkovskiy's ideas on space travel and reactive technology, which increased from year to year and attracted an increasing number of inventors, imitators, and popularizers. The first printed works on this subject began to appear abroad in 1913.

Tsiolkovskiy preserved from this time onwards various isolated sketches and drawings, which show what he was then thinking; these at home, not exactly the same as that sent to Nauchnoye Obozreniye":

Tsiolkovskiy.

This manuscript (not complete) was sent to Vestnik Vozdukhoplavaniya (Herald of Aeronautics) 8 and 9 Oct. 1911.

Not returned at all".

12. Manuscript "Exploration of the Universe with Reactive Machines". Article 2 (fs, No. 181), ink on both sides (f 1/2 s), 180 pp. No date, but with following note (p, 00) by the author:

"The first article should have appeared in No. 2 of Nauchnoye Obozreniye, 1903 (February); appeared in May (No. 5)".

Originally the article was headed: "Basis of the theory of reactive machines for study of space (paper two)", but this has been struck out, the heading given above being entered in pencil.

This is clearly the second part of "Exploration of the Universe with Reactive Machines" prepared by Tsiolkovskiy for Nauchnoye Obozreniye but not sent to that journal, or some draft of it.

13. Manuscript "The Reactive Vehicle as a Means of Flight in a Vacuum and in the Atmosphere. 1908, August" (6 s, f 1/2 s, bs, cc).

From this year onwards Tsiolkovskiy took copies of his manuscripts. For this purpose he laid out on a board or piece of stiff card sheets of writing paper interleaved with carbon paper; he wrote in pencil, thereby obtaining 3 or 4 copies at once. But it was inconvenient to write in this way on a desk, so he sat in an armchair and rested the board with the sheets of paper on his knees. He maintained this way of writing to the end of his life. The event that drove Tsiolkovskiy to provide himself with copies, and that in the most economical way (at the time he did not have access to a typewriter) was the loss of his major manuscript "Report on Experiments on the Resistance of Air (1900-1902) to the Russian Academy of Sciences," which he sent via Professor Speranskiy to Professor N. Ye. Zhukovskiy in Moscow. During this transmission Tsiolkovskiy's sole copy of the manuscript was mislaid, and in spite of all efforts and assistance from friends he was had formed the basis of his two parts of "Exploration of the Universe ...," and he then wrote a paper which was given the title "The Reactive Vehicle -- the Rocket." But all these attempts only led after many years (in 1926) to a publication under the old title "Exploration of the Universe with Reactive Machines," in which he developed the idea further on the basis of papers written in previous years and of the latest scientific data.

17. Manuscript "In the Year 2000 (on the rocket)." 26 August 1913, 10 s, bs (f 1/2 s, p, oo) and 10 s of carbon copy (ac 1, No. 180).

The author describes how in the year 2000 some scientists and rich men have become convinced of the theoretical possibility of flight in interplanetary space by means of reactive vehicles and have decided to give a practical test of the idea. He relates how they set about the work, and, in particular, describes tests of burning hydrocarbons with liquid oxygen in thin-walled steel tubes. The manuscript was not completed. It is clear from notes by the author that he originally intended it to be part of his projected work "Rockets," but subsequently (1917-1920) he extended it as a long science-fiction story "Beyond the Earth," which he had printed in full in Kaluga in 1920.

17a. Pamphlet "Exploration of the Universe with Reactive Machines (on parts I and II of a work of the same name)." Kaluga, published by the author, 1914, 16 pp. and cover, but no title page, with 1 fig.

The first half presents briefly the history of the work; the second gives new explanations and supplements to the two previously printed parts.

Only the second part of the pamphlet is included in this volume.

18. Article "Without Gravity" printed in Priroda i lyudi (Nature and Mankind), Petrograd, 1914; this is a reprint, much shortened of "Speculations on Earth and Sky" (1895).

19. Manuscript of the author's foreword to the science-fiction tale "Beyond the Earth," printed in Priroda i lyudi in 1918 (aç 1, No. 10). The time when Tsiolkovskiy wrote this is indicated by a note in his hand on the envelope of a letter to him from Ya. I. Perel'man dated March 16, 1917 in the name of the editors of the above journal with a request to write and send a foreword:

"March 29. I promised to complete it by the end of the month, and the continuation (50 pp.) and foreword in 10 days. Answered March 23, 1917."

The editors altered this foreword to read as though it came from them, not from the author. He considerably extended this foreword in the Kaluga edition of this tale of 1920.

20. Manuscript "On Vesta" (5 pp., f 1/2 s); in the author's hand the note: "Written before 1919." The original title had been struck out; it was "Conditions of Life on Other Worlds." On the cover to the manuscript: Biology of the Cosmos, '19. Conditions of life. On Vesta (excerpts). How life may appear on an asteroid. Read January 5, 1932." This last phrase indicates that Tsiolkovskiy had reread the manuscript. Similar notes, sometimes accompanied by critical remarks, occur on many of Tsiolkovskiy's manuscripts.

21. Manuscript "Life in the Ether, 1919" (ac 1, No. 7), 62 pp. (f 1/2 s, p, bs, oo). On the first page is the date "Sept. 13, 1919 to April 1, 1920. Thursday." At the top of the page: "Reread in February 1923." On cover: "9 (Life in Ether), '19. Conditions of Life in the Asteroid Belt."

The manuscript deals with the phenomena that will be observed when astronauts enter these spaces and the conditions of life there.

22. Book "Beyond the Earth," science fiction. Published by the Kaluga Society for the Study of Nature and the Countryside. Kaluga, 1920, 118 pp., IX (without figs.). Foreword "From the publisher" written by Tsiolkovskiy. On p. 1 the author states that the part up to "Eternal Spring" he wrote in 1896. Unfortunately, this part of the manuscript is not preserved in his archive; but the dates when this material was written for "Priroda i lyudi" in 1917 are precisely stated on the document listed above as No. 19. The tale contains the following sections:

Castle in the Himalayas. Enthusiasm at opening. Discussion of project. The castle and its inhabitants. Continuation of chats on the rocket. Newton's first lecture. Second lecture. Two tests with the rocket in the atmosphere. Another astronomical lecture. Preparation for flight around the Earth. Eternal spring. The composite rocket. Relation to the outer world. Location or rocket. Leads. Those remaining on Earth. In the rocket flying around the Earth. They come out of the water. Discussions. Subjective state. Work, sleep, reading, eating. Physical and chemical experiments. Concert. Opening of shutters. Protests. Tosca after work. Artificial gravity.

The rocket is transformed into a flowering garden. Dressing in diving (space) suits. Leaving the rocket for ethereal space. Tale of the overalled ones (spacemen). Controls for rocket temperature. Tales of the effects experienced by the spacemen. Talks on life in the ether. Bath. Summary on life in the ether. Picture of a bather. The greenhouse. Equipment of greenhouse. Inexhaustible vital products. Life without sorrow. Telegraphy with the Sun's light. State of humanity in 2017. A strange star. The Earth accepts that the expanses of space are open to man. Outside the Earth. Conference on a new spiral flight around the Earth. A secret knock. Sentinel in the ether. Flight along a spiral. Travelers' impressions. Bolides. Orbit of Moon reached. Decision to fly to the Moon. Doubts about flight to Moon. Founding of new colonies. Voyage from lunar orbit to the Moon. On the mountains and valleys of the Moon. Farewell, Moon! Departure from the Moon. Once more in the large rocket. Telegram to the Earth about the Moon. Earth's affairs. Picture of resettlement and life in space colonies. Union of the colonies. With scientists in the orbit of the Moon. First conference. Second conference. Around the Sun beyond the Earth's orbit. On an unknown planet. Once more in the rocket. We fly to Mars. Encounter gas rings on the way. Approach to Mars. Possibility of visiting the planet. Towards the Earth, a short journey. On Earth. Meeting in the castle. Plans for new space excursions.

The ideas and technical content of this work have formed the basis of all foreign plans (in Europe and America) for interplanetary communication, machines, and artificial Earth satellites for aggressive purposes, which have been particularly widely publicized in recent times in the USA.

23. Manuscript "Cosmic Rocket. Conquest of the Solar System," November 29, 1923 (5 pp., bs, 1/2 s). First part of a projected popular article (not completed).

24. Manuscript. Sketches, with note on title page "For 2nd part of rocket." November 22, 1923, f 1/2 s, 15 pp.

25. Manuscript "A Reactive Vehicle." April 1924, 14 pp. (f 1/2 s).

Calculations, sketches of devices for testing the action of a rudder on a rocket, and so on.

26. Manuscript "A Spaceship." Popular article written for Tekhnika i zhizn' (Technology and Life) of Leningrad at the request of Transpechat' Publishing House of June 24, 1924, the purpose being

to describe in the journal "the construction of an interplanetary ship." The article was written on the basis of sketches Tsiolkovskiy already had (see items 23 and 24 above). On July 24, 1924 the editor confirmed that it had been received, but that in view of its considerable length it had been decided to print it as a separate pamphlet. However, this was not done; after the editors had retained it for over $1^1/_2$ years, they returned the manuscript to the author, and this has been reproduced in this volume.

27. Pamphlet "A Rocket in Outer Space." Kaluga, published by the author, 1924, 32 pp. (Introduction in German.)

This is an exact reprint, apart from change of title, of "Exploration of the Universe with Reactive Machines: printed in the May issue of Nauchnoye Obozreniye for 1903. This is clearly why the title page states "Second edition".

28. Letter to the editor of Svyaz' (Communications), organ of the Moscow Communications Commission; printed in No. 18 for 1925, p. 14, with picture of Tsiolkovskiy.

In the letter he states that only less than a month previously he had obtained a solution in final form for the distribution (density, temperature, and speed) of exploding gases in various parts of a tube.

29. Manuscript "Voyages Beyond the Atmosphere. Principle of a Self-Moving Body. November 7, 1925" (f 1/2 s, bs), carbon copy. Popularization.

30. Manuscript "Calculations and Tables on Cosmic Journeys and Facilities for Living Away from the Earth. June 13, 1926," 50 pp., full sheets, pencil on both sides (f 1/2 s). Note by author: "1. Work of gravity, cosmic speeds. 2. Energy of the Earth. 3. Guns and rockets." Unfinished.

31. Manuscript "Exploration of the Universe. A Rocket in Cosmic Space. June 26, 1926" (14 pp., f 1/2 s). This and No. 29 would appear to be rough drafts for the book of the same name appearing in that year.

32. Book "Exploration of the Universe with Reactive Machines." Kaluga, published by the author, 1926, 125 pp., no title page. In his pamphlet "Published Works of K. E. Tsiolkovskiy" he calls this "the fourth and most extensive work on the same theme" and states that in this edition he proposes only to reprint previous works with certain additions. But "I am obliged by material conditions to re-

strict this to largely one new one." Reproduced in this volume from his "Selected Works." Published 1934 with certain corrections.

33. Pamphlet "A Spaceship. Experimental Preparation." Kaluga, published by the author, 1927, 27 pp. (no cover or title page). In his "Published Works" (p. 24) he says that this was an attempt to indicate the preparatory tests in the design of a space vehicle. On p. 1 of the pamphlet he made the following note: "Only those familiar with my study of '26 can understand and evaluate this work."

As an appendix at the end of the pamphlet (pp. 22-24) there is "Objection to Eng. Lademann." This engineer published a review of Tsiolkovskiy's "Study of outer spaces ... " of 1926 in the German aviation journal ZfM of April 12, 1927; in this, amongst other things, he cast considerable doubt on the proposal to fit the reactive flying vehicle with rudders at the rear. This objection now appears as a curiosity, but at that time (28 years ago) the bold and novel technical ideas of the forward-looking Russian scientist were so far in advance of their time that even those with higher technical education, authors of papers in this field, were unable to appreciate them and even cast doubt on them.

34. In his book "Air Resistance and the Express Train" (published by the author, Kaluga, 1927, 72 pp.) Tsiolkovskiy gave as an appendix the foreword to his "Beyond the Earth" of 1920 (see item 22).

35. In the pamphlet "Published Works of K. E. Tsiolkovskiy" (published by the author, Kaluga, 1927) he gave notes and comments on his published works, including ones on reactive flying vehicles and interplanetary travel (pages 7, 9, 15, 20, and 24).

36. Manuscript entitled "Untimely," September 16, 1927, 4 pp., pencil (one side, f 1/2 s).

37. Manuscript "Works on the Spaceship 1903-1927" (May 1928, 8 pp., f 1/2 s, typed), corrected by the author in 1931 (ac 1, No. 205).

38. Manuscript "Conquest of Solar Systems. A Science Fiction Tale." November 1928, 24 typed pages (f 1/2 s). With insertions dated June 20, 1929. Unfinished.

39. Book "Cosmic Rocket Trains." Picture of the author (plate) and author's foreword. Published by the Kaluga section of Scientific Workers. Kaluga, 1929, 38 pp.

In the foreword the author says: "I am already 72. It is long since I worked with my hands or experimented." The book deals with his proposals for attaining maximum height and range with composite rockets. He foresees that "the workers expect great disappointments, because a satisfactory solution is far more difficult than even the most percipient minds imagine." "We shall need many fresh and enthusiastic teams. Flight to the stars cannot be compared with flight in the air ...." "If they understood the difficulties, many now working with enthusiasm would abandon it" (p. 8). Here we print the third edition from the manuscript.

40. Manuscript "The Reactive Aeroplane. December 1929. Taken from a large manuscript, so numbers not in order." He evidently has in view his unfinished manuscript "A New Aircraft for Great Heights" (40 typed pages); ac. 1, No. 158. Both were used in his "Reactive Aeroplane" of 1930 (item 48).

41-43. Pamphlet "A New Aeroplane," which includes "Beyond the Earth's Atmosphere" (pp. 25-33) and "A Reactive Engine" (pp. 34-36), which explain the contents of the first article. Kaluga, published by the author, 1929, 38 pp. and 1 page of drawings.

44. Pamphlet "On the Moon." Tale of fantasy. GIZ, Moscow, 1929, 75 pp., 8 figs. Republication of article of the same name in Vokrug Sveta of 1893, with foreword by Ya. Perel'man.

45. Pamphlet "Objects of Flight to the Stars." Kaluga, published by the author, 1929, 40 pp. (cover, no title page). Popularization.

46. Manuscript "From Airplane to Astroplane." November 25, 1930, 14 pp. (typed, f 1/2 s).

47. Pamphlet "To the Astronauts." Kaluga, published by the author, 1930, 32 pp.

This contains several arguments of the author's on the use of reactive engines and energy from the pressure of the Sun's rays for future interplanetary ships, although the last is viewed with scepticism: "I recognize that even I have little faith in this pressure, even though experiments confirm it" (p. 4).

This is printed on p. /339 of the present volume.

48. Pamphlet "The Reactive Aeroplane." Kaluga, published by the author, 1930, 24 pp. It is demonstrated to be technically

possible to construct a purely reactive airplane provided that the fuel has the highest calorific value of any known. Such an airplane makes it possible to attain in high levels of the atmosphere speeds inaccessible to airplanes with propellers. Tsiolkovskiy's intuition led him to predict correctly at the end of this article that "After the era of propeller aeroplanes must follow the era of reactive or stratosphere aeroplanes."

48a. Manuscript ("Semireactive Stratoplane"), 1930 (f 1/2 s, typed). Some pages missing. In part printed in pamphlet of the same name in 1932 (item 56).

49. Manuscript "Ascending Accelerated Motion of a Rocket Plane." October 1930 (typed), 27 pp. (ac 1, No. 64). Printed in: "K. E. Tsiolkovskiy, Works on Rocketry," Moscow, Oborongiz, 1944 under the title "Rocket Plane." It is here printed from the original under the above title of the author's.

50 and 51. Manuscripts "Formulas of the Stratoplane," January 30, 1931 (14 pp., pencil, one side) and "The Stratoplane: Tables and Formulas," March 3, 1931 (40 pp., f 1/2 s, pencil), which are rough drafts and working copies for "The Semireactive Stratoplane," 1932 (item 62).

52. Article "From Airplane to Astroplane" in the journal Iskry Nauki (Moscow) for 1931, No. 2, pp. 55-57. A short historical review of the development of the idea of reactive flying machines. The principles of a semireactive stratoplane are described in the second half of the article.

53. Book "On the Moon," Ukrainian translation of Tsiolkovskiy's science-fiction tale of the same name (1893, item 6 above). Kharkov, 1931, with foreword by Ya. Perel'man.

54. Article "Theory of Reactive Motion" in V boy za tekhniku (Struggle for Technology), Moscow, 1932, No. 15-16 (August). A brief description in popular form of a rocket with wings capable of attaining cosmic speeds, together with an outline of the problems of interstellar flight.

55. Article "Density of Various Layers of the Atmosphere" in Samolet (The Airplane), 1932, No. 8-9, p. 36.

56. Pamphlet "The Semireactive Stratoplane." Kaluga, published by the author, 1932, 32 pp., with 4 figs. on inside of cover.

Description of schemes and rough calculations for a novel stratospheric aeroplane, whose design and power plant were taken up several years later by the Italian firm of Caproni.

57. Article "Reactive Motion and its Advantages" in Samolet (The Airplane), Moscow, 1932, No. 6 (popularization).

58. Article "Flight in the Stratosphere" in the newspaper Tekhnika (Technology), Moscow, for September 18, 1932 (4 figs.).

Abridged reprint of "The Semireactive Stratoplane," which was published in the same year (item 56).

59. Article "The Astroplane" in Znaniye-sila (Knowledge is Power), 1932, No. 23-24, p. 15 (popularization).

60. Text of Tsiolkovskiy's jubilee lecture given at the meeting of social organizations on September 9, 1932 in Kaluga on the occasion of his 75th birthday. Printed in the pamphlet "Konstantin Eduardovich Tsiolkovskiy, 1857-1932", edited by B. A. Monastyrev and D. S. Semenov, Moscow-Leningrad, ONTI, 1932, pp. 36-42, with picture of Tsiolkovskiy.

61 and 62. Article "My Dirigible and Stratoplane" in the newspaper Izvestiya (TsIK i VTsIK), Moscow, for October 18, 1932 and the same article in Red Star (Moscow) for that day.

In the first part of the article Tsiolkovskiy details the advantages of his all-metal dirigible over other types; in the second part he deals with the basic design principles of his stratoplane.

63. Article "The Semireactive Stratoplane" in the journal Khochu vse znat' (I Wish to Know All), Moscow, Zhurgazob'yedineniye, 1932, No. 29, October, pp. 5-7, 4 figs.

Abridged form of pamphlet of the same name appearing in that year (item 46).

In 1932 the press widely reported Tsiolkovskiy's 75th birthday as that of a particularly popular Soviet scientist; newspapers and journals reprinted his recent scientific and popular articles on his main themes, since they could not obtain from him especially commissioned articles, because in that year Tsiolkovskiy was especially busy with scientific work on reactive flying machines and on experimental work with dirigibles.

64. Articles "The Dirigible, the Stratoplane, and the Airplane as Three Stages in the Great Achievements of the USSR" in the Aeroflot journal Grazhdanskaya aviatsiya (Civil Aviation), 1933, No. 9 (p. 78, 5 figs.), No. 11 (pp. 22-24, 4 figs.), and No. 12 (p. 41, 1 fig.).

The author briefly describes the principles of his all-metal dirigible of volume adjustable during flight, of the semireactive stratoplane, and of a rocket with wings.

65. Pamphlet "Gravity has Vanished" (a science fiction tale), Moscow, Gosmetizdat, 1933, 119 pp., 20 figs.

This is Tsiolkovskiy's "Speculations on Earth and Sky" (1893, item 8) in abridged form.

66. Book "On the Moon." Published by the Junior Library of Avtoaviaizdat, Moscow, 1933, 40 pp., 5 figs.

Reprint of Tsiolkovskiy's science-fiction tale of 1893, with foreword by Ya. Perel'man.

67. Manuscript "Album of Cosmic Journeys," June 21, 1933, 26 pp. (typed). Written in connection with Tsiolkovskiy's work as principal scientific adviser in the production by Sovkino of the full-length film "A Cosmic Voyage" (director V. N. Zhuravlev). Tsiolkovskiy attached great importance to the cinema in popularizing scientific ideas and advances, and he agreed to direct the scientific part of the work, in spite of a heavy load of scientific tasks. He considered that the work would be facilitated if the film-studio workers were acquainted with simple astronomy and with recent advances towards interplanetary travel, so he wrote this and illustrated it with simple sketches. This served as a text for lectures and discussions held with the film workers on "A Cosmic Voyage," which he had conceived together with Zhuravlev in Kaluga. This careful attention to the planning and performance of the studio work over a period of several months in 1933 placed the film on a sound scientific basis.

68. Sketches designed as illustrations for "Album of Cosmic Journeys," dated November 11, 1933 and March 17, 1934. These figured in Tsiolkovskiy's talks to the film-studio workers. He also intended to publish the Album. The work remained unfinished.

69. Manuscript "Cosmic Voyages" dated November 11, 1933 (15 pp., typed), evidently conceived as continuing in some form his "Beyond the Earth" of 1920 and as an attempt to sketch the future life of man colonizing the cosmos. This remained unfinished.

70. Article "Beyond the Atmosphere" in Vokrug sveta (Around the World), Moscow, 1934, No. 1, pp. 10-14 (popularization).

71. Article "Principle of Reactive Motion" in V boy za tekhniku, 1934, No. 6 (June), p. 25 (popularization).

Contains a critical survey of machines for an interplanetary rocket described in No. 4 of this journal for that year.

72. Book "Selected works of K. E. Tsiolkovskiy." Volume II. "Reactive Motion." Edited by Engineer F. A. Tsander, with foreword by him. Moscow, Gosmashmetizdat, 1934, p. 216.

This contains the following works by Tsiolkovskiy on jet technology and interplanetary travel:

A Rocket in Cosmic Space (pp. 11-40). Exploration of the Universe with Reactive Machines (pp. 41-120). The Cosmic Rocket: Experimental Preparation (pp. 121-134). Rocket Cosmic Trains (pp. 135-159). A New Aeroplane (pp. 160-174). The Reactive Aeroplane (pp. 175-200). The Semireactive Stratoplane (pp. 201-210).

73. Article "Research and Study of the Stratosphere" in the newspaper Komsomolets Ukrainy (Ukraine Komsomol) for August 18, 1934.

Written for aviation day at the request of the editors, who desired to mark the traditional national occasion with an article by Tsiolkovskiy.

74. Letter to the editors of the newspaper Kino (Moscow, Zhurgazob'yedineniye) in No. 273, February, 1934.

On the occasion of screening of "A Cosmic Voyage," for which Tsiolkovskiy was the principal scientific adviser.

75. Article "Reactive Vehicles in the Study of the Stratosphere" in the newspaper Rabochaya Moskva (Working Moscow) for March 3, 1935, No. 51.

This was written on the occasion of the opening in Moscow of the First All-Union Conference on the Use of Reactive Flying Vehicles in the Study of the Stratosphere.

76. Manuscript "Principles of Construction of Gas Machines, Engines, and Flying Vehicles," 1935. Unfinished manuscript, which was intended to contain 11 sections. Section 1 is dated August 12,

1934, and in it the author defines its purpose as follows:

"The object here is practical: to give in condensed form material needed by inventors and builders of gas machines. The general and principal purpose is for the construction of land, water-borne, atmospheric, and space means of propulsion."

Tsiolkovskiy evidently strived to accelerate the publication of this by including as the third section a work he wrote in 1932 that had not been published: "Friction in Gases" (ac 1, No. 10) and as the fifth his "Density of Various Layers of the Atmosphere," which had appeared in Samolet for 1932 (No. 8-9, p. 36). Two sections remained unstarted, while of the rest there survives in more nearly finished form section 8 "The Greatest Speed of a Rocket," which is printed in this volume. This was the work he had in mind in a talk with the representative of the newspaper Na strazhe (On Guard) of the Osoaviakhim in June 1935*, when he said:

"At present I am writing a major treatise on stratospheric flying machines, which consists of 10 sections, including ones on the compression and expansion of gases, on the density of the atmosphere, on rough calculations on rockets, and finally on new gas-turbine engines."

Tsiolkovskiy was unable to finish this, on account of an illness of fatal outcome.

77. Article "Is it Only a Fantasy?" in the newspaper Komsomolskaya Pravda for July 23, 1935.

78. Article "From the Balloon to the Astroplane" in the newspaper Pishchevaya industriya (Food Industry), Moscow, for September 2, 1935, No. 127.

This was preceded by an introduction from engineer B. Vorob'yev "The Creative Path of K. E. Tsiolkovskiy."

79. Article "Flight in the Future" in the newspaper Kommuna (The Commune), Kaluga, for August 18, 1935, No. 184, with picture of Tsiolkovskiy.

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*"What I Am Working On." E. Gol'der's interview with K. E. Tsiolkovskiy. Na Strazhe, Moscow, June 27, 1935 (B. V.).

This is his last article, in which he says:

"Everything of which I speak is merely a feeble attempt to foresee the future of aviation, aeronautics, and rocketry.

"In one thing I firmly believe, that the Soviet Union will be first. Capitalist countries are also working on these topics, but capitalist system hinders innovations. Only in the Soviet Union do we have a powerful aviation industry, abundant scientific institutions, general interest in problems of aeronautics, and a great love of all working people for their motherland, which will ensure success in our efforts."

Tsiolkovskiy's last lines printed in his lifetime consist of a letter to Stalin of September 9, 1935, which was widely published in the Soviet press; he wrote:

"All my work on aviation, rocketry, and interplanetary travel I pass on to the Bolshevik party and the Soviet government, the firm guides to progress in man's culture. I am convinced that they will carry this work to a successful conclusion ...."

From Stalin the ailing scientist soon received a warm and encouraging reply:

"To Comrade K. E. Tsiolkovskiy, an outstanding worker in science.

"Please accept my thanks for your letter and for your complete confidence in the Bolshevik party and Soviet government.

"I wish you health and further fruitful work for the good of the workers.

"I shake your hand."

J. Stalin

This highly valuable document from the history of our science is a magnificent final tribute to the great life of Tsiolkovskiy, who to the end devoted unceasing labor for the good of his country and for all mankind.

FARADAY TRANSLATIONS
15 PARK ROW
NEW YORK, N.Y. 10038

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