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WORKS ON ROCKET TECHNOLOGY

By K. E. Tsiolkovskiy

Publishing House of the Defense Industry
Moscow, 1947

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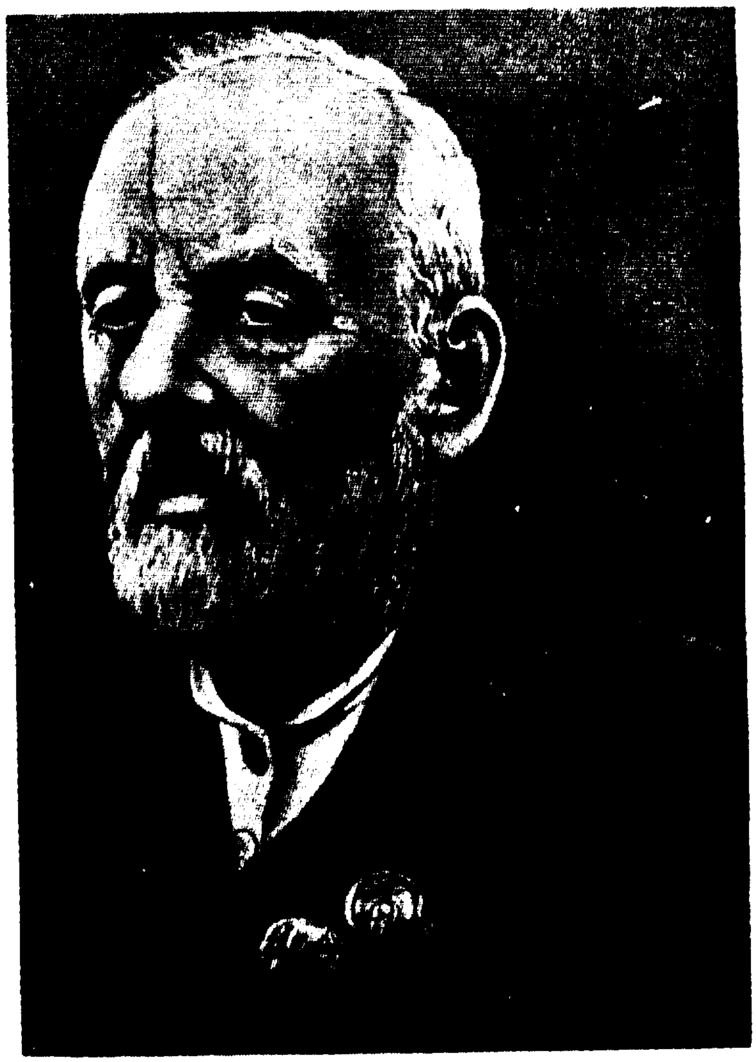

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INTRODUCTION

THE WORKS OF K. E. TSIOLKOVSKIY ON ROCKET TECHNOLOGY /3*

K. E. Tsiolkovskiy devoted a rather substantial portion of his works to the problem of flight by means of various reactive devices. We may state without exaggeration that Tsiolkovskiy considered his efforts in this direction to be of prime importance. Up to the time of his death Tsiolkovskiy continuously published articles, notes, and calculations devoted to a comprehensive analysis of the possibilities and methods of interplanetary communications.

The grandeur of the problem and the consequences of its solution were not known to anyone else as clearly as they were known to Tsiolkovskiy. None of the authors concerned with the problems of interplanetary flights went as far as Tsiolkovskiy in discussing the future social and economic implications of the solution of this problem.

The problem of rocket flight is extremely broad. Tsiolkovskiy developed it in considerable detail, beginning with the stratospheric semirocket airplane with a flight altitude of approximately 30 km and ending with an interplanetary rocket ship for travel into interstellar space. Among the works of Tsiolkovskiy the reader will find propositions on the use of reactive exhaust from aircraft engines, projects for powerful semirocket engines for an airplane, a project of air-breathing rocket engines for flights into the stratosphere, outlines of a rocket airplane for flying out of the atmosphere, considerations on the structure of interplanetary stations, and finally, a proposition on future colossal settlements somewhere in the region of the asteroids. He considered all of these subjects in a scientific manner; they were not the products of his fantasy. Logical conclusions were expressed by Tsiolkovskiy, based on results obtained by mathematical calculations and by the utilization of the state of the art in all fields of science and technology.

The present volume contains the most important works of Tsiolkovskiy on rocket technology. However, in developing the problem of rocket flight, Tsiolkovskiy could not bypass other problems associated with it. Therefore, Tsiolkovskiy's works in aviation which are directly associated with rocket technology could not be omitted.

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*Numbers given in the margin indicate the pagination in the original foreign text.

All of the works of Tsiolkovskiy contained in the present volume may be divided into two groups, one of which is given a technical treatment, while the other is given a popular treatment. The latter group, however, is of a unique nature; although it is popular in form it sometimes contains original technical ideas and therefore cannot be excluded from the scientific legacy of Tsiolkovskiy. Therefore, we have considered as scientific and technical articles not only those which present the mathematical proof of some proposition, but also those which describe projects, propositions, etc. /4

A special place is occupied by those works of Tsiolkovskiy in which he propagandized his technical ideas. Behind the dry mathematical computations was a man very much interested in life. He was concerned with rockets not because of a simple interest in a new problem, but because of idealism concerning the future material welfare of mankind which he envisioned. Tsiolkovskiy dreamed of sending mankind to the entire solar system; he dreamed of the possibility of a total utilization of solar energy; he dreamed of a more comfortable life in a medium without gravity and of cities in interplanetary space. It was only necessary to find a means for achieving all this, and Tsiolkovskiy found it in the rocket. However, a large amount of work and energy would have to be expended to realize an interplanetary ship. Tsiolkovskiy knew that a tremendous amount of work was yet to be done. (Remarks in the letter by H. Oberth to Tsiolkovskiy on October 24, 1929.) However, he was convinced that an interplanetary rocket would be realized. Therefore, all of the articles Tsiolkovskiy devoted to the problem of interplanetary travel are of great interest and point to the striving goal of all his work in the field of rocket flight.

One might say that "officially" Tsiolkovskiy started on the rocket problem in 1903, when he published his first work on this subject entitled "Investigation of Universal Space by Means of Reactive Devices." Subsequently this title was changed by the author to "A Rocket into Cosmic Space." Actually, Tsiolkovskiy started his work on rockets at a much earlier date. He began his theoretical investigations on the possibility of applying rockets to cosmic travels in 1896. During that year, after obtaining a copy of the little book by A. P. Fedorov entitled "A New Principle of Atmospheric Flight" (Petersburg, 1896), Tsiolkovskiy started his own work. He wrote: "The book (i.e., the book of Fedorov) was not clear to me, and in cases of this type I start to carry out my own calculations. I got nothing out of the book, but, nevertheless, it pushed me towards serious works." (See "The Investigation of Universal Space by Means of Reactive Devices," 1926.)

However, it was much earlier that Tsiolkovskiy actually proposed the utilization of the rocket principle for propulsion in interplanetary space. B. N. Vorob'yev, who examined the manuscripts left after the death of Tsiolkovskiy, found a paper entitled "Free Space" which was written in 1883 (started in February and finished in April) from which it is clear that even at that time Tsiolkovskiy knew about the rocket principle of propulsion and thought of applying it to propulsion in space free of air and gravity. /5

Here are a few excerpts from this work of Tsiolkovskiy:

"Here are some of the applications of the laws of motion of two interacting bodies to free space[1].

"Exerting all my available force, I threw a stone in the direction opposite to that in which I wished to travel. The stone attained a velocity of 10 m. The mass of the entire body is 100 kg, consequently my body was pushed with a velocity less by a factor of 100 than the velocity of the stone, i.e., with a velocity of 1/10 m.

"The stone will continue to travel in space until it meets (perhaps not for a thousand years) some large mass which attracts it.

"An inanimate object (stone) was necessary, in the example, for imparting motion to man. This stone is also carried off into space, and if it is not captured and returned by some means to its owner, it is lost forever.

"In this case we may say 'Unless we lose matter, motion in free space is impossible.'

"When the support has a relatively insignificant mass, then even though the velocity of the repelled body is much less than the velocity of the support, the velocity of the repelled body nevertheless may be arbitrarily large.

"Let us assume that we have a barrel which is filled with a highly compressed gas. If we open one of its valves the gas will flow out of the barrel in a continuous jet and the elasticity of the gas which repels its particles into space will also repel the barrel continuously.

"As a result of this there will be a continuous change in the motion of the barrel.

"With a sufficient number of valves (6), we may control the exit of the gas so that the motion of the barrel or of an empty sphere will depend entirely on the desires of the one controlling the valves, i.e., the barrel may travel along any curve, following any law of velocities.

[1]By the term "free space" Tsiolkovskiy meant space in which the force of gravity is entirely absent or is quite weak. -Editor's Comment.

"In any case, the total free center of the body and of the outgoing molecules of gas always retains its initial motion or its initial state of rest.

"A change in the motion of the barrel is possible only until all of the gas leaves it.

"However, since the loss of the gas takes place continuously, and under average conditions this loss is proportional to time, motion may be arbitrary only for a limited period of time--for minutes, hours, or days--and then it becomes uniform. /6

"In general, curvilinear uniform motion or rectilinear nonuniform motion in free space is associated with a continuous loss of substance (support).

"In the same manner, discontinuous motion is associated with the periodic loss of substance."

Of course, what is described here is not the rocket, but the principle of motion in air-free space is correctly pointed out. Apparently Tsiolkovskiy himself forgot about these pages.

Thirteen long years elapsed and the book of Fedorov mentioned above pushed Tsiolkovskiy toward a new investigation.

In 1896, Tsiolkovskiy wrote the beginning of a story entitled "Outside the Earth."[1] In the third chapter he points to the rocket as the device for interplanetary travel. The eighth chapter is called "Two Experiments With a Rocket at the Limits of the Atmosphere" while the tenth chapter is called "Preparations for Flight Around the Earth."

During the years 1896-1901, Tsiolkovskiy was occupied with experiments and investigations on aerodynamics, the construction of the first wind tunnel in Russia (1897), and with experiments on the resistance of air. At the beginning of 1903, he prepared the first part of his work "Investigation of Universal Space by Means of Reactive Devices."

In this chain of events we must note the dates: 1883, 1896 and 1903. This exhausts all of the arguments concerning the priority of Tsiolkovskiy in the field of rocketry of which Tsiolkovskiy himself wrote: "Priority exists today but disappears tomorrow" (see his article in "From the Airplane to the Astroplane"); "I never claimed a

[1] Specifically, the first ten chapters. In this connection see the Preface by the publisher to the book of K. E. Tsiolkovskiy entitled "Outside the Earth," 1920, and also see "The Resistance of Air and Fast Train," 1927. Both of these were published at Kaluga.

complete solution of the problem" (see "Investigation of Universal Space by Means of Reactive Devices," 1926). However, there is no doubt that Tsiolkovskiy was the first clearly to see the prospects of the rocket in achieving interplanetary flights.

After 1903, Tsiolkovskiy's next work on rockets appeared in 1910. Later in 1911-1912 he published Part 2 and in 1914 a supplement to Parts 1 and 2 of "Investigations of Universal Space by Means of Reactive Devices." After this he published nothing for ten years and it was only after the October Revolution that he began to continue the development of his ideas on the subject of rocket flight. His manuscript entitled "Cosmic Ship" written in 1924 has been preserved. Articles written by Tsiolkovskiy followed each other very rapidly and after 1926 he produced several each year. The productivity of Tsiolkovskiy's mind is quite amazing. It should be noted that we are speaking exclusively of his work devoted to rockets. We should not forget that /7
he also had time to write and work on the problems of atmospheric flight, astrophysics, geology and geochemistry, philosophy, and other subjects.

A few words should be said concerning the attitudes of the old caste of graduate scientists of Tsarist Russia toward the works of Tsiolkovskiy. At that time Tsiolkovskiy remained an unacknowledged amateur inventor. Even the efforts of the greatest scientists such as Mendeleyev and Stoletov to attract the attention of society towards the ideas of the talented innovator were met with indifference by the bourgeois Tsarist Russia.

Nothing annoyed Tsiolkovskiy more than the statements concerning the untimeliness of his technical ideas. On this subject he once wrote a letter in which he repudiated narrowmindedness and the lack of foresight. Here is the letter almost in its entirety.

"If, indeed, things and enterprises are untimely, they die by themselves without any external influence. At the same time we know that all great undertakings were untimely and although they were not forbidden, but not arousing interest, they died or proceeded very slowly with great efforts and sacrifices. Thus railroads were also considered untimely. Commissions of well-known scientists and specialists found them to be not only untimely but detrimental and a health hazard. The steamer was considered to be a toy not by just anyone, but by the great Napoleon himself and by the brilliant men of his time.

"Any invention, any original idea was treated with ridicule, persecuted as a health hazard, or, in the best case, as being untimely. There was also a large number of stupid ideas and impractical discoveries and inventions, and their percentage was huge. However, history has shown that neither scientists nor specialists nor the wise men were ever able to distinguish between a great discovery and an insignificant discovery.

"Let us assume that a man appears among us who is as unusual as G. Bruno, Galilei, Copernicus, etc. No one would understand this man; a small circle of his students would doubt him and even if they were sympathetic would be unable to do anything to help him. The editors of magazines would not accept his articles, would find them unscientific and contradicting modern views. These editors always require the wisdom of encyclopedic dictionaries. Who will agree with the unknown man who attacks the universally recognized authorities?

"We do not listen to that which is quiet and suppressed but to that which rumbles beyond our boundaries. However, we do not have the strength to criticize and analyze that which rumbles in the press. To do so would require brilliant people, but we are mediocre people.

"And what is it that rumbles! It is the authority which is permitted to make errors and to lie--anyone who has connections by virtue of noble birth, capital, or inherited property. What utter nonsense has been published and is now being published in various journals! In /8
some respects this may be good: lies defeat themselves and should not hinder the propagation of ideas. However, it is bad that the right to speak is possessed only by the strong or established authorities and by graduate scientists. All others are suppressed by this caste."[1]

This letter was quite different from the one written by Tsiolkovskiy before his death. Writing to Stalin he said "Only October has brought recognition to the works of a self-taught person."

After the revolution Tsiolkovskiy gave up teaching and expended all his energy in the direction of further development of his ideas and on the publication and popularization of his work. It was for this reason that he was so productive in the post-October period of his life.

At the present, leading Soviet scientists and engineers have very highly appraised the scientific work of Tsiolkovskiy. The masses of young technical people have joined in this appraisal. However, there are some skeptics who in one way or another stand in the way of Tsiolkovskiy's technical ideas and who still call them untimely. The words of Tsiolkovskiy contained in the letter quoted above apply fully to these people.

The great possibilities of our Socialist Nation in which science and technology serve the interests of the people permit us to state with assurance that the most useful development of rocket technology will take place in the USSR. Tsiolkovskiy was convinced of this at

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[1]The text is from the manuscript contained in the archives of K. E. Tsiolkovskiy.

the time of his death when he transferred "all his works on aviation, rocket flight and interplanetary communication to the party of the Bolsheviks and the Soviet power--the real guardian of the progress in human culture." (Taken from the letter of Tsiolkovskiy to Comrade Stalin.)

The role played by the work of Tsiolkovskiy in the development of rocket technology in our nation cannot be insignificant. Tsiolkovskiy pointed to the most rational paths in the development of this new form of technology and gave a series of schemes for rocket devices which are of practical importance not only for the future but also for today.

This role was also quite substantial beyond our boundaries. In the 1920's when the ideas of Tsiolkovskiy began to penetrate into Germany and then into France, the priority of Tsiolkovskiy was not questioned by many workers in rocket technology originating at that time. The works of Tsiolkovskiy aroused the interest of scientists as well as engineers. In 1929, H. Oberth wrote to Tsiolkovskiy: "I send you my greetings...I hope that you shall live long enough to see your great goals accomplished...you have turned on the light and we shall continue to work until the great dream of mankind is achieved...I am sending you my new book and would be very grateful if you can send me /9
your latest works in exchange..." (excerpts from this letter were first published in an Appendix to the book by Tsiolkovskiy "A New Airplane," Kaluga,[1] 1929).

The ideas of Tsiolkovskiy were discussed in the pages of the technical press; they were criticized and sometimes condemned. For example, the proposition made by Tsiolkovskiy to place the rudder for rocket control into the gas jet flowing from the nozzle of the rocket engine and thereby to achieve control of the rocket in empty space or in the upper layers of the atmosphere was rejected by the German engineer Lademan[2]. The article by Lademan in which, incidentally, he made a series of remarks concerning Tsiolkovskiy's "Investigation of Universal Space by Means of Reactive Devices," K, 1926, in turn produced objections from Tsiolkovskiy which were published by him together with the work "Cosmic Rocket. Experimental Preparation," K., 1927. Fifteen years later Tsiolkovskiy was proven to be right: in July of 1942, a successful flight of the German rocket A4, later known as the V-2, was undertaken. This rocket was equipped with rudders exactly as

[1]In the future all of the works of Tsiolkovskiy published at Kaluga will be designated by the letter "K."

[2]ZFM, April 28, 1927.

proposed by Tsiolkovskiy. The rudders were made from a graphite mass and placed in the gas jet of the rocket engine. The rationality of this device was completely confirmed by experiments. It is known that the V-2 rocket was used by the Germans in the last war as a long range missile.

In the last war a series of advances were made in rocket technology and if we compare them with the ideas of Tsiolkovskiy, we shall see that he (in his work of 1903) predicted the modern liquid fuel rocket almost exactly. Tsiolkovskiy wrote of a rocket utilizing liquid oxygen as an oxidizer, of a rocket in which the fuel is supplied to the combustion chamber by pumps and about a rocket which is automatically controlled. "It is necessary to have automatic devices which control the motion of the rocket and of the explosive force in accordance with a predetermined program"--he wrote in his article of 1903. The same article showed the advantage of placing the rudder in the jetstream from the nozzle of the engine. In the V-2 rocket, which has a length of 14 m and an initial weight of 13,000 kg, all these ideas of Tsiolkovskiy are realized.

At the present time airplanes with rocket engines are being developed. Tsiolkovskiy distinguished between two types of such airplanes. He called the first a stratoplane and the second a rocketplane. In his work "Semi-reactive Stratoplane" (1932) he spoke of an airplane designed for flight at high altitudes and at high speeds with an engine which we refer to today as the air-rocket type. A similar airplane was realized with an engine of the same type, but of different /10
construction in accordance with the Campini design by the firm of Caproni in 1941, i.e., nine years later. In the works "The New Airplane" (1929), "Reactive Airplane" (1930), and "The Rocketplane" (1930), Tsiolkovskiy spoke of airplanes with rocket engines utilizing liquid fuel. A similar airplane became practical in 1942-1944 in a number of countries. For example, in 1944, Messerschmidt produced the airplane ME-163 with a rocket engine following the Lippisch design.

The scientific legacy of Tsiolkovskiy has remained in the form of books most of which were published by himself at his own expense, and in the form of manuscripts.

The language used by Tsiolkovskiy is simple, clear, and brief. The text of most of his works is broken down into short, numbered sections which simplify references to different portions of his works but which, at the same time, make the presentation somewhat dry and synoptic. In the present edition we have retained the numbering of the sections as given by Tsiolkovskiy. The omission of certain sections is due to the fact that the author himself eliminated certain sections which he considered of no significance. However, in some articles where the sequential numbering was disrupted, we changed the numbering of the sections to make it easier to refer to different points in these articles.

The presentation of Tsiolkovskiy has been left almost without editorial change. We have only replaced a series of inaccurate expressions in those manuscripts which remained after the death of Tsiolkovskiy in very rough form. Certain condensations were inevitable due to the occurrence of verbatim repetitions. In some cases individual phrases were dropped which have no actual technical meaning and which make the presentation more difficult to understand.

However, we did not attempt to condense his earlier published works. Therefore, in the present volume of his works it was impossible to eliminate repetition completely, especially in those articles which serve to propagandize the ideas of rocket technology. However, there are not too many places where this occurs.

It is of course true that not all of the statements made by Tsiolkovskiy are convincing. There was much that he could not foresee, particularly where practical proof and experimentation was required. Tsiolkovskiy's works were purely theoretical and he did not carry on any practical work in the field of rocketry. Therefore, we cannot leave without criticism all that has been written by Tsiolkovskiy. However, it was not our problem to criticize. We leave this to the readers of his works, particularly since Tsiolkovskiy always fought for the right to publish his own works with the hope that "there would be readers among the people who would evaluate this work properly" (from the article by Tsiolkovskiy entitled "The Fate of Thinkers, or Twenty Years on Trial," 1924). /11

The terminology used by Tsiolkovskiy is quite unique. We have left without change the term "reactive" in those places where it is today referred to as "rocket," but we have replaced, for example, "compressibility" by "compression," etc. In some places we have left the terminology of Tsiolkovskiy, but have provided footnotes giving the current terminology with an effort to leave the writings in the form prepared by him.

If the language of Tsiolkovskiy is very clear, we cannot say the same concerning the mathematical side of his works. He used primarily the Russian alphabet for the representation of symbols in equations since he was apparently used to this. In any case, only one work on rockets is known, which was published at Kaluga and which used Latin symbols. This is the second edition "Rockets in Cosmic Space." Such an outline of symbols differing erratically from those commonly used in our country and in the world has made it rather difficult to read the text. Only in "The Selected Works of Tsiolkovskiy" of which only 1,500 copies were published by ONTI in 1934, were the transcriptions of the equations changed.

The second inconvenience, which from our point of view makes it difficult to understand Tsiolkovskiy's conclusions, is his practice of illustrating equations by means of tables. Tsiolkovskiy does not use the graphic representation of functions in any of his works, which is unfortunate since the scientists and engineers of the entire world are used to such graphic representations. Tsiolkovskiy thought in terms of images. To carry out some proof he required approximate data which would roughly characterize some physical relationship. According to him this purpose was best served by short tables. We have not introduced any changes in this method of representation.

Most of the mathematical calculations were used by Tsiolkovskiy as a rough proof of some technical idea. It is doubtful that the mathematical calculations of Tsiolkovskiy will be used by engineers in the practical realization of corresponding engineering projects. A large number of calculations made by Tsiolkovskiy are very approximate and should be approached with care. However, many of the technical ideas which have been proven by Tsiolkovskiy will doubtless be utilized.

In the present edition we have adopted the chronological order of presenting Tsiolkovskiy's work. This edition does not contain all of the works of Tsiolkovskiy, but all of the most important works on rockets which were published during his life as individual books or as articles in various journals. This edition also contains certain manuscripts of /12 a scientific and engineering nature not published previously. Thus, the present volume is the most complete collection of Tsiolkovskiy's works on rockets.

Some of the works of Tsiolkovskiy are published for the first time while others are published for the second time, specifically those which were published by Tsiolkovskiy (we should point out, however, that these editions were not sold and were distributed exclusively by Tsiolkovskiy himself) or were placed by him in the periodic press. Finally, there are those works which are being published for the third time. These are primarily those contained in the second book "Selected Works."[1]

We can speak very well of this edition published under the editorship of the late F. A. Tsander, who was most knowledgeable in the problems of rocket flight. We have used the text of this book and have considered it necessary to retain almost all of the remarks made by Tsander and contained in this volume of Tsiolkovskiy's works.

Unfortunately, however, this edition contained only those works of Tsiolokovskiy which were a subject of mathematical analysis, while some basic statements made by Tsiolkovskiy were dropped. As we have already pointed out, very few copies were published. Therefore, at the present time, many people know Tsiolkovskiy not from his works but from articles

[1] K. E. Tsiolkovskiy, "Selected Works," Volume 2, Reactive Motion, edited by F. A. Tsander. Gosmashmetizdat, 1934, 216 pp.

about him in popular magazines and other publications. The works of Tsiolkovskiy contained in "Selected Works" are published from the text of the Tsander edition.[1] Many of the omissions have been reinstated.

We should say a few words concerning the distribution of Tsiolkovskiy's works on rockets. His basic works were published in the periodic press during 1903-1912 in quantities of approximately 4,000 copies. The Kaluga editions of Tsiolkovskiy himself were usually published in lots of 2,000 copies and were distributed entirely by him. If we add to this the "Selected Works" we find that there were only 7,500 copies of his works. For a period of 30 years this is a very insignificant number!

As far as we know the works of Tsiolkovskiy were not published abroad. His works were only abstracted and popularized by individual workers and enthusiasts in rocket technology.

From this we can see that the distribution of Tsiolkovskiy's works on rockets and interplanetary travel was entirely inadequate. /13

We shall now consider the individual writings of Tsiolkovskiy which are contained in the present volume.

First of all we draw attention to a series of articles which may be combined under one general title "Investigation of Universal Space By Means of Rocket Devices." This includes the earlier works of Tsiolkovskiy on rockets.

"Rocket in Cosmic Space," Tsiolkovskiy's first work on rockets, was first published in the journal "Nauchnoye obozreniye" No. 5, 1903, under the title "Investigation of Universal Space by Means of Reactive Devices." Subsequently, Tsiolkovskiy called this publication the first part of his work. In 1924, it was published at Kaluga as an independent brochure under a new title which is the one adopted in the present volume.

The change in the title, as we might suspect, is explained by the fact that in 1923 Oberth published his book "Die Rakete zu den Planetenräumen." Tsiolkovskiy adopted the almost literal translation of this book in protest to the fact that the Oberth book was accepted as a new discovery, whereas Tsiolkovskiy proposed the same ideas back in 1903. Therefore, in the 1926 edition Tsiolkovskiy included as a preface the articles "The Fate of Thinkers, or Twenty Years on Trial" in which he complained about the neglect of his works. This article has been omitted by us.

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[1] Our edition has three types of footnotes: a) footnotes made by Tsiolkovskiy himself, b) those by Tsander, and c) those by the present Editor.

In the "Selected Works"[1] of 1934, the work of Tsiolkovskiy was included in its entirety. We present it in this volume as it appeared in 1924. According to Tsiolkovskiy the first edition (in the journal "Nauchnoye obozreniye") was published in a very careless manner.

The work of Tsiolkovskiy entitled "A Rocket into Cosmic Space" undoubtedly is one of his principal works on rockets. At the same time the work may be looked upon as a classic treatment of this field. Everyone interested in the problem of interplanetary flight and in reactive propulsion in general should be familiar with it.

The term "reactive device" which Tsiolkovskiy uses frequently is a general term which covers all flying devices moved by thrust produced by rocket engines.

"The Investigation of Universal Space By Means of Reactive Devices" (or briefly "The Investigations of 1911-1912") was published in the journal "Vestnik Vozdukhoplavaniya" in 1911 in Nos. 19-22 and in 1912 in Nos. 2-9. We publish this article using the text in this journal introducing those corrections and additions which Tsiolkovskiy made in his /14
own handwriting on the text printed in the journal. Tsiolkovskiy called "Investigations of 1911-1912" the second part of his major work.

Subsequently, in the publication of "Investigations of 1926" Tsiolkovskiy took from "Investigations of 1911-1912" the entire preface and chapters entitled "The Work of Gravity When Moving Away From a Planet" and "The Velocity of Flight and Time of Flight." The latter work is known better and is more substantial, therefore we have left the preface and the two chapters in "Investigations of 1926" while in "Investigation 1911-1912" we dropped the preface. In the "Investigations of 1926" the preface was followed by an expansive "Summary of the Works of 1903." We have condensed this substantially, leaving only the principal proposition since this summary presents in brief form the contents of the article " A Rocket into Cosmic Space."

"Investigation of Universal Space By Means of Reactive Devices" (supplement to Parts 1 and 2 of the work bearing the same title) was published in 1914. We copied the text of this edition and omitted several pages at the beginning, which contained the favorable replies of the specialists of that era to Parts 1 and 2 of his works.

The article "Cosmic Ship" is published for the first time from the 1924 manuscript. Tsiolkovskiy wanted to publish the article and in 1924 sent it to the journal "Tekhnika i Zhizn'." However, the editor returned

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[1] In the future this edition is abbreviated as "Sel. W."

the article to the author and would not publish it. The article contains an interesting proposition on the utilization of braking against Earth's atmosphere during the descent of an interplanetary ship to Earth. A similar method was later proposed by Homann in his "Die Erreichbarkeit der Himmelskörper" (1925).

The article "Investigation of Universal Space By Means of Reactive Devices" (or, briefly, "Investigations of 1926") was published by Tsiolkovskiy in 1926 at Kaluga. The cover contained the following: "Republication of the Works of 1903 and 1911 With Certain Changes and Additions." However, this is actually not correct. Also, the subsequent statement of Tsiolkovskiy: "For economic reasons it was necessary to consider only the new material," is not entirely correct. There is no doubt that this work is not a republication of works conducted in prior years, but at the same time the works of 1903 and 1911 are reflected in it.

In the "Selected Works" of 1934, statements of a general nature were excluded. We publish this work almost in its entirety. As we have already pointed out, the preface to this work was written in 1911. The article "Investigations of 1926" is contained in the present volume before the article "Cosmic Ship" (1924).

A manuscript entitled "The Album of Cosmic Travel" was found in the /15 Tsiolkovskiy archives. The text of this album is dated June 21, 1933, while the drawings are dated over the period of October 1933 to March 1934. The text is devoted principally to the stability of interplanetary stations. The drawings in the album correspond to the subjects in the text. Judging from the inscriptions, the album contained material for the Soviet motion picture industry. According to B. N. Vorob'yev this was in connection with the planning of the film "Cosmic Voyage" for which Tsiolkovskiy was invited as an editor.

The drawings in the album (there are over 100 of them) are very primitive. Tsiolkovskiy presented sketches assuming that these could be reproduced. The drawings represent primarily the various effects produced by the absence of gravitation. They are not of great interest, but some of them can be used to illustrate various points in the preceding works, and we therefore retained them. Figures 3, 5, 7, 8 and 9 (the numbering system adopted in the album) represent suitable illustrations for the article "Reactive Motion." Figures 11, 12, and 13 show various methods of turning the rocket in free space. Figure 49 may be related to the article "Cosmic Ship," and only Figure 54 relates directly to the question of the interplanetary station. The inscriptions on the figures were made by Tsiolkovskiy. Other articles related in subject to a given group of "investigations" are referenced at the end of each article.

The following articles by Tsiolkovskiy are devoted to an airplane with a rocket engine:

"The New Airplane." The work was published by Tsiolkovskiy in 1929 (K.) and is contained in the "Selected Works" published in 1934. This work is his final work on conventional airplanes, and at the same time it is the first work on the rocket airplane, more precisely, on the initial stage of the development of the rocket method of flying. Concerning his article "The New Airplane" Tsiolkovskiy wrote the following: "Many of the conclusions made by me in "The New Airplane" turned out to be similar to the conclusions from the work of Corvin-Krukovskiy (USA, 1929), as, for example, the fact that the velocity of the airplane is proportional to the square root of the decrease in air density, while the required energy is proportional to the velocity of the airplane. These conclusions as well as others were made by me back in 1895 in the work called 'Airplane' which was published in the journal Nauka i Zhizn' and forgotten even by me." (See Paragraph 83 and others.)[1] The preface prepared by Tsiolkovskiy to his article "The New Airplane" omitted in "The Selected Works" is published here.

"The Reactive Airplane." The manuscript for this is dated 1929 and was published by Tsiolkovskiy in 1930 at Kaluga. The cover has the notation "Taken from the large manuscript;" however, the corresponding manuscript was not found in the Tsiolkovskiy archives. We may assume, as we shall see later, that this manuscript was being reworked by the author into an independent article. The work "The Reactive Airplane" was contained in "Selected Works" of 1934. /16

"The Rocketplane." This article is published here for the first time. A large incomplete manuscript was found in the archives entitled "The Ascending Accelerated Motion of a Rocketplane." The content of this manuscript is as follows: (1) the design and weight specification of a rocketplane (Sections 1-46), (2) the ascent of the rocketplane (Sections 47-66), (3) the exit of the rocketplane from the atmosphere (Section 128 to the end of the manuscript). Sections 67-127 were not found and may have been omitted. There are many references in the manuscript to "The Rocket Airplane." Since the article "The Reactive Airplane" is concerned primarily with the energy side of the problem which is not treated in the discovered manuscript, we may assume that some of the missing sections were used by the author for the article "The Reactive Airplane" and published in a separate pamphlet. The remaining part of the manuscript (Tsiolkovskiy's notation) was being reworked in 1930 into a separate article. If our proposition is correct, the manuscript must have been started in 1929.

Under the title "The Rocketplane" we publish the first and second parts of the manuscript, i.e., Sections 1-66. The last part which is

[1]See the remarks of the author on p. 30 of "Pressure on A Plane," 1930, K. - Editor's Note.

concerned with the exit of the rocketplane from the atmosphere has been dropped completely, since the calculations contained in it are of a preliminary nature and were apparently carried out to find the right approach to the solution. At first, Tsiolkovskiy did not take into account the effect of the wings of the rocketplane; the method of calculation presented here resembles the one in "Investigations of 1926." However, as a result of his calculations, the author saw that the lift produced by the body alone is inadequate and therefore he began to take into account the wings. The calculations are not completed.

"Semi-reactive Stratoplane." An excerpt from this work was published by Tsiolkovskiy under the same title at Kaluga in 1932. This excerpt was contained in the "Selected Works" of 1934. In his annotations to this article Tsiolkovskiy wrote "I shall try to publish the continuation of this work separately," but he did not have time to do this. After Tsiolkovskiy's death a large incomplete manuscript was found in his archives entitled "The Ascending Accelerated Motion of an Airplane." Part of this manuscript consisted of the excerpt published by Tsiolkovskiy.

As we can see from the drafts of his manuscript Tsiolkovskiy had the idea of a semireactive stratoplane in 1930. The manuscript itself is dated 1931.

We publish this manuscript under the title "Semi-reactive Stratoplane." As an introduction we use part of the draft "High Altitude Airplane or Stratoplane" written by Tsiolkovskiy. The numbering of the different sections of the manuscript does not coincide with the numbering of the excerpt published earlier. The original had 39 sections; /17
Tsiolkovskiy omitted 17 of them. In our manuscript the first sections are numbered from 1 to 50 and a series of sections is also omitted. We retained the numbers of the original article up to Section 51, after which we used Tsiolkovskiy's numbering. Thus it would appear that 11 sections are missing in our presentation; actually nothing has been omitted.

Several pages are missing in the manuscript which is pointed out in this text. Also several tables are missing. We publish the manuscript up to Sections 143, inclusive. The subsequent part of the manuscript contained the calculation for the ascent of a stratoplane in which Tsiolkovskiy considered gravity, but not the lift produced by the wings. At the end of the manuscript he wrote that he had also neglected to take into account the decrease in weight of the device as fuel is consumed. Therefore all these calculations are apparently quite preliminary and were dropped because they are of no interest.

"Reactive Motion." This article was written in May 1932, and was published in the journal "V. Boy za Tekhniku," Nos. 15-16 August 1932, under the title "The Theory of Reactive Motion." We publish the article from the manuscript with an insignificant condensation of certain portions which repeat verbatim previous works.

The idea of a folding construction for the surface of the rocket slated for flights into cosmic space was proposed by Tsiolkovskiy in 1925.

"Fuel for the Rocket." This article was composed by Tsiolkovskiy from two manuscripts: "Explosives and Fuels," completed on June 29, 1932,[1] and "Explosives for the Astroplane," completed on March 1, 1933. This article was entitled "Attaining the Stratosphere." The article was contained in the collected works "Reaktivnoye Dvizheniye" No. 2, 1936, under the title "Fuel for the Rocket." We retained this title. The 1933 manuscript begins with the section "Selecting the Explosive Elements."

"Missiles Which Achieve Cosmic Speeds on Land or Over Water." The article was published from the manuscript finished December 3, 1933. In this article Tsiolkovskiy returns to the problems considered in "Accelerated Motion of the Rocketplane."

The works devoted to the problem of the engine for such an airplane are directly related to the articles on rocket airplanes.

"Steam Gas Turbine Engine" is published for the first time from the original manuscript. Altogether three manuscripts were found on the same general subject. In (1) "Airplanes and Stratoplanes" Tsiolkovskiy shows the advantages of a gas turbine engine. The manuscript was completed October 22, 1934. (2) "Steam Gas Turbine Engine for Dirigibles, Airplanes, Stratoplanes, Automobiles, and for Other Purposes" contains a short description of an engine. However, the figure could not be found and is missing. The manuscript was completed August 29, 1933. (3) "Powerful Engines of Minimum Weight and Volume" is dated November 5, 1934, and is a development of the previous two manuscripts. Unlike the first manuscript, the text is broken down into sections which are numbered beginning with Section 201 and ending with Section 207. Beyond this point the presentation is made without numbered sections. Sections 1-200 were not found and their contents is not known. Only some references in this manuscript permit the conclusion that there were calculations on the compression of air during high speed ramming in the missing Sections 154-158. /18

We have made the first manuscript the introduction, and have combined the second and third manuscripts, dropping the numbering of sections.

[1]We have assumed that the date given at the end of the manuscript is the date of its completion.

Before considering the other articles of Tsiolkovskiy it is necessary to examine his large work which he called "Principles of Construction of Gas Machines, Engines and Flying Devices." He labored over this during the last year of his life and did not complete it. He began work on it at the end of 1934, and made wide use of his previous studies. He thought that "Principles of Construction of Gas Machines" would consist of twelve chapters, and he changed the titles and order of various chapters several times.

As we can establish from the more or less complete manuscripts, the contents of the entire works was to be as follows:

Chapter I, "Compression and Expansion of Gases," was initially entitled "The Principles of Gas Machine Construction Known and Unknown." This chapter was finished on August 12, 1934.

Chapter II, "The Pressure of a Normal Air Flow on a Plane," is a continuation of the article "Pressure on a Plane during its Normal Motion in the Air," 1930, and was finished on October 24, 1934.

Chapter III, "Friction in Gases," exists in three variations and consists of a rewritten article of the same title which was completed on June 18, 1932; it was sent by Tsiolkovskiy to the journal "Tekhnika Vozdushnogo Flota" but was not accepted.

Chapter IV, "The Resistance of the Air to the Motion of a Smooth (Bird-Like) Body," has no date.

Chapter V, "Density, Temperature, and Pressure of Different Layers of the Atmosphere," was completed on May 9, 1932, and published under the same title in the journal "Samolet," Nos. 8-9, 1932. /19

Chapter VI, "The Energy of the Chemical Bond of Substances and the Selection of the Component Parts for an Explosion," was later published as an article in the collected works "Raketnaya Tekhnika," No. 1, 1936. In all probability this article was written at the beginning of 1935.

Chapter VII, "The Maximum Rotation Velocity of Bodies and the Storage of Their Mechanical Energy," is undated.

Chapter VIII, "New Engines of Two Types," is dated March 29, 1935, and is incomplete. In this chapter Tsiolkovskiy wanted to consider two types of engines which use the atmospheric air as oxidizer--the first type was to include the use of water while the second was without water. The manuscript of Chapter VIII is concerned more or less with only the second type. The first type is only briefly described. This manuscript has much in common with the article by Tsiolkovskiy entitled "Steam Gas Turbine Engine" and apparently is an expansion.

Chapter IX, "The Second Type of Engine With a Stored Oxygen Compound," is dated April 17, 1935, and is the last work of Tsiolkovskiy on rocket technology.

Chapter X, "The Maximum Speed of a Rocket," was written in January, 1935, and deals with a special method of achieving high flight speeds. The basic principles of the method proposed by Tsiolkovskiy were popularized by Ya. I. Perel'man.[1]

Chapter XI, "An Approximate Calculation of the Flight of a Rocketplane to an Altitude of 30 Kilometers," is dated March 21, 1935, but is incomplete.

Chapter XII, "Cooling of the Combustion Chamber," was not written at all.

The book consisting of these chapters does not convey the impression of a finished work; its nature is that of a rough draft. The manuscripts have many corrections. Some pages are missing. Various parts are not finished to the same extent and are interconnected almost mechanically. The cover of Chapter XI, for example, has the note "Everything must be rewritten. Not suitable. The new one is correct."

In a short table of contents preceding the entire work and prepared by Tsiolkovskiy, he makes the following remark concerning Chapters VIII and IX: "A great deal of work remains to be done on these chapters."

We have given up the idea of publishing "Principles of Gas Machine Construction" and have only reproduced Chapter X, entitled "The Maximum Speed of a Rocket." This chapter is published from the manuscript.

This chapter may be looked upon as the final chord of the creative genius of Tsiolkovskiy and is the chapter of most interest to rocket technology in the manuscript "Principles of Gas Machine Construction." The method of achieving cosmic speeds is discussed here; it consists of the transfusion of fuel from one rocket to another, followed by a gradual decrease in the number of flying rockets, and is preferable to a multistage rocket which, incidentally, was also not discounted by Tsiolkovskiy. In this case Tsiolkovskiy proposes the transfusion method, not for simple liquid rockets[2] but for rocketplanes. /20

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[1]See Ya. I. Perel'man, "Tsiolkovskiy," 1937. From the letter of Tsiolkovskiy to Perel'man it follows that the idea for this method occurred to Tsiolkovskiy in December, 1934.

[2]As mentioned in the book by Ya. I. Perel'man, 1937.

As an appendix to our edition of the works of Tsiolkovskiy we have felt it desirable to give "The Preface and Remarks" written by F. A. Tsander to the 1934 edition of "The "Selected Works of K. E. Tsiolkovskiy." They are very interesting for evaluating the creative genius of Tsiolkovskiy and will be useful to the reader studying these works. F. A. Tsander himself was a contemporary of Tsiolkovskiy and worked on the problems of rocket engineering in line with developing the ideas of Tsiolkovskiy.

As stated, the present volume is not a complete collection of Tsiolkovskiy's work on rocket technology. The following manuscripts of Tsiolkovskiy are not published.

1. "The Year 2000." The manuscript is dated September 26, 1913, and represents an unfinished fiction book on the subject of interplanetary travels.

2. "Voyages Beyond the Atmosphere." The manuscript is dated November 7, 1925, is not completed and constitutes a variation of "Investigations 1926." It may be the first rough draft. Half of the manuscript is repeated verbatim in "Investigations 1926," the second half covers material which is treated in more detail in the same publication "Investigations 1926."

3. "The Conquest of the Solar System." (Science fiction.) The manuscript is dated November, 1928. Additions to it are dated June 22, 1929. The manuscript is not finished.

4. "To the Inventors of Reactive Machines." This manuscript was completed on April 28, 1930, and gives a description of several self-propelled toys whose motion depends on the utilization of the reactive principle of motion.

5. "Steam Turbine." The manuscript is dated August 1933, has several omissions, and is a somewhat schematic presentation.

6. "Principles of Gas Machine Construction," (except Chapter X).

7. "Cosmic Travels." Unfinished manuscript dated November 11, 1933, is the beginning of a fiction book on interplanetary subjects.

8. "Flights In the Atmosphere and Outside It." The manuscript is dated February 12, 1934, and is a brief repetition of the previous works on rockets. /21

The present volume does not contain the following previously published works on interplanetary travel:

1. The article "Works on the Cosmic Rocket (1903-1927)" written in 1928 and published after his death in the collected works of the Reaction Section of the Stratosphere Committee of TeS Osoaviakhima SSSR "Reaktivnoye Dvizheniye," No. 2, 1936. In this article Tsiolkovskiy summarizes his work over a period of 25 years and presents a short general program for practical investigation of rocket technology.

2. A short article entitled "Beyond the Earth's Atmosphere" published together with "The New Airplane," K., 1929.

3. The article "From the Airplane to the Astroplane." Published in "Iskry Nauki," No. 2, 1929.

4. The article "The Purpose of Astro-flights," K., 1929. This article was published for the second time in the collected works entitled "K. Tsiolkovskiy" by the editing department of Aeroflot, 1939.

5. The article "To the Astronauts," K., 1930, was an expansion of the article "From the Airplane to the Astroplane."

6. The article "The Compressor of Gases," K., 1931.

7. The article "How to Increase the Energy of Explosive (Thermal) Engines," K., 1931.

(Articles 6 and 7 have no direct relation to the basic subject matter of the present collected works of Tsiolkovskiy.)

8. The article "Beyond the Atmosphere" written in March, 1932 and published with some changes in "Vokrug Sveta," No. 1, January, 1934.

9. The article "Reactive Motion and Its Progress," written in March, 1932 and published in "Samolet," No. 6, 1932.

10. The article "Astroplane," published in "Znaniye-sila," No. 23-24, December, 1932.

11. A scientific newspaper article entitled "Will the Earth Ever Be Able to Inform the Inhabitants of Other Planets of the Existence of Intelligent Life on It," published in "Kaluzhskiy Vestnik," No. 68, 1896.

12. A popular science story entitled "Outside the Earth," which was published in the journal "Priroda i Lyudi," in 1918 (No. 2-14) and as a separate booklet at Kaluga in 1920.

13. The article "A Reactive Device as a Means of Flight in Vacuum and in the Atmosphere," a short summary of "Rockets in Cosmic Space," was published in "Vozdukhoplavatel'," No. 2, 1910.

14. The article "Semi-reactive Stratoplane" published in "Khochu vse Znat'," No. 29, 1932, is a short summary of the well-known "Semi-reactive Stratoplane," K., 1932.

15. The article "The Application of Reactive Devices and the Investigation of the Stratosphere" published in the newspaper "Rabochaya Moskva," No. 51, March 3, 1935. The manuscript for this article was finished on February 27, 1935. The article briefly propagandized the idea of a rocket. /22

The question may be asked concerning the order in which the works of Tsiolkovskiy on rockets should be presented to the reader. To answer this question, it is first necessary to point out the basic idea which covers all Tsiolkovskiy's works on rockets from beginning to end.

Even if one is not too attentive in reading the works of Tsiolkovskiy, it becomes clear that the author never considered that the interplanetary flight of the rocket could be realized without a considerable amount of preliminary work associated with difficulties and temporary failures. Tsiolkovskiy assumed that aviation was the first step on the road to cosmic flights and that the ability to fly in the atmosphere was the first step in the art of flying beyond the atmosphere. According to Tsiolkovskiy, the airplane of the future could be transformed into a cosmic ship. This point of view is diametrically opposed to the technical ideas of Oberth and his school, who ignored the role of aviation in the development of rocket technology.

Tsiolkovskiy pictures the gradual metamorphosis of the airplane into an interplanetary ship in the following manner. The aviation engine begins to utilize the released heat, a reactive exhaust is established, and the engine gradually is redesigned so that the exhaust rather than the propeller is used to produce more and more thrust. The cylinders of the engine are transformed into the combustion chamber of a rocket engine. The engine contains a compressor and is placed in the tube in which the products of combustion are completely burned up and in which a process takes place peculiar to the air-breathing rocket engine. The airplane is transformed into a semi-reactive stratoplane, since propellers are still required. The flight altitude is substantially increased. The piston engines are replaced by turbines.

As the next step, the oxygen content in the fuel oxidizer is increased by placing tanks with special oxidizers aboard the stratoplane. The altitude is increased further. Finally, the use of air is completely abandoned, and some type of oxidizer carried aboard in liquid form is used. The stratoplane is transformed into a rocketplane which, depending on the quantity of fuel which it carries, may fly beyond the limits of the atmosphere.

By using a combination of several rocketplanes, either in the form of a multistage rocket or of devices which undergo transfusion of fuel from one another, a velocity of 8 km/sec may be reached so that one plane becomes a satellite of the Earth. By sending supplies from the Earth this satellite may be converted into a station, from which an interplanetary ship will be dispatched to more distant cosmic travels. /23

When all of this is achieved, the time will come for organizing "colonies in the ether," the name given by Tsiolkovskiy to interplanetary station cities.

From the standpoint of this rather elegant and successive concept, the works of Tsiolkovskiy may be placed in the order shown below. We recommend this order for systematic reading.

First we mention two major works which contain the basic principles of his theory and which must be studied initially. These are:

"A Rocket into Cosmic Space" (1903) and "The Investigation of Universal Space By Means of Reactive Devices" (1926). Following these we have:

1. "The New Airplane."

2. "The Reactive Engine."

3. "Semi-reactive Stratoplane."

4. "Cosmic Rocket. Experimental Preparation."

5. "Missiles Which Attain Cosmic Speed on Land and on Water."

6. "Reactive Airplane."

7. "Rocketplane."

8. "A Cosmic Rocket Train."

9. "The Maximum Velocity of a Rocket."

10. "The Cosmic Ship."

11. "The Investigation of Universal Space By Means of Reactive Devices," 1911-1912.

We should point out that by no means do we expect to include all the works of Tsiolkovskiy in this scheme. The ideas of Tsiolkovskiy in the field of rocket technology are very diverse. In addition to the concepts here presented, Tsiolkovskiy did not rule out the possibility of the direct flight of a rocket beyond the limits of the atmosphere into cosmic space. In his works he proposed to use the incline ascent of a rocket with its preliminary acceleration for this purpose. From this point of view, the path through aviation is the path to obtain experience for the purpose of developing the art to fly beyond the atmosphere. Only after reading and studying the works of K. E. Tsiolkovskiy is it possible to make a correct evaluation of the significance of his /24 works, which laid the basis for a truly scientific approach to the rocket as a means of transporting man into the atmosphere and interplanetary space.

In conclusion we wish to point out that the meticulous preparatory work by B. N. Vorob'yev, who went through and organized the entire archives of K. E. Tsiolkovskiy and who studied the manuscripts of these archives very carefully, has been very useful in the preparation of this introductory article. The author of the latter has used substantially the factual material from the manuscripts of Tsiolkovskiy, as collected by B. N. Vorob'yev.

Moscow
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M. K. Tikhonravov

A ROCKET INTO COSMIC SPACE /25

(1903)

The Altitude Achieved by Air Balloons; Their Dimensions and Weight; The Temperature and Density of the Atmosphere

1. Small unmanned aerostats with automatic sensors have achieved altitudes to date not greater than 22 km.

The difficulties of reaching high altitude by means of aerial balloons increase very rapidly with altitude.

Let us assume that we wish the aerostat to reach an altitude of 27 km and lift a load of 1 kg. At an altitude of 27 km, the air has a density approximately 1/50 of the air density at the surface of the Earth (760 mm pressure at 0° C). This means that the sphere at this altitude must occupy a volume 50 times greater than at sea level. It would be necessary to fill the balloon with 2 m^3 of hydrogen at sea level which, at the altitude specified, would occupy 100 m^3. The balloon will lift a load of 1 kg, i.e., it will lift the automatic sensor, while the balloon itself will weigh approximately 1 kg. When its diameter is 5.8 m the surface of its shell will be not less than 103 m^2. Consequently, each m^2 of the material, including the attached net, must weigh 10 g.

One m^2 of ordinary writing paper weighs 100 g, while 1 m^2 of tissue paper weighs 50 g. Thus, even tissue paper will be five times heavier than that material which must be used to construct our aerostat. A material of this type cannot be used in the aerostat because the shell formed of it will tear and permit the gas to escape. Balloons of larger dimensions may have a thicker shell. A balloon with an unprecedented large diameter of 58 m will have a shell whose weight per m^2 is 100 g, i.e., slightly heavier than ordinary writing paper. It will lift a load of 1,000 Kg which is much more than is required for an automatic recorder.

If we retain the same large dimensions for the aerostat, but limit ourselves to a lifting force of 1 kg, the shell may be made twice as heavy. Generally speaking, in this case, the aerostat may be quite expensive, but we must not assume that it is impossible to construct it.

Its volume at an altitude of 27 km will be 100,000 m^3, and the surface of the shell will be 10,300 m^2.

Meanwhile the results are rather miserable! We reach only an altitude of some 27 km. /26

What can be said about sending instruments to a high altitude! The dimensions of the aerostats must be even greater; however, we must not forget that as the dimensions of the balloon increase, the forces which tend to rupture the shell increase more rapidly than the resistance of the material.

The launching of instruments beyond the atmosphere by means of a balloon is, of course, impossible; from observations of falling stars we can see that these limits do not exceed 200-300 km. Theoretical calculations show that the limit of ascent is 54 km, if we assume that the temperature drops by 5° C each kilometer of ascent, which is very close to what actually happens, at least for the accessible layers of the atmosphere.[1]

Altitude at Atmosphere km	Temperature °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	1:3,900
48	-240	1:28,000
54.5	-272	0

This is a table of altitudes, temperatures, and densities of the air which I have computed on this basis. We can see from this table that the difficulty of reaching a high altitude increases very rapidly.

[1] It is now known that the temperature drop takes place only up to the limits of the troposphere, i.e., up to 11 km.

The divisor in the last column shows the difficulties which may be met in the construction of a balloon.

2. Let us consider another idea for flying to high altitudes--by means of shells fired by a gun.

In practice, the velocity of shells does not exceed 1,200 m/sec. Such a shell fired vertically will reach an altitude of 73 km, if flight takes place in space devoid of air. In air, depending on the shape and mass of the shell, the altitude achieved will be much smaller. /27

If the shape of the shell is good, the altitude achieved may be substantial; however, it is impossible to place recorders inside the shell because they will be shattered either when the shell returns to the Earth or during its motion in the gun barrel. The danger during the motion of the shell in the gun barrel is less; however, it is quite great from the standpoint of keeping the instruments intact. Let us assume, for simplicity, that the pressure of the gases on the shell is uniform so that the acceleration of its motion is W m/sec^2. Then all of the objects in the shell are subjected to the same acceleration. Due to this, an apparent relative force of gravity equal to W/g will be developed inside the shell where g is the acceleration due to gravity at the surface of Earth.

The length of the cannon L is given by the equation

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

from which

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

where V is the velocity attained by the shell when it leaves the barrel.

From the above equation we can see that W and, consequently, the increment of relative gravity inside the shell is decreased as the length of the cannon is increased when V is constant, i.e., the greater the length of the cannon, the greater is the safety factor for devices inside it during the firing of the shell. However, even in the case of a very long cannon (which cannot be realized in practice), the apparent gravity during the acceleration of its motion in the gun barrel is so great that sensitive instruments will be unable to bear it without damage. Moreover, it will be impossible to send anything alive inside the shell if it became necessary to do so.

3. Thus, let us assume that we have constructed a cannon which is 300 m high. Further, let us assume that this cannon is situated next to the Eiffel Tower which, as we know, has the same altitude. And let us assume that the shell under the influence of uniform gas pressure achieves an exit velocity sufficient to raise it beyond the limits of the atmosphere to an altitude of 300 km from the surface of Earth. Then the velocity V required for this purpose is computed from the equation

$$V = \sqrt{2gh.}$$

When h is 300 km, we obtain a value of approximately 2,450 m/sec for V. By eliminating V from the last two equations we find

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

where W/g gives us the relative or apparent gravity in the shell. From this equation we find that it is equal to 1,001. /28

Consequently, the weight of all the devices in the shell must increase by a factor of 1,000, i.e., an object which weighs 1 kg is subjected to an apparent gravity pressure of 1,000 kg. It is questionable whether any physical device will stand up to this pressure. What would be the shock experienced by a body in a short cannon and in flight to beyond 300 km!

In order not to confuse someone with the words "relative or apparent gravity," I wish to state that I am speaking of the force which depends on the acceleration of the body (for example, of the shell); this acceleration also occurs during the uniform motion of the body if such motion is curvilinear, in which case it is called the centrifugal force. In general, it always appears on the body or inside the body, if some force acts on the body to change its inertia. Relative gravity exists as long as the force which produces it exists: when the latter ceases, the relative gravity also disappears. I call this force gravity only because its temporary action is entirely identical to the action of the force of gravity. Every material point of a body is subjected to gravity, and in the same way relative gravity appears at every point of the body contained within the shell; this takes place because the apparent gravity depends on inertia to which all material parts of the body are subjected in the same manner. Thus, the instruments inside the shell will become heavier by a factor of 1,001. Even if it were possible to preserve these instruments under this excessive, though short-lived (0.24 sec) acceleration, there would be many other obstacles associated with using a cannon to send something into celestial space.

First of all, it will be very difficult to construct such cannons, even in the future. Secondly, the initial velocity of the shell will be extremely great; indeed, in the lower dense regions of the atmosphere the velocity of the shell will suffer due to air resistance; and the losses in velocity will sharply curtail the altitude to which the shell can rise. Furthermore, it will be very difficult to obtain a uniform pressure of gases on the shell during its motion through the barrel, which will make the force of gravity much greater than what we have computed (1,001). Finally, the safety of the shell during its return to Earth would be more than doubtful.

Rocket and Cannon

4. As a matter of fact, the large increase in gravity in itself is sufficient to discredit the idea of using cannons for our purpose.

In place of the cannons and of aerostats, I propose a reactive device for investigating the atmosphere, i.e., a type of rocket--however, a very grandiose rocket and one constructed in a special manner. The idea is not new, but the calculations which pertain to it give such striking results one cannot keep quiet about them. /29

This work of mine is far from considering all of the aspects of the problem and does not solve any of the practical problems associated with its realization; however, in the distant future, looking through the fog, I can see prospects which are so intriguing and important it is doubtful that anyone dreams of them today.

Let us visualize a projectile consisting of a metallic, oblong chamber (the shape of least resistance) equipped with light; oxygen; absorbers of carbon dioxide, miasmas, and other animal excretions, and designed not only to house various physical instruments, but also to house man to control this chamber (we shall consider the problem in as broad a manner as possible). The chamber contains a large supply of substances which, when mixed, immediately produce a combustible mass. These substances, which explode in the proper manner and rather uniformly at a special place designated for this purpose, flow in the form of hot gases along tubes which diverge towards their ends like a horn or a musical wind instrument. These tubes are placed along the walls of the chamber in the direction of its length. The mixing of the combustible substances takes place at one narrow end of the tube: here, condensed and ignited gases are obtained. At its other expanded end, after expansion and cooling, the gases flow out of the tube at a tremendous relative velocity. It is clear that such a rocket-like projectile will go up in altitude under certain conditions.

It will be necessary to have automatic instruments to control the movement of the rocket (our name for this device) and to control the force of explosion in accordance with a preestablished program.

The schematic form of the rocket (Figure 1). The two liquid gases are separated by a partition. We show the place where the gases mix and explode, and the funnel-shaped opening for the exhaust of expanded and cooled vapors. The tube is surrounded by a jacket containing a rapidly circulating metallic liquid. We picture the rudder used for controlling the motion of the rocket.

If the uniform force of explosion does not pass exactly through the center of inertia of the projectile, the projectile will rotate and consequently will be useless. It will be impossible to achieve mathematical accuracy in this case because the inertial center will oscillate due to the movement of substances in the projectile, and, similarly, the direction of uniform gas pressures in the tube cannot have a mathematically constant direction. In the air it is still possible to direct the projectile by means of a rudder similar to the one used by birds, but what can be done in free space where the ether will hardly provide any support? /30

The fact is that if the resultant force is as close as possible to the center of inertia of the projectile, its rotation will be rather slow. However, as soon as it starts, it would displace some mass inside the projectile until the displacement of the center of inertia causes the projectile to be displaced in the opposite direction. Thus, by following the motion of the projectile and displacing inside it a small mass, we shall achieve the oscillation of the projectile first in one and then in the other direction, while its general motion will remain unchanged.

It may turn out that manual control of the motion of the projectile will be not only difficult but entirely impossible to achieve. In this case automatic control will be necessary.

The attraction of the Earth cannot be used as the basic force for control, because the projectile will contain only relative gravity and

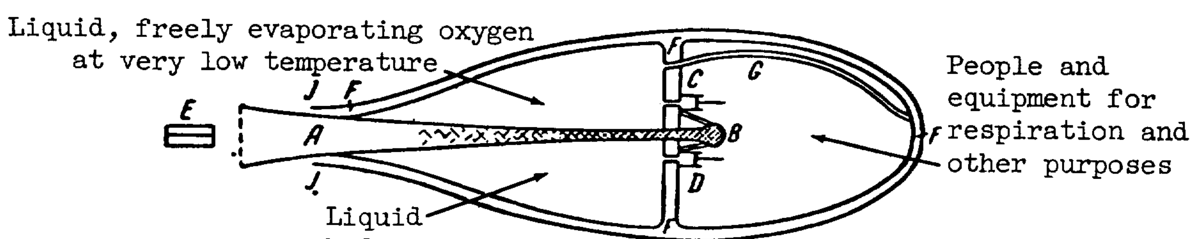

Figure 1.

acceleration W, whose direction coincides with the relative direction of the explosive substances flowing out or directly opposite to the direction of their resultant pressure. Since this direction changes with the rotation of the projectile and the tube, this gravity cannot be used to control the direction of the projectile.

We may use for this purpose the magnetic needle or the force of solar rays concentrated by means of a double convex lens. Whenever the projectile turns, the small and bright image of the sun changes its relative position with respect to the projectile. This may excite the expansion of the gas, pressure, electric current and mass movement, and thus reestablish a definite direction of the tube during which the light spot hits the neutral nonsensitive area of the mechanism.

There must be two masses which are automatically displaced.

The basic control for the direction of the projectile may also consist of a small chamber with two flat disks rotating rapidly in different planes. The chamber is suspended in such a way that its position or, more precisely, its direction, does not depend on the direction of the tube. When the latter turns, the chamber, due to its inertia (if we neglect friction), retains its initial absolute direction (with respect to the stars); this property is exhibited to a large extent during the rapid rotation of chamber disks. If thin springs are attached to the chamber, then during the rotation of the tube the change in the relative /31 position of the chamber is transmitted to the shell, which may cause a current to flow and move the control masses. Finally, the rotation of the open end of the tube may serve as a means for preserving a definite direction of travel for the projectile. The simplest method of controlling the rocket may consist of a double rudder situated outside the rocket close to the exit end of the tube. The rotation of the rocket around its longitudinal axis may be prevented by turning a plate situated in the direction of the motion of gases and situated within them.

The Advantages of a Rocket

5. Before presenting the theory of the rocket or of a similar reactive device, I shall attempt to interest the reader in the advantages of the rocket over a cannon shell.

(a) Compared with a gigantic cannon, our device is relatively light as a feather; it is relatively cheap and easy to realize.

(b) The pressure of the exploding substances will be substantially uniform and will produce a uniformly accelerated motion of the rocket which develops the relative gravity; we shall be able to control the magnitude of this temporary gravity at will, i.e., by controlling the force of explosion, we can make it arbitrarily small or make it exceed the normal Earth's gravity by many times. If we assume, for simplicity, that the force of explosion decreases in a manner proportional to the mass of the projectile combined with the mass of the remaining unburned explosive substances, the acceleration of the projectile and consequently the magnitude of the relative gravity will be constant. Thus, from the standpoint of the relative apparent gravity, it will be safe to send not only instruments in the rocket, but people as well, whereas in a cannon shell (even in a large cannon as tall as the Eiffel Tower) the relative gravity increases by a factor of 1,001 during ascent to an altitude of 300 km.

(c) Another major advantage of the rocket is that its velocity increases in any desired progression and in any desired direction; it may be constant and may decrease uniformly, which will permit a safe descent to a planet. Everything depends on the proper control of explosion.

(d) During the beginning of the ascent, while the atmosphere is dense and the air resistance is very great at high velocities, the rocket moves rather slowly, loses little to resistance of the medium and is not heated very much.

The velocity of the rocket increases very slowly; but then, as altitude is gained and the atmosphere becomes rarefied, it may increase more rapidly; finally, in free space, this increasing velocity may increase even more. Thus, we shall have to do a minimum amount of work to overcome the resistance of air.

The Rocket In a Medium Free of Gravity and Atmosphere /32

The Relationship of the Masses in a Rocket

6. First we shall consider behavior in a medium free of gravity and surrounding matter, i.e., free of atmosphere. As far as the latter is concerned, we consider only its resistance to the motion of the projectile and not to the motion of the explosive vapors. The effect of the atmosphere on the explosion is not completely clear. On the one hand, it is beneficial because the exploding substances have a certain support in the surrounding material medium which they carry along during their motion and, therefore, help to increase the velocity of the rocket. However, on the other hand, the same atmosphere with its density and elasticity interferes with the expansion of gases beyond a

certain known limit; thus, the explosive substances do not achieve the velocity which they could achieve in free space. This latter effect is not beneficial because the increment of the velocity of the rocket is proportional to the velocity of the ejected products of explosion.

7. We shall designate by M_1 the mass of the shell with all its contents except for the supply of explosives; we designate the mass of the latter by M_2; finally, we designate by M the variable mass of the explosives unexploded in the shell up to a given instant of time.

Thus, at the beginning of the explosion, the total mass of the rocket will be equal to $(M_1 + M_2)$; after a certain period of time, it will be expressed by a variable quantity $(M_1 + M)$; finally, at the completion of the explosion, it will be given by a constant quantity M_1.

In order for the rocket to attain a maximum velocity, it is necessary that the ejection of the products of explosion be in one direction with respect to the stars. To achieve this, it is necessary that the rocket does not rotate; for the rocket not to rotate it is necessary that the resulting force of explosion, passing through the center of their pressure, also pass through the center of inertia of all the flying masses. The question of how to achieve this in practice has already been analyzed by us to some extent.

By assuming that we have the optimum ejection of gases in one direction, we obtain the following differential equation from the law of the conservation of momentum

8. $$dV(M_1 + M) = V_1 dM.$$

9. Here dM is an infinitesimally small quantity of matter ejected with a constant velocity V_1 with respect to the rocket.

10. I should like to point out that the relative velocity V_1 of ejected elements under equal conditions of explosion is the same during the entire period of explosion, based on the law of relative motion: dV is the increment of the velocity V of the rocket together with the remaining explosive material; this increment dV is obtained by ejection of element dM with a velocity V_1. We shall determine the latter at the proper time. /33

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

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

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

Here C is a constant. Then $M = M_2$, i.e., before explosion, $V = 0$; on this basis we find

14. $$C = +\ln(M_1 + M_2);$$ therefore

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

The maximum velocity of the projectile will be achieved when $M = 0$, i.e., when the entire supply M_2 has been exploded; then, by assuming that $M = 0$ in the preceding equation, we obtain

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

17. From this we can see that the velocity V of the projectile increases without limit as the quantity of explosive M_2 increases. This means that by storing various quantities of the explosives for different voyages we may obtain the most diverse final velocities. We can also see from equation (16) that the velocity of the rocket, after a definite supply of explosive substance has been used, does not depend on the rate or nonuniformity of explosion. It is only necessary that the particles of ejected material move with the same velocity V_1 with respect to the projectile.

However, as the supply M_2 is increased, the velocity V of the rocket increases at a slower rate, even though without limit. Approximately, it increases as the logarithm of the increase in the quantity of explosives M_2 (if M_2 is large compared with M_1, i.e., if the mass of the explosive substances is several times greater than the mass of the projectile).

18. Further calculations will be interesting when we determine V_1, i.e., the relative final velocity of the exploded element. Since the

gas or vapor expands and cools substantially when it leaves the funnel-shaped opening (when the tube is sufficiently long), and even turns into a solid state--into dust moving at terrifically high velocity--we may assume that the entire energy of combustion or chemical bond is transformed during explosion into the motion of the products of combustion or into kinetic energy. Indeed, let us consider a definite quantity of gas which expands into vacuum without the aid of any devices; it will expand in all directions and, as a result, will cool until it is transformed into drops of liquid or into fog. /34

This fog is transformed into crystals, not because of expansion, but because of evaporation and radiation into the universe.

In the course of its expansion the gas will liberate all its apparent, and some of its intrinsic energy, which will finally become transformed into the rapid movement of the crystals in all directions, since the gas expands freely in all directions. However, if we cause it to expand in a reservoir within a tube, then the tube will direct the gas molecules in a definite direction; this is what we utilize for our purposes, i.e., for the motion of the rocket.

It would seem that the energy of motion of the molecules is transformed into kinetic motion as long as the substance retains its gaseous state. But this is not exactly so. Indeed, part of the substance may change into a liquid state; in this case energy is released (the latent heat of transformation), which is transmitted to the remaining gaseous part of the matter and retards for some time its transition into liquid state.

We can observe this phenomenon in a steam cylinder when the steam operates by its own expansion, while its exit from the steam boiler into the cylinder is closed. In this case, no matter what the temperature of the steam, part of it is transformed into fog, i.e., a liquid state, while part of it is retained in a gaseous state and operates by borrowing the latent heat of the vapors condensed into a liquid.

Thus, the molecular energy will be transformed into kinetic energy, at least until the liquid state. When the entire mass transforms into droplets, the transformation to kinetic energy will almost cease, because the vapors of liquid and solid bodies at low temperature have very insignificant elasticity and their utilization in practice is difficult, requiring very large tubes.

Yet another insignificant part of the energy will be lost to us, i.e., will not be transformed into kinetic energy, namely that lost by friction along the tube and heat radiation at the heated parts of the tube. As a matter of fact, the tube may be covered with a shield in which some liquid metal is circulating; it will transmit the heat from the highly heated part of one end of the tube to its other part cooled by high expansion of vapors. Thus, even this loss due to radiation and heat conductivity may be utilized or made very insignificant. Because the period of explosion lasts only 2-5 minutes in the limiting cases, the loss due to radiation is quite insignificant even without special devices. The circulation of the metallic liquid in the shield surrounding the tube is necessary for another reason: to maintain an overall low temperature of the tube, i.e., to preserve its strength. In spite of this, it is possible that part of it will be fused, oxidized and carried off with the gases and vapors. It is possible that to prevent this, the internal part of the tube will be lined with some special fire-resistant material: carbon, tungsten or something else. Although part of the carbon will burn up, the strength of the metallic tube which will be heated very little cannot suffer from this. /35

The gaseous product of combustion of carbon--carbon dioxide--will only increase the lift of the rocket. A form of crucible material may be applied--some mixture of materials. In any case, I shall not solve these problems or some others related to reactive devices.

In many cases I am forced to guess or to assume. I do not deceive myself and know very well that I cannot solve the problems completely, and that at least 1,000 times more work will have to be done on them compared to what I have done. My purpose is to arouse interest in this problem, to point to its great significance in the future, and to the possibility of its solution....

At the present time the transformation of hydrogen and oxygen into their liquid states poses no special difficulties. The hydrogen may be replaced by a liquid or condensed hydrocarbons, for example, acetylene and petroleum. These liquids must be separated by a partition. Their temperature is quite low. Therefore, it is useful to use them around the shields with circulating metal or around the tubes directly.

Experience will show which approach is easier to realize. Some metals become stronger when they are cooled; it is precisely these metals which should be used, as for example, copper. I do not remember very well, but some experiments on the resistance, I believe, of iron in liquid air, have shown that its viscosity at low temperature increases by tens of times.[1] I cannot vouch for their authenticity, but these experiments, as they apply to our problem, require extreme attention. (Why not cool ordinary cannons in this manner before firing from them; liquid air is now such a simple thing.)

[1] In general, the elongation of metals at very low temperatures is substantially reduced; however, resistance to rupture increases to a large degree. - Editor's Note.

Liquid oxygen as well as liquid hydrogen, pumped from their containers and supplied at a definite rate to the narrow beginning of the tube and mixed in small quantities, could give us an excellent combustible material. Water vapor, formed during the chemical combination of these liquids, is at an extremely high temperature and will expand, moving towards the end of the tube until it is cooled to a point when it is liquidized, carried in the form of a thin fog along the length of the tube towards its exit. /36

19. Hydrogen and oxygen in gaseous state combine to form 1 kg of water and develop 3,825 calories. Under the term "calorie" we mean a quantity of heat required to raise 1 kg of water by 1° C.

This quantity (3,825), in our case, will be slightly smaller since the oxygen and hydrogen are in the liquid state and not in the gaseous state (the one to which the number of calories refers). Indeed, the liquid must first be heated and then transformed into a gaseous state; this requires an expenditure of a certain amount of energy. In view of the insignificant magnitude of this energy compared to the chemical energy, we shall keep our number without decreasing it (this problem is not entirely clear to science, but we take hydrogen and oxygen merely as an example).

Assuming the mechanical equivalent of heat to be 427 kg-m we find that 3,825 calories correspond to a work of 1,633 kg-km; this is sufficient to raise the products of explosion, i.e., 1 kg of substance to an altitude of 1,633 km from the surface of the Earth's sphere, if we assume that the force of gravity is constant. This work converted into motion corresponds to an energy of 1 kg mass moving with a velocity of 5,700 m/sec. I do not know of any group of bodies which during their chemical combination would release such a tremendous amount of energy per unit mass of the resulting product. In addition to this, certain other substances combine without producing volatile products and thus are entirely unsuitable for our purposes. Silicon, which burns in oxygen ($Si + O_2 = SiO_2$), releases a tremendous amount of heat, specifically, 3,654 calories per unit mass of the resulting product (SiO_2), but unfortunately nonvolatile bodies are formed.

Taking liquid oxygen and hydrogen as the material most suitable for explosion, I gave a number for the expression of their mutual chemical energy per unit mass of the resulting product (H_2O), which is somewhat greater than the true value, since the substances combining in a rocket must exist in a liquid and not gaseous state, and also at a very low temperature.

I should like to point out to the reader here that in the future we may hope to achieve not only this energy (3,825 calories), but a much greater energy. Indeed, if we consider the quantity of energy obtained from chemical processes of various substances, we note in general, not without exceptions, of course, that the quantity of energy obtained per /37
unit mass of the product reaction depends on the atomic weights of the combining simple bodies; the smaller the atomic weight of bodies, the greater is the quantity of heat liberated during their combination. Thus, in formation of sulphur dioxide (SO_2) only 1,250 calories are released, while in formation of copper oxide (CuO_2) only 546 calories are released, and carbon during formation of carbon dioxide (CO_2) liberates 2,204 calories per unit mass. Hydrogen and oxygen, as we have seen, liberate even more (3,825).

In evaluating these data as they apply to my idea presented above, we know the atomic weights of these elements: hydrogen, 1; oxygen, 16; carbon, 12; sulphur, 32; silicon, 28; copper, 63.

Of course, there are many exceptions to this rule, but in general it is valid. Indeed, if we imagine a series of points whose abscissas express the sum (or product) of the atomic weights of combining simple bodies, while the ordinates represent the corresponding energy of chemical combination, then by passing a curve through the points we shall see a continuous decrease of the ordinates as the abscissas are increased, which proves our point of view.

Therefore, if at some time in the future, the so-called simple bodies turn out to be complex and are broken down into new elements, the atomic weight of the latter must be less than that of the simple bodies known.

According to this, the newly discovered elements must release a substantially larger quantity of energy during combination than those bodies which are now arbitrarily called simple and which have a relatively high atomic weight.

The very existence of ether with its almost infinite elasticity and tremendous speed of its atoms points to an infinitesimally small atomic weight of these atoms and an infinite energy in the case of their chemical combination.

20. No matter what happens at the present time, we cannot assume a value of greater than 5,700 m/sec for V_1 (see 15 and 19). However, in time perhaps this number will be increased by several magnitudes.

Assuming 5,700 m/sec, we may compute by means of equation (16) not only the ratio of velocities V/V_1, but the absolute value of the final (maximum) velocity V of the projectile as a function of the ratio M_2/M_1.

21. We can see from equation (16) that the mass of the rocket with all passengers and all instruments M_1 may be arbitrarily large without any loss in the velocity V of the projectile, if the supply of the fuel M_2 is increased proportionally to the mass M_1 of the rocket.

Thus, projectiles of any size with any number of passengers may obtain velocities of any desired magnitude. As a matter of fact, an increase in the speed of the rocket is accompanied, as we have seen, by an incomparably large increase in the mass M_2 of the fuel. Therefore, although it is easy to increase the mass of the projectile lifted into space, it is difficult to increase its velocity. /38

Flight Velocity as a Function of Fuel Consumption

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

M_2/M_1	V/V_1	Velocity V m/sec	M_2/M_1	V/V_1	Velocity V 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	2.393	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

23. We can see from the table that the velocity obtained by reactive means is far from being small. Thus, when the mass of the explosive substances is greater than the mass M_1 of the projectile (rocket) by a factor of 193, its velocity at the end of the explosion, when all

of the supply M_2 has been used up, is equal to the velocity of the Earth around the sun. Do not think that it will be necessary to have a large mass of strong material to build containers for the explosive elements. Indeed, hydrogen and oxygen in liquid form exhibit high pressure only when the vessel which contains them is closed, and when the gases themselves are heated under the influence of surrounding warm bodies. In /39
our case, these liquefied gases must have free exit into the tube (in addition to the one which carries them there in liquid form), where they combine chemically and explode.

The continuous and rapid flow of gases, which corresponds to the evaporation of the liquids, cools these latter until their vapors exert almost no pressure on the surrounding walls. A large mass of material is therefore not required as containers of the explosives.

24. When the supply of the explosives is equal to the mass of the rocket ($M_2/M_1 = 1$), the velocity of the latter is almost twice as large as the one necessary for a stone or gun shell, fired from the surface of our moon, to leave it and become a permanent satellite of the Earth.

This velocity (3,920 m/sec) is almost sufficient for the permanent removal of bodies thrown off the surface of Mars or Mercury.

If the ratio M_2/M_1 is equal to 3, then, when all of the fuel supply is used, the projectile will have a velocity slightly less than the one necessary for it to orbit around the Earth as its satellite beyond the limits of the atmosphere.

When the ratio M_2/M_1 is equal to 6, the velocity of the rocket is almost sufficient to move it away from the Earth and cause it to rotate permanently around the sun as an independent planet. When the fuel supply is sufficiently large, it is possible to reach the belt of asteroids and even the heavy planets.

25. We can see from the table that even when the supply of combustible materials is not too great, the terminal velocity of the projectile is still sufficient for various practical purposes. Thus, when the supply is only 0.1 part of the rocket's weight, the velocity is equal to 543 m/sec, which is enough to lift the rocket to an altitude of 15 km. We can also see from the table that when the fuel supply is insignificant, the velocity at the termination of the explosion is approximately proportional to the mass of the fuel supply (M_2); consequently, in this case, the altitude reached by the projectile is proportional to

the square of this mass (M_2). When the fuel supply is half the mass of the rocket $M_2/M_1 = 0.5$, the latter will rise far beyond the limits of the atmosphere.

The Efficiency of the Rocket during Ascent

26. It is interesting to determine what part of the total work performed by the combustible materials, i.e., what part of their chemical energy, is transmitted to the rocket.

The work performed by the explosive substances will be expressed by $\frac{V_1^2}{2g}M_2$, where g is the acceleration due to gravity; the mechanical work of the rocket traveling with a velocity V, is expressed in the same units: $\frac{V^2}{2g}M_1$, or, on the basis of equation (16), /40

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

Now, dividing the work of the rocket by the work of the explosive material we obtain

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

From this equation we compute the efficiency with which the rocket uses the explosive materials (see table).

From this equation and the table we see that for very small quantities of explosive material its efficiency is equal to M_2/M_1, i.e., it is proportional to the relative amount of explosive substances.[1]

As the relative mass of explosives increases, the efficiency increases and attains its maximum value of (0.65) when M_2/M_1 is equal to approximately 4. /41

[1]Indeed, $\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} \ldots$. Consequently, approximately,

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

M_2/M_1	Efficiency	M_2/M_1	Efficiency
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	Infinite	Zero

A further increase in the quantity of explosives decreases the efficiency, although rather slowly; when their quantity is infinitely large the efficiency is zero, as is the case when the quantity of fuel is infinitely small. We can also see from the table that when the ratio M_2/M_1 varies from 2 to 10, the efficiency is greater than one half; this means that more than half of the potential energy of the explosives is transformed into the kinetic energy of the rocket. In general, the efficiency is quite high when the mass ratio is 1 to 20 and is very close to 0.5 in this range.

The Rocket under the Influence of Gravity

Vertical Ascent

27. We have determined the velocity achieved by the rocket in free space, where there is no gravity, as a function of the mass of the rocket, the mass of the explosives, and the energy of their chemical combination.

Now let us study the effect of the constant force of gravity on the vertical motion of a projectile.

We have seen that when gravity is absent the rocket achieves great velocities, and the utilization of the explosion energy is quite efficient. This would also be true for a medium with gravity if the explosion were to take place instantaneously. However, such an explosion is not suitable for our purposes because a deadly shock will be obtained, which the projectile, as well as the objects and people inside, will be unable to withstand. It is obvious that we require a slow explosion; however, during a slow explosion the efficiency decreases and may even become equal to zero.

Indeed, let us assume that explosion takes place so slowly that the acceleration of the rocket produced by this explosion is equal to the acceleration g of the Earth. The projectile will then remain motionless in the air without any support. Of course, in this case, it does not achieve any velocity and the efficiency of the explosives, despite the large quantity expended, will be equal to zero. It is therefore very important to analyze the effect of gravity on the projectile.

Determining the Velocity Which can be Achieved. Analysis of the Numerical Values. Altitude of the Lift

When the rocket moves in a medium free of gravity, the time, t, during which the entire supply of explosive materials is expended is equal to

28. $$t = \frac{V}{p},$$

where V is the velocity of the projectile when explosion is completed, while p is the constant acceleration imparted to the rocket by the explosives each second of time. /42

The force of explosion, i.e., the quantity of substances expended during explosion per unit time in this simple case of a uniformly accelerated projectile, is not constant; it decreases proportionally to the decrease in the mass of the projectile and the remaining unexploded materials.

29. If we know p or the acceleration in a medium without gravity, we may also express the magnitude of the apparent (temporary) gravity inside the rocket during its period of acceleration or during the period of explosion.

If we assume that gravity at the surface of the Earth is equal to unity, we can find the magnitude of the temporary gravity in the projectile equal to p/g, where g is the acceleration due to the gravity of Earth. This equation gives us a factor by which the pressure on the bases of articles placed in the rocket is greater than the pressure on the same articles on the table in our room under normal conditions. It is very important to know the relative gravity in the projectile, because it determines the safety of instruments and the welfare of people embarked on a journey to study unknown spaces.

30. When we have the effect of a constant or variable gravity of any strength, the time during which the same amount of explosives is used up will be the same as in the case when gravity is absent; it will be expressed by equation (28), or by

31. $$t = \frac{V_2}{p - g},$$

where V_2 is the velocity of the rocket when explosion has ceased, in a medium with constant gravitational acceleration, g. Of course, we assume here that p and g are parallel and opposite; p - g expresses the observed acceleration of the projectile (with respect to the Earth), which is the result of two opposing forces: the force of explosion and the force of gravity.

32. The action of the latter on the projectile has no effect on the relative gravity within the projectile, and it is expressed without any change by equation (29) p/g. For example, if p = 0, i.e., if no explosion occurs, then there is no temporary gravity, because p/g = 0. This means that if explosion stops and the projectile moves in some direction only under the action of its own velocity and under the gravitational effects of the sun, Earth, and other stars and planets, then the observer in the projectile will apparently have no weight and will be unable to detect it in any of the objects, even by means of the most sensitive spring balances. By rising or falling inside it due to inertia, even near the surface of the Earth, the observer will not experience even the smallest gravity until, of course, the projectile meets some obstruction in the form of atmospheric resistance, water or hard soil. /43

33. If p = g, i.e., if the pressure of exploding gases is equal to the weight of the projectile (p/g = 1), then the relative gravity will be equal to the Earth's gravity. If the projectile is initially at rest, it will continue to remain at rest during the entire action of the explosion; if, on the other hand, the projectile had some initial velocity (up, sideways or down) then this velocity will remain unchanged until all of the explosives are used up; here the body, i.e., the rocket, is in equilibrium and moves due to its inertia as if it were in a medium devoid of gravity.

On the basis of equations (28) and (31), we obtain

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

From this, if we know the velocity, V_2, which the projectile must have when the process of explosion is completed, we compute V from which by equation (16) we determine the required quantity M_2 of explosives.

From equations (16) and (34) we obtain

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

36. From this equation as well as from the preceding one it follows that the velocity attained by the rocket is less when gravity is present than when it is not present (16). The velocity, V_2, may even be equal to zero, although we have a large supply of explosives, if $p/g = 1$, i.e., if the acceleration imparted to the projectile by the explosives is equal to the acceleration due to the Earth's gravity, or if the pressure of the gases is equal and directly opposite to the action of gravity (see equations (34) and (35)).

In this case, the rocket remains stationary for several minutes and does not rise; when the supply has been exhausted it drops like a stone.

37. The greater p is with respect to g, the greater is the velocity, V_2, achieved by the projectile for a given quantity, M_2, of explosives (equation (35)).

Therefore, if we wish to go higher, we must make p as large as possible, i.e., we must make the explosion as active as possible. However, in this case, it is necessary to have, first of all, a stronger and more massive projectile and secondly, stronger objects and instruments in the projectile, because from (32) the relative gravity within the projectile will be quite large and particularly dangerous for a living observer dispatched in the rocket.

In any case, on the basis of equation (35), we have in the limit /44

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

i.e., if p is infinitely large or if the explosion takes place instantaneously, then the velocity V_2 of the rocket in a medium with gravity is the same as in the medium without gravity.

According to equation (30), the explosion time does not depend on the force of gravity, but only on the quantity M_2/M_1 of the explosives and on the rate of their explosion.

39. It is interesting to determine this quantity. Let us assume in equation (28) that $V = 11{,}100$ m/sec (Table 22), while $p = g = 9.8$ m/sec^2, then, $t = 1{,}133$ sec.

This means that in a medium free of gravity the rocket would travel with uniform acceleration for a period less than 19 minutes--and this would be the case when the quantity of explosives compared to the mass of the projectile is quite high (Table 22).

If the explosion took place at the surface of our planet, the projectile would remain stationary for the same period of 19 minutes.

40. If $M_2/M_1 = 1$, then, according to this table, $V = 3{,}920$ m/sec; consequently, $t = 400$ sec, or 6-2/3 min.

When M_2/M_1 is equal to 0.1, $V = 543$ m/sec, while $t = 55.4$ sec, i.e., less than 1 min. In the latter case, the projectile would remain motionless for 55-1/2 sec at the surface of the earth.

We can see from this that explosion at the surface of the planet or, generally, in any medium not free of gravity, may produce no results, even though it occurs for a long period of time, but with insufficient force. Indeed, the projectile will remain in place and will not have any forward velocity unless it had been acquired earlier; in the latter case, it will undergo some displacement with uniform velocity. If this displacement takes place upward, the projectile will perform a certain amount of work. If the initial velocity is horizontal, then the displacement will also occur in the horizontal direction; in this case no work will be done.[1] However, in this case, the projectile may be used for the same purposes as a locomotive, steamer or a guided aerial balloon. The projectile may perform this function of displacement for only a few minutes, while the explosion is taking place. However, during this period of time, it may travel a substantial distance, particularly if it moves above the atmosphere. As a matter of fact, we reject the /45
practical application of a rocket for atmospheric flight.[2]

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[1]If we do not take into account the work done by atmospheric resistance. Editor's Note.

[2]We must not forget that this statement was made in 1903, before the first flight of the Wright Brothers and, consequently, before the beginning of aviation. This thought of Tsiolkovskiy was based on the low efficiency of an airplane with a rocket engine. - Editor's Note.

The period during which the device remains fixed in a medium with gravity is inversely proportional to g, i.e., to the force of this gravity.

Thus, at the moon, the device would remain stationary without any support for a period of 2 hours if M_2/M_1 is equal to 6.

41. Let us substitute in equation (35) for a medium with gravity $g/p = 10$, $M_2/M_1 = 6$; then we compute $V_2 = -9{,}990$ m/sec. As before the

relative gravity will be equal to 10, i.e., a man weighing 70 kg during the entire period of explosion (approximately 2 min) will experience a force of gravity 10 times greater than at the Earth and will weigh 700 kg on a spring balance. A traveler will be able to sustain this gravity without injury only if special conditions are observed: if he is submerged in a special liquid under special conditions.

On the basis of equation (28) let us compute the period of explosion or the period of this increased gravity; we obtain 113 sec, i.e., a period less than 2 min. This period is very short and at first glance appears amazing. How can the projectile during this insignificant period of time attain a velocity almost sufficient to escape from the Earth and move around the sun in a manner similar to that of a planet?

We have found $V_2 = 9{,}990$ m/sec, i.e., a velocity only slightly less

than the velocity V, which is attained in a medium free of gravity under the same conditions of explosion (Table 22).

In addition, since the projectile reaches a certain altitude during the explosion, we may even think that the total work performed by the explosives has not decreased at all compared with the work performed by them in a medium free of gravity.

44. We shall now examine this problem.

The acceleration of the projectile in a gravitational field will be given by $p_1 = p - g$.

We shall assume g to be constant over distances from the surface of the Earth which do not exceed several hundred versts. This will not introduce any appreciable error and the error will be favorable, i.e., the true numbers will be more favorable for the flight than those we compute.

The altitude achieved by the projectile during the period t when the explosion is taking place, will be

45. $$h=\frac{1}{2}p_1t^2=\frac{p-g}{2}t^2.$$ /46

Eliminating t, according to equation (31) we obtain

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

where V_2 is the velocity of the projectile in the gravitational medium when all of the explosives have been exhausted.

By eliminating V_2 we obtain from (34) and (46)

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

where V is the velocity attained by the rocket in the medium free of gravity.

Efficiency

The useful work performed by one unit of mass of the explosives in a medium without gravity will be given by the expression

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

In a medium with gravity, however, the work, T_1, will depend on the altitude reached by the projectile and its velocity at the time when explosion ceases:

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

The ratio of this work to the preceding ideal work is equal to

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

Eliminating h and V from this equation by equations (46) and (34), we find

51. $$\frac{T_1}{T} = 1 - \frac{g}{p},$$

i.e., the work performed in a medium with gravity by a definite quantity of explosives, M_2, is less than in a medium without gravity: this dif-

ference g/p is smaller when the gases explode faster or when p is greater. For example, in the case (41) the loss is only 1/10, while the efficiency according to (51) is equal to 0.9. When p = g or when the projectile remains stationary in air without even constant velocity, the losses will be complete and the efficiency will be equal to zero. The efficiency will also be the same if the projectile has a constant horizontal velocity. /47

52. In Section 41 we computed V_2 = 9,990 m/sec. Applying equation

(46) to case 41, we find h = 565 km; which means that during the period of explosion the projectile will reach a point beyond the limits of the atmosphere and will attain a forward motion of 9,990 m/sec.

We note that this velocity is less by 1,110 m/sec than that in a medium without gravity. This difference represents exactly one tenth of the velocity in the medium without gravity (Table 22).

From this we can see that the loss in velocity follows the same law as the loss of work (51) which, as a matter of fact, follows from equation (34). If we transform the latter we obtain

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

We find from (51)

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

where T_1 is the work obtained by the projectile from the explosives in a medium with gravity where acceleration is equal to g.

In order for the projectile to perform all the necessary work while gaining altitude, resisting the atmosphere, and achieving the desired terminal velocity, it is necessary that the sum of all these works be equal to T_1.

After we determine all these works, we compute T by means of equation (56). If we know T, we can compute V, i.e., the velocity in a medium free of gravity, according to the equation

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

Now, knowing V, we may compute the required mass, M_2, of explosives by equation (16).

Thus, by using these methods we find

$$M_2 = M_1\left[e^{\sqrt{\frac{T_1 p}{T_2(p-g)-1}}}\right]. \quad (57)$$

In carrying out our calculations, we replace $M_1 \frac{V_1^2}{2g}$ by T_2 for simplicity.

Therefore, if we know the mass of the projectile M_1 with its entire contents, except the explosives M_2, the mechanical work T_2 of the explosives when their mass is equal to the mass of the projectile M_1, the /48 work T_1, which must be performed by the projectile during its vertical ascent, the acceleration caused by the force of explosion p, and force of gravity g, we can then determine the quantity of explosives M_2, necessary for lifting the mass M_1, of the projectile.

The ratio, T_1/T_2, in the equation will not change if it is reduced by M_1. Therefore, by T_1 and T_2 we understand the mechanical work T_1 performed by the unit mass of the projectile and the mechanical work T_2 of the unit mass of explosives.

By g we understand the total sum of accelerations due to the forces of gravity and the forces of friction of the medium. However, the force of gravity decreases gradually as we move away from the center of the Earth so that a larger quantity of mechanical work of the explosives is utilized. On the other hand, the resistance of the atmosphere will be rather insignificant compared with the weight of the projectile and, as we shall see, it decreases the utilization of the energy of explosives.

Furthermore, we can see that the latter decrease (which lasts for a short period of the flight time through the air) is more than compensated by the decrease in gravitational attraction at substantial distances (500 km), where the action of the explosives ceases.

Equation (20) may be readily applied to the vertical flight of the projectile in spite of the complication due to the variation of gravity and resistance of the atmosphere.

Gravitational Field
Vertical Descent to the Earth

59. First, let us consider coming to a stop in a medium without gravity or coming to an instantaneous stop in a medium with gravity.

Let us assume, for example, that, due to the force of explosion produced by partial consumption of the fuel, the rocket has attained a velocity of 10,000 m/sec (Table 22). In order to bring the rocket to a stop, it is necessary to attain the same velocity in the opposite direction. Obviously, the remaining quantity of explosives according to Table 22, must be 5 times greater than the mass, M_1, of the projectile.

At the end of the first part of the explosion, the projectile must therefore contain a supply of explosives whose mass is given by the equation $5M_1 = M_2$.

60. The entire mass, including the fuel supply, is $M_2 + M_1 = 5M_1 + M_1 = 6M_1$. The initial explosion must accelerate this mass $6M_1$ to a velocity of 10,000 m/sec and for this purpose, we must have a quantity of explosives also 5 times (Table 22) greater than the projectile and the mass of the fuel supply for bringing the projectile to a stop. This means we must increase $6M_1$ by a factor of 5: we obtain $30M_1$ which, together with the supply for bringing the projectile to a stop, $5M_1$, constitutes $35M_1$.

We designate the number in Table 22 which gives the ratio between the mass of the explosive material and the mass of the projectile by $q = M_2/M_1$. Then we can express M_3/M_1 as /49

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

or, by adding and subtracting unity from the second part of the equation, we have

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

from which it follows that

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

The latter expression is easy to remember.

When q is very small, the quantity of explosive substances is approximately equal to 2q (because q^2 will be negligible), i.e., it is twice as large as that necessary to achieve velocity once.

63. On the basis of equations which we have obtained and on the basis of Table 22, we make up the following table in a medium without gravity.

V m/sec	M_2/M_1	M_3/M_1	V m/sec	M_2/M_1	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	Infinite	-	Infinite

We can see from this table how prohibitively large the reserve of explosives must be if we are to attain a high velocity and then lose it. /50

From (62) and (16) we have

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

We note that the ratio $-2V/V_1$ is positive because the velocities of the projectile and of the gases are opposite in direction and consequently have different signs.

64. If we are in a medium with gravity, then in the simplest case of vertical motion the process of coming to a stop and descending to the Earth will be as follows: when the rocket under the influence of its terminal velocity has reached a certain altitude and stopped, it begins to fall to the Earth.

When the projectile has descended to the point at which the action of the explosive substances had ceased during the ascent, it is again subjected to the action of the remaining fuel in the same direction as before and in the same order. Obviously, at the end of their action and the expenditure of the fuel supply, the rocket will stop at the same point on the surface of the Earth from which it started its ascent. The method of ascent is strictly identical to the method of descent; the only difference is that the velocities are opposite at each point of the path.

It requires more explosives and more work to come to a stop in a gravitational field than in a medium without gravity; therefore q (in equations (61) and (62)) must be greater.

We designate this large ratio by q_1, and on the basis of what we have stated we find

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

from which

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

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

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

Here, M_4 designates a quantity or mass of the explosives necessary for ascending from a given point and returning to the same point when the rocket is brought to a complete stop and when it moves in a medium with gravity.

67. On the basis of the last equation we may 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 and the remaining ex- /51
plosives. For this, Table 5 gives only the work $V^2/2g$; the velocity, on

the other hand, will be less because part of this work is used for producing lift in a medium with gravity.

For the Gravity Field

V m/sec	M_2/M_1	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

The Field of Gravity. Inclined Ascent

68. The vertical motion of the rocket would seem to be more advantageous because the atmosphere is penetrated more rapidly and the projectile reaches a higher altitude. However, on the one hand, the work required to penetrate the atmosphere compared with the total work of the explosives is rather insignificant and, on the other hand, with inclined motion we may provide for a permanent observatory moving beyond the limits of the atmosphere for an indefinitely long period of time around the Earth, just like our moon. In addition, and this is most important, if the flight is inclined, we utilize a much larger part of the energy of explosion than during vertical motion.

First, let us consider a specific case--the horizontal flight of a rocket.

If we let R (Figure 2) be the uniform horizontal acceleration component of the rocket, and p the acceleration due to the action of explosion, and g the acceleration due to gravity, we have

69. /52

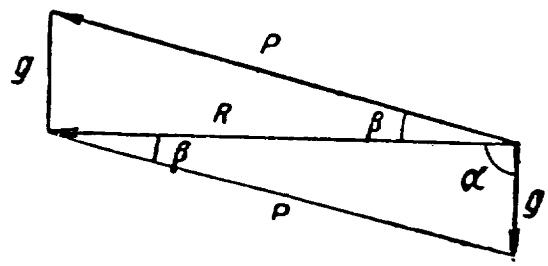


Figure 2.

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

On the basis of the last equation, the kinetic energy imparted to the projectile after a period of time, t, is equal to

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

where t is the period of explosion. This is the entire useful work obtained by the rocket. Indeed, the rocket does not rise at all if we assume that the direction of gravity is constant (in practice this is only true for a small trajectory of the projectile). On the other hand, the work of the explosives imparted to the rocket in the medium free of gravity is equal to

72. $$\frac{p}{2}t^2\frac{p}{g}=\frac{p^2}{2g}t^2.$$

Dividing the useful work (71) by the total work (72), we obtain the efficiency during the horizontal flight of the rocket

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

As before, we do not take into account air resistance at this time.

From the last equation we can see that the loss in work compared with the work in a medium free of gravity is given by the expression

$(g/p)^2$. It follows that this loss is substantially smaller than for the case of vertical motion. Thus, for example, when $g/p = 1/10$ the loss constitutes 1/100, i.e., 1 percent, whereas, during vertical motion, it is given by g/p, or equals to 1/10, i.e., 10 percent.

74. We present a table in which β is the slope of the acceleration, p, with respect to the horizon: /53

The Horizontal Motion of the Rocket

p/g	$(g/p)^2$	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

Ascent Along an Inclined Path. The Work of Ascent with Respect to the Work in a Medium without Gravity. Losses of Work.

75. Let us solve the general problem when R has any arbitrary slope. The case when the trajectory is horizontal or the resultant is horizontal is not advantageous, because in this case the path of the projectile through the atmosphere is substantially increased and the work for penetrating the atmosphere is also increased.

Let us remember that α or the slope of the resultant with respect to the vertical is greater than a right angle; we then have

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

where $\gamma = \alpha + \beta$ (the obtuse angle of the parallelogram) on the drawing.

Furthermore,

77. $$\gamma=\alpha+\beta;\ \sin\alpha:\ \sin\beta:\ \sin\gamma=p:g:R$$

and

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

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

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

Consequently, the work of ascent of the projectile will be

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

where t is the period of explosion of the entire supply of explosives. /54
The total work imparted to the projectile in a medium with gravity, according to (71) and (80), is

81. $$\frac{R_2}{2g}t + \frac{-\cos\alpha}{2}Rt = \frac{Rt^2}{2}\left(\frac{R}{g} - \cos\alpha\right).$$

By 1 unit of work we understand the ascent of the projectile by 1 unit of altitude in a medium with acceleration g. If $\alpha > 90^\circ$, for example, in the case the projectile ascends, cos α is a positive quantity and vice versa.

The work in a medium free of gravity, according to (72), will be equal to $\frac{p^2}{2g}t^2$ (we must not forget that the period t of explosion does not depend on the force of gravity).

By taking the ratio of these two works, we obtain the efficiency with which the energy of explosives is utilized compared with the efficiency of their utilization in a medium devoid of gravity, i.e.,

82. $$\frac{Rt^2}{2}\left(\frac{R}{q} - \cos\alpha\right) : \left(\frac{p_2}{2g}t^2\right) = \frac{R}{p}\left(\frac{R}{p} - \frac{g}{p}\cos\alpha\right).$$

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

83. $$1 + \frac{g^2}{p^2} + 2\cos\gamma\frac{g}{p} - \cos\alpha\frac{g}{p}\sqrt{1 + \frac{g^2}{p^2} + 2\cos\gamma\frac{g}{p}}.$$

Equations (51) and (73), for example, represent only the specific case of this equation.

84. Let us now apply the equation which we have derived. Let us assume that the rocket moves up at an angle of 14.5° with respect to the horizon; the sine of this angle is 0.25; this means that the resistance of the atmosphere increases by a factor of 4 compared with its resistance during the vertical motion of the projectile inasmuch as its resistance is approximately inversely proportional to the sine of the slope angle (α - 90°) of the rocket's trajectory with respect to the horizon.

85. The angle $\alpha = 90 + 14\text{-}1/2 = 104\text{-}1/2^\circ$ and $\cos\alpha = 0.25$; if we know α we may determine β. Indeed, from (77), we find

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

so that if $g/p = 0.1$, then

$$\sin\beta = 0.0968;\ \beta = 5^1/_2{}^\circ,$$

from which

$$\gamma = 110^\circ,\ \cos\gamma = 0.342.$$

Now, by means of equation (83) we compute an efficiency of 0.966. The losses are 0.034 or approximately 1/20, more precisely, 3.4 percent.

This loss is 3 times smaller than for vertical motion. The result is not bad if we also consider that the resistance of the atmosphere even for inclined motion ($14\text{-}1/2^\circ$) is in no case greater than 1 percent of the work necessary to remove the projectile from the Earth. /55

86. For various considerations we present the following table. The first column shows the slope of the motion with respect to the horizon, the last column shows the losses in the work; β is the deviation in the direction of the pressure produced by the explosives from the line of true motion (69).

Inclined Motion

	Degrees				
$\alpha - 90$	α	β	$\gamma = \alpha + \beta$	Efficiency	Losses
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

87. For very small slope angles (α - 90°) equation (83) may be substantially simplified by replacing the trigonometric terms with other terms and by making other simplifications.

Then we obtain the following expression for the losses 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 is the slope angle of motion (α - 90°), expressed in terms of the length of its arc with radius equal to unity, while x is the ratio g/p. By neglecting infinitesimals of higher orders in the last equation, we obtain an expression for the losses

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

We may let δ = 0.02N, where 0.02 is the part of the circumference corresponding approximately to 1° (1-1/7), while N is the number of these new degrees. Then the losses of work are expressed approximately by /56

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

From this equation it is easy to prepare a table by setting

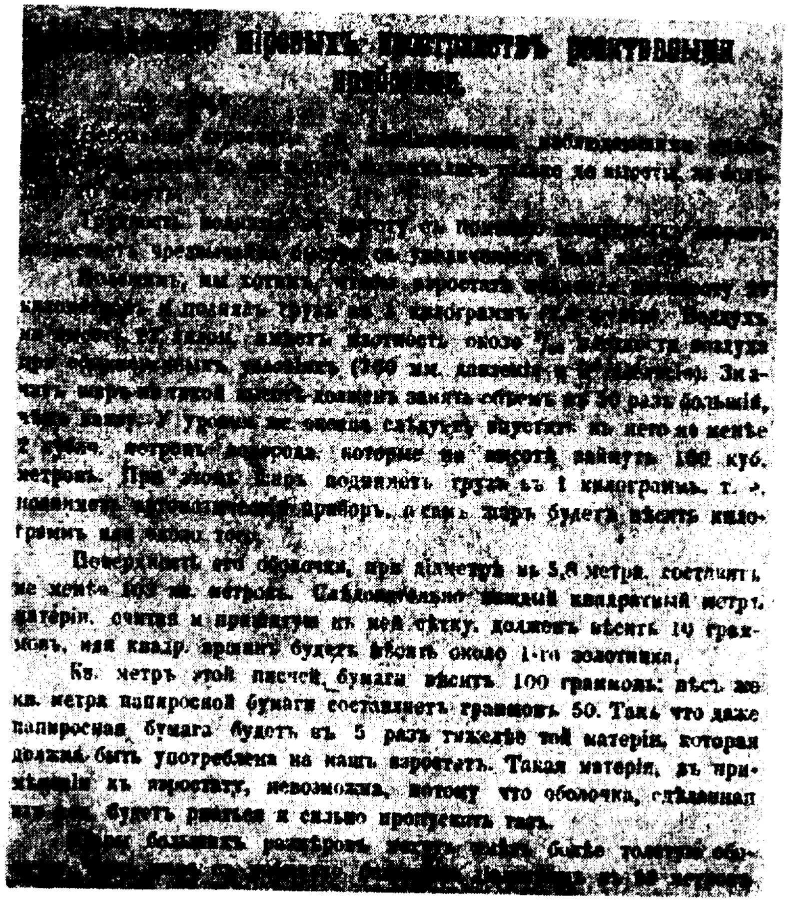
$$\frac{g}{p}=0.1,$$

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

We can see here that even for large angles (up to 10°) the discrepancy between this table and the preceding, more accurate, is very small.

We could consider many other aspects of the problem: the work of gravity or the resistance of the atmosphere; we have said nothing about how the explorer can spend a long time or even an indefinite time in the medium with no traces of oxygen. We have not mentioned the heating of the projectile during the short flight through the air, and we have not presented the general picture of flight and of the very interesting phenomena associated with it (theoretically). We have said very little about the great prospects if the flight can be accomplished, which at the present time appear to us only in a fog. Finally, we could have drawn cosmic curves for the motion of the rocket in space.

/57


[illegible]

Кв. метръ этой писчей бумаги вѣситъ 100 граммовъ; вѣсъ же кв. метра папиросной бумаги составляетъ граммовъ 50. Такъ что даже папиросная бумага будетъ въ 5 разъ тяжелѣе той матеріи, которая должна быть употреблена на нашъ аэростатъ. Такая матерія, въ примѣненіи къ аэростату, невозможна, потому что оболочка, сдѣланная [illegible] будетъ рваться и сильно пропускать газъ.

[illegible]

Figure 3. A page from the journal "Nauchnoye Obozreniye," No. 5, 1903.

Printed for the first time in the Journal "Nauchnoye Obozreniye" No. 5, 1903, under the title "Investigation of Universal Space by Means of Reactive Devices." In 1924, the article was published as a separate pamphlet at Kaluga. It was included in "The Selected Works," Vol. 2, 1934. K. E. Tsiolkovskiy considered the continuation of this work to be "The Investigation of Universal Space by Means of Reactive Devices," Part 2 (Investigations of 1911-1912). - Editor's Note.

THE INVESTIGATION OF UNIVERSAL SPACE BY MEANS OF REACTIVE DEVICES /58

(1911)

A Summary of the Works of 1903

In the course of our work on the reactive device since 1896 we have come to the following conclusions.

The exterior view of the projectile has the form of a wingless bird which separates the air in front of it with ease (Figure 1).

A large part of the projectile's interior is occupied by two substances in liquid form: hydrogen and oxygen. The liquids are separated /59
by a partition and are mixed only in small quantities. The remaining part of the chamber, which has a smaller volume, is designed to house an observer with the various instruments and equipment necessary to preserve his life, to conduct scientific observations, and to control the rocket.

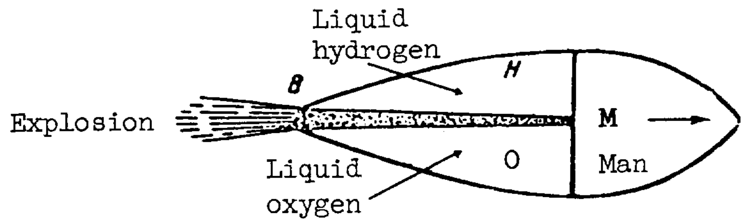


Figure 1.

The hydrogen and oxygen are mixed in the narrow part of a gradually diverging tube, unite chemically, and form water vapor at an extremely high temperature. This vapor possesses very high elasticity and is ejected from the nozzle of the tube with a tremendous velocity along the direction of the tube or the longitudinal axis of the chamber.

The simplest way of controlling the rocket is to rotate the end of the exhaust nozzle or the rudder in front of it. The energy of the chemical combination of hydrogen and oxygen is tremendous. A substantial part of it, specifically up to 0.65 (65 percent) is imparted to the rocket, i.e., is transformed into the energy of its motion. The remaining part (35 percent) is used to move the water vapor. This large part of the energy of explosives is imparted to the rocket in a medium free of gravity; on the other hand, in a medium with gravity, such a utilization of energy can only be accomplished if we have an instantaneous explosion, which, from the practical standpoint, is entirely unsuitable. The slower the explosion, the longer it lasts in a medium with gravity and the stronger the latter, the less is the efficiency of utilization of the energy of explosives.

In a medium without gravity the utilization of energy does not depend on time and order of explosion.

Due to the acceleration of the rocket, an apparent or temporary gravity is formed inside it which becomes greater when explosion takes place faster, or when the pressure of the vapors ejected from the tube is greater. This relative gravity, from the standpoint of its effect inside the projectile, does not vary in any way from natural gravity.

The highest efficiency (65 percent), both in a medium with gravity as well as in a medium without gravity, is obtained when the quantity of combustible mixture is 4 times greater than the weight of the missile with all its contents; in any other case the efficiency is less than 65 percent. With this ratio of the quantity of explosives to the weight of the projectile, the latter attains a velocity up to 9 km/sec. The projectile may also obtain an arbitrarily large or arbitrarily small velocity, but in this case a smaller portion of the energy of explosives is effectively utilized. The efficiency becomes smaller as the relative quantity of combustible substances deviates further from the value 4.

When this ratio is between 1 and 18 the efficiency is greater than 48 percent; the corresponding velocities in the medium without gravity vary from 3.9 to 16.9 km/sec. The latter velocity is greater than that necessary to overcome the attraction of the sun and the Earth, and to move the rocket between the stars if it is launched in the direction of the annual motion of the Earth. /60

K. E. Tsiolkovskiy in 1910

In my calculations I have assumed that the temporary gravity in the rocket is 10 times the normal gravity; however, the magnitude of this gravity is under our control and we can make it only slightly greater than that of the Earth, particularly when the launching is inclined or horizontal.

Let us imagine something that is absolutely impossible: let us assume that a beautiful vertical or inclined highway is constructed for a distance of thousands or millions of kilometers with cars, machines, and all devices for convenient travel beyond the limits of the atmosphere. As we rise along this highway to a definite altitude, we shall expend a definite quantity of useful work. If we achieve our claim by means of some prime movers, even those which are the most perfected under the present state of the art, we shall utilize not more than 10 percent of the chemical energy of the fuel we take with us.

If we were to reach the same altitude, without a ladder or elevators, but by means of our projectile, we utilize, as we have seen, not less than 50 percent of the chemical energy of combination of hydrogen and oxygen under rational conditions. Thus, if we were to use the imaginary vertical highway, we would use at least 5 times more fuel than would be used by a reactive device. This conclusion is only valid if we are to reach an altitude not less than 700 km, in which case a large portion of the energy of explosives is utilized.

The result may be quite deplorable when the relative gravity is small and the altitude is low.

It is precisely these miserable reactive phenomena which are usually observed on Earth. This is why they have never inspired any one to dream and to investigate. Only intelligence and science could point to the transformation of these phenomena into those magnificent ones almost beyond comprehension.[1]

The Work of Gravity during Movement Away from the Planet /61

By means of a very simple integration we obtain the following relation for the work T necessary to remove a unit mass from the surface of a planet with radius r_1 to an altitude of h:

$$T=\frac{g}{g_1}r_1\left(1-\frac{r_1}{r_1+h}\right).$$

Here g is the acceleration due to gravity on the surface of the given planet, while g_1 is the acceleration due to Earth's gravity on its surface.

Let us assume that in this equation h is equal to infinity. Then we determine the maximum work in removing a unit mass from the surface of the planet to infinity and obtain

$$T_1=\frac{g}{g_1}r_1.$$

We note that g/g_1 is the ratio of the acceleration due to gravity on the surface of the planet to the acceleration due to gravity on Earth. The work performed to remove a unit mass from the surface of the planet to infinity is equal to the work of raising this mass from the surface to an altitude equal to 1 r of the planet, if we assume that the force of gravity does not decrease as we move away from the surface.

[1]The following sections contain the equations (left out here) in the article "A Rocket Into Cosmic Space."- Editor's Note.

From the last equation we can see that the limiting work T_1 is proportional to the force of gravity g/g_1 at the surface of the planet and to the magnitude of its radius.

For planets of the same density, i.e., for planets with the same density as Earth, namely 5.5, the force of gravity at the surface, as we know, is proportional to the radius of the planet and is expressed as the ratio of the radius of the planet r_1 to the radius of Earth r_2.

Consequently,

$$\frac{g}{g_1}=\frac{r_1}{r_2}$$

and

$$T_1=\frac{r_1}{r_2}r_1=\frac{r_1^2}{r_2}.$$

From the preceding equations 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 expressed the work T done in ascending to an altitude h from the surface of the planet of radius r_1 with respect to the total maximum work T_1.

Required Velocity of the Body to Move Away from the Planet /62

We shall not present the calculations which are used to determine these velocities, but only concern ourselves with the conclusions.

The velocity V_1 required to raise the rocket to an altitude h with a terminal velocity V, is equal to

$$V_1=\sqrt{V^2+\frac{2gr_1h}{r_1+h}}.$$

If we assume here that V = 0, i.e., if the body moves upwards until it is stopped by the force of gravity, we find

$$V_1=\sqrt{\frac{2gr_1h}{r_1+h}}.$$

When h is infinitely large, i.e., if we continue to rise indefinitely and if the terminal velocity is 0, then the velocity required at the surface of the planet is given by the expression

$$V_1=\sqrt{2gr_1}.$$

From this equation we compute for Earth: V_1 = 11,170 m/sec.

For planets of the same density as Earth, we obtain

$$V_1=r_1\sqrt{\frac{2g_1}{r_2}},$$

where g_1 and r_2 refer to the Earth's sphere. We can see from the equation that the limiting launching velocity V_1 in this case is proportional to the radius r_1 of the given planet.

To achieve eternal orbiting around the planet we require only half of the work and the velocity, which is smaller by a factor $\sqrt{2} = 1.41...$ than the one required for escape into infinity.

Period of Flight

We shall not present here the rather complex equations which determine the period of flight of the projectile. This question is not new and has been solved, so that we would repeat something already known.

Let us make use of only one conclusion which is extremely simple and useful for solving the simplest problems on the period of motion of the rocket.

The period of fall of a body initially at rest onto a planet (or sun) concentrated at one point (with the same mass) is given by the expression

$$t=\frac{r_2}{r_1}\sqrt{\frac{r_2}{2g}}\left(\sqrt{\frac{r_2}{r}-1}+\arcsin\sqrt{\frac{r}{r_2}}\right).$$

Here r_2 is the distance from which the body begins to fall; r is the path traveled by the falling body; r_1 is the radius of the planet, /63 and g is the acceleration due to gravity at the surface of the planet.

Of course, the same equation expresses the period of fall from $r_2 - r$ to r_2 when the body loses all its velocity.

If we assume that $r = r_2$, i.e., if we determine the period of fall to the center of the concentrated planet, we obtain from the last equation

$$t = \frac{\pi}{2} \frac{r_2}{r_1} \sqrt{\frac{r_2}{2g}}$$

Under ordinary conditions, this equation also gives us approximately the period of fall to the surface of the planet or the time it takes the rocket to rise from this surface until it comes to a stop.

On the other hand, the period of one complete orbit of some particular body, e.g., a projectile, around the planet (or the sun) is equal to

$$t_1 = 2\pi \frac{r_2}{r_1} \sqrt{\frac{r_2}{g}},$$

where r_1 is the radius of the planet with acceleration g at the surface while r_2 is the distance of the body from the center of the planet.

By comparing both equations, we find

$$\frac{t_1}{t} = 4\sqrt{2} = 5.657.$$

Thus, the ratio of the period of revolution of a satellite to the period of its central fall to a planet, which is concentrated at one point, is equal to 5.66.

To determine the time of fall of some heavenly body to the center around which it rotates, the sidereal period of rotation of this body must be divided by 5.66.

However, a rocket launched from Earth and coming to a stop at the distance of the moon would fly for a period of 4.8 days, or approximately 5 days.

In the same way a rocket launched from the sun which comes to rest at the distance of the Earth, due to the strong action of solar gravitation and insufficient velocity would take 64 days or over 2 months to perform its flight.

Resistance of the Atmosphere

Let us determine the work performed by the rocket in penetrating the air during its normal rectilinear uniform acceleration; we must take into account the variable density d of the atmosphere at various altitudes.

It is equal to (see my work "Aerostat and Airplane," 1905) /64

$$d = d_1\left(1 - \frac{d_1 h}{2(A+1)f}\right)^{2A+1} \tag{1}$$

where

$$A = \frac{d_1 M T_1 C}{f}.$$

In these equations d_1 is the density of the air at sea level (d_1 = 0.0013); h is the altitude of the projectile or the altitude of the atmosphere under consideration; f is the air pressure at sea level per unit area (f = 10.33 ton per m^2); M is the mechanical equivalent of heat (M = 424 ton-meters); T_1 is the temperature of absolute 0 (T_1 = 273); C is the specific heat of the air at constant volume (C = 0.169). Then A = 2.441, and the first equation takes the form

$$d = d_1\left(1 - \frac{h}{h_1}\right)^{a}, \tag{2}$$

where a = 2A + 1 = 5.88, h_1 = 54.540 km and expresses the limiting theoretical altitude of the atmosphere under the assumptions which have been made. Indeed, if in equation (1) d = 0, then

$$h = \frac{2(A+1)f}{d_1}.$$

By letting this altitude be equal to h_1 we obtain equation (2).

Although this altitude of 54.5 km is extremely small, as we can see from observations on falling stars, there is no doubt however, that the atmosphere above 54 km is so rarefied that its resistance may be neglected. Indeed, if we compute the density of the air cover at this altitude, assuming a constant temperature equal to the one at sea level and, consequently, that the atmosphere is without bounds, then in this case we find $d/d_1 = 0.001$, i.e., at this altitude the air is 1,000 times less dense, which means that above 54 km there is not more than one thousandth (0.001) of the mass of the entire atmosphere.

However, since the temperature decreases, this remaining mass is obviously much smaller.

The differential of the work T of resistance is given by

$$dT = Fdh,$$

where F signifies the resistance of the air to the motion of the projectile. It is equal to

$$F = \frac{KSdV^2}{2gU}.$$

Here K is the coefficient which according to Langley is equal to 1.4; /65

S is the area of the maximum cross section of the projectile;

d is the density of the air at the place where the rocket moves at a given time; d, of course, is a variable because the air density decreases very rapidly with altitude;

V is the velocity of the projectile;

g is the acceleration due to Earth's gravity at the surface of the Earth ($g = 9.8$ m/sec^2);

U is the efficiency of the rocket shape; this number shows how much the resistance decreases due to the bird-like form of the projectile compared with the resistance of the area of its maximum cross section. U is also a variable which, as shown by many experiments, increases when the velocity V of the moving body increases; we might also point out that it increases with an increase in the dimensions of the body. We shall assume U to be constant.

Furthermore, since the air resistance is small compared with the pressure exerted on the rocket by the explosives (approximately 1 percent or less), the velocity V of the projectile may be set equal to

$$V=\sqrt{2(p-g)h},$$

where (p - g) is the true acceleration of the projectile per second. This proposition, which increases the velocity, also increases the work of atmospheric resistance, and consequently corrects for the error due to the contraction of the altitude of the atmosphere.

On the basis of equation (2) and of the three last equations we obtain

$$dT=b\left(1-\frac{h}{h_1}\right)^a h\,dh;$$

here

$$b=\frac{Kd_1S(p-g)}{Ug}$$

and

$$a = 5.88.$$

Integrating by parts and determining the constant, we find

$$T=b\left\{\frac{h_1^2}{(a+1)(a+2)}\left[1-\left(1-\frac{h}{h_1}\right)^{a+2}\right]-\right.$$
$$\left.-\frac{h_1h}{a+1}\left(1+\frac{h}{h_1}\right)^{a+1}\right\} \tag{11}$$

If we let $h = h_1$, we obtain the total work T_1 of atmospheric re- /66
sistance. Specifically:

$$T_1=\frac{bh_1^2}{(a+1)(a+2)}.$$

Let us assume that $K = 1.4$; $d = 0.0013$; $S = 2\ m^2$; $p/g = 10$; $g = 9.8\ m/sec^2$; $U = 100$; then $b = 0.0003276$; $a = 5.88$ and $h_1 = 54{,}540$ m.

Then $T_1 = 17{,}975$ ton-meters.

The work performed by 1 ton of explosives when we obtain 1 ton of water from hydrogen and oxygen is equal to 1,600,000 ton-meters. If the projectile with all its instruments and the traveler were to weigh 1 ton, and if the supply of explosives were to be 6 times that or 6 tons, then the rocket would carry with it a potential energy of 9,600,000 ton-meters. More than half of this energy would be transformed into the mechanical work of rocket motion.

The work of atmospheric resistance in this case would then constitute only 1/300 of the work of gravity. We obtain the same result by directly comparing the work of atmospheric resistance (17,975) with the total work of gravity (6,336,000). This gives us approximately 1/353.

I introduce here a table which shows, under conditions which we have assumed, the time in seconds from the beginning of the vertical flight, the corresponding velocity of the rocket in meters, the altitude achieved in meters, and the density of the surrounding air, assuming that the density at sea level is unity and that the temperature drops uniformly by 5° C every kilometer. /67

Period of Flight of Rocket in sec	Velocity of Ascent of Rocket m/sec	Altitude of Ascent m	Relative Density of Air
0	0	0	1
1	90	45	-
2	180	180	-
3	270	405	-
5	450	1,125	1:1.13
7	630	2,205	-
10	900	4,500	1:1.653
15	1,350	10,125	-
20	1,800	18,000	1:10.63
30	2,700	40,500	1:2828
40	3,600	72,000	Approaching
50	4,500	112,500	zero
70	6,300	220,550	0
100	9,000	450,000	0
113	9,900	574,000	0

The entire period of explosion, when we have 6 times the fuel weight, lasts for 113 seconds, and at the end of this time the body has a speed of 9,990 m/sec and rises to an altitude of 575 km; ascent of the body beyond this point will be due to its inertia.

The work of atmospheric resistance is rather small; the loss during vertical motion due to the force of gravity is not quite as small: specifically, the first loss is 35 times smaller than the second. Therefore, it is advantageous to incline the path of the rocket in order to increase several times the resistance of air, and at the same time to decrease the loss of energy due to the effects of gravity.

It is easy to see that the work of atmospheric resistance is approximately proportional to $\operatorname{cosec}^2(\alpha - 90^\circ)$, where $(\alpha - 90^\circ)$ is the angle of inclination of the projectile's trajectory with respect to the horizon.

We present a table based on the previous law, which is quite valid when we depart to some degree from horizontal flight.[1]

The first column shows the angle of inclination of trajectory with respect to the horizon in degrees; the fourth column gives the sum of all losses when the efficiency U of rocket shape is assumed to be 100.

Angle of inclination of trajectory with respect to horizon $\alpha - 90^\circ$	Losses		
	due to gravity[2]	due to atmosphere U = 100	Sum of losses
0	0.010	∞	-
2	0.014	2.47	2.48
5	0.020	0.395	0.417
10	0.027	0.099	0.126
15	0.035	0.0477	0.0827
20	0.045	0.0255	0.0205
30	0.057	0.0120	0.069
40	0.070	0.0073	0.0773
45	0.075	0.0059	0.0809
90	0.100	0.0030	0.1030

In a medium without gravity when the weight of the explosives is 6 times that of the projectile, 0.63 percent of all latent energy of the explosives is utilized. /68

[1]The table is presented with corrections made by Tsiolkovskiy. The corrections were made by him before 1931. - Editor's Note.

[2]See table in Paragraph 86 "Rocket in Cosmic Space." - Editor's Note.

If, in the worst case, we destroy 8 percent of this, we find that during inclined motion we may utilize 58 percent of the entire chemical energy of the explosives.

The work done by the resistance of air may be decreased by several times if the flight starts from the peak of a high mountain, or if the rocket is raised by means of an airship to a sufficient altitude and the flight is started there. A flight which starts at an altitude of 5 km will decrease the work done by air resistance by half, while flight from an altitude of 10 km will decrease it by a factor of 4.

Picture of the Flight

Relative phenomena. Although space travel is very far off, let us assume nevertheless that everything is ready: everything has been invented, perfected, and tested and we are situated inside the rocket and are ready for blast-off, while our friends are observing us.

We shall refer the phenomena to our rocket, our friends will refer them to Earth and the astronomers on Mars will refer them to their own planet, etc. All these phenomena will be relative and entirely different, because a phenomenon of any type depends on the form of motion of the body to which it is referred.

We have started on our voyage and shall experience rather strange, completely amazing and unexpected sensations which we shall now describe.

The signal has been given; the explosion, accompanied by deafening noise, has started. The rocket has shivered and is on its way. We experience a tremendous increase in weight. The 4 poods of my weight have been transformed into 40 poods. I have fallen to the floor, have been knocked out or even have died; this is not the time for carrying on observations! There are means of surviving such terrible gravity, but this has to be done in a special packed way or by being placed into a liquid (we shall discuss this later).

If we are placed into a liquid, it is also doubtful that we would feel like making any observations. No matter what is done, the gravity in the rocket apparently has increased by a factor of 10. We could learn of this from spring balances or a dynamometer (1 pound of gold hanging on a hook changes its weight to 10 pounds), from the accelerated swinging of a pendulum (it oscillates more than 3 times faster), a more rapid fall of bodies, from a decrease in the size of drops (the diameter decreases by a factor of 10), from an increase in weight of all objects, and many other phenomena.

If the density of Earth were to increase by a factor of 10 or if we were on a planet where the force of gravity is 10 times greater, we would not distinguish between the phenomena in the rocket and the phenomena on the planet with increased gravity. The force of gravity could be less in the rocket, but then the explosion period would be longer, /69 although the rocket would rise to a lower altitude and would achieve a lower terminal velocity with the same fuel consumption. We are considering the case of vertical ascent when the direction of the relative gravity is the same as it is on Earth. If we were in an inclined flight, we should see the change in direction of relative gravity, but by not more than 90°, while for the case of the optimum flight by not more than $75-80^{\circ}$, compared with its direction on Earth at a given place.

If, in this case, we were to look out of the window of the rocket, Earth would appear to us as an almost vertical wall moving towards the sky on one side and to the abyss on the other.

The hellish gravity which we experience will last for 113 seconds or approximately 2 minutes, until the explosion and its noise have ceased. Then when dead silence occurs, gravity disappears as quickly as it appeared. Now we have risen beyond the limits of the atmosphere to an altitude of 575 km. Gravity has not only weakened: it has disappeared without any trace. We do not experience even Earth's gravity to which we are accustomed as we are accustomed to air, but which is not at all as necessary for us as the latter. At 575 km--this is a very short distance--we are almost at the surface of the Earth and gravity should have decreased insignificantly. This is, indeed, the case. However, we are dealing with relative phenomena and for them gravity does not exist.

The force of Earth's gravity has the same effect on the rocket as on the bodies contained within the rocket. Therefore, there is no difference in the motion of the rocket and of the bodies placed inside of it. They are carried by the same stream and by the same force, and for the rocket there appears to be no gravity.

We become convinced of this by many signs. All the objects which have not been secured inside the rocket have moved from their places and hang in air, not touching anything; and even if they are touching, they do not exert pressure on each other or on the supports. We also do not touch the floor and we assume any position and direction: we stand on the floor, on the ceiling, on the wall; we stand perpendicular and at an angle; we float in the middle of the rocket like fish, but without any exertion and without touching anything; none of the objects press on each other unless they are deliberately pressed together.

Water does not flow from the pitcher, the pendulum does not swing and hangs sideways. A huge mass attached to a hook of a spring balance does not produce stress in the spring and the reading is always zero. The beam balance is also useless: the beam assumes all types of positions regardless of whether equal or unequal weights are placed in the cups. Gold cannot be sold by weight. Mass cannot be determined by the usual methods used on Earth.

Oil shaken out of the bottle with some difficulty (since the pressure or elasticity of the air we breathe in the rocket interferes) takes on the shape of an oscillating sphere; after a few minutes the oscillations cease and we have a liquid sphere of unusual precision: we break /70
it into parts and obtain groups made up of small spheres of different size. All this creeps in different directions, flows over walls and wets them.

The mercury barometer has risen to the top and the mercury has filled the entire tube.

The double-knee syphon does not transfuse the water.

An object released from the hands carefully does not drop, while one that has been pushed moves in a straight line at uniform speed until it hits the wall or some other obstacle, after which it again begins to move, although with smaller velocity. In general it also rotates simultaneously like a toy top. It is even difficult to push a body without causing it to rotate.

We feel well and light as if we were lying on the most gentle feather bed. However, the blood goes slightly to our head; this is detrimental to those who are full-blooded.

We are capable of making observations and of reasoning. In spite of the fact that the powerful hold of Earth continuously retards the ascent of the projectile, i.e., the force of Earth's gravity does not cease for one moment; in the rocket we feel exactly the way we would on a planet whose gravity suddenly disappeared by some miracle or was paralyzed by a centrifugal force.

Everything is quiet, well, and peaceful. We open the external shutters of all the windows and observe through thick glass in all six directions. We see two skies, two hemispheres, which together form one sphere at whose center we appear to be. We feel as if we were inside a ball consisting of two colored halves. One half is black, with stars and the sun; the other is yellowish, with a multitude of bright and dark spots and with expansive spaces which are not so bright. This is Earth, which we have just left. It does not appear convex like a sphere, but on the contrary, according to the laws of perspective, it appears concave like a round cup whose inside we are observing.

In the month of March we took off from the equator at noon and therefore Earth occupies almost half the sky. By flying at night or in the morning we would see that it covers a quarter of the sky in the form of a gigantic curved sickle; at midnight we would have seen only the zone or ring glowing with a purple light--the light of dawn--which separates the sky into two: one half, without stars, is almost black, just slightly reddish; the other half is black as soot, populated with an infinite number of rather bright stars which do not twinkle.

As we move further away from the surface of Earth, the zone becomes smaller and smaller, but also brighter and brighter. The Earth's sphere either in this form or in the form of a sickle or a cup appears to become smaller and, at the same time, we observe an ever increasing part of its surface. Now it appears to us in the form of a huge dish, which gradually decreases and turns to a saucer. Later it looks like a moon.

Strictly speaking, the rocket does not have top and bottom, since /71
there is no relative gravity and a body left without support does not gravitate to any part of the rocket; however, subjectively the feeling of top and bottom still remains. We feel top and bottom only when their positions change, as our body changes its direction in space. In the direction where we have our head we see the top, and where we have our feet we see the bottom. Thus, if our head is towards the planet, it appears to be up high; if our feet are towards the planet, it appears to be below us. The picture is magnificent and, at first sight, it is frightening; then we get used to it and truly lose our concept of top and bottom.

Those who observed us from Earth saw how the rocket started to buzz, moved from its place and flew upwards like a falling stone except in the other direction and with 10 times the energy. The velocity of the rocket increases all the time, but it is difficult to see this, due to its high speed. After 1 sec the rocket has reached an altitude of 45 m; after 5 sec it is at an altitude of 1 verst and after 15 sec it is up to 10 versts; it is hardly noticeable in the form of a thin vertical line rapidly moving upwards. After half a minute it is at an altitude of 40 km, but we continue to observe it with our naked eyes because, due to its ever increasing motion, it has become white hot and its protective, highly resistant and nonoxidizing shell shines like a star. This star-like flight continues for over a minute; then everything disappears gradually because, having left the atmosphere, the rocket is no longer subject to air friction, it cools and gradually fades. Now it can be discovered only by a telescope.

The heat did not penetrate to us as we sat in the rocket because we were protected by a heat-insulating layer, and in addition to this we had a huge source of cold: the evaporation of liquid gases. Besides, we only had to be protected for 1-2 minutes.

The apparent absence of gravity in the projectile continues as long as there is no explosion and as long as the rocket does not rotate. It moves away from Earth and moves at a tremendous distance from its planet along some curve, but there is no gravity. The rocket races round the sun, it flies to the stars and is subject to the strong or weak action of all suns and all planets. We do not detect any gravity: all of the phenomena peculiar to a medium devoid of gravity are observed in the rocket and close to it, as before. This conclusion is not strictly accurate but is approximately true; the effect of its inaccuracy cannot be stated within the limits of rocket space, it cannot even be stated for tens, hundreds, and sometimes thousands of versts around it. There is a small effect produced by the force of attraction of the rocket itself on the people and the objects they have taken with them. However, /72
their interaction is very small and is detected by the displacement of strictly stationary bodies only over periods of hours. If the objects, however, have an insignificant motion, the effect of Newton's gravitation cannot be detected.

Around the Earth

By limiting the explosion it is possible to ascend only up to a desired altitude; then, when we have lost almost all speed, in order not to fall back on the planet, we rotate the rocket by rotating the bodies inside it and produce a new explosion in the direction perpendicular to the initial one.

Again relative gravity is born; but in this case we can limit it to a substantially small value. Again all the phenomena well-known in the presence of gravity are repeated; and again they disappear. Peace and quiet prevail, and the rocket is now prevented from falling; it assumes the velocity normal to the radius vector, i.e., a velocity along a circle like the moon and, like the latter, it will rotate around Earth indefinitely.

Now we can become completely calm since the rocket has obtained a stable position; it has become Earth's satellite.

From the rocket we can see the huge sphere of the planet in one or another phase like the moon. We can see how the sphere rotates, and how within a few hours it shows all its sides successively. The closer it is to the rocket the larger it appears, the more concave its form, the more brightness it gives to its satellite (rocket) and the faster the latter rotates around Earth. This distance can be so small that travel around it can be carried out in 2 hours, and we shall observe various points on the surface of Earth for several minutes from different sides and very closely. This picture is so majestic, attractive and infinitely varied that I wish with all my soul that you and I could see it. Every two hours the rocket is eclipsed and enters the Earth's shadow and night. This latter lasts for less than an hour; then for over an hour the sun shines before giving way again to darkness.

If we wanted to make use of a larger quantity of light, i.e., of a longer day, we must either move further away from Earth or rotate not in the direction of the equator but in the direction of the meridian, so that our path would intersect the poles of Earth. In this case, i.e., when the orbit of the rocket is normal to the rays of the sun, even at the relatively small distance from the planet we will experience a longer day lasting a month or more; the picture of Earth in this case is even more varied, more enchanting and more unexpected, because we shall see the relief of the edges of the illuminated part of Earth, which will also be moving very rapidly. The poles will be particularly clear.

We do not feel the motion of the rocket just as we do not feel the motion of Earth (when we are on it)--and it seems to us that the planet itself is racing past us together with the entire magic horizon; to our senses the rocket becomes the center of the universe, the way Earth never was!... /73

The Trajectory of the Rocket and Its Velocity

During vertical ascent of the rocket in the absence of Earth's rotation, the relative path of the rocket will be very simple; it will be a straight line, more or less long, depending on the quantity of explosives.

The path of the rocket will be the same, if it is launched from the poles of a rotating planet, if we neglect the effect of other heavenly bodies. When the quantity of explosives is 8 times greater than the mass of the rocket, the path of the latter which starts on the surface of Earth has no end; it is infinite and the rocket will never return to Earth, assuming, of course, the absence of heavenly bodies and their gravitation.

As far as Earth is concerned, the minimum velocity for moving away from it to infinity is equal to 11,170 m/sec, or more than 11 km/sec.

The weak rotation of a planet, which is observed in all average and small planets of the solar system beginning with Earth, has a very small effect on the straightness of the path; specifically, the path of the rocket becomes a rather elongated ellipse in the case when the projectile returns to Earth--and into a parabola or hyperbola in the case when it moves away to infinity.

When speaking of the rocket's trajectory, we did not have in mind the relatively short portion corresponding to the period of explosion when, as a matter of fact, it is close to a straight line, if the direction of explosion does not change.

First, during the period of explosion, movement of the rocket is accelerated very rapidly. Later, velocity changes more slowly--only under the influence of the forces of gravity. Specifically, when we rise or move away from the center of the planet, the velocity which has been obtained by the projectile during the period of explosion decreases; as we approach the planet or fall, the velocity increases.

If we are moving away to infinity, the velocity of the projectile during this infinite time approaches zero or some constant value. In this and in other cases, the rocket will never stop and will never return to Earth, if we do not take into account the friction of ether and the attraction of other heavenly bodies.

However, vertical ascent is not advantageous--an inclined ascent is more advantageous. In the case of initial (i.e., during the period of explosion) horizontal flight, the path of the projectile is one of the curves of the second order tangent to Earth's sphere at the point of initial motion. The focus of the curves will be at the center of Earth. When we have an insufficient relative quantity of explosives (less than 3-4), flight will not take place and the rocket will touch Earth or fall /74
on the planet like an ordinary cannon shell fired horizontally.

If the velocity of the rocket produced by the action of the explosives is less by a factor $\sqrt{2}$ than the minimum velocity necessary for escape to infinity (11,170 m/sec), then the path of the rocket will be a circle coinciding with the large circle of Earth's sphere (with the equator or the meridian). This case also has no application because the rocket which flies continuously in Earth's atmosphere rapidly loses all its velocity due to air resistance and falls to Earth. However, if the atmosphere were absent or if the rocket were to begin its flight from a mountain whose peaks protrude above the limits of the atmosphere, then the path of the rocket would be circular and eternal; like the moon, it would never fall to Earth. Apparently this too is impossible.

On the basis of what we have said the required angular velocity is computed approximately as 8 km/sec or 7,904 m/sec.

If we make use of Earth's rotation and launch the rocket at the equator in the direction of motion of the equatorial planes on Earth's sphere, then the necessary velocity will be decreased by 465 m/sec (such is the small velocity of rotation of Earth's points), i.e., it would be equal to 7441 m/sec. We can see that this is slightly more advantageous. The required relative quantity of explosives would be expressed by the number 3 to 4 (if the weight of the rocket is taken to be equal to 1).

The work done during movement along the circle is exactly half of the minimum work required for infinite escape from the planet.

When the velocity of the rocket is further increased, we obtain an ellipse which gradually extends beyond the limits of the atmosphere. A further increase in the velocity will elongate the ellipse more and more until it is transformed into a parabola; in this case the work and the velocity necessary for the projectile to combat the force of gravity, will be the same as for the case of permanent escape in the direction of the planet's radius (for Earth: 11,170 m/sec).

When the velocity of the rocket is further increased, the path becomes a hyperbola. In all these cases the rocket loses a great deal of velocity due to resistance of the atmosphere; therefore this path, which is tangential to Earth, is also not practical.

We have seen that the most advantageous path for the rocket is one inclined by 20° to 30° with respect to the horizon. In this case the losses due to gravity and the resistance of the atmosphere are only 7 percent of that energy which the rocket attains in space free of air and of gravity. The path of the rocket in this case is the same, i.e., it is one of the second order curves (ellipse, parabola and hyperbola); however, the curve is no longer tangent to the surface of Earth's sphere. If the quantity of explosives is insufficient or very small, then after tracing an ellipse and moving a short distance, the rocket returns to Earth. In this case it becomes necessary to explode a new quantity of materials in order to stop slowly and not perish. The total amount of /75
explosives necessary to ascend and return safely from a short distance is twice as large as required for only the ascent; for large altitudes it is three times greater and for even greater altitudes it is four times greater, etc.[1]

If we wanted to leave the rocket permanently in air-free space and make it a constant satellite of Earth, then at its most remote point from Earth (apogee) we must again explode a certain quantity of fuel to increase the velocity of the projectile. When this point is not too far

[1]See equation (66) "A Rocket into Cosmic Space." - Editor's Note.

from the surface of Earth, the necessary rocket velocity is close to 8 km/sec, and the quantity of the entire supply of explosives would be only 3-4 times greater than the weight of the remaining mass of the projectile. As a matter of fact, no matter how far away our observation station is, even if it were a million versts from the center of Earth, the quantity of explosives will be less than that necessary for permanent escape from the planet along a straight line or along a parabola. It would be expressed by a number less than 8.

With a new explosion a circular orbit may be transformed into an elliptic orbit and the latter, as we have described, may again be transformed into a circular orbit with a greater radius. Thus we can arbitrarily change the magnitude of the radius of our circular motion, i.e., we may move further away or closer to Earth's sphere at will.

If, after we have achieved circular motion, we produce a very weak explosion but one which is constant and which is in the direction of motion, the rocket, during the entire period of explosion, will move along a spiral orbit whose equation depends on the manner in which the explosion takes place.

The subsequent trajectory of the rocket, after explosion has ceased, will be some second order curve, e.g., a circle, which depends entirely on us. In the case of an explosion which retards the motion of the projectile, the spiral curves inside the initial circular orbit, and the rocket approaches Earth.

For motion along the spiral which is almost perpendicular to the direction of the forces of gravity, almost the same percentage (up to 65 percent) of the energy of the explosives is utilized as in the medium without gravity; the same thing takes place during the process of transforming the elliptical orbit into a circular orbit.

During the inclined ascent of the rocket to its elliptical path, the moon will produce a greater effect than when there is a more extended orbit, which in turn depends on the relative quantity of expended explosives and the relative positions of the moon and the rocket. It may turn out, or we may program the movement of the rocket in such a manner, that under the influence of lunar attraction the rocket will leave its orbit and fall to the moon.

The velocity of fall will be not less than 2,373 m/sec, i.e., twice /76
as great as the velocity of a cannon shell. However, this velocity is less than the one achieved when the projectile falls to Earth. The energy of fall on the latter is 22 times greater than during the fall to the moon.

If we take into account the velocity and rotation of the moon and also the movement of the rocket, we may compute the insignificant quantity of explosives required for a safe landing on the surface of the moon. I can report that the total quantity of explosives for a safe voyage to the moon is expressed by a figure not greater than 8. At a sufficiently insignificant distance from the moon, the velocity of the rocket must be continuously decreased by means of explosions. Everything must be computed and controlled in such a way that at the instant the surface of the lunar soil is touched, this relative velocity becomes equal to zero. The problem is, of course, rather delicate but quite feasible. An error in this calculation may be corrected by a new explosion provided we have a sufficient reserve of explosives.

In the case of a miss, i.e., if the rocket flies close to the moon but does not touch its surface, the rocket will not become the satellite of the moon but, having approached it, will leave it again and rotate around Earth along a rather complex curve which sometimes passes close to Earth and sometimes close to the moon. The possibility of falling onto one or the other remains. At the instant of the closest approach to the moon, it is possible to set off another explosion with the idea of retarding the motion of the rocket; thus it becomes an eternal satellite of the moon and a great-grandson of the sun. From this circular orbit it is also possible to descend to the moon or move away from it by various methods.

From the description of the flight we can see that the rocket may become an eternal satellite of Earth moving around it like the moon. The distance of this artificial satellite, the small brother of the moon, from Earth's surface may be arbitrarily small or great; its motion is eternal because the resistance of ether has not been observed even for small bodies of low density, such as the aerolites which apparently enter into the composition of comets. If small bodies were, indeed, to experience resistance from ether, then how could the rings of Saturn exist millions of years? According to the conclusions of astronomers these rings consist of small individual solid bodies which move extremely rapidly around Saturn.

The movement around Earth of a series of rockets fully instrumented to house intelligent beings may serve as a base for further propagation of mankind. By settling around Earth in a multitude of rings similar to the rings of Saturn, people will increase the supply of solar energy by a factor of 100-1,000, compared to what they have on the surface of Earth. However, this may not satisfy man either, and, having conquered /77 these bases, he may extend his hands for the remaining solar energy which is two billion times greater than that received by Earth. In this case eternal motion around the Earth must be replaced by similar motion around the sun. For this purpose it will be necessary to move further away from Earth and become an independent planet--a satellite of the sun and a brother of Earth. By means of explosions it will be necessary to impart to the rocket a velocity in the direction of the Earth's orbit around the sun, when the rocket moves with the maximum velocity with respect to the sun. The amount of energy required for this purpose depends on the magnitude of the distance between the rocket and Earth: the greater the distance, the less the work. However, the total energy necessary for circular motion around Earth and then for almost complete escape from Earth does not exceed the energy required for escape from Earth, if we assume that the sun and other heavenly bodies are absent, i.e., a seven-fold or eight-fold quantity of explosives (compared with the remaining mass of the projectile).

When an even larger quantity of energy is consumed, the circle becomes a more or less extended ellipse, whose perigee (minimum distance from the sun) is approximately the same distance from the sun as the Earth.

In the first case, when an average amount of energy is consumed, the rocket will travel under the influence of a new shock at a much greater velocity than necessary for circular motion around the Earth and even around the sun; then, due to Earth's gravity (we neglect the effect of the moon), this velocity will be decreased more and more and finally, at a considerable distance from Earth (by approximately 1,000 Earth's diameters), it will become equal to the velocity of the latter around the sun. The Earth and the rocket will follow the same circle at the same velocity and therefore may not see each other for hundreds of years. However, it is improbable that this equilibrium will last for centuries. To maintain a decent distance, it will be necessary to accelerate or to slow down the rocket, so that the Earth and other planets do not disturb this distance. If this is not done, the rocket may fall to Earth.

In the second case, when a great deal of energy is used up and when the path of the rocket is elliptical, it is also possible to collide with the Earth; however, the escape of the rocket may be used to get to some "upper" planet: to Mars or its satellites, to Venus or to some other of the 500 small planets (planetoids, asteroids).

I am not speaking of reaching the heaviest planets, such as Jupiter, Saturn, and others because it will require a tremendous amount of explosives to make a safe landing on these planets, and at this time we should not even dream about it. However, it would be easier to become their satellites, particularly remote ones; it is easier to reach the ring of Saturn and to join it. The quantity of energy required to reach some planetary orbit (but not to descend to the planet) depends on its distance from Earth's orbit: the greater this distance, obviously the greater will be the energy required. However, no matter how large this distance is, the required work will be less than that necessary to /78 escape completely from the solar system and to travel among the stars. This work too is not as great as it may appear at first glance. Indeed, would it be possible to overcome the powerful attraction of the sun whose mass is 324,000 greater than the mass of Earth? Calculations show that if the rocket is launched during its most rapid movement around the sun, or directly from the surface of Earth at an opportune time and in an optimum direction, the velocity with respect to Earth necessary for total escape from it and from the sun does not exceed 16.3 km/sec, which corresponds to an expenditure of explosives corresponding to the relative mass of the rocket equal to 20. Under the most unfavorable rocket launching this velocity reaches a value of 76.3 km/sec, and the quantity of explosives relative to the remaining mass of the rocket must be extremely high. The escape velocity from the sun would be the same regardless of how we launch the rocket. In favorable case the energy is 25 times less because we derive it from the motion of Earth, which, in this case, will be retarded by an insignificant amount.

The circular path of the rocket around the sun may be made elliptical by increasing or decreasing the velocity of the projectile by explosions.

When the velocity is decreased, the perigee of the rocket will be less than the distance from Earth to the sun, and the rocket will then be capable of reaching one of the lower planets: Venus or Mercury. Their masses are not very high and a descent to them will not require the impossible quantity of explosives necessary to descend to Jupiter, Saturn or Neptune. The energy required to descend to Mercury, as well as to Mars, is 5 times less than that required to descend to our planet; at the same time the energy required to descend to Venus is 0.82 of the energy required to descend to Earth. As far as the asteroids and the large number of planetary satellites (moons) are concerned, the mass of explosives required to make a safe descent to their surface is quite insignificant.

Theoretically it is possible to approach the sun closer, or even to fall into it, with a complete loss of velocity relative to the sun. If the rocket is already rotating around the sun like the Earth and at the same distance away, the stoppage of its motion requires a relative (reverse) velocity of approximately 30 km/sec. The quantity of required explosives will be expressed by the figure 200. The descent to the sun will last for a period of 64-1/4 days, i.e., approximately 2 months. /79

Thus we can see that in order to descend to the fiery ocean of the sun, we shall require 10 times more explosives than is necessary for escape from our sun and approach to a new one.

As in the case of motion on Earth, by using interrupted and extremely small explosions we may cause the rocket to travel along any trajectory. We may cause it to travel along any path with respect to the sun, e.g., along a spiral, and to reach the desired planet, to approach or move away from the sun, to drop to the sun or to leave it completely, thereby becoming a comet which travels for many thousands of years in darkness among stars, until one of these is reached and becomes a new sun for the travelers or their descendants.

We note that in all cases when we wish to decrease the velocity of the rocket, the explosives must be ejected in the direction of motion of Earth; however, the motion of the rocket with respect to the sun will remain the same, i.e., in the direction of motion of our planet.

The program for the future exploitation of solar energy will apparently be carried out as follows:

Mankind will send his missiles to one of the asteroids and make it a base for preliminary work. He will make use of the material of the small planetoid and will decompose it or take it apart to the center to construct the first ring traveling around the sun. This ring, filled with intelligent beings, will consist of mobile sections similar to the ring of Saturn.

Having broken down and utilized these and other tiny asteroids, the intelligent beings will construct a series of other rings in space free of asteroids, somewhere between the orbits of Mars and Jupiter.

For various technical and other requirements other rings will be placed close to the sun between the orbits of the "lower" planets.

When solar energy is expended, the intelligent beings will leave it and move to another sun which has only recently become lighted and which is in its prime. Maybe this will take place even sooner: some of the beings will want to move to another world or to populate the deserts.

It is not necessary to have anything to do with the surface of the sun, even when it has become a cold crust; nor is it necessary to be on the heavy planets except perhaps for purposes of investigation. It is difficult to reach them; to live on them means to chain oneself to gravity which sometimes is stronger than the chains on earth, to subject oneself to a multitude of obstacles, to attach oneself to meaningless space, to live a miserable life in the womb of matter. A planet is a ship of intelligence, but we cannot live in a ship forever.

Subsistence During Flight

/80

Nourishment and Respiration

First of all we need oxygen for respiration; we take a large quantity of it for explosions; we may take even more, so that there will be enough for respiration for a given period of time.

It is doubtful that pure oxygen is suitable for man even in a rarefied state. Indeed, in this case its pressure on the body will be insufficient and bleeding may take place for purely mechanical reasons.

It would probably be necessary to use a mixture of oxygen with some other gas which is safe for breathing, e.g., nitrogen, but not carbon dioxide which impedes removal of carbon dioxide from the lungs and skin of the animal and which poisons the animal. It is quite good to breathe a mixture consisting of 20 percent oxygen and 80 percent nitrogen under a pressure of 1,000 to 500 mm Hg. Nitrogen is preferred to hydrogen because it does not present the danger of explosion.

Obviously the cabin for the passengers must be hermetically sealed and sufficiently strong to withstand gas pressure not exceeding 1 kg/cm^2 on the walls during ascent into the rarefied layers of the atmosphere and beyond its limits. The elongated fish-like or bird-like form of the rocket is desirable for penetrating the air, is suitable for preserving the gases, and is good for the strength of the rocket, which must withstand an acceleration equal to 10 times that of gravity. The metallic material prevents the loss of gas by diffusion.

However, it is not enough to have a mixture of nitrogen and oxygen. It is also necessary to add oxygen because part of it is converted to carbon dioxide, and to destroy or, more accurately, to separate the products of respiration: carbon dioxide, ammonia gas, excess humidity, etc. There are many substances which absorb carbon dioxide, e.g., water vapor, ammonia gas, etc. Therefore, a supply of these substances will also be required. Of course, if the trip is carried out for only a few minutes or hours, then such supplies together with breakfast will not overload the rocket. However, the situation is different if we have to travel for weeks or years or if we do not return at all, in which case this approach must be rejected.

In order to exist for an indefinite period of time without the atmosphere of the planet, we may utilize the energy of solar rays. Our artificial atmosphere may be replenished in exactly the same way as Earth's atmosphere is purified by plants with the aid of the sun. On Earth the plants absorb impurities by means of their leaves and roots and in return produce food. In the same way we can utilize plants taking them with us on our travels. All the beings on earth utilize the same quantity of gases, liquids and solid bodies, and this quantity does not ever increase or decrease (if we do not take into the account the fall of aerolites). In the same way we can live indefinitely with the aid of materials which we take with us. On Earth there is an endless cycle of mechanical and chemical substances. This cycle can also take place in our small world. From the scientific point of view there is no doubting the possibility of what we have stated. Now let us see how it can be realized in the future--perhaps in a very distant future. /81

According to Langley, 1 m^2 of a surface exposed to solar rays receives a quantity of solar energy equal to 30 cal per min. This means that 1 kg of water spilled over 1 m^2 of the surface and illuminated by perpendicular solar rays is heated by 30° C per min, if we neglect heat losses due to radiation, heat transfer, etc.

By transforming this thermal energy into mechanical energy we obtain 12,720 kg. Thus, in one 24 hr period at the distance of the Earth from the sun we obtain 18,316,800 kg, or 43,200 cal. (In one second we obtain 0.5 cal or 212 kg, i.e., a continuous work of almost 3 hp.)

According to Timiryazev, during physiological experiments with plants approximately 5 percent of solar energy is utilized, which corresponds to 2,160 cal per day stored in the roots, leaves and fruits of plants.

On the other hand, according to Lebon, 1 kg of flour contains almost twice as much energy, so that the daily supply of potential energy of a plant corresponds to 0.5 kg of flour, or almost 1/2 kg of bread.

This same gift of the sun utilized over one square meter of the surface continuously illuminated by solar rays, may be expressed by any of the following quantities: 4 kg of carrots, 5 kg of cabbage, 2/3 kg of sugar, and more than 0.5 kg of rice.

In the experiments which we mentioned, 5 percent accumulation takes place in all parts of the plants. The fruits will, of course, contain a much smaller percentage. These experiments were conducted under the best possible conditions, but our artificial atmosphere and feeding of the plants may take place under conditions even more favorable. According to Timiryazev, a field, in the optimum case, will use 5 times less, i.e., approximately 1 percent of the solar energy. From this we can see that artificial conditions turn out to be even 5 times better.

Let us turn directly to practical results. One hectare (10,000 m^2) yields up to 25,000 poods of bananas each year, which corresponds to 0.11 kg per day per 1 m^2 of cultivated area (1 pood = 36.11 lb).

However, Earth has clouds and is covered with a thick layer of atmosphere and water vapor which absorb much of the energy; Earth has a period of night and the solar rays are inclined; the quantity of carbon dioxide in the air is also unfavorable as shown experimentally (according to Timiryazev the optimum amount is 8 percent whereas Earth contains less than 1/10 of 1 percent). If we take into account what we have said, we must increase the solar gifts by at least a factor of 10 and assume that the productivity of 1 m^2 in our artificial vegetable garden will be not less than 1.1 kg of bananas per day. According to Humbolt, the bread tree is almost as productive as the banana tree. /82

It follows from what we have said above that 1 m^2 of greenhouse directed toward the solar light is sufficient to feed 1 man.[1]

However, who prevents us from taking a greenhouse with a large surface area with us in a packaged form, i.e., in a small form! When the orbit around Earth or the sun is established, we collect and extend from the rocket hermetically sealed, cylindrical boxes with various plants and a suitable soil. The solar rays will penetrate the transparent cover of the greenhouse and will quickly set our splendid table for us. They will give us oxygen and in the process purify the air and the soil of animal excretions. Since neither objects nor people will experience gravity, the strength of the vessels containing plants need only be sufficient to combat the elasticity of contained gases. Of these the principal ones are carbon dioxide and oxygen. In Earth's atmosphere carbon dioxide constitutes not more than 1/2,000 of its composition. Nitrogen and other gases also play a role in the feeding of plants, but their density (like the density of oxygen of which they use 20 times less than, according to Timiryazev) of carbon dioxide may be quite small without any ill effects on the plants.

Thus the atmosphere of our greenhouses may be so rarefied that the gas pressure on the walls will be 1,000 times less than the air pressure at sea level.[2]

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[1] All of these reasonings of Tsiolkovskiy were necessary to prove the possibility of a closed and autonomous life cycle in cosmic space. The conditional value of his calculations is justified by the fact that the problems were not investigated sufficiently. - Editor's Note.

[2] In the margin of his book opposite this statement Tsiolkovskiy wrote "what about water vapor?" - Editor's Note.

Thus, we can see that we shall not have to combat gravity or the elasticity of gases, so that for every passenger, if necessary, we may take hundreds of square meters of these narrow glass boxes with vegetables and fruits growing inside them.

It is entirely possible on Earth to develop and test methods which provide for respiration and nutrition of man in isolated space.

It would be possible to determine the minimum square surface illuminated by solar rays and sufficient for man for respiration and nutrition; it is possible to select and test plants suitable for this purpose. It is true that conditions on Earth are quite different from those in ether away from the planet; however, the latter still can be made to approach those of Earth. Thus, in the medium free of gravity it /84
is quite easy to produce day and night; for this purpose it is only necessary to give the greenhouse a slow rotating motion. Then light will alternate with darkness at any arbitrary rate. Due to inertia the motion will last indefinitely. I believe that the conditions there are even more favorable than they are on Earth. Indeed Earth plants mostly suffer and even die due to unfavorable temperature changes during the night or in winter; they also suffer from bacteria, parasitic fungus, worms, insects, rodents, and birds, and from lack of moisture and soil depletion. In ether space these enemies are absent, because everything taken from the soil is returned to it. The temperature fluctuations are under our control as well as the duration of night; there will be no time of the year, if the motion of the rocket is circular; there will be no detrimental bacteria or insects when the greenhouse's compartments are small, because those can easily be destroyed by suitable pesticides, by raising the temperature or directly by solar light which kills bacteria and other harmful germs. Moisture will not escape due to the hermetically sealed space.

On Earth it would be quite difficult to construct experimental greenhouses, particularly such as are well insulated from external air and with the favorable rarefied medium. It would be necessary to have very strong material and massive construction to resist the external atmospheric pressure. In experimental greenhouses we must be satisfied at first with having the same pressure inside and outside. This corresponds to the most favorable mixture of gases for the plants. The sum of the internal pressures will be equal to 1 atm, whereas in ether space we will be able to expand the gaseous mixture to a more favorable degree. During experiments on Earth, the rays of light pass not only through the glass, but also through a heavy layer of atmosphere filled with water vapor, fog, and clouds, which makes access of virgin solar energy to the plants very difficult. We are virtually unfamiliar with the true energy of solar light which has never touched the air. It may be entirely unusual in its chemical properties.

ее можно регулировать при жилищах удлиненных вдоль лучей солнца: чем он длиннее, тем температура будет ниже.

54 Почва сбивается от вращения дальше от оси так, что лучи скользят вдоль ее поверхности и засаженных на ней растений. На дне же шара почва не удержится, растений там не будет и сила солнца будет пропадать даром. Однако при длинных конусах, наклон поверхности и почвы будет не велик, она останется на месте и растения будут освещены косыми лучами до самой оси. Достигнем и умеренной температуры и использования солнечных лучей

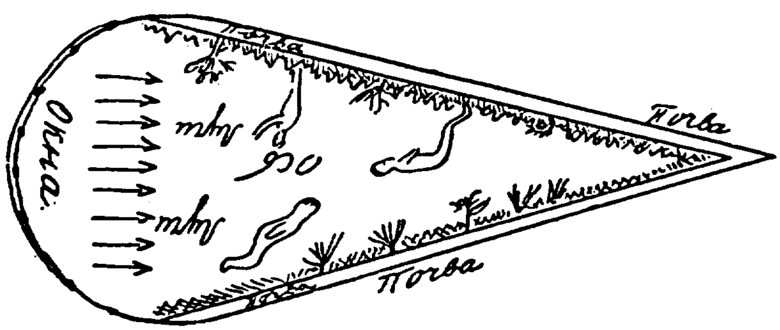


Figure 2. Greenhouse. This drawing is taken from Tsiolkovskiy's manuscript "Album of Cosmic Travels" (see introductory article). The inscriptions on the drawing are made in Tsiolkovskiy's handwriting. - Editor's Note.

Safety from Increased Gravity

At the very beginning of the flight when the explosives are still producing noise, the relative gravity in the projectile increases several times. Let us assume that it increases by a factor of 10.

The question may be asked as to whether man can withstand this increased gravity for several minutes without ill effects. This problem may also be solved on Earth, and optimum conditions can be developed /85 under which this gravity or even greater gravity can be endured by man without ill effects. Sometime ago I carried out experiments with various animals, subjecting them to increased gravity on special centrifugal machines. I was unable to kill any creature--of course, this was not my purpose; however, I felt that it could happen. I remember that I increased the weight of a cockroach, removed from the kitchen, by a factor of 300, and the weight of a chicken by a factor of 10; I did not notice at the time that the experiment had any harmful effects on them.

In preliminary experiments with man, the apparent gravity may be increased most simply by means of a centrifugal machine with a vertical axis of rotation and with as large a radius as possible, i.e., with the largest possible dimensions in the horizontal direction. The greater the distance between the axis and the experimental chamber with man, the easier it will be, because there will be less chance of vertigo.

Rotation harms an organism, even when the centrifugal force is small or when the absolute velocity is small with high angular velocity, i.e., when the radius of rotation is small. Everyone has experienced this insignificant harm when as a child he spun around somewhere in the garden or on the lawn.

As a matter of fact, rotation and the resulting disorders do not take place when gravity is increased by the rocket moving along the rectilinear path. The fact that sufficiently slow rotation does not produce painful sensations or is even noticeable, can be seen from the phenomenon of the continuous rotation of the Earth, to which we are subjected from the time of our birth. The same conclusion can be made by observing the amusement of children and adults on merry-go-rounds. Once I saw two young girls on the merry-go-round who day and night rode on wooden horses to attract the public.

Any experiment on the effect of increased gravity need last only 2 to 10 min, i.e., the time during which explosion in the rocket takes place.

I shall not derive the well-known equations from which we can make the following conclusions. It is possible to obtain by experimental means any desired artificial gravity; the more we wish to reduce rotation, the greater must be the velocity of the chamber to obtain the same gravity. For a radius of 100 m and the velocity of 100 m/sec and with a complete revolution every 6.3 sec, we get a force of gravity 10 times greater than normal; if the radius is 10 times smaller than for the same artificial gravity, the number of revolutions or the angular velocity must be 3 times greater, and the circumferential absolute velocity will be less by the same factor.

By carrying out experiments with centrifugal machines or by rapid circular motion of a car along an inclined track, we may determine the maximum safe value of gravity which may be endured by a subject during a certain period of time. If, contrary to expectations, these experiments were to show that even a small, for example, double gravity is the limiting safe gravity, even then we should not consider our case lost: first, because during its inclined motion the rocket may utilize the work of explosives more advantageously even with this small gravity inside it, and, in the second place, because by placing a man in water and by conducting experiments on the effect of gravity on the subject in this state, we shall probably obtain more encouraging results. /86

Let us explain what happens. Let us take a very strong open or closed vessel with a liquid and immerse in it some thin figure made of very fragile material with density equal to the density of the liquid in the vessel. This figure by itself, i.e., outside the liquid, is very fragile and delicate, so that it shatters when it is dropped and is very difficult to hold in the hand without crumbling or breaking. Now let us take it with the vessel where it is under equilibrium in the liquid, such that it remains stationary at the point or in the position in which we wish it to be (like the oil sphere in the wine during Plato's experiment).

If experiments on the centrifugal machine are carried out, not by using a human being, but by using this fragile, thin figure which outside the liquid barely sustains its own weight, the results will be most brilliant: the figure will remain intact and even motionless, no matter how much the relative gravity is increased.

Furthermore, without using a centrifugal machine, we may strike the vessel on the table or hit it with a hammer; as long as the latter is not broken and the liquid has not run out, the figure will remain unharmed. However, let us assume that the liquid is removed; then the entire effect disappears: even strong objects break during sufficiently rapid rotation or when the blows are sufficiently hard. The same successful experiments can be carried out using small fish in water. From this we can see that the fluid surrounding a body with the same density as the body apparently eliminates the destructive consequences of gravity, no matter how high it is. Thus, if we are to take a liquid with density equal to the average density of man and place the man inside it, then our experiments on the effects of increased gravity should give results which are at least partially good. I say partially, because everything we have said pertains to bodies all of whose parts have the same density. The various organs of animals do not have this property; particularly the density of bones and the air cavities of animals are different in density from other organs. The bones of a body submerged in the liquid will exert a downward force in the direction of relative gravities; the lighter parts will tend to move upwards, and stresses will develop between various cells which may end with their rupture and even death of an organism, if gravity is increased by a sufficient amount. /87

The greatest gravity which can be endured by a human being without detrimental effects is, therefore, not unlimited even when submerged in a liquid. I think this limit is not less than 10, and that it can be determined for each subject only by means of experiment. It is best that, during the time of the experiment, the human being place his body horizontally in a case of approximately the same shape and volume as himself; then filling the empty spaces with a liquid will require only a small quantity of this liquid (this is important from the economic standpoint during actual rocket travel). Mouth, nose, and ears must be covered very thoroughly with a hood, with a tube for free breathing.

There is no doubt that the human being will be able to endure great gravity without being placed in a liquid. Indeed, when a body falls from a height, it hits the soil; the latter, due to its elasticity, imparts an accelerated motion in the opposite direction to the man to cancel the velocity which the man achieved during his fall. Here the elasticity of the animal's body also plays a role, particularly that of the cartilages between the bones. In a skillful jump the force of the muscles of bent legs also has an effect. In this case an apparent rather high gravity must be developed, because the time of impact is short, while the reverse accelerated motion at this instant of time is rather high.

In these cases nature itself does not ignore this property of liquid to prevent the destructive action of relative gravity, and therefore thoughtfully immerses all gentle organs of an animal in special fluids contained within strong natural vessels. The brain is like this and floats in a liquid filling the skull; such also is the fetus of a mammal, which is surrounded by a liquid until it is ready to be born. Even industry uses this principle for preserving fragile fruits by replacing the liquid with its rough likeness--a loose material: grapes are covered with wood or cork shavings.

Combatting the Absence of Gravity

Now the explosion in the rocket has ended and with it the tremendous gravity. We emerge safely from our case, remove the remnants of the liquid from our body and put on our clothes. As if rewarded for the increased gravity which we have just survived, we now become completely free of it. /88

The question may be asked as to whether this absence of gravity would not have a fatal effect on us. Must we here take some preventive means?

During the time of fall or of a simple jump on the surface of our planet when our feet have not yet touched the soil, we also remain free of gravity with respect to our body, our clothing, and objects on our person. However, this phenomenon lasts only a fraction of a second. During this period of time the various parts of our body do not press on each other, the coat does not press on the shoulders, the watch does not weigh down the pocket, and the glasses on our nose do not tend to form a horizontal line. When we bathe on the surface of Earth the weight of our body is also almost completely negated by the opposite action of water. Such an absence of weight may prevail for an indefinite period of time, if the water is sufficiently warm. We can see that it is hardly necessary to carry out experiments to show that the medium free of gravity is harmless. Possibly, for obese people who tend towards apoplexy and the influx of blood to the brain, such a medium may be responsible for premature death, just as is untimely horizontal position or swimming. All other mortals, we may assume, will quickly become accustomed to the new order of things. For the majority of sick and weak persons this medium will be outright beneficial.

Horizontal position also increases blood pressure many times, making this state approach lack of gravity. We cannot assume that the position of lying down is fatal. For weak and sick people it is beneficial, while healthy people must curtail their nourishment so that it does not become unhealthy for them to lie down.[1]

If it were to turn out that people cannot live without gravity, then it may be easily produced artificially in a medium where it does not exist. In this case the abode of the human being, even if it be the rocket, must simply be rotated; then, due to the centrifugal force, an apparent gravity will be formed of any desired magnitude, depending on the size of the abode and the velocity of its rotation. This

[1]The last three phrases were inserted by Tsiolkovskiy at a later date. - Editor's Note.

transformation of the medium will not cost us anything, since the rotation of the body in air-free space, and particularly space free of gravity, will persist indefinitely once it is started. This gravity is particularly useful because it may be arbitrarily small or large, may be eliminated at any time, or be reactivated. However, this gravity, like natural gravity, will require greater strength in the construction of the abode and other objects, since it will tend to destroy them; in addition, rapid curvilinear motion has a bad effect on the organism.

The action of increased gravity on plants was investigated a long time ago, but nothing unusual was noted. However, when gravitational direction is changed, the direction of growth is also changed: specifically, the trunk is pointed to the side directly opposite that of artificial gravity. It would be interesting to know which way it would grow if gravity were removed completely; in all probability the direction of growth would be a matter of chance or would depend on the action of light. /89

The Future of Reactive Devices

In the first published work on reactive devices we dreamed of future, as yet undiscovered, more elementary substances whose combination would be accompanied by a tremendous release of energy, compared with that of known simple bodies, e.g., of hydrogen and oxygen. In this case the volatile product of combination would have to achieve a very high velocity V_1 as it leaves the nozzle of the reactive tube.

From equation (35)[1] we see that as V_1 increases, V_2, i.e., the velocity of the rocket, also increases proportionately when we have the same relative consumption of explosives (M_2/M_1).

It is believed that radium, which breaks down continuously into more elementary materials, gives off particles of different gases which move with astonishingly, unimaginable velocity close to the velocity of light. Atoms of helium, which are emitted, move with the velocity of 30,000-100,000 km/sec. The atoms of helium are four times heavier than the atoms of hydrogen. Other bodies emitted by radium are 1,000 times lighter than hydrogen, but move with the velocity of 150,000-250,000 km/sec. The total mass of these bodies (electrons) is substantially less than the mass of helium atoms. These velocities are 6,000-50,000

[1]See Section 35 in "A Rocket into Cosmic Space." - Editor's Note.

times greater than the velocity of gases flowing out of a nozzle of our reactive tube. Therefore, if it were possible to accelerate the breakdown of radium or other radioactive materials, and apparently all bodies are radioactive, then by utilizing this breakdown we would obtain (see equation (35) and all other conditions being equal) a velocity for the reactive device with which we could reach the closest sun (star) in 10-40 years.

Then, for a rocket weighing one ton, we would only require a pinch of radium, equation (16), to break its ties with the solar system.

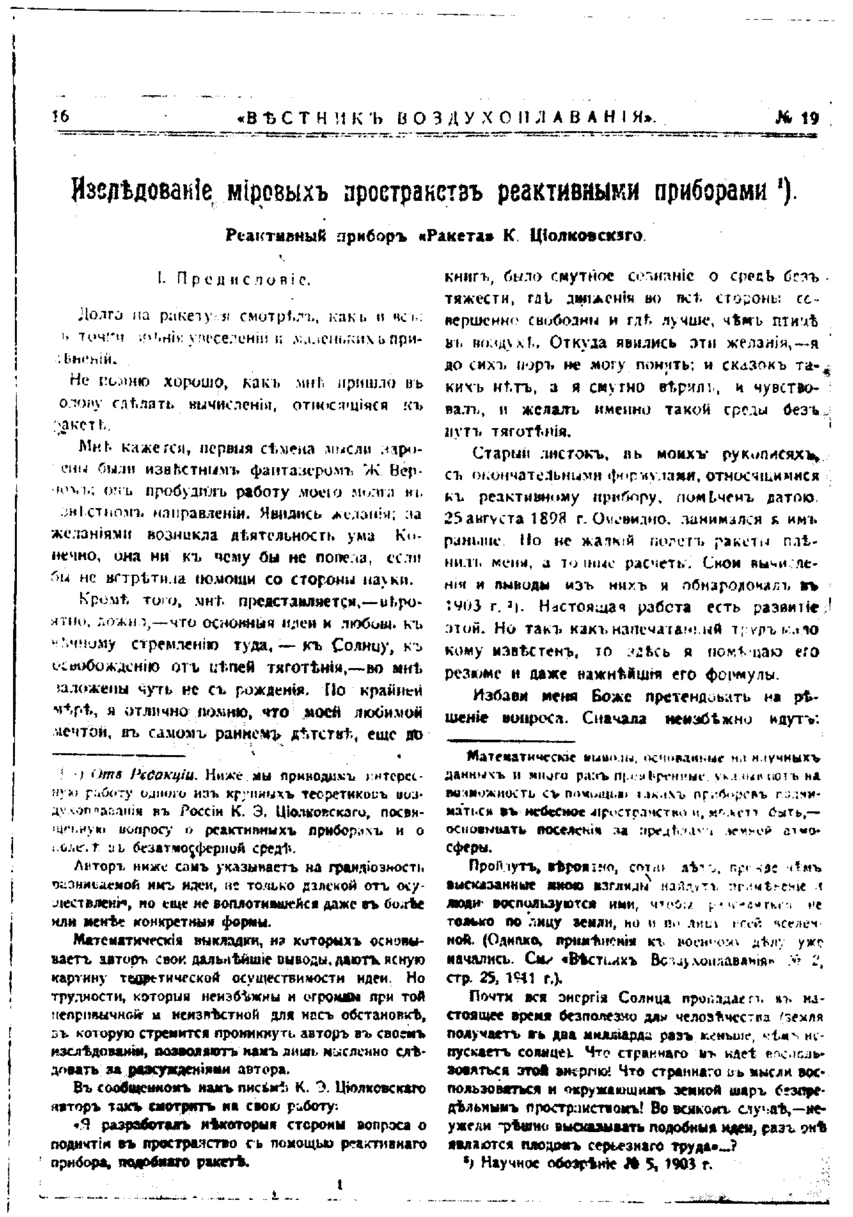
It is possible that future discoveries in science will show that this is not so, but it is good that even now we can dream about it.

It is possible that in time we may use electricity to produce a huge velocity for the particles ejected from the rocket device. It is known at the present that the cathode rays in Crookes' tube, just like the rays of radium, are accompanied by a flux of electrons whose individual mass is 4,000 times less than the mass of the helium atom, while the velocities obtained are 30,000-100,000 km/sec, i.e., 6,000 to 20,000 times greater than the velocity of the ordinary products of combustion flying from our reactive tube. /90

What Is Impossible Today Will Become Possible Tomorrow

There was a time, and not too far back, when the idea of the possibility of establishing the composition of heavenly bodies was considered foolhardy even by famous scientists and thinkers. Now this time has passed. The idea of the possibility of a much closer direct investigation of the universe at the present time will, I believe, appear even more absurd. To place one's feet on the soil of asteroids, to lift a stone from the moon with your hand, to construct moving stations in ether space, to organize inhabitated rings around Earth, moon and sun, to observe Mars at the distance of several tens of miles, to descend to its satellites or even to its own surface--what could be more insane! However, only at such a time when reactive devices are applied, will a new great era begin in astronomy: the era of more intensive study of the heavens. Does not the frightening huge force of gravity scare us more than it should!

A shell leaving a cannon with the velocity of 2 km/sec does not appear to us surprising. Why should a missile flying at a velocity of 16 km/sec and escaping forever from the solar system into the universe, overcoming Earth's gravity, the gravity of the sun, and of the entire system--horrify us. Is there such a big abyss between numbers 2 and 16! One is greater than the other only by a factor of 8.



Изслѣдованіе міровыхъ пространствъ реактивными приборами [1]).

Реактивный приборъ «Ракета» К. Ціолковскаго.

I. Предисловіе.

Долго на ракету я смотрѣлъ, какъ и всѣ: съ точки зрѣнія увеселеній и маленькихъ примѣненій.

Не помню хорошо, какъ мнѣ пришло въ голову сдѣлать вычисленія, относящіяся къ ракетѣ.

Мнѣ кажется, первыя сѣмена мысли заронены были извѣстнымъ фантазеромъ Ж. Верномъ; онъ пробудилъ работу моего мозга въ извѣстномъ направленіи. Явились желанія; за желаніями возникла дѣятельность ума. Конечно, она ни къ чему бы не повела, если бы не встрѣтила помощи со стороны науки.

Кромѣ того, мнѣ представляется,—вѣроятно, ложно,—что основныя идеи и любовь къ вѣчному стремленію туда,—къ Солнцу, къ освобожденію отъ цѣпей тяготѣнія,—во мнѣ заложены чуть не съ рожденія. По крайней мѣрѣ, я отлично помню, что моей любимой мечтой, въ самомъ раннемъ дѣтствѣ, еще до книгъ, было смутное сознаніе о средѣ безъ тяжести, гдѣ движенія во всѣ стороны совершенно свободны и гдѣ лучше, чѣмъ птицѣ въ воздухѣ. Откуда явились эти желанія,—я до сихъ поръ не могу понять; и сказокъ такихъ нѣтъ, а я смутно вѣрилъ, и чувствовалъ, и желалъ именно такой среды безъ путъ тяготѣнія.

Старый листокъ, въ моихъ рукописяхъ, съ окончательными формулами, относящимися къ реактивному прибору, помѣченъ датою 25 августа 1898 г. Очевидно, занимался я имъ раньше. Но не жалкій полетъ ракеты плѣнилъ меня, а точные расчеты. Свои вычисленія и выводы изъ нихъ я обнародовалъ въ 1903 г. [2]). Настоящая работа есть развитіе этой. Но такъ какъ напечатанный трудъ мало кому извѣстенъ, то здѣсь я помѣщаю его резюме и даже важнѣйшія его формулы.

Избави меня Боже претендовать на рѣшеніе вопроса. Сначала неизбѣжно идутъ:

Математическіе выводы, основанные на научныхъ данныхъ и много разъ провѣренные, указываютъ на возможность съ помощью такихъ приборовъ подниматься въ небесное пространство и, можетъ быть,—основывать поселенія за предѣлами земной атмосферы.

Пройдутъ, вѣроятно, сотни лѣтъ, прежде чѣмъ высказанные мною взгляды найдутъ примѣненіе и люди воспользуются ими, чтобы расселяться не только по лицу земли, но и по лицу всей вселенной. (Однако, примѣненія къ военному дѣлу уже начались. См. «Вѣстникъ Воздухоплаванія» № 2, стр. 25, 1911 г.).

Почти вся энергія Солнца пропадаетъ въ настоящее время безполезно для человѣчества (земля получаетъ въ два милліарда разъ меньше, чѣмъ испускаетъ солнце). Что страннаго въ идеѣ воспользоваться этой энергіей! Что страннаго въ мысли воспользоваться и окружающимъ земной шаръ безпредѣльнымъ пространствомъ! Во всякомъ случаѣ,—неужели грѣшно высказывать подобныя идеи, разъ онѣ являются плодомъ серьезнаго труда»...?

[1]) Отъ Редакціи. Ниже мы приводимъ интересную работу одного изъ крупныхъ теоретиковъ воздухоплаванія въ Россіи К. Э. Ціолковскаго, посвященную вопросу о реактивныхъ приборахъ и о полетѣ въ безатмосферной средѣ.

Авторъ ниже самъ указываетъ на грандіозность развиваемой имъ идеи, не только далекой отъ осуществленія, но еще не воплотившейся даже въ болѣе или менѣе конкретныя формы.

Математическія выкладки, на которыхъ основываетъ авторъ свои дальнѣйшіе выводы, даютъ ясную картину теоретической осуществимости идеи. Но трудности, которыя неизбѣжны и огромны при той непривычной и неизвѣстной для насъ обстановкѣ, въ которую стремится проникнуть авторъ въ своемъ изслѣдованіи, позволяютъ намъ лишь мысленно слѣдовать за разсужденіями автора.

Въ сообщенномъ намъ письмѣ К. Э. Ціолковскаго авторъ такъ смотритъ на свою работу:

«Я разработалъ нѣкоторыя стороны вопроса о поднятіи въ пространство съ помощью реактивнаго прибора, подобнаго ракетѣ.

[2]) Научное обозрѣніе № 5, 1903 г.

Figure 3. Page from the journal "Vestnik vozdukhoplavaniya" No. 19, 1911, with a preface to his article by K. E. Tsiolkovskiy.

If a unit velocity is possible, why is a velocity equal to 8 times this unit impossible. Does not everything progress and move ahead with great speed which amazes our mind?

It was not so long ago that a 10 mile-per hour movement over the Earth appeared incredible to our grandmothers; now the automobile makes 100-200 versts per hour, i.e., 20 times faster than during Newton's time. Not so long ago it was strange to utilize any force other than that of human muscle, wind, and water! If we speak on the subject, we may never end.[1]

[1]We omit several general remarks made by Tsiolkovskiy on the question of adapting living organisms to ether space. - Editor's Note.

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К. Ціолковскій.

Изслѣдованіе

міровыхъ пространствъ реактивными приборами

(дополненіе къ I и II части труда того-же названія)

Цѣна 15 коп.

Калуга, Коровинская, д. № 61, К. Э. Ціолковскому.

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Калуга.
Типографія С. А. [illegible]
1914.

Title page to 1914 edition of "The Investigation of Universal Space by Reactive Devices."

THE INVESTIGATION OF UNIVERSAL SPACE BY REACTIVE DEVICES /93

(Supplement, 1914)

In this supplement I would like to present a popular exposition of my ideas, to clarify them to some extent and to refute the viewpoint that the rocket is something far removed from us in time.

Below are some of the theorems which I have proven.

Theorem 1. Let us assume that the force of gravity does not decrease when the body moves away from the planet. Let us assume that this body has risen to a height equal to the radius of the planet; it will then perform work equal to that necessary for entirely escaping the force of gravity of the planet.

For Earth, e.g., and for 1 ton of material, this work is equal to 6,366,000 ton-meters. If the projectile, as described by Esno Peltri, operates for 24 minutes and weighs 1 ton, it is easy to see that for every second of time its engine must supply to the rocket work equivalent to 4,420 ton-meters or 58,800 horsepower, and not 400,000, as computed by Esno Peltri.[1]

In my device explosion takes place faster and lasts only for 110 seconds. Thus, in 1 second, the projectile weighing 1 ton must release 57,870 ton-meters, which constitutes 771,600 horsepower. Of course, everyone will say: is this possible? A projectile weighing only one ton releases almost one million horsepower!

The lightest engines at the present time release not more than 1,000 horsepower per ton of weight.

However, the fact is that we are not speaking of a conventional engine, but of devices which are similar to a cannon.

Let us imagine a cannon 10 m long, which fires a projectile weighing 1 ton with the velocity of 1 km/sec.

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[1] See article by K. E. Veygelin, Priroda i lyudi, No. 4, 1914. Obviously I am here correcting a typographical error and not Esno Peltri's error.

This is not too far from reality. What is the work performed by the explosive and imparted to the shell? It is easy to compute and show that it is approximately 50,000 ton-meters--and this is released during a small fraction of a second. The average velocity of the shell in the cannon is not less than 500 m/sec. Consequently, the projectile travels a distance of 10 m in 1/50 of a second. This means that the work performed by the cannon per second of time is equal to 2,500,000 ton-meters, or approximately 33,300,000 horsepower.

From this we can see that the useful work performed by the artillery piece is 566 times greater than the work performed by the rocket of Esno Peltri and 43 times greater than that performed by my reactive device. /94

Thus, qualitatively speaking, there is nothing in common between a reactive missile and an ordinary motor.

Theorem 2. In the medium without gravity the terminal velocity "of the rocket," when the direction of explosion is constant, does not depend on the force and order of explosion, but only on the quantity of explosives (with respect to the mass of the rocket), its quality and the construction of the explosive tube.

Theorem 3. If the mass of the explosives is equal to the mass of the rocket, then almost half of the work performed by the explosives is transmitted to the rocket.

This can be easily verified if we imagine two spheres of equal mass with a spring between them. When the spring expands, it divides the energy equally between the two spheres.

If, e.g., we have a shell with a tube and an equal mass of hydrogen which explodes from it at zero temperature, the latent energy of hydrogen will be divided by half, of which one part will be imparted to the shell. It is well known that the velocity of the molecules of hydrogen is approximately 2 km/sec. Therefore, the shell will achieve the velocity of approximately 1,410 m/sec. However, if we take into account the specific heat of hydrogen or the rotational motion of the two atoms of which a molecule is composed, the shell will obtain a velocity of approximately 2 km/sec.

After this, it should not be difficult to believe my calculations; they show that during the chemical combination of hydrogen and oxygen the velocity of the newly formed molecules of water ejected from the stationary tube is greater than 5 km/sec, and that the velocity imparted to the moving tube of the same mass is, therefore, greater than 3-1/2 km/sec. Indeed, if all of the heat of combustion were transmitted to the compound, i.e., the water vapor, its temperature would reach 10,000°C (if it did not expand). In this case the velocity of the water vapor particles will be approximately 6 times greater than at 0° (plus 273° absolute temperature).

The velocity of molecules of water vapor at 0° as we know, is greater than 1 km/sec; consequently, when a vapor is formed from oxygen and hydrogen, a velocity of 6 km/sec is developed due to chemical reaction.

Of course, I am making only a rough and illustrative verification of my previous computations.

When the mass of burning gas is equal to the mass of the rocket, its velocity of 3-1/2 km/sec is quite natural, and this number is very conservative.

Theorem 4. When the mass of the rocket plus the mass of explosives contained within it increase in geometric progression, the velocity of the rocket increases in arithmetic progression. /95

This law is expressed by two series of numbers:

Mass.	2	4	8	16	32	64	128
Velocity.	1	2	3	4	5	6	7.

Let us assume, for example, that the mass of the rocket and of the explosive constitutes 8 units.

I eject 4 units of explosives and obtain a velocity which we shall set equal to unity.

Then I eject 2 more units of explosives and obtain another unit of velocity; finally, I eject the remaining unit of mass of explosives and achieve one more unit of velocity; altogether we have 3 units of velocity.

It is clear from this theorem that the velocity is far from proportional to the mass of the explosives: it increases rather slowly, but without a limit.

There is an optimum ratio of the quantity of explosives for which the energy is utilized most efficiently. This number is close to 4.

However, the absolute velocity of the rocket increases as the supply of explosives becomes substantial. Below we show the relative supply of explosives and the corresponding velocity in kilometers per second:

The mass of explosives. . .	1	3	7	31	63	127	256
Velocities.	3-1/2	7	10-1/2	14	17-1/2	21	24-1/2

Theorem 5. In a medium with gravity, for example, on Earth, when the rocket rises vertically, part of the work performed by explosives disappears--more so when the pressure of the exploding gases approaches the weight of the rocket.

For example, if the rocket with all its contents weighs 1 ton and the pressure of the explosives on the missile is also 1 ton, then the efficiency is equal to 0, and the explosion does not produce any results since the rocket remains stationary in one place and no energy is transmitted to it.

This is why, in my projects, I propose to use pressure on the rocket which is ten times greater than the weight of the projectile with all its contents.

Esno Peltri took a rocket weight of 1 ton, of which 1/3 was for the explosives. If the explosive is radium and if it releases its energy a million times faster than it actually does, interplanetary flight is assured.

I have also dreamed of using radium. However, recently I have carried out a series of calculations which show that if the particles (alpha and beta) released by radium are directed in a parallel beam, its weight decreases by approximately one millionth of its natural weight.

After this, I gave up my thoughts on using radium. Discoveries of all types are possible, and our dreams may come true quite unexpectedly, but I wanted to stand on more practical ground. /96

Esno Peltri computes that 1/3 of 1 ton of burning gas is capable of transmitting only 1/130 of the required work to the rocket for escaping the force of gravity.

My calculations show that even a smaller part is transmitted, specifically 1/540. The reason for this is not only that the relative quantity of explosives (1/3) seems insignificant, but principally because the gas pressure on Peltri's projectile is assumed to be only 1/10 greater than the weight of the rocket. This pressure is 100 times smaller than the one I propose.

On the basis of the last theorem (5), we see that explosion in the medium with gravity may not produce any results if the pressure of the gases in the device is equal to its weight.

Indeed, the relative quantity of explosives (1/3) proposed by Esno Peltri is far from the optimum (4); therefore, according to my tables the projectile will achieve a velocity of not greater than 1-1/2 km/sec, and that only when the pressure of the gases is the same as in my case. However, since his pressure is 9 times less, the efficiency is 10 times less and the velocity will be only approximately 0.5 km/sec. To overcome Earth's gravity we must have a velocity of 11 km/sec; consequently, the velocity must be 22 times greater and the energy consumed for this purpose 484 times greater.

I repeat that the errors which I noted in the report of Esno Peltri are apparently simple typographical errors, as happens frequently; however, I think that it is useful to correct them.

The successful construction of the reactive device, to my way of thinking, is associated with extreme difficulties and will require many years of preliminary work as well as theoretical and practical investigation. Nevertheless, these difficulties are not so great that we must limit ourselves to dreaming about radium and about phenomena in bodies which do not exist at the present time.

Is it possible to carry a supply of explosives which is several times the weight of the rocket?

Let us imagine that half of an elongated spindle-shaped rocket is filled with liquid freely evaporating explosives.

These explosives are under the influence of the increased relative gravity, because of the acceleration of the rocket and, therefore, the walls of the latter experience a pressure (produced by the liquid) which is greater than that during the stationary position of the rocket on Earth. Calculations show that if we use steel with a safety factor of 6, and have a rocket length of 10 m and gravity which is 5 times greater than Earth's gravity, the weight of the explosives may be 50 times greater than the weight of the rocket with all its other contents. This is true for the most common material and with the greatest factor of safety. /97
Theory also shows that when the size of the rocket is increased, the relative supply of explosives decreases, and vice versa. Therefore, it is desirable to have a rocket of small dimensions: 10 m of length will be quite sufficient.

Another important problem concerns the temperature of the explosives.

Calculations show that for the case of free expansion (as in our explosive tube) of the products of combination of the detonating gas, the maximum temperature must reach 8,000°C.

However, in practice, detonating gases do not even fuse lime. Consequently the temperature is far from very high. The reason lies in the phenomenon of dissociation.

When hydrogen and oxygen begin to combine chemically, the temperature rises so high that it prevents large numbers of molecules from producing a chemical compound (the latter is impossible at high temperatures). Water begins to decompose into hydrogen and oxygen even at 1,000°C. DeVille discovered that the temperature for the decomposition of water vapor is from 900 to 2,500°C. Therefore, we may assume that the maximum temperature of a burning detonating gas does not exceed 2,500°C.

The problem of finding materials which can withstand this temperature is not insurmountable. Here are some of the fusion temperatures of materials known to me: nickel - 1,500°, iron - 1,700°, indium - 1,760°, palladium - 1,800°, platinum - 2,100°, iridium - 2,200°, osmium - 2,500°, and tungsten - 3,200°; carbon does not fuse even at a temperature of 3,500°C. On the one hand, the explosive tube must be subjected to forced cooling; on the other hand, the investigators must find materials which are both strong and fire-resistant.

Investigations must also be carried out to find the most suitable explosives. Of all known chemical reactions, the maximum amount of heat is released by the combination of hydrogen and oxygen.

We will show here the amount of heat liberated per unit weight of various substances during their combination with oxygen. During formation of water, hydrogen gives off 34,180 calories and 28,780 cal during formation of steam; carbon gives off 8,080 cal during formation of carbon dioxide and hydrocarbons produce from 10,000 to 13,00 cal. However, these are not the numbers of interest to us; we are more interested in those which apply to the unit mass of the products of combustion: only they tell us whether the combustible materials are suitable for a rocket. For a unit mass of water vapor we find 2,200 for carbon dioxide and 2,370 to 3,200 calories for benzene. In general, hydrocarbons during combustion give a larger number per unit of their mass than carbon, i.e., greater than 2,200, but less than 3,200. The more hydrogen there is in a hydrocarbon, the more efficient it is for a rocket. We can not use materials which give nonvolatile products, such as calcium oxide or lime.

One of the gases in liquid forms, specifically oxygen, is very useful for cooling the explosion tube. Hydrogen in liquid form may be replaced by a liquid or condensed hydrocarbon. We must seek those compounds of hydrogen and carbon which contain as much hydrogen as possible and which were formed from the elements with large absorption of heat, like, e.g., acetylene which, unfortunately, contains little hydrogen. In the last respect turpentine or methane are most satisfactory; the latter is unsuitable, however, because it is very difficult to compress it into a fluid. /98

It would be desirable to find a similar compound for oxygen.

It is necessary to find a stable combination with itself (like ozone), or with other bodies which would give stable and volatile products when they combine with the elements of hydrocarbon, and release a large quantity of heat.

If we use benzol or benzene instead of hydrogen in the rocket, then in the case when the mass of explosives is equal to the mass of the rocket with its other contents, we find that the velocity of the particles leaving the tube is no longer 5,700 m/sec, but only 4,350 m/sec. The velocity of the rocket will be only 3,100 m/sec. Therefore, in this case we obtain the following table for the mass of explosives and the velocity of the rocket:

Mass.	1	3	7	15	31	63	127
Velocity, km/sec. . . .	3	6	9	12	15	18	21

These velocities are also sufficient for interstellar travel.

Hydrocarbons are desirable because they give very volatile products: water vapor and carbon dioxide; in addition, a liquid hydrocarbon at ordinary temperature does not absorb any substantial quantity of heat like the liquid and very cold pure hydrogen.

The question concerning the weight of the explosion tube is very important. For this purpose it is necessary to know the pressure of the gases inside. This question is complicated and requires special mathematical formulation (I shall prepare this for the press). At the present time we shall consider it very briefly.

Let us imagine the beginning of the explosion tube, where gases in liquid form arrive in a definite ratio (for example, hydrogen and oxygen). Only part of the atoms engage in chemical union, because the temperature which has risen to 2,500° impedes the union of other atoms. If we assume that the density of the gas mixture is unity, we find that its elasticity (if we take into the account the high temperature) will not be greater than 5,000 atmospheres or approximately 5,000 kg/cm^2 on the tube surface at its very beginning.

During the motion of the gases in the tube and during their expansion, the temperature should drop, but this will not take place for some time because a drop in the temperature will immediately extend the chemical reaction, which, in turn, will raise the temperature to 2,500°. Thus, to some degree of gas expansion the temperature will remain constant, since it will be sustained by the heat of combustion. /99

After the total combination of atoms and the formation of water vapor there will be a rapid drop in temperature. Calculations show that when the volume is increased by a factor of 6, the absolute temperature drops by half. On this basis we construct the following table, showing the expansion and corresponding absolute and ordinary temperatures (approximately):

Expansion	1	6	36	216	1296	7776
Absolute Temperature	2800	1400	700	350	175	87
Temperature, °C	+2500	+1100	+400	+50	-125	-213

We can see that when expansion by a factor of 200 has taken place, almost all of the heat is converted into the work of the forward motion of the gases in the rocket. With further expansion the vapor turns into a liquid and even into crystals of ice which travel with amazing speed from the tube.

Such is a rough picture of the phenomena in the explosion tube.

Let us assume, for simplicity, that it is of cylindrical form, and let us determine its maximum thickness and the area of its base.

Let us assume that the weight of the rocket with the man and with other parts, excluding the explosives, is 1 ton; we assume that the quantity of explosives is 9 tons.

We assume that the pressure on the rocket is equal to 5 times its weight. The relative gravity of the rocket and of all objects in it will be 5, i.e., 5 times greater than the gravity on Earth. The person inside the rocket must be in a reclined position and submerged in a case with water. In this case we may guarantee the entire safety of his body.

The pressure of the gases on the rocket or on the base of the tube will then be 50 tons or 50,000 kg. Since the gases at the beginning of the tube produce a pressure of 5,000 kg per cm^2, the area of the tube's base will be 10 cm^2. The thickness of the wall of the tube, if we utilize the best steel and the ordinary factor of safety (6), will be equal to 4.5 cm with an internal diameter of 3.6 cm. Then the external diameter will be less than 13 cm and the internal diameter less than 4 cm.

The weight of 1 dm of such a tube will be approximately 10 kg and the weight of 1 m will be 100 kg. We must not forget that the weight of the tube will decrease rapidly as we move away from its origin, since the gases will expand rapidly and their pressure will decrease proportionately, to say nothing of the temperature drop which does not start immediately, but at a certain distance from the beginning of the /100
tube.

Nevertheless, it is clear that the tube consumes a large part of the rocket's weight. Therefore, investigations must be directed toward finding materials which are much stronger than the ordinary steel. The latter may not necessarily satisfy our purpose, except perhaps by being easily fused.

It is difficult to determine the total weight without applying higher mathematics. We shall leave this problem until we present a more comprehensive treatise.

The explosive materials must be forced into the tube by some means; a tremendous amount of work will be required for this purpose, which is one of the principal difficulties. However, we should not close our eyes to this. If the rocket weighs 1 ton and the explosives weigh 9 tons and the acceleration of the rocket is 50 m/sec^2, the pressure on the rocket during its inclined ascent (more advantageous) will be approximately 50 tons. The initial elasticity of gases and the base of the tube will be 50 tons. We have assumed that the pressure of gases per square centimeter is 5 tons. From this data we find that in order to obtain a velocity of 10 km/sec, an explosion must last for approximately 200 sec; we must supply approximately 45 kg of explosives to the tube each second.

The velocity of their flow, assuming that their average density is unity, will be about 45 m/sec. The work performed in forcing the explosives under very high pressure into the orifice will be equivalent to 2,250 ton-meters during a period of 1 sec, which is equal to 30,000 steam horses!!

We have obtained a result unthinkable for engines at the present state of technology. Therefore, we must reject the idea of using the conventional pumping methods. The simplest thing to do is to insert a specific charge into the tube and to let it explode and evaporate. Then, when the pressure is absent in the tube, a second charge should be introduced, etc. This must be performed by a machine and with unusual rapidity. We see difficulties here, too.

We know that the useful work performed by the explosives in our missile will be, on the average, not less than 400,000 horsepower, which is 13 times greater than the work done in forcing the explosive material into the tube. Would it not be possible to force this material by using the energy of the explosion, like Giffard forces water into the boiler by using the steam pressure inside the boiler?

At its mouth the tube must have a branch pipe through which the gases are redirected back to the mouth, and with their high velocity pull and push the explosives in a continuous stream into the very mouth of the explosion tube.

There is no doubt that this could be realized, if we could find structural materials with the necessary strength and heat resistance.

If we consider the huge pressure force produced by the gases on the rocket, 5 tons and more per ton of rocket, the question of controlling the rocket will not appear simple. If we bend the exit end of the ex- /101
plosion tube and thus change the direction of the exhaust gases, we will produce a lateral force and change the position of the rocket. However, the total pressure on the rocket is so great that before you have finished turning the exhaust, the rocket will receive a very strong deviation or may even tumble. Rockets and projectiles designed for military purposes are usually made to rotate around their longitudinal axes to achieve stability of direction. We cannot do this with our rocket, because rotation will produce a centrifugal force which will harm the living being. However, we may achieve stability if we place two rapidly rotating bodies inside, with mutually perpendicular axes of rotation. This will increase the weight of the rocket, which is not very attractive.

Even among the educated people the concepts of phenomena in the rocket during its ascent are very hazy. Science fiction writers either do not describe these phenomena or else describe them incorrectly.

The apparent gravity in the rocket depends on acceleration obtained from the pressure of gases. Thus, if the acceleration of the rocket is 50 m/sec^2, then the relative gravity inside the rocket will be 5 times greater than earth's gravity, since the acceleration due to the latter is 10 m/sec^2. Therefore, during explosion there will be increased gravity in the rocket for a period of 3-4 minutes; after explosion has ceased, gravity will appear to vanish because there will be no acceleration. Increased gravity may be endured by placing yourself into a strong box of human form containing a very small amount of water. Preliminary experiments must be made by a centrifugal machine which also produces artificial gravity.

Similar experiments will have to be conducted to work out conditions necessary for respiration and nutrition of man when the rocket is in the air.

What we have presented above is sufficient to provide a concept of a reactive projectile for cosmic travel.

The rear, stern part of the rocket consists of two chambers separated by a partition.

The first chamber contains liquid, freely evaporating oxygen. It has a very low temperature and surrounds part of the explosion tube and other components subjected to high temperature.

The other compartment contains hydrocarbons in liquid form. Two branch tubes move away from the mouth of the tube and contain rapidly moving gases which attract and force the liquid explosives into the mouth in a manner similar to that of the jet steam pump.

The freely evaporating, liquid oxygen in gaseous form and in a cold state flows through the intermediate space between the two shells of the rocket and prevents the internal part of the rocket from overheating during /102
its rapid movement in the air.

The compartment in the bow which is isolated, i.e., enclosed from all sides, contains the following:

1. Gases and vapors necessary for respiration.

2. Devices for preserving the life of beings from a 5-fold or 10-fold increase in the force of gravity.

3. Food supplies.

4. Devices for control in spite of the reclined position in water.

5. Substances which absorb carbon dioxide, miasmas, and all detrimental products of respiration in general.

Let us make some more rough calculations to compare the artillery devices with the rocket tube.

Although I have read that experiments with the cannon shells have yielded velocities up to 1200 m/sec, in practice I am satisfied with a velocity of 500 m/sec. In this case, if we do not take into account the resistance of the air, the shell moves vertically to an altitude of 12-1/2 km. If it is launched at an angle of 45°, it passes the maximum distance in the horizontal direction, specifically 25 km. In the first case the shell flies for about 100 seconds; in the second case it flies for 70 seconds.

On the other hand, when the velocity is 1,000 m/sec the maximum altitude is 50 km, while the maximum horizontal displacement is 100 km. The time of flight will be twice as great.

With a 14" gun 10 m long and with a shell weighing 1 ton, we find that the average pressure in the barrel is approximately 1,250 kg/cm^2 or 1,250 atmospheres. When the velocity of the shell is double, the average pressure reaches a value of 5,000 atm. The maximum value of the pressure is, of course, much higher. Consequently, the pressure in a cannon is close to the pressure which we have assumed for the rocket (5,000 atm).

If we assume that the mass of explosives in our cannon is 1 ton and that the shell moves in a channel in 1/25 sec (the terminal velocity is 500 m/sec), we find that on the average 25 tons of explosive is consumed every second.

In our rocket we consume only 45 kg, i.e., 555 times less. It is clear that the bulk of the rocket explosion tube is also not very large.

In the explosion tube of the rocket we eject only molecules of gas, rather than a heavy shell. It is natural that this velocity is much greater than the velocity of the shell and reaches the value of 5 km/sec. The velocity achieved by the rocket is of the same order of magnitude. The hot gases transmit their work to a cannon shell in a very incomplete way, and only while the latter is in the barrel. Having left the barrel the gases still have tremendous elasticity and high temperature, as exhibited by the sound and light flash accompanying an explosion. The explosion tube of the rocket which diverges gradually is so long that the temperature and elasticity of the gases at the exit are entirely negligible. In the rocket chemical energy is therefore utilized almost without a loss.

This article was first published in 1914.

INVESTIGATION OF UNIVERSAL SPACE BY REACTIVE DEVICES /103

(1926)

Preface

I owe my interest in space travel to the well-known science fiction writer Jules Verne. He has caused my mind to work in this direction. A desire was born. This desire in turn was followed by activities of the mind. Of course, this would not have led to anything had I not found assistance in science.

Even as a young man I found the path to cosmic flights in the form of centrifugal force and rapid motion (see my article "Earth and Sky," 1895). The first compensates for gravity and reduces it to zero. The second lifts bodies into the sky and carries them far away, depending on their velocity. Calculation showed me those velocities which had to be achieved in order to escape from Earth's gravity and reach the planets. But how could these velocities be obtained? This is the question that tormented me all my life, and it was only in 1896 that I became confident it could be solved.

For a long time, like everyone else, I considered the rocket as a form of amusement with but few applications. It never interested me even as a toy. However, ever since the distant past, many people have looked upon the rocket as one of the methods in aeronautics. If we search history, we shall find many inventors in this field. Such were the inventors Kibal'chich and Fedorov. Sometimes ancient drawings themselves show that there was a desire to use the rocket for aeronautics.

In 1896 I purchased by mail a copy of the book by A. P. Fedorov entitled "A New Principle of Aeronautics" (St. Petersburg, 1896). The book appeared quite vague to me (since it contained no calculations of any kind). In a case like this I make my own calculations beginning with the A, B, C's. This was the beginning of my theoretical investigations on the possibility on applying reactive devices to cosmic travel. Before me, no one had mentioned the book by Fedorov. I got nothing out of it, but, nevertheless, it directed me toward serious work just like the fall of the apple directed Newton to the discovery of gravity.

It is quite possible that there is still a very large number of serious works on rockets unknown to me and which perhaps were published a long time ago. In the same year, after many calculations, I wrote a story entitled "Beyond the Earth" which was later published in the journal "Priroda i lyudi," and was even published as a separate book (1920). /104

An old piece of paper with the final equations, accidentally preserved, is dated August 25, 1898. However, it is obvious from the preceding that I was concerned with the theory of the rocket before this time, specifically since 1896.

I never claimed to have solved this problem completely. Initially there is an inevitable trend of thought, phantasy and fiction. These are followed by scientific calculations. And only at the very end does realization crown the thoughts. My works on cosmic travels pertain to the middle phase of creativity. More than anyone else, I comprehend the abyss which separates the idea from its realization, because in the course of my life I not only thought and made calculations, but I also worked with my hands.

However, an idea must exist: realization must be preceded by thought, accurate calculations must be preceded by phantasy.

This is what I wrote to M. Filippov, the editor of "Nauchnoye obozreniye," before I sent him my notebook (published in 1903): "I have developed some aspects of the problem of going up into space by means of a reactive device similar to a rocket. Mathematical conclusions are based on scientific data and have been checked many times and point to the possibility of using such devices to go up into the sky and possibly to go beyond the limits of Earth's atmosphere. Apparently hundreds of years will pass before the ideas expressed by me will find application, and people will use them to settle not only over the face of Earth but over the face of the entire universe.

"Almost the entire energy of the sun at the present time is useless for mankind because Earth obtains two billion (more precisely 2.23) times less energy than what is released by the sun.

"What is so strange about utilizing this energy! What is so strange about the idea of controlling the infinite space which surround Earth's sphere...."

Everyone knows how limitless and great the universe is. Everyone also knows that the entire solar system with its hundreds of planets is a point in the Milky Way. And the Milky Way itself is nothing but a point in the ether island. The latter is a point in the universe.

Let us assume that people have penetrated the solar system, and have it under their control like the housewife has her home: will the mysteries of the universe be revealed at that time? Not at all! This will be like examining some tiny stone or shell which does not reveal the secrets of the ocean. Even if mankind were to achieve control over other suns or even over the entire Milky Way with its billions of suns and hundreds of billions of planets, even then the answer will be the same. These billions also constitute a point which will not reveal all the secrets of the heavens.

It was not so long ago that efforts to fly in the air were punishable by execution, and discussions on the rotation of Earth were punished by burning at the stake. Is it possible that even today mankind must make errors of this type! /105

It is rather difficult to obtain copies of my earlier works. Therefore, in this edition of mine I combine my previous works with my more recent achievements.

A Space Ship Must be Similar to the Rocket

The principal action of every vehicle and ship is the same: they repel some mass in one direction and move in the opposite direction. The steamer repels the water, the airship and the aeroplane repel the air, man and the horse repel the Earth's sphere; a reactive device, for example, a rocket, and Segner's wheel repel not only the air, but the substance which is contained within them: gun powder, water. If the rocket were situated in vacuum or in ether, it could still achieve motion, since it would carry its own supply of repelling material: gunpowder or other explosives, containing both mass and energy.

It is obvious that the device for propulsion in space must be similar to the rocket, i.e., it must contain not only energy but its own structural mass.

In order to travel outside the atmosphere and in any other material medium at an altitude of 300 km or further among the planets and stars, we require a special device which we shall call a rocket for the sake of brevity.

We know that the ether which exists between the stars is the same material medium as water, but it is rarefied to a point that it cannot serve as a support for anything. It is not considered to be immaterial only conditionally. Even heavenly stones (bolides, aerolites and falling stars), which weigh several g, may move with a tremendous velocity (up to 50 km/sec and more) without encountering any noticeable resistance. In other words, as far as resistance to bodies is concerned, ether may be considered a vacuum. Similarly, its fluxes in the form of radiant or electrical energy exhibit only very small pressure on the body. For the time being we may neglect this pressure.

Explosion may be used not only to rise from the surface of the planet, but also to descend to it; it can be used not only to gain velocity, but also to lose it. A projectile is capable of escaping from Earth, moving among the planets, among the stars, to visit planets, their satellite rings and other heavenly bodies, and to return to Earth. It is only necessary to have a sufficient amount of explosives containing energy. As a matter of fact, we shall see that there are possibilities for descending to a planet with atmosphere without expending any explosives.

Basic Data Which Are Required to Study the Problem /106

The Work of Gravity during Escape from the Planet

By simple integration we obtain the following expression for the work T necessary to remove a particle of unit mass from the surface of a planet of radius r_1 at altitude h

$$T=\frac{g}{g_1}r_1\left(1-\frac{r_1}{r_1+h}\right).$$

Here g is the acceleration due to gravity on the surface of the given planet, and g_1 is the acceleration due to gravity on the surface of Earth.

Let us assume in the above equation that h is equal to infinity. Then we find the work required to remove the mass from the surface of the planet to infinity and obtain

$$T_1=\frac{g}{g_1}r_1.$$

If we note that g/g_1 is the gravity at the surface of the planet with respect to the gravity on Earth, we find that the work required to remove the unit mass from the surface of the planet to infinity is equal to the work required to move this same mass from the surface to an altitude of 1 r of the planet, if we assume that the force of gravity does not decrease as we move away from the surface. Thus, although the space to which the force of gravity of any planet extends is infinite, this force constitutes a wall or sphere of insignificant resistance, covering the planet at the distance of its radius. If you overcome this wall and break through this illusive equi-planetary shell, gravity is conquered over its entire infinite extent.

From the last equation we see that the limiting work T_1 is proportional to the force of gravity (g/g_1) at the surface of the planet, and to the magnitude of its radius.

For planets of the same density, for example, those having the same density as Earth (5.5), the force of gravity at the surface is proportional to the radius of the planet and is given by the ratio of radius r_1 of the planet to the radius r_2 of Earth.

Consequently,

$$\frac{g}{g_1}=\frac{r_1}{r_2} \text{ and } T_1=\frac{r_1}{r_2}r_1=\frac{r_1^2}{r_2}.$$

This means that the limiting work T_1 decreases very rapidly as the radius r_1 of the planet decreases exactly as its surface decreases.

Thus, if the work for Earth's sphere $(r_1 = r_2)$ is equal to r_2 or /107
6,366,000 kgm, then for a planet with a diameter 10 times smaller, it is equal to 63,600 kgm.

However, from some point of view it is not very great for Earth. Indeed, if we assume that the heat content of petroleum is 10,000 cal, then it is sufficiently accurate to assume that the energy of combustion will be equivalent to mechanical work of 4,240,000 kgm per 1 kg of fuel.

It turns out that the escape of a unit mass from the surface of our planet will require a quantity of work stored as potential energy in 1-1/2 mass units of petroleum.

If we apply this to a man weighing 70 kg, we obtain a quantity of petroleum equal to 105 kg.

We only lack the ability to make use of this tremendous chemical energy.

However, it becomes clearer why an 8-fold quantity of explosive material compared with the weight of the projectile may help the latter in overcoming the force of Earth's gravity.

According to Langley, 1 m^2 of surface illuminated by the normal rays of the sun yields 30 cal per minute, or 12,720 kgm.

To obtain all of the work necessary for 1 kg to overcome Earth's gravity, we must use an area of 1 m^2 illuminated by the sun's rays for a period of 501 minutes, or approximately 8 hours.

This is all quite small, but in comparing the human force with the force of gravity, the latter will appear very huge to us.

Let us assume that a man climbs a perfectly constructed ladder to a height of 20 cm every second. Then he will perform the limiting work only after 500 days of hard labor, if we give him a 6 hour rest period every day. If we utilize 1 horsepower to achieve the climb, the work will be reduced by 5 times. If we use 10 horsepower, then only 10 days will be required, and if the work is done continuously, it will only take 1 week.

If we use the energy consumed by a flying aeroplane (70 hp), only 1 day will be required.

For the majority of the asteroids and for the moons of Mars, this work required to overcome gravity completely is amazingly small. The moons of Mars are not greater in diameter than 10 km. If we assume that they have Earth's density of 5.5, then the work T_1 will not be more than 4 kgm, i.e., equal to that necessary to climb a birch tree 4 m in height. If our moon or if Mars were to contain intelligent beings, it would be much easier for these beings to overcome gravity than it would be for the inhabitants of Earth.

Therefore, T_1 is 22 times smaller for the moon than for Earth.

On large planetoids and satellites of planets it would be extremely easy to overcome gravity by the reactive devices I have described. For example, on Vesta T_1 is 1,000 times smaller than on Earth because the cross section of Vesta is equal to 400 km. A cross section of Metissa is /108
approximately 107 km, and T_1 is 15,000 times smaller.

However, these are the huge asteroids; most of the others are 5-10 times smaller. For them T_1 is millions of times smaller than for Earth.

From the preceding equations we find the following expression valid for any planet

$$\frac{T}{T_1}=\frac{h}{h+r_1}=\frac{\frac{h}{r_1}}{1+\frac{h}{r_1}}.$$

We have expressed the work T necessary to achieve the altitude h from the surface of the planet of radius r_1 with respect to the total maximum work T_1. From this expression we compute

h/r_1 = 1/10, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 9, 99, infinity.

T/T_1 = 1/11, 1/6, 1/5, 1/4, 1/3, 1/2, 2/3, 3/4, 9/10, 99/100, 1.

The first line shows the altitude in terms of planet radii; the second gives the corresponding work, if we assume that the work for complete escape from gravity is unity. For example, to move from the surface of the planet by a distance equal to its radius, we must perform half of the total work, and if we are to move to infinity, we must only perform twice as much.

The Necessary Velocities

It is interesting to know the velocities that must be achieved by the rocket (by the action of explosives) to overcome gravity.

We shall not present the calculations used to determine these velocities and shall limit ourselves only to the conclusions.

Thus, the velocity V_1 necessary to lift the rocket to an altitude h and give it a velocity of V, is equal to

$$V_1=\sqrt{V^2+\frac{2gr_1h}{r_1+h}}.$$

If we let V = 0, i.e., if the body moves upwards until it is brought to a stop by the force of gravity, we find

$$V_1=\sqrt{\frac{2gr_1h}{r_1+h}}.$$

When h is infinitely large, i.e., if we rise without limit and the terminal velocity is zero, then the velocity at the surface of the planet required for this purpose will be given by

$$V_1 = \sqrt{2gr_1}.$$

Using this equation we find that for the Earth V_1 equals 11,170 m/sec, which is 5 times greater than the velocity of the fastest cannon shell when it leaves the gun barrel. /109

For our moon V_1 = 2,373 m/sec, i.e., it is close to the velocity of the shell and to the velocity of hydrogen molecules. For the planetoid Agata, which is 65 km in diameter, if we assume that its density is not greater than the density of the Earth (5.5), V_1 is less than 5.7 m/sec; we also find that for the satellites of Mars the velocity V_1 is almost the same. On these bodies of the solar system it is sufficient to start running in order to become eternally free of their gravity and to become an independent planet.

For planets with the same density as Earth, we have

$$V_1 = r_1 \sqrt{\frac{2g_1}{r_2}},$$

where g_1 and r_2 refer to the Earth's sphere. From the equation we can see that the limiting exit velocity V_1 in this case is proportional to the radius r_1 of the given planet.

Thus, for the small planetoid Vesta whose diameter is 400 km we find that V_1 = 324 m/sec.

This means that even a rifle bullet will leave Vesta permanently and become an aerolite rotating around the sun.

The latter equation is convenient for getting a quick idea of the exit velocities on planets of various dimensions but of equal density. Thus Metissa, one of the large asteroids, has a diameter approximately 4 times smaller than that of Vesta, and, consequently, the velocity will also be smaller by the same factor, i.e., approximately 80 m/sec.

Permanent orbiting around the planet requires half as much work and velocities, which are less by a factor $\sqrt{2} = 1.41...$, than those required for escape to infinity.

Flight Duration

We shall not present the rather complicated equations used to compute the flight time of the projectile. This problem is not new and has been solved, and we would only repeat what is already known.

We shall make use of only one conclusion, a very simple and useful one to solve the simplest problems pertaining to the flight time of the rocket.

The time t required for a body initially at rest to fall to the planet (or to the sun) which is concentrated at one point (the point having the same mass) is given by

$$t=\frac{r_2}{r_1}\sqrt{\frac{r_2}{2g}}\left\{\sqrt{\frac{r_2}{r_1}-1}+\arcsin\sqrt{\frac{r}{r_2}}\right\}.$$

Here r_2 is the distance from which the body begins to fall; r is the magnitude of this fall; r_1 is the radius of the planet, and g is acceleration due to gravity during this time on its surface.

The same equation, of course, gives ascent time from $(r_2 - r)$ to r_2, when the body loses all its velocity. /110

If we assume that $r = r_2$, i.e., if we determine the time of fall to the center of the concentrated planet, we obtain from the last equation

$$t=\frac{\pi}{2}\frac{r_2}{r_1}\sqrt{\frac{r_2}{2g}}.$$

Under ordinary conditions this equation also expresses the approximate time of fall to the surface of the planet or the time it takes the rocket to ascend from the surface of the planet until it comes to a stop.

On the other hand the period of total circular rotation of some body, for example, that of a projectile around the planet (or around the sun), is equal to

$$t_1 = 2\pi \frac{r_2}{r_1} \sqrt{\frac{r_2}{g}},$$

where r_1 is the radius of the planet with acceleration g at the surface, and r_2 is the distance of the body from its center.

If we compare both equations we find

$$t_1 : t = 4\sqrt{2} = 5.657.$$

Consequently, the ratio of the period of rotation of some satellite to the period of its central fall onto a planet concentrated at one point is equal to 5.66.

In order to obtain the time of fall of some heavenly body (for example, our rocket) to the center (or approximately to the surface) around which it revolves, we must divide the sidereal period of its rotation by 5.66. Thus we establish that the moon will fall to Earth in 4.8 days, while Earth will fall into the sun in 64-1/4 days.

Conversely, the rocket launched from Earth and coming to a stop at the distance of the moon will fly 4.8 days or about 5 days.

Similarly, a rocket launched from the sun, and coming to a stop due to the sun's gravity at the distance of the Earth, would have spent 64 days on its flight or over 2 months.

The Work of Solar Gravity

Let us determine the work of solar gravity performed when the rocket is dispatched from the Earth's sphere. It would, of course, be most advantageous for the projectile to have a velocity in the direction of the annual motion of Earth around the sun. We may also make use of the rotation of our planet around its axis.

The work of the rocket is composed of two parts. The first is required to overcome Earth's gravity, the second to overcome atmospheric resistance. For a unit mass, for example, of 1 ton, the first work is given by 6,366,000 ton-meters or a velocity of 11,170 m/sec. If the rocket is launched in the direction of the annual motion of Earth, then it will escape from Earth and become a satellite of the sun like Earth. It will also have a velocity (average) of 29.5 km/sec. In order for the rocket to escape completely from the sun, the work of its annual motion must be increased by a factor of 2 or its velocity by $\sqrt{2}$, i.e., it must have a velocity increment equal to $29.5\ (\sqrt{2} - 1) = 12.21$ km/sec. The total work is expressed by the relative number $(11.17)^2 + (12.21)^2$, while the velocity required to perform all the work will be $\sqrt{11.17^2 + 12.21^2} = 16.55$ km/sec. Since the rocket does not have a second support, it must acquire this velocity immediately after it leaves Earth. If it makes use of the rotation of points on the equator of Earth, then this velocity will be further decreased by 465 m/sec and will be 16,085 m/sec, i.e., about 16 km/sec. This velocity is more than is necessary to reach any planet of the solar system. If we achieve this velocity, we can float between the stars, (suns), without ever stopping. However, it will not be possible to escape from our Milky Way. If we were to initiate our flight against the annual motion of Earth, then a huge velocity would be required and a tremendous amount of work would have to be done to overcome our solar gravity. Indeed, in the first case we move away from Earth but do not lose our annual velocity of 29.5 km/sec. If we leave Earth in the opposite direction and wish to move away from the sun, we must acquire this velocity and also acquire the velocity of 41.7 km/sec opposite to that of the annual motion, i.e., a total of 71.2 km/sec. The entire velocity necessary for our purpose will be $\sqrt{71.2^2 + 11.2^2} = 72.1$. This velocity is 4-1/2 times greater and the work is 20 times greater, and the quantity of explosives becomes unbelievably high. It would be less disadvantageous to launch the projectile in the direction normal to Earth's annual path. /111

The Resistance of the Atmosphere to the Motion of the Projectile

At this time we shall show that the work done to overcome the resistance of the atmosphere is insignificant compared to the work done to overcome gravity. Later we shall consider these problems in more detail. Let us assume that the projectile has a vertical motion. If its acceleration is 30 m/sec, it will penetrate a distance of 53 km, i.e., almost the entire atmosphere, in a period of 33 sec. Under these conditions its maximum velocity will be 1 km/sec. However, this velocity exists at an altitude where there is almost no atmosphere. We may assume

that the average velocity is not greater than 0.5 km. With this velocity the pressure on 4 m^2 of the rocket's cross section will not exceed 100 tons, according to the well-known equations. But since the rocket is very long and has a suitable shape and moves very rapidly, this pressure on the cross section will be decreased at least by a factor of 100. Therefore, it will be not more than 1 ton. Our large rocket weighs not less than 10 tons, and the pressure on it will not be less than 40 tons. /112
Therefore, this pressure will be 40 times greater than that which expresses the average resistance of the atmosphere. The total work performed by the projectile or the work of gravity will, of course, be 1,000 times greater than the work performed to resist the atmosphere. From this we also see that air should have no substantial effect on the velocity of the rocket.

Available Energy

We present the table which shows the quantity of energy released when 1 kg of various substances is burned.

We have seen that the work performed by Earth's gravity on 1 kg mass is $6.37 \cdot 10^6$ kgm or a velocity of 11 km/sec. We shall compare this work with the energy at the disposal of man. The upper part of the table refers to the case when we are flying in a vacuum and carry the oxygen /113
supply with us. In this case the energy of explosives is at least 4 times smaller than that required to achieve escape velocity, if we assume that the energy is completely utilized. The corresponding velocity would be twice as small. The lower part of the table refers to flight in the atmosphere, when we can acquire oxygen from surrounding medium without storing it in the rocket. In this case the available energy will be 2 times greater than necessary, and the velocity will also be more substantial.[1]

In general, it turns out that the energy supplied by the explosives is quite insufficient for these substances to acquire the escape velocity from Earth's gravitation even by themselves.[2]

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[1]The last column in Table 1 gives the ratio of the work obtained from 1 kg of a given explosive to the work obtained from 1 kg of CO + O_2 when it is burned to produce CO_2.

[2]This pertains to the case when the entire mass of the explosives must escape from Earth's gravitation. - Remark by Tsander.

Table 1

Combustion: oxygen self-contained	Large cal	Work kgm	Velocity m/sec	Ratio of the works
H_2 and O_2 with water vapor forming	3,200	$1.37 \cdot 10^6$	5,180	1.455
The same, with water forming	3,736	$1.6 \cdot 10^6$	5,600	1.702
The same, with ice forming	3,816	$1.63 \cdot 10^6$	5,650	1.730
C and O_2, with CO_2 forming	2,200	$0.94 \cdot 10^6$	4,290	1.000
Benzene H_6C_6 and O_2, forming H_2O and CO_2	2,370	$1.01 \cdot 10^6$	4,450	1.078
Combustion: oxygen supplied externally	**Large cal**	**Work kgm**	**Velocity m/sec**	**Ratio of the works**
H_2 burns, and H_2O is formed	28,780	$12.3 \cdot 10^6$	15,520	13.08
C burns, and CO_2 is formed	8,080	$3.46 \cdot 10^6$	8,240	3.673
A hydrocarbon burns and CO_2 and H_2O are formed	10,000	$4.28 \cdot 10^6$	9,160	4.545
	13,000	$5.56 \cdot 10^6$	10,440	5.909
Radium	$1.43 \cdot 10^9$	$0.611 \cdot 10^{12}$	$3.44 \cdot 10^6$	$0.65 \cdot 10^6$

It is simple to show that, in spite of this, the projectile may achieve any desired velocity as long as we can provide a large enough supply of explosives. When the ratio of the fuel supply to the weight of the empty projectile is equal to unity, it is obvious that the velocity will be close to 5 km/sec,[1] since the repelled masses are the same (see Table 1). When the relative supply is equal to three units, the velocity of the rocket will become 10 km/sec. Indeed, if we discard 2 units of explosives, we obtain a rocket velocity (with the remaining fuel) of 5 km/sec. Exploding the remaining fuel will impart another 5 km/sec to the velocity of the projectile. The total velocity will be 10 km/sec. It is therefore easy to show that when the relative fuel supplies are 7, 15, and 31, the velocities achieved by the ship will be 15, 20, and 25 km/sec, respectively. At the same time, to escape solar gravitation a velocity of 16-17 km/sec is sufficient.

The breakdown of atoms is a source of great energy, as we can see from the last line of Table 1. This energy is 400,000 times greater than the most powerful chemical energy. Its disadvantage is that it is extremely expensive, inaccessible and takes place very slowly, even though for thousands of years. Even if we were to procure 1 kg of radium (a quantity not yet produced in the whole world), the total energy released by it would be only 15 kgm/sec. Therefore, an engine of this type, of the same weight as an aeroplane engine, will be at least 7 times less powerful than the other. Furthermore, we do not yet possess the radium motor, and the price of radium per kg is no less than one billion rubles. However, we must not be convinced that in the future cheap sources of quickly released energy will not be available.

General Problems of Obtaining Cosmic Speeds /114

We can obtain this velocity on the planet. Having achieved it, we move into ether space and float among the planets or even among the stars. However, if we do not have a reactive device, then our motion there will be similar to the motion of a bolite, i.e., we shall be unable to control it. Consequently, we cannot do without a reactive device.

There would be a tremendous advantage in achieving the velocity on Earth, because if we move along its surface we could have a continuous inflow of energy without using up our supply.

I list below the unrealized methods of obtaining cosmic velocities.

1. It is impossible to launch a projectile from a rotating wheel or from a gigantic merry-go-round, because the velocity at the circumference of the wheel, regardless of its size, cannot be more than 500-1,000 m/sec, and this velocity is not cosmic. Even at this velocity, the wheel would break down under the action of centrifugal force. In

[1] In this case it is assumed that the explosive remains in place, while the empty projectile flies with a given velocity. - Remark by Tsander.

addition, not a single organism will be able to survive this centrifugal force, even if the diameter of the wheel is 1 km.

2. A short cannon is also impossible because the relative gravity produced in the projectile will destroy living organisms. Even a cannon 6 km long is too small. It does not matter whether the projectile is placed in motion by an explosive or an electromagnetic force.

3. A vertical cannon is impossible because high constructions of this type cannot be implemented.

4. A horizontal cannon is also impractical, regardless of length, since the projectile leaving the cannon will quickly lose almost all its velocity in the dense air of the atmosphere (Table 2). From the 8th line of Table 2 we see that the rocket, weighing 10 tons and a cross section area of 4 m^2, during horizontal velocity of 8 km/sec loses 20 percent of its kinetic energy. This occurs when it travels 50 km. However, with this velocity it will follow a curvilinear path and will not leave the atmosphere. Therefore, it will quickly lose all its velocity or fall to Earth sooner. At a velocity of 16 km/sec, it will lose 80 percent of its energy. If the rocket has a smaller mass, i.e., without a supply of explosives, for example, of mass of 1 ton, then with a velocity of 4 km/sec it will lose half of its energy. The massiveness of the projectile makes the flight much easier. From the 10th line of Table 2 we see that a cannon placed on the top of the highest mountains is acceptable, because the shell loses only 13.6 percent of its energy at a velocity of 12 km/sec.

5. It is impossible to achieve cosmic velocities on small circular paths, since the centrifugal force will kill the organism, although it may not destroy the runway which is firmly secured to the ground.

6. It is also impractical to achieve cosmic velocities along great paths situated horizontally along the equator, because the resistance of the air, as in the previous case, will absorb all the energy of motion. Wheels (to decrease friction) are unsuitable for a moving cosmic vehicle. /115

There is some possibility in the use of a gas or, particularly, an electromagnetic gun whose length is not less than 60 km, inclined on a mountain, so that the exit is at an altitude of 8 km where the air is already quite rarefied.

Much has already been written about the fact that the cannons cannot be very short. We shall repeat a few of these thoughts. Let us assume that the man placed into water is able to withstand a relative gravity of 100. Then the acceleration of the projectile in the cannon cannot

be more than 1000 m/sec^2 (10 x 100). If we are to escape Earth's gravity, /116

Table 2. Weight of the Rocket is 10 Tons. Area of the Rocket's Cross Section is 4 m^2. Efficiency of the Shape is 100 Percent. Specific Weight of the Air is 0.0013 Times the Specific Weight of Water. Air Resistance and the Work Performed during the Constant Velocity of the Projectile

1. Velocity in km/sec	4	6	8	10	12	16	17
2. Air pressure[1] on the plane 4 m^2 in tons $P = 0.0001\ c^2\ 4$	6,400	14,400	25,600	40,000	576,000	102,400	115,600
3. Pressure on the rocket with efficiency of 100 percent, in tons	64	144	256	400	576	1,024	1,156[1]
4. Work performed by the rocket when displaced by distance of 10 km, in thousands of tons	640	1,440	2,560	4,000	5,760	10,240	11,560

5. If the rocket weighs 10 tons and is to escape the Earth's gravity, we must perform work not less than $6,370,000 \cdot 10 \cdot 2 = 127,400,000$ ton-meters. We multiply this by 2, since the efficiency is not greater than 50 percent of the energy of the explosives

6. Work performed to overcome friction compared with work performed by the explosives in percent; path equal to 10 km	0.50	1.13	2.02	3.15	4.54	8.06	9.10

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[1]It is necessary to point out that in the new edition of the book called "Pressure on the Plane," published in 1930, K. E. Tsiolkovskiy derives equations which show that the air pressure on the body is substantially greater and increases, proportionately, to the seventh power of the velocity (see paragraph 67 in the referenced book). Although this law represents only the first approximation, nevertheless the resistances computed in the present book require corrections which would tend to increase them at velocities greater than the velocity of sound. - Remark by Tsander.

Table 2 - Continued

7. The same with respect to work associated with the motion of the projectile, percent	1.00	2.26	4.04	6.30	9.08	16.12	18.20
8. The same, but with a travelled path of 50 km, percent	5.00	11.30	20.2	31.5	45.4	80.6	91.0
9. The same, if the empty rocket weighs 1 ton, percent	50	113	202	315	454	806	910
10. Cannon at an altitude of 8 km weighing 10 tons, travelled path 50 km, work, percent	1.5	3.4	6.0	9.4	13.6	24.2	27.3

we would require a velocity of 12 km/sec in the barrel. This may take place in a period of 12 sec. The average velocity of the projectile will be 6,000 m/sec. In 12 sec it will travel a distance of 72 km. This is the minimum length of the cannon. However, in all probability it must be 10 times greater, since a human being placed in a liquid will probably not be able to withstand a relative acceleration greater than 10. Short steel cannons are only suitable for firing solid steel shells. Such cannons must also be at least one hundred times longer than conventional artillery pieces, otherwise the shells which do not contain people will also be shattered.

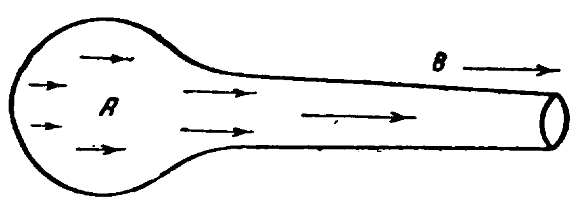

Figure 1

At first glance it would appear that a gas with particles whose velocity at ordinary temperature does not exceed 2 km/sec cannot produce cosmic velocity. But this is an error which we shall now clarify.

Let us consider a large reservoir A with hydrogen or another gas and with an attached barrel B (Figure 1). The shell is subjected to pressure, which is more constant if the reservoir A is greater compared with the volume of the cylinder B. This means that in the limiting case the work obtained by the shell is proportional to the square root of this length. Consequently, it is infinitely high. This strange paradoxical conclusion is explained by the fact that the work is performed at the expense of the entire gaseous mass A; and, since it can be very high, the work transmitted to the projectile may also be very large. High velocity is only reached by an insignificant mass of the gas in the barrel and by the projectile itself. The remaining mass in the reservoir A has small velocity, but is cooled. Release of this tremendous heat provides the work necessary to move the projectile and the gas in the barrel. It is clear that to obtain maximum work and maximum velocity, the gas should be heated by steam jets or by numerous other methods. It is also convenient to use an electric current for producing heat (by passing the current through conductors inside A).

In the subsequent calculations we shall assume that the pressure on the projectile is constant, i.e., the reservoir A is very large, is filled with hydrogen, and is heated. The action of gravity on hydrogen is 14-1/2 times less than it is on air (compared with the condensation below), and we shall therefore assume, even though the altitude of the cannon's mouth /11' is very high, that the density of the gas in the entire system is constant.

We obtain equations

$$P = p_a \cdot n \cdot F. \quad (1)$$
$$j : g_e = P : G. \quad (2)$$
$$V = \sqrt{2j \cdot L}. \quad (3)$$
$$t = \sqrt{2L : j}. \quad (4)$$
$$K = j : g_e. \quad (5)$$

From these equations we find

$$j = g_e \cdot K. \quad (6)$$
$$P = (G \cdot j) : g_e. \quad (7)$$
$$n = P : (F \cdot p_a). \quad (8)$$
$$L = V^2 : (2j). \quad (9)$$

Here

K is the relative gravity in the projectile;
j is the acceleration of the projectile per second;
P is the pressure on the projectile;
n is the pressure in atmospheres;
L is the length of the cannon, in km;
t is the time spent in the barrel;
F is the cross section area of the cannon's channel;
V is the maximum velocity in seconds;
D is the cross section of the shell and of the cannon's channel;
p_a = 10 tons/m^2; pressure 1 atm;
G is the weight of the projectile measure on the surface of Earth;
g_e is the acceleration due to gravity on Earth.

By using these equations we compiled Table 3.

Table 3 shows that when the gas is condensed to 1,000 atm and the length of the cannon is 720 km, we obtain a velocity of 380 km/sec, whereas to escape from the sun and float in the Milky Way we only need a velocity of 17 km/sec. In the sixth column of Table 3 we see that this velocity is obtained when the relative gravity is 100, the gas is compressed by a factor of 100, and when the length of the cannon is 145 km. In the eighth column we see that a velocity of 4 km is obtained when the relative gravity is 10, when compression is 10 atm, and when the length of the cannon is 80 km. If the cross section of the channel is increased by a factor of 4 or the diameter is increased by a factor of 2, then (col. 14) the velocity of the same mass will be doubled, i.e., the first cosmic velocity will be reached (the velocity necessary to become Earth's satellite close to its surface). The length of the cannon and the compression of the gas remain the same, but the acceleration and the relative gravity are increased by a factor of 4.

Electromagnetic guns have a tremendous advantage because they do not require a reservoir of energy, are easier to construct, are more economical, and have an ample inflow of useful energy over their length easily supplied by conductors from side stations.

In time cannons may have a great application for mass launching of projectiles, for cosmic migration on a large scale, and as a supplement to the rocket method. Indeed, if the first cosmic velocity of 8 km/sec is achieved by means of a cannon, the projectile returns to Earth and breaks up, because its velocity is not parallel to the equator (or to the meridian). For the first important achievements, i.e., for migration close to Earth but outside the atmosphere, it is necessary to combine the cannon method with the rocket method: the projectile will achieve a velocity of less than 8 km/sec, but will later increase this velocity by

Table 3. Acceleration Due to Earth's Gravity $g = 10$ m/sec^2. Weight of the Projectile[1] G = 10 Tons. Atmospheric Pressure $p_a = 10$ 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	1,000	1,000	1,000	1,000	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	720	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

[1] As we can see from equations (2) or (7), G represents the weight of the projectile on the surface of Earth and not the mass M which was incorrectly introduced at this point by Tsiolkovskiy. - Remark by Tsander.

/118

explosions, like a rocket. Since the direction of the explosion is variable and is controlled by us, the projectile may achieve sufficient velocity along its circumference and may become a close and small moon of Earth.

We may eliminate the rocket device when the projectile (ejected from the cannon) is to be placed in the orbit of Earth or pass close to the planets of our system. The same is true for the case when it is to escape from the gravitational force of the sun and float among other stars in the Milky Way.

In any case, cannons (and electromagnetic ones) due to their large size are extremely expensive and very difficult to construct (at the present time); furthermore, a reactive device can be made to work without them. /119

Action of the Rocket

A rocket compared with a cannon is the same as a battery compared with an elephant. I used the term "rocket" to describe a reactive device which moves by repelling a substance previously stored in it. There are no machines or organisms which do not repel matter from themselves: the human being constantly gives off steam from his skin, and the steam engine does the same; but this action is weak compared with the other forces which work inside them, and therefore devices of this type cannot be called reactive. The rocket is similar to the toy rocket. It differs from other vehicles and ships in that the latter repel substances which are not contained within them.

Efficiency of the Rocket

First, let us imagine that we are dealing with weightless energy like electricity, with negligible mass. Let us also assume that the projectile is not subjected to the forces of gravity or to other external forces. Then, for the case of two stationary masses repelled by an intermediate immaterial force, the laws of the conservation of momentum give us the following equation

$$M_1 W + M_2 c = 0. \tag{12}$$

If the velocity of the rocket c is assumed to be positive, the exhaust velocity W will be negative, because the momentum will be zero and cannot be changed by internal forces. M_1 and M_2 designate the ejected mass and the mass of the rocket, respectively.

The work obtained by a rocket will be

$$E_2 = \frac{M_2 c^2}{2}. \tag{13}$$

The work of repelled mass will be

$$E_1 = \frac{M_1 W^2}{2}. \tag{14}$$

The efficiency of the rocket will be

$$\eta = \frac{E_2}{E_1 + E_2} = 1 : \left(1 + \frac{E_1}{E_2}\right) = 1 : \left(1 + \frac{M_1 W^2}{M_2 c^2}\right). \tag{15}$$

However, from equation (12) we see that

$$M_1 : M_2 = -c : W. \tag{16}$$

Therefore, the efficiency of the rocket is equal to

$$\eta = 1 : \left(1 - \frac{W}{c}\right) = 1 : \left(1 + \frac{M_2}{M_1}\right). \tag{17}$$

It is clear that as the mass of the rocket decreases, with respect to the mass of the ejected material, the efficiency goes up. Table 4 has been prepared on the basis of the last equation. /120

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	η	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Same in percent	%	0	10	20	30	40	50	60	70	80	90	100

Table 4 shows that in practice the efficiency cannot be equal to unity, since the rocket always has some mass. When the mass of the rocket is equal to the mass of the ejected material, efficiency is 50 percent.

However, the situation will not be the same if the projectile with its supply of fuel already has some velocity which, for example, was obtained by an electromagnetic gun by explosion or by other methods. Here we may have an interesting case, when utilization of energy may be 100 percent regardless of the ejected mass. Indeed, if, for example, the rocket has a velocity of 1 m/sec, then if we throw the ejected element in the opposite direction with the relative velocity of 1 m/sec, we obtain a small ejected particle with an absolute velocity equal to 0. It is obvious that all of the consumed energy was used entirely for the benefit of the projectile. In this case, instead of equation (12), we obtain

$$M_1(W+V)+M_2(c+V)=(M_1+M_2)V. \tag{18}$$

By reduction we obtain equation (12) and all of the conclusions which follow from it. Here V is the total initial velocity of the system before ejection. Further we have

$$E_2=\frac{M_2}{2}(c+V)^2. \tag{19}$$

$$E_1=\frac{M_1}{2}(W+V)^2. \tag{20}$$

$$\eta=1:\left[1+\frac{M_1(W+V)^2}{M_2(c+V)^2}\right]. \tag{21}$$

From equations (18) and (12), in place of this, we find

$$\eta=1:\left[1-\frac{c\,(W+V)^2}{W(c+V)^2}\right]. \tag{22}$$

If the rocket has an increment in velocity (of course, in the same direction), then the ejected matter has a negative velocity. If, however, the velocity of the ejected matter is equal to the total velocity of the rocket[1] $V = W$, then the numerator in equation (22) is equal to 0, and therefore $\eta = 1$, i.e., the efficiency will be 100 percent. It is thus more advantageous for the particles of ejection to be repelled in a direction opposite to that of the projectile, with a velocity equal to that of a rocket itself; we then obtain the ideal utilization of work. /121

However, we have in mind obtaining the maximum projectile velocity from a given supply of ejected mass. It is advantageous to combine energy with ejected matter, so that the ejected matter would itself be the source of energy. Otherwise things will be much worse. Indeed, if we take sand, for example, for the ejected material and carbon and oxygen (as the combination of energy with the ejected material), we shall gain less than if we take only the supply of combustible materials.

In the second case, when the mass of the fuel supply is the same, the energy per unit mass of supply will be greater and therefore we shall achieve a much greater ejection velocity, and hence a much greater velocity for the rocket. In general, energy is of a material nature. Even electricity and light are material, to say nothing of explosives. In order for a projectile to achieve maximum velocity, it is necessary that each particle of the products of combustion or of any other ejected material obtain the maximum relative velocity. This velocity is constant for specific ejected substances. What happens if we save energy by not having an ejection? In this case there would be no economy of energy: it is impossible and undesirable. In other words, the basic principle of the theory of rockets must be taken as a constant relative velocity of the particles of ejected material. The situation is different for a case of a reactive aeroplane using air as the ejected substance. In this case it is desirable to save the stored energy which, incidentally, must also be used as an ejected material. However, a projectile of this type is not a purely reactive device.

Velocity of the Rocket When External Energy is Utilized

We may have a case when, in addition to the energy of ejected material, we also have an influx of energy from the outside. This influx may be supplied from Earth during the motion of the projectile in the form of radiant energy of some wavelength, as well as in the form of α and β particles; it can also be obtained from the sun.

The influx of energy from Earth is attractive, but there are few data available for its consideration. The influx of energy from the sun

[1]In absolute value. - Remark by Tsander.

takes place when the rocket is already outside the atmosphere. In both cases it is unnecessary to have a supply of ejected materials; hence the energy which flows from the outside contains the ejection material in the form of α and β particles. It is only necessary to know how to direct them opposite to the desired movement of the rocket. The situation will /122 be clearer, if we take a supply of radioactive material. The velocity of its particles is so large that its supply may be very small compared with the mass of the rocket. Then the latter may be considered constant, as in the case when energy flows in from the outside.

In this case we have

$$\frac{dW}{W}=\frac{dM_1}{M_2}, \tag{23}$$

where W is the relative velocity of the ejected particles, for example, of alpha particles. Assuming that the direction of ejection is constant and integrating, we have

$$c=\frac{W}{M_2}M_1+c_0, \tag{24}$$

where c_0 is the initial velocity of the rocket before ejection or explosion. If it is equal to zero, then

$$c=\frac{M_1}{M_2}W. \tag{25}$$

We can see from the equation that the final velocity of the projectile is proportional to the relative supply of ejected material (or, in general, to the ejected material, since its supply may not exist) and to the relative velocity of ejection (for example, of α-particles).

If

$$W=3\cdot10^8 \text{ m/sec} \quad M_1=M_2,$$

then

$$c=3\cdot10^8 \text{ m/sec}.$$

This velocity is 18,000 times greater than the one necessary for escaping the attraction of the sun. The energy of this motion is 324 million times greater than is required. Flying with this speed, the ether ship reaches the closest sun in a period of 4 years. Here we assume that we are going to derive energy from the outside. In applying the equations to a radioactive substance, it is necessary that the ratio $M_1:M_2$ be small. If, for example, it is equal to 0.1, then to reach some other neighboring sun will require 40 years.

It is impossible to obtain so many particles from the sun because, as we move away, the flux of these particles almost ceases. The known radioactive materials, in addition to this, break down very slowly and produce an insufficient amount of work every second. The quantity of these materials in the hands of man is rather negligible. However, the future is unknown: Earth's sphere and its materials have not been investigated very much. It may yet yield many unexpected things.

Let us substitute in equation (25)

$$W=30\cdot 10^6 \text{ m/sec} \quad \text{while} \quad c=17\cdot 10^3 \text{ m/sec},$$

i.e., a projectile velocity only slightly greater than the one necessary to escape permanently from the sun. /123

By dropping the sign which appears in equation (16), i.e., taking the same sign for c and W, we obtain

$$\frac{M_1}{M_2}=\frac{c}{W}=0.00057. \qquad (26)$$

This means that the relative mass of the ejected material or of the radioactive substances constitutes in this case approximately 1/2,000 of the projectile's mass. If, e.g., the projectile weighs 1 ton, the mass of the ejected material will be only 568 g or less than 1-1/2 pounds. The mass of the ejected material is so small that the mass of the rocket may be considered constant, and the equations are valid almost without error for the utilization of future suitable radioactive materials, if the velocity of the particles are of the same order as the velocity of α-particles (electricity or radium).

What will be the utilization of energy? We have

$$E_2 = \frac{M_2}{2} c^2. \tag{27}$$

$$E_1 = \frac{M_1}{2} W^2. \tag{28}$$

The efficiency will be (23)

$$\eta = 1 : \left(1 + \frac{M_1}{M_2} \frac{W^2}{c^2}\right). \tag{29}$$

By means of (26) we obtain

$$\eta = 1 : \left(1 + \frac{W}{c}\right) = 1 : \left(1 + \frac{M_2}{M_1}\right). \tag{30}$$

When we are dealing with radioactive substances or with energy which flows from the outside, the ratio in the last equation is very large and therefore we have

$$\eta = \frac{c}{W} = \frac{M_1}{M_2}. \tag{31}$$

Thus, in the case considered, where $M_2 : M_1 = 1{,}765$, the efficiency is approximately 1/2,000. Although the efficiency is poor, the supply of material to be ejected is negligible.

In the Franklin wheel the efficiency is better, because the particles give motion to a rather large mass of air (electric wind). But in a vacuum the utilization of energy is so small the wheel does not turn, i.e., the work obtained is insufficient to overcome friction. The principle of the Franklin wheel may have an application in the flight of the projectile through air.

Conversion of Thermal Energy into Mechanical Motion /124

Let us consider explosive materials. The source of their energy is chemical. In general, they give us only heat, i.e., an irregular motion of particles (molecules). Special machines are required to obtain from this motion (from heat) a movement of particles which is coordinated, parallel, and directed towards one side, in other words, a simple visible motion. For a reactive device, it is necessary that the largest possible part of the thermal or chemical energy of the particles be transformed into coordinated forward motion. Then heat will disappear, and in its place we shall have mechanical motion or a rapidly moving jet. A long tube is used to achieve this. Explosion or combustion takes place at one end of the tube, while from its other end gases and vapors fly out. The walls of the tube have the property of directing the random (in all directions, oscillating) thermal or chemical motion (which is invisible and is felt as heat), and to transform it into a stream, like that of a river. However, it is necessary that the products of combustion be a gas or a vapor (volatile) with the lowest possible temperature of condensation.

If this is so, then the gas which expands in the tube is cooled more and more, the heat disappears and is replaced by the gas jet. If the tube is short, then the gas flies out of it at high temperature and its energy is not utilized (as is the case with cannons and guns). After it has left the tube, gas continues to expand and to cool, but motion takes place in all directions, so that it is unsuitable for us. Things are even worse if the explosion takes place without a tube. An extremely long tube is desirable, but it overloads the rocket with its mass and is therefore also unsuitable.

During the 6-fold expansion of the gases the absolute temperature drops in half. The utilization of the heat will be 50 percent. If expansion takes place by a factor of 36, then 75 percent is utilized, etc. The tube must therefore be long enough, so that the gas which leaves it has expanded at least 36 times. It would still be better if it had expanded by 1,300 times. Then only 5 percent of the entire thermal energy is lost. Substances which give nonvolatile products are entirely unsuitable, as, for example, calcium oxide; the energy is very high, but it is difficult to utilize it since we do not have it in gaseous form (it exists only at a very high temperature like the one on the sun), and there is no expansion. The energy is transformed into radiant energy and is lost in the ether.[1] Vapor-forming products may be tolerated, particularly when

[1] My recent investigations show that if we use metallic fuel in air-reactive engines, where the nitrogen of the atmosphere is a volatile gas and is added to the solid products of combustion, it will be profitable, particularly when part of the rocket's structure, which, for example, is made out of aluminum or magnesium alloy, is used as fuel. There will be enough fuel to reach cosmic velocities. The same is true when oxygen is used, when there is simultaneous application of fuel giving volatile products. - Remark by Tsander.

they are mixed with gaseous products. For example, when hydrocarbons burn with oxygen or with its nitrogen compounds, gases are liberated (carbon dioxide, nitrogen) and water vapor. During strong expansion the water vapor is the first to condense into droplets. However, in the presence of gases, these droplets transmit their heat to the gases which utilize their energy. Similarly, we can make use of the energy released during freezing of water. The absolute temperature of the exploded gas at the initial moment must reach 10,000°; however, at this temperature only a small part of the elements are combined, the remaining part decomposing. The first complex part increases gradually only when it expands and when the temperature drops. Therefore, it is doubtful that the temperature of the explosives exceeds 3,000°. On this basis, in Table 5, we express by numbers not the degree of heat, but the degree of potential energy. As a matter of fact, beginning at 1,000-2,000, this will be only an approximate temperature. /125

Table 5. Utilization of Heat in the Tube

Expansion of gases	1	6	36	216	1,300	7,800	46,800
Absolute temperature of energy	10,000	5,000	2,500	1,250	625	312	156
Temperature in °C	9,727	4,727	2,227	977	352	39	-147
Thermal efficiency, percent	0	50	75	87	95	97	98.4
Losses, percent	100	50	25	13	5	3	1.6
Approximate density of gases with respect to air	1,000	167	28	4.6	0.77	0.13	0.02

We can see that when the efficiency is 95 percent, the temperature is still 352°C. At this temperature the vapors do not condense, so that here even the latent heat of condensation is not utilized. Therefore, further expansion is desirable, but this can only take place in a vacuum. In this case the tube must be even longer.

Explosion at high pressure is particularly necessary during flight through the atmosphere. The explosion must not produce pressure less than atmospheric pressure. Otherwise there will be no expansion and no flow. But even at a much higher pressure the efficiency will be less when the pressure is small, compared with air pressure. If, for example, the gas pressure is 6 times greater than air pressure, then the efficiency cannot be greater than 50 percent. If the gas pressure is 36 /126 times greater than the pressure of the medium, then the efficiency is less than 75 percent (Table 5).

In a vacuum things are different. There the elasticity of exploding gases may be small; only the tube will be wider, while its weight remains almost unchanged. Theoretically our efficiency is not lost, no matter how small the pressure of the explosion, if the rocket is in space. It turns out, therefore, that at the beginning of the projectile's flight, the pressure in the tube must be very high compared with atmospheric pressure; then, as the projectile moves up, this pressure may be proportionately increased, and in the ether outside the atmosphere it may be arbitrarily small. In practice this has little application, since for this purpose the tube must be first narrow with heavy walls, and then wide with thin walls.

It is necessary to select the average pressure, which, of course, exceeds atmospheric pressure, and maintain it until a stable position is achieved, like the position of heavenly bodies. After this the pressure may be arbitrarily small.[1]

The pressure of the same explosives may vary from 5,000 atm to any desired small value. The fact is that in the same tube the force of explosion depends on a thorough mixing of the elements of combustion. Mixing may be carried out in such a way that the explosion will be instantaneous. And, to the contrary, it may be slow, like combustion, during poor mixing, when the parts of the combining substances are very large. The pressure is controlled in this way. A more or less strong action of gunpowder depends, therefore, on its preparation.

At high pressure utilization of energy is high, but a prohibitively large amount of work is required to push the mass into the explosion tube. Therefore, maximum pressure in the tube must be lowered without losing too much efficiency. As far as temperature is concerned, we do not gain anything in this case. It is unavoidably high, specifically 3,000-4,000°C. Artificial cooling of the outer walls of the tube becomes necessary.

We can now state the required minimum pressure. It would be determined by the effect of the atmosphere, by its pressure. If the flight is started from high mountains, then the atmospheric pressure may be assumed to be 0.3 kg/cm^2. This constitutes about 1/3 of the pressure

[1]The author here neglects friction in the tube; due to friction, kinetic energy is transformed into heat, and at very high gas temperatures and small pressures the velocity of the gases in the tube again decreases. The very low temperature is obtained only under special conditions. - Remark by Tsander.

at sea level. This means that the gases which fly out from the tube must not have less than 0.3 kg/cm^2. On the other hand, at the beginning of the tube the pressure must be at least 36 times greater (efficiency of 75 percent). The maximum pressure of the gases must not be less than 10 atm. In the lower layers it must not be less than 30 atm. In any case, we can set the limit as 100 atm.

Let us compute the area of the base of the cylindrical explosion tube under this pressure. If the rocket weighs 1 ton, and 5 tons with the explosives, and if the pressure on it due to explosion exceeds its weight by a factor of 2, then the pressure at the base must be 10 tons. The area of the base of tube will be equal to 100 cm^2. The diameter of the circular area of the base will be 11.3 cm^2. We have already stated how to obtain low pressure: the larger the elements of combustion, i.e., the worse they are mixed, the weaker the explosion. Nevertheless, in a closed space the pressure eventually reaches a very high value. However, in the first place the tube is wide and open, and in the second place mixing is such that the desired pressure is obtained. I repeat: we do not lose any energy of combustion due to low pressure. When we have an irregular explosion (a partial explosion in a general mass), cooling and violent motion (of the vapors) takes place. However, this motion does not perform any work and is immediately converted into heat, restoring the temperature. Even if the utilization of the energy at low pressure is worse, the guilty party in this case is the atmosphere. It does not permit explosives to expand indefinitely. When the pressure is high, the tube will be shorter, giving economy in weight. By extending the length of the tube we may achieve an efficiency up to 100 percent in vacuum; however, the tube in this case will be prohibitively long. I have shown many times that the work of pushing explosives into the tube is rather large, and it is insurmountable when the pressure is very high. To prevent this, we may cause the pressure at the beginning of the tube to vary periodically, for example from 200 atm to 0 and from 0 atm to 200 atm. It will have a wave form. The average pressure in this case may be quite large, if the human being could only endure it. The explosives in this case will be pushed in during the instant of low pressure, periodically. Then the work of pushing in the fuel will be insignificant, and the utilization of the heat or of the chemical affinity will be much larger. The shocks will not have a detrimental effect on a person in water. /127

Motion of a Rocket Produced by Explosion in a Vacuum or in a Medium Free of Gravity

Although it is undesirable to give the ejected material a relative velocity greater or smaller than the absolute velocity of the projectile, nevertheless, when explosives are used, their relative velocity is necessarily constant. In general, the greater it is, the greater is the velocity obtained by the device. In this case the initial velocity of the ejected particles is greater than the velocity of the rocket, and efficiency is very small; then both velocities are the same and utilization is complete. Later, the velocity of the ejected material is smaller and efficiency drops. In short, the utilization of energy or its transformation into the motion of the rocket starts with 0, increases /128 gradually, reaches a value of 100 percent and then decreases continuously, reaching a value of 0 as the limit.

During explosion we have two losses. First of all, not all of the heat energy is transformed into the motion of ejected particles. However, as the tube becomes longer and the products of ejection more gaseous, the losses decrease. At the limit the losses are equal to 0. In practice the efficiency should not be less than 75 percent. The second loss of energy depends on the fact that the ejected material has the same relative maximum velocity, which is not equal to the accelerated motion of the projectile. As we shall see, at cosmic velocities this loss is not less than 35 percent and the efficiency is not greater than 65 percent. In a medium with gravity such as on Earth, it is much less. If we assume that the second efficiency is 50 percent, the rocket converts into its motion approximately 37 percent (0.75 x 0.5) of the entire potential energy of the explosives.

Determining the Velocity of the Rocket

In vacuum and in a medium free of gravity we have

$$WdM_1+M_2dc=0. \tag{32}$$

However, M_2 consists of a constant mass M_0 (i.e., of the projectile, people, supplies, and various accessories) and of a variable mass of the explosives M_1 which are burned and ejected from the rocket. Therefore, $M_2 = M_0 + M_1$. Now in place of (32) we have

$$WdM_1+(M_0+M_1)\,dc=0. \tag{33}$$

From this, we obtain

$$-W\frac{dM_1}{M_0+M_1}=dc. \tag{34}$$

i.e., the increase in velocity will be extremely slow. (3) The velocity of the rocket does not change if the ratio M_1'/M_0 remains constant. We can see here that cosmic velocity does not depend on the absolute value of the projectile's mass, in other words, the mass of the projectile and its load are arbitrarily large if we neglect other conditions. (4) The final velocity does not depend on the order of explosion. Whether it takes place uniformly or not and whether it happens every second or every thousand years is not in the least significant. Even interruptions have effect.

Let dt be an element of time.

From (34) we find

$$\frac{dc}{dt}=\frac{W}{M_0+M_1}\frac{(-dM_1)}{dt}. \quad (39)$$

The first part gives the acceleration of the rocket per second, i.e., the relative force of gravity initiated by it (although under our condition there is no gravity all around). As we can see from (39), it is proportional to the intensity of consumption of the material $(-dM_1:dt)$. In addition, as M_1 is consumed, the apparent gravity increases as M_1 decreases and $dM_1 < 0$.

In order for the relative gravity to remain unchanged, it is necessary to decrease the intensity of explosion gradually. Then from (39) we obtain

$$\frac{-W}{M_0+M_1}\frac{dM_1}{dt}=K, \quad (39_1)$$

where K is the constant relative gravity.

From this

$$\frac{-WdM_1}{M_0+M_1}=Kdt. \quad (39_2)$$ /130

Integrating, we find

$$c = -W \ln(M_0 + M_1) + \text{const} \tag{35}$$

(ln signifies a natural logarithm). Let us assume that at the beginning of the explosion the rocket is not moving, i.e., $c = 0$ and $M_1 = M_1'$.

$$c = W \ln(M_0 + M_1'). \tag{36}$$

Consequently,

$$c = W \ln\left(\frac{M_0 + M_1'}{M_0 + M_1}\right). \tag{37}$$

Maximum velocity is achieved by the rocket when the supply of the explosives is used up or when $M_1 = 0$.

In this case

$$c_1 = W \ln\left(1 + \frac{M_1'}{M_0}\right). \tag{38}$$

From the last equation we can see that (1) maximum velocity of the projectile c_1 increases as the velocity of ejection W increases. (2) c_1 may increase without limit as the relative quantity of ejection M_1'/M_0. However, this increase is rather rapid at first and then becomes slower and slower. If the ratio M_1/M_0 is very small, then the mathematicians will easily show that $c_1 = W\, M_1'/M_0$. This means that in this case c_1 is proportional to the supply M_1'. On the other hand, at the limit when the ratio (equation (38)) is very large, /129

$$\bar{c}_1 = W \ln\left(\frac{M_1'}{M_0}\right),$$

Integrating, we find

$$-W \ln (M_0+M_1)=Kt+\text{const.} \tag{39_3}$$

Period of Explosion

If $M_1 = M_1'$, then $t = 0$; consequently,

$$t=\frac{W}{K} \ln \left(1+\frac{M_1'}{M_0}\right). \tag{39_4}$$

If $M_1 = 0$, i.e., if the entire combustible material is used up, then

$$t_1=\frac{W}{K} \ln \left(1+\frac{M_1'}{M_0}\right). \tag{39_5}$$

This means that the period of the entire explosion is inversely proportional to the resulting relative gravity and increases with the mass of the ejected matter.

From (39_1) we find

$$-\frac{dM_1}{dt}=\frac{K}{W}(M_0+M_1) . \tag{39_6}$$

From this we see that the minimum intensity of the explosion or the minimum consumption occurs at the end of the explosion, when M_1 is small, and the maximum consumption occurs at the beginning when $M_1 = M_1'$.

In the first case

$$-\frac{dM_1}{dt}=\frac{M_0K}{W}, \tag{39_7}$$

In the second case

$$-\frac{dM_1}{dt}=\frac{(M_0+M_1')K}{W}. \qquad (39_8)$$

The ratio of the maximum (at the beginning) to the minimum consumption (at the end) will be

$$1+\frac{M_1'}{M_0}. \qquad (39_9)$$

The greater the ratio $M_1':M_0$, the stronger is the change in the consumption of the explosives and, conversely, it is almost constant when this ratio is small. In practice it is inconvenient to change the force of explosion - it is simpler to provide means for withstanding the action of variable gravity by placing the people and other delicate objects into a liquid.

The period of explosion (uniform) of the entire supply, when the acceleration of the rocket and the relative gravity increase but when the consumption of explosives is the same, may also be expressed in the form /131

$$t_1=M_1'\frac{dt}{dM_1}. \qquad (39_{10})$$

Here the derivative may be replaced by the consumption of combustible material per second. At the same time during the uniform acceleration of the rocket and the constant relative gravity in the projectile (39_1), but with a nonuniform consumption of the ejected material, it will be equal to

$$t_1=c_1:j=c_1:\frac{dc}{dt} \qquad (39_{11})$$

The derivative $j = dc/dt$ expresses the constant increase in the velocity of the projectile per second.

Mechanical Efficiency

It is interesting to know what part of the total work performed by the moving, ejected particles is transmitted to the rocket. We have

$$E_1 = 0.5 M_1' \cdot W^2. \tag{40}$$

$$E_2 = 0.5 \cdot M_0 c_1^2. \tag{41}$$

From this

$$\frac{E_2}{E_1} = \frac{M_0}{M_1'} \left(\frac{c_1}{W}\right)^2 \tag{42}$$

or on the basis of (38)

$$\frac{E_2}{E_1} = \frac{M_0}{M_1'} \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2. \tag{43}$$

From this we can compute that the efficiency cannot be greater than 65 percent, and to achieve cosmic velocities we may assume it to be 50 percent. If the supply of explosives is relatively small then, approximately, instead of (43) we have

$$\frac{E_2}{E_1} = M_1' M_0, \tag{45}$$

or more precisely

$$\frac{E_2}{E_1} = \frac{M_1'}{M_0}\left(1 - \frac{M_1'}{M_0}\right); \tag{46}$$

we may obtain a more precise equation by expanding the expression

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} \ldots \tag{47}$$

Table 6 /132

Ratio of mass of ejected material to mass of rocket $M_1':M_0$	c_1, if velocity of ejected material is 5,000 m/sec, equation (38)	c_1, if velocity of ejected material is 4,000 m/sec, equation (38)	Average efficiency $E_2:E_1$ in percent, (43)	Approximate elevation in km when Earth's gravity is considered constant
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
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	
8	10,985	8,788	60.5	
9	11,515	9,212	58.9	In practice
10	11,990	9,592	57.6	the ascent
15	13,865	11,092	51.2	is higher
20	15,220	12,176	46.3	because
30	17,170	13,736	39.3	gravity
50	22,400	17,920	31.0	becomes
100	26,280	21,040	21.0	weaker
193	30,038	24,032	14.4	
∞	∞	∞	0	

The equations show that initially when the supply is small, the efficiency increases proportionately to the supply; then it increases more slowly, achieves a maximum value and then decreases slowly, finally achieving a value equal to 0. /133

The ratio $M_1':M_0 = x$, corresponding to the maximum efficiency, is given by the equation

$$\ln(1+x)=\frac{2x}{1-x}x$$

and in magnitude is close to 4 (i.e., the fuel supply exceeds the weight of the rocket by a factor of 4), and the efficiency is 65 percent. In Table 6 we present quantities for various cases of interest to us.

In addition to what we have derived analytically, we can see from Table 6 that the maximum efficiency (up to 65 percent) of the energy of ejected material occurs when its weight is 4 times greater than the weight of the rocket. However, the efficiency in general is not very small (approximately 50 percent) when the relative quantity of the ejected material varies from 1 to 20, while the corresponding velocity varies from 3-15 km/sec. These are entirely sufficient cosmic quantities. The two velocities in Table 6 refer to different explosives. The larger value refers to the mixture of pure hydrogen and oxygen, the smaller value to hydrocarbons and endogenous compounds of oxygen. For illustration I have added the fifth column, which shows the maximum elevation achieved by the body, under conditions of constant gravity, in km.

Our investigations may be applied in the following cases:

(1) in the medium without gravity, for example, between suns or Milky Ways where the gravity is close to zero;

(2) on small asteroids, small moons (the moons of Mars) and on all heavenly bodies, for example, on the rings of Saturn where gravity may also be neglected;

(3) in Earth's orbit;

(4) at any point of any solar system and at any distance from a heavenly body, if the projectile is outside the atmosphere and has achieved or has not achieved a velocity which prevents it from touching a heavenly body or its atmosphere.

We shall see later that, in order to prevent energy losses, the direction of explosion must be normal with respect to the uniform force of gravity.

We can see that it is sufficient just to be free of the planet's atmosphere and to become a satellite of this planet, if only at a short distance from it, in order to guarantee future movement and displacement over the entire universe. Indeed, any explosion after that may be very weak, and the energy required for this purpose may be obtained from the energy of the sun. The support material will be provided by the α and β particles which are scattered everywhere, or by bolites or cosmic dust.

The first great step of humanity consists of flying outside the atmosphere and becoming an Earth's satellite. The rest is relatively /134 easy, including the separation from our solar system. Of course, I do not have in mind the descent to massive planets.

Motion of the Rocket in a Medium with Gravity, in Vacuum

Let us imagine that the atmosphere has been removed or that we are on the moon or on some other planet with dry land and not surrounded by gases or vapors. We shall neglect the slow rotation of the planet. The flight of the projectile may be (1) vertical, (2) horizontal, and (3) inclined.

Let us consider the problem in general (see Figure 2).

Determining the Resultant Acceleration

The rocket is under the action of the force of gravity g expressed in acceleration per second; then the force of explosion acts on it in the direction of the longitudinal axis of the projectile, giving it an acceleration per second of j. An angle α greater than 90° is formed between the directions of these forces. The angle between the direction of explosion and the horizon will be $\alpha - 90^\circ = y$. This constitutes 3 given quantities. The unknown factors are: the direction of motion of the rocket, given by the angle β or the angle $x = \beta - 90^\circ$, and the resultant p, i.e., the true acceleration of the projectile per second.

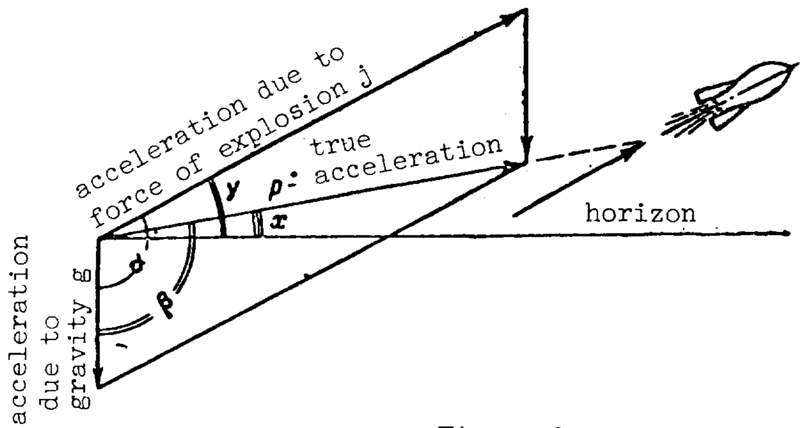

Figure 2

From trigonometry we have (see Figure 2)

$$\alpha = y + 90;\ \sin\alpha = \cos y;\ \cos\alpha = -\sin y;$$
$$\cos\beta = -\sin x;\ x = \beta - 90;\ \operatorname{tg}\beta = \operatorname{ctg} x.$$
$$\operatorname{tg}\beta = \operatorname{ctg} x = \frac{j\sin\alpha}{g + j\cos\alpha} = \frac{j\cos y}{g - j\sin y}. \qquad (48)$$
$$p = \sqrt{j^2 + g^2 + 2jg\cos\alpha} = \sqrt{j^2 + g^2 + 2jg\sin y}. \qquad (49)$$

It is simpler to have a known angle y and an unknown angle x, because they are less than a right angle and determine the slope of the explosion force with respect to the horizon (also the axis of the rocket) and the resultant (the true direction of the motion of the projectile).

Work Performed by the Rocket and by the Ejected Material; Mechanical Efficiency

What will be the efficiency in a medium with gravity, in a vacuum?

$$E_2 = 0.5 M_0 c_1^2 + A. \qquad (65)$$

A is the work done in lifting the rocket, while E_2 is the work performed by the rocket

$$A = -l \cos\beta\, M_0 g = l \sin x\, M_0 g. \tag{66}$$

l designates the length of the projectile's path.

If p and j are constant then

$$l = \frac{c_1^2}{2p} \tag{67}$$

and (from 65-67)

$$E_2 = 0.5 M_0 c_1^2 \left(1 + \sin x \frac{g}{p}\right). \tag{68}$$

Furthermore,

$$E_1 = 0.5 M_1' W^2. \tag{69}$$

From (68) and (69) we obtain

$$\eta = E_2 : E_1 = \frac{M_0}{M_1'} \frac{c_1^2}{W^2} \left(1 + \frac{g}{p} \sin x\right). \tag{70}$$

Trigonometry shows that for any angle

$$\cos\beta = \frac{\operatorname{ctg}\beta}{\sqrt{1 + \operatorname{ctg}^2\beta}}. \tag{71}$$

From this and from (48)

$$\cos\beta = \frac{g + j\cos\alpha}{\sqrt{j^2 \sin^2\alpha + (g + j\cos\alpha)^2}} = \\ = -\sin x = \frac{g - j\sin y}{\sqrt{j^2\cos^2 y + (g - j\sin y)^2}}. \tag{72}$$

Now from (70) we may eliminate the unknown sin x. However, we must also eliminate c_1. We have

$$t_1 = \frac{W}{K} \ln\left(1 + \frac{M_1'}{M_0}\right). \tag{73}$$

This is the total period of explosion when the relative gravity K is constant.

However,

$$K = j \quad \text{and} \quad c_1 = pt_1. \tag{74}$$

Consequently, from (39_5) and (74)

$$c_1^2 = p^2 \frac{W^2}{j^2} \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2. \tag{75}$$

Now from (70), (72) and (75) we find

$$\eta = \frac{p^2 M_0}{j^2 M_1'} \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2 \times$$
$$\times \left[1 - \frac{g \cdot (g - j \cdot \sin y)}{\sqrt{j^2 \cos^2 y + (g - j \sin y)^2}\sqrt{j^2 + g^2 - 2jg \sin y}}\right]. \tag{77}$$

When gravity is absent, g = 0 and p = j. In this case the last equation gives equation (43). We determine from (77) the efficiency for the case when explosion takes place horizontally, i.e., when y = 0. Then we again obtain equation (43). It is also easy to see that when the direction of explosion is normal to the force of gravity (horizontal), the efficiency is the same as in the case when gravity is completely absent. Close to the planet (at its very surface), horizontal explosion is not feasible since the rocket will drop and touch the soil. However, at some altitude, even in air, it is feasible and also when the rocket, having achieved cosmic velocity, does not touch the atmosphere but flies like a heavenly body. It is also applicable to planets without atmosphere, when the projectile moves along a smooth horizontal path. Later we shall also see an application for motion in the atmosphere.

We may verify equation (77) by considering one other specific case. Let us assume that the motion of the projectile is vertical, i.e., $y = 90^\circ$ and $p = j-g$.

Then we find

$$\eta = \frac{M_0'}{M_1'}\left[\ln\left(1+\frac{M_1'}{M_0}\right)\right]^2\left(1-\frac{g}{j}\right). \quad (80)$$

(This equation was derived earlier and is contained in the works of 1903.)

We can see from the equation that the vertical motion of the rocket is very disadvantageous, particularly when j slightly exceeds the magnitude of g. On the other hand, the greater j is with respect to g, the smaller are the losses and the greater is the efficiency. By comparing the efficiency in a medium without gravity (43) with the efficiency in a medium with gravity, for the case of vertical motion (80), we see that the efficiency is less than that of the first case by 1:(1-g/j). /137

The relative losses are expressed by the fraction g/j. If, for example, the force of explosion is 10 times greater than the weight of the rocket, the losses are 0.1. However, when both forces are equal, the losses are equal to 100 percent, i.e., the entire energy is used up without serving any useful purpose for the projectile. Indeed, in this case the rocket remains stationary, does not rise or achieve any velocity. When the force of explosion is infinite, the efficiency is the same as for the case of a medium without gravity. However, a strong explosion kills everything and destroys the inside of the projectile. It can be applied only to projectiles without people or complex equipment.

Table 7. Medium with Gravity. Vertical Motion of the Rocket

j:g	1	2	3	4	5	10	∞
Efficiency, percent	0	50	66.7	75	80	90	100
Velocity, percent	0	70.7	81.7	86.6	89.4	94.9	100

As we can see, vertical motion is associated with a high energy loss, particularly when the explosion force j is small. In this case j must be greater than g, otherwise no motion is obtained. The last line expresses in percent the maximum corresponding velocity. Actually the velocity is expressed by the second line, because part of the energy is used to produce the lift during the period of explosion (shown in 1903).

Flight of the Rocket in a Medium with Gravity, in the Atmosphere

Let us assume that a horizontally placed rocket in a medium with gravity also moves under the action of the horizontal force. First, the force of gravity will cause it to drop at an angle of 90° or less. More precisely, the tangent of this angle is equal to g:j. However, after several seconds the horizontal component of the rocket's velocity will be so large that the vertical motion of the projectile with its large surface will be entirely unnoticeable, compared with the horizontal component. Then the rocket moves almost horizontally, as if it were on a track. We can compute that the fall of the rocket due to resistance of the air, when the side surface of the projectile is substantial (vertical projection), may only be very small, and it becomes smaller and smaller as the speed of the rocket is increased. The situation will /138 be the same when the projectile moves along an inclined path, if this inclination does not exceed 20-40°. After several seconds the projectile will move as if it were going up an inclined track. The drop of a well-constructed rocket, when horizontal motion is absent, is only about 20-30 m/sec. However, when the forward velocity is very great, it must reach a value of 1 m/sec or less. What is this compared with cosmic velocity?

Velocity, Acceleration, Flight Duration, and Work Performed by the Rocket and the Ejected Matter, and the Mechanical Efficiency, Assuming That Motion Takes Place Along an Inclined Plane

From Figure 3 we have, approximately,[1]

$$c_1'=pt. \tag{83}$$

$$p=j-g\sin y. \tag{84}$$

$$K=j:g. \tag{85}$$

$$c_1=(j-g\sin y)\frac{W}{j}\ln\left(1+\frac{M_1'}{M_0}\right). \tag{86}$$

$$t_1=\frac{W}{j}\ln\left(1+\frac{M_1'}{M_0}\right). \tag{395}$$

[1] This approximation is permissible for large values of j compared with g. - Editor's Remark.

This takes place when j is constant.

The equations are even more applicable when the projectile moves along an inclined stationary plane, i.e., when it accelerates up the slope of a mountain.

Let us determine the efficiency.

$$E_2 = 0{,}5 M_0 c_1^2 + A. \tag{87}$$

$$A = M_0 \cdot g \cdot h = M_0 \cdot g \cdot l \sin y. \tag{88}$$

Here h is the altitude achieved by the projectile.

From here

$$E_2 = \frac{M_0}{2} c_1^2 \left(1 + \frac{g}{p} \sin y\right). \tag{89}$$

Furthermore,

$$E_1 = \frac{M_1'}{2} W^2. \tag{90}$$

Consequently,

$$\frac{E_2}{E_1} = \eta = \frac{M_0}{M_1'} \frac{c_1^2}{W^2} \left(1 + \frac{g}{p} \sin y\right). \tag{91}$$

By means of (86) and (84) we find /139

$$\eta = \frac{M_0}{M_1'} \left[\ln \left(1 + \frac{M_1'}{M_0}\right)^2 \left(1 - \frac{g}{j} \sin y\right) \right]. \tag{92}$$

If we simplify equation (77) for small angles y, we obtain approximately the same equation (92); see also equation (49).

If the rocket is horizontal and y = 0, then the efficiency from (92) may be obtained in accordance with equation (43). Similarly, from

(92), if $y = 90^\circ$, we obtain the well-known equation (80). η presents the mechanical efficiency, and if we multiply it by the thermal efficiency (see Table 5), we obtain the total efficiency.

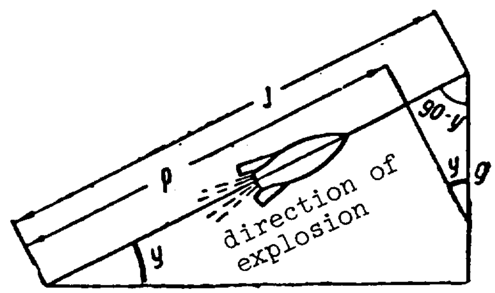

Figure 3

We see that the efficiency in space (77) is generally not the same as it is in the atmosphere or, more correctly, in a vacuum, when the projectile moves along an inclined plane.

The losses compared with those in the medium without gravity will be

$$\frac{g}{j} \sin y. \tag{93}$$

If, for example,

$$g : j = 0.3; \; y = 20^\circ; \; \sin y = 0.342,$$

then the losses are 5.7 percent. We enclose Table 8.

From this we can see that it would be desirable to launch the /140
rocket using the greatest possible explosion, if it were not for the destructive action of this explosion and the technical difficulties associated with its realization. It would also be advantageous to direct the rocket at the smallest angle, if there were no resistance of the atmosphere. Generally speaking, the loss with a small explosion force may be reduced to 1 percent.

Table 8. A Medium with Gravity in the Atmosphere.
Inclined Motion

Angle of inclination in degrees		1	2	5	10	15	20	25	30	35
Energy losses in	10	0.17	0.34	0.85	1.7	2.6	3.4	4.2	5	5.7
percent for	5	0.34	0.64	1.7	3.4	5.2	6.8	8.4	10	11.4
various j:g	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

A More Accurate Determination of Atmospheric Resistance

In the following presentation I simplify the equations which were given by me in 1911-1912. I assume that the temperature of the air is constant. Due to this the atmosphere extends infinitely. Then we have the well-known equation

$$h = \frac{f_1}{d_1} \ln \frac{d_1}{d}, \tag{95}$$

where f_1/d_1 is the altitude of the fictitious atmosphere h_1 with constant density d_1; f_1 is the atmospheric pressure corresponding to d_1.

Then,

$$\frac{h}{h_1} = \ln \frac{d_1}{d} \tag{96}$$

and

$$d = d_1 e^{-\frac{h}{h_1}}. \tag{97}$$

The air resistance or its pressure W on the rocket due to its motion will be

$$W = \frac{F}{a} d \frac{c^2}{2g}. \tag{98}$$

This pressure is not given in absolute units but in ordinary measures, for example, in tons. F is the midship cross section area of the rocket; a is the efficiency of the rocket's shape, i.e., a coefficient which becomes greater when the resistance W decreases. When the rocket moves along an inclined path the length of the path l is given by the equation

$$l = h : \sin y. \tag{99}$$

We have

$$p = j - g \sin y. \tag{84}$$
$$c = \sqrt{2pl}. \tag{84$_1$}$$

From this it follows that

$$c = \sqrt{2(j - g \sin y)l}. \tag{100}$$

The element of work performed by the air resistance is given by

$$dT = W dl \tag{101}$$

From (97), (98), (99), and (100) we find /141

$$dT = \frac{Fd_1}{ag}(j - g \sin y) l e^{\frac{l \sin y}{h_1}} dl. \tag{102}$$

We let

$$\frac{l \sin y}{h_1} = \frac{h}{h_1} = x;$$
$$dx = \frac{\sin y}{h_1} dl = \frac{dh}{h_1}; \quad dl = \frac{h_1 dx}{\sin y}. \tag{103}$$

Then we find

$$dT = \frac{F(j - g \sin y)\, d_1}{ag \sin^2 y} \cdot h_1^2 x e^{-x} dx. \tag{104}$$

We assume that

$$\frac{F(j - g \sin y)}{ag \sin^2 y} d_1 h_1^2 = A. \tag{105}$$

Integrating and determining the constant of integration, we find

$$T = A\left[1 - \left(1 + \frac{h}{h_1}\right) e^{-\frac{h}{h_1}}\right] = A\left[1 - \left(1 + \frac{l \sin y}{h_1}\right) e^{-\frac{l \sin y}{h_1}}\right]. \tag{106}$$

Taking into account (103) we also obtain

$$T = A\,[1 - (1 + x)\, e^{-x}]. \tag{107}$$

We must determine the total work of atmospheric resistance. To do this we must substitute

$$h = \infty \quad \text{or} \quad x = \infty.$$

We have

$$e^{-x} = 1 : e^x = 1 : \left(1 + \frac{x}{1} + \frac{x^2}{1 \cdot 2} + \frac{x^3}{1 \cdot 2 \cdot 3} + \ldots\right). \tag{108}$$

Consequently

$$(1+x)e^{-x}=e^{-x}+xe^{-x}=e^{-x}+x:\left(1+\frac{x}{1}+\frac{x^2}{1\cdot 2}+\dots\right)=$$
$$=\frac{1}{e^x}+1:\left(\frac{1}{x}+1+\frac{x}{1\cdot 2}+\frac{x^2}{1\cdot 2\cdot 3}+\dots\right). \tag{109}$$

We can see that if h or x are equal to infinity, then expression (109) becomes equal to 0. This means that the work of resistance is

$$T = A. \tag{110}$$

We obtain the total work of vertical motion from equation (104), if we substitute $y = 90^\circ$. Then we find

$$T=\frac{F(j-g)}{ag}d_1h_1^2. \tag{111}$$

Comparing this work with the total work of inclined motion, we see /142
that the latter is greater than the first by the factor

$$\frac{j-g\sin y}{(j-g)\sin^2 y}. \tag{112}$$

If j is large or if y is small, we may assume approximately that the work of inclined motion is inversely proportional to the square of the sin of the slope angle. This means that when the slope is zero and motion is horizontal, the total work performed by air resistance is infinite. However, this is not correct since atmospheric layers of uniform density cannot be considered horizontal, as we have assumed due to the spherical shape of Earth. In other words, the equations are invalid for small angles. If we assume that the altitude of the atmospheric pressure, where it is noticeable, is 50 km, it is easy to compute that the horizontal path is greater than the inclined path by a factor of 15.5. If, on the other hand, we assume this altitude to be 5 km, the horizontal path will be greater than the vertical path by a factor of 155. This shows that horizontal work cannot be infinite. From equation (104) we may compute the total work during vertical motion. Let us assume that $F = 2\ m^2$;

$j = 100\ m/sec^2$; $g = 10\ m/sec^2$; $h_1 = 8{,}000$ m; $d_1 = 0.0013\ tons/m^3$; $a = 100$.

Then T = 14,976 ton-meters. It is entirely insignificant even compared with the work performed by the motion of the rocket alone, having a mass of 10 tons (without explosives) and which escapes from Earth's gravity (11 km/sec velocity). This work is more than 60 million ton-meters. Therefore, it is 4,000 times greater than the work of atmospheric resistance during vertical ascent. If we launch the projectile from the highest mountain, where the air is 3-4 times less dense, we can see from equation (104) that this work will decrease even more, proportionately to rarefaction, i.e., also by a factor of 3-4. If the motion is inclined, it will not increase too greatly. From equation (112) we may compute this by letting j = 30, j = 20 and g = 10.

Table 9

y	10	20	30	40	50	90
T for j = 30	46.7	11.3	5	2.85	1.92	1
T for 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

From the second line of Table 9 we see that when the slope is 20°, the work is increased by a factor of 11. By comparing the second and third lines with the fourth line we see that, very roughly, we may consider the work to be proportional to $1:\sin^2 y$. As j increases this close relationship becomes more substantial, and vice versa. The third line shows the increase in the work when j = 20. For small angles the /143
actual work is much less, due to the spherical shape of Earth.

We have seen that the work of resistance during vertical motion is 1:4,000 part of the work performed by the motion of the rocket; however, when the motion is inclined, it is still less than 1 percent.

It is interesting to know the work performed by resistance as a function of the travel path and the achieved altitude h. The total work is given by equation (104), the remaining work by equations (107) and (108). It depends on the altitude which is reached.

This relationship is shown in Table 10.

Table 10. Relative Remaining Work Performed by Resistance in Percent[1]

h	4	8	16	24
$h:h_1$	0.5	1	2	3
Relative remaining work in percent	91	74	41	20

Optimum Angle of Flight

With equation (77) or (93) we compute the work lost due to inclined flight in a medium with gravity. From equation (104) we determine the corresponding losses due to the resistance of the atmosphere. If we prepare a table and determine the sum of losses, we shall see which slope corresponds to the least losses.

However, even without tables we may determine, approximately, the optimum slope angle. The losses due to the inclined motion of the projectile are given by (see (93))

$$g/j \sin y \text{ in absolute units.} \tag{113}$$

The losses due to atmospheric resistance in absolute units will be

$$Ag = \frac{F}{a} \frac{(j - g \sin y)}{\sin^2 y} d_1 h_1^2. \tag{114}$$

The work performed by the rocket will be (see (104)) /144

$$E_2 = 0.5 M_0 c_1^2 = 0.5 M_0 W^2 \left[\ln \left(1 + \frac{M_1'}{M_0} \right) \right]^2 \text{[see (38)]}. \tag{115}$$

[1] It was necessary to recompute Table 10 because Tsiolkovskiy made an error in equation (105); in his calculations the remaining relative work turned out to be dependent on the slope angle, which is actually not so. From Table 10 we see that after a flight of 4 km we must yet perform 91 percent of the entire work, and after a flight of 24 km, 20 percent. - Remark by Tsander.

Therefore, both losses in absolute units will be

$$E_2 \frac{g}{j} \sin y + Ag = E_2 \frac{g}{j} \sin y + \frac{F}{a} d_1 h_1^2 \left(\frac{j - g \sin y}{\sin^2 y} \right) = Z. \tag{116}$$

By taking the derivative of this expression and setting it equal to 0, we obtain an equation which is inconvenient to solve with respect to sin y.

However, the optimum angle is not very large. In the second term, therefore, we may neglect the expression g sin y.

Then equation (116) will be transformed into

$$Z = E_2 \frac{g}{j} x + \frac{F}{a} d_1 h_1^2 \frac{j}{x^2}. \tag{117}$$

Here sin y = x. Differentiating this equation and setting the derivative equal to zero and determining x, we find

$$x = \sin y = \sqrt[3]{\frac{2 F d_1 h_1^2 j^2}{a E_2 g}}. \tag{118}$$

By means (115)

$$\sin y = \sqrt[3]{\frac{4 F d_1 h_1^2 j^2}{a M_0 W^2 \left[\ln \left(1 + \frac{M_1'}{M_0} \right) \right]^2 g}}. \tag{119}$$

From this we can see that the optimum angle y increases with explosion energy j and the cross section area F of the rocket, and decreases as the shape efficiency a increases, and as the ratio of the projectile's mass to the mass of the ejected material $M_1':M_0$ increases.

On a planet with large gravity g it also decreases and vice versa. Let us substitute in (119) F = 2; d = 0.0013; h = 8,000; j:g = 10; a = 100; M_0 = 10; W = 5,000.

Then we compute

$$\sin y = 0.167 \text{ and } y = 9^\circ 35'.$$

When j = 20, we obtain sin y = 0.057 and y = $3^\circ 20'$.

However, at these small angles the resistance of the atmosphere due to its spherical shape will be substantially less, and the optimum angle will also be much less.

From equation (117) we determine the relative losses due to both reasons

$$\frac{Z}{E_2} = \frac{g}{j} x + \frac{Ed_1 j}{aE_2 \lambda^2} h_1^2 = \frac{g}{j} x + \\ + \frac{2Fd_1 j h_1^2}{aM_0 W^2 \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2 x^2}. \tag{120}$$

We present a simple equation for determining the percent losses. /145

If we divide the second term by the third in equation (120), we find the factor by which the losses due to the effect of gravity are greater than the losses due to air resistance. By eliminating x from this ratio and using (119), we obtain the value 2. We can see that for the case of the optimum slope the losses due to gravity are twice as large as the losses due to the air resistance. Consequently

$$Z : E_2 = \frac{g}{j} x + \frac{g}{2j} x = \frac{3}{2} \frac{g}{j} x. \tag{121}$$

Thus, when the angles are 9° and 3°, we find the total losses to be 0.025 and 0.0428, i.e., 2.5 percent and 4.3 percent, respectively.

From (121) and (119) we derive the total relative losses

$$Z : E_2 = \sqrt[3]{\frac{27 \cdot Fd_1 h_1^2 g^2}{2 \cdot a \cdot M_0 W^2 \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2 j}}. \tag{122}$$

The area of the body, which varies in this manner, increases proportionately to the square of its dimensions, while its volume and mass are proportional to their cube. Consequently the losses decrease as the dimensions of the rocket increase, and also when the shape a of the projectile is improved and when j or the force of combustion is increased. However, this increase takes place very slowly. For example, if j increases by a factor of 8, the losses will decrease only by a factor of 2. It is very advantageous to fly with a small j, in which case, as we can see, we lose very little. When $j = 10$, $x = \sin y = 0.036$; $y = 2^{\circ}10'$ and $Z:E_2 = 0.054$. Consequently the angle is very small and the losses are 5 percent. Under actual conditions they are much smaller, due to the spherical shape of Earth.

Let us substitute $a = 50$ in the equations and, as before,

$$F = 2;\ d_1 = 0.0013;\ h_1 = 8{,}000;\ M_0 = 10;\ W = 5{,}000;$$

j will be assigned different values.

We prepare Table 11.

When the slope is small it is also necessary to have low acceleration, which is very desirable from a technical standpoint. It is unfortunate that the losses in these cases are maximum (up to 14.6 percent).

We consider an acceleration for the projectile from 1 to 200 m/sec^2, which is 0.1 to 20 of the acceleration due to Earth's gravity (10 m/sec^2). If, for example, the rocket weighs 10 tons, then the pressure of explosives changes the slope from 0.5 to 20°. The loss of energy due to gravity and air resistance varies from 15 to 2.5 percent. It seems strange that the losses are less at high inclination; however, this is explained by the extremely large value of acceleration j. Actually the losses at small angles are even less, due to the curvature of the atmosphere on the spherical surface of Earth.

If the mass of the rocket M_0 is 8 times less, then from equations (119) and (122) we see that the sines of the angles and the losses (see Table 11) increase by a factor of 2. When $j = 30$, the angle will be approximately 11°, while the losses will be approximately 9.5 percent.

From Table 11 and equation (114) it is easy to see that the approximate equations do not introduce a very large error, even when j = 1. When j is large, it is much smaller.

Gravity, Atmospheric Resistance, and Earth's Curvature

From (101), (98), (97), and (100) we obtain the following in ordinary units

$$dT=\frac{Fd_1}{ag}(j-g\sin y)e^{-\frac{h}{h_1}}\dot{l}dl. \tag{122$_1$}$$

For the flat earth we also have from equation (99)

$$l=h:\sin y.$$

However, for the true shape of Earth it can be used only when the angles y are not too acute. For any arbitrary angles we can find a more accurate equation

$$h=l\sin y+\frac{l^2}{2R}=l\left(\sin y+\frac{l}{2R}\right), \tag{123}$$

where R is the radius of Earth.

From this we compute

$$l=-R\sin y\left(1-\sqrt{1+\frac{2h}{R\sin^2 y}}\right). \tag{124}$$

We let

$$\frac{2h}{R\sin^2 y}=X;\quad \sqrt{1+X}=1+\frac{X}{2}-\frac{X^2}{8}+\frac{X^3}{16}\ldots \tag{125}$$

If we limit ourselves to three terms we have

Table 11

Acceleration of rocket without gravity j	1	2	3	4	5	6	7	8	9
sin y = x	0.0097	0.0154	0.0204	0.0246	0.0292	0.0326	0.0356	0.0392	0.0422
Angle y in degrees	0.56	0.88	1.17	1.41	1.68	1.86	2.07	2.26	2.43
$Z:E_2$ = losses in percent	14.6	11.6	10.2	9.23	8.57	8.07	7.66	7.33	7.05

Acceleration of rocket without gravity j	10	15	20	25	30	40	50	60	80	100	200
sin y = x	0.0453	0.059	0.072	0.083	0.094	0.114	0.133	0.150	0.182	0.211	0.333
Angle y in degrees	2.60	3.41	4.16	4.75	5.41	6.55	7.66	8.66	10.50	12.16	19.50
$Z:E_2$ = losses in percent	6.80	5.94	5.40	4.97	4.71	4.28	3.98	3.75	3.40	3.16	2.50

/147

$$l = -R\sin y\left(-\frac{X}{2}+\frac{X^2}{8}\right)=\frac{h}{\sin y}-\frac{h^2}{2R\sin^3 y}=$$
$$=\frac{h}{\sin y}\left(1-\frac{h}{2R\sin^2 y}\right). \tag{126}$$

We solve the problem of the work performed by the resistance of the atmosphere for a specific case when the flight is horizontal and y = 0.

Then

$$h=\frac{l^2}{2R} \quad \text{and} \quad l=\sqrt{2Rh}. \tag{127}$$

Furthermore, from (102)

$$dT=\frac{Fd_1}{ag}\,je^{-\frac{h}{h_1}}l\,dl=\frac{Fd_1}{ag}\,je^{\frac{-l^2}{2Rh_1}}l\,dl. \tag{128}$$

We let

$$\frac{l^2}{2Rh_1}=u.$$

Then

$$l\,dl=Rh_1\,du, \tag{129}$$

and in place of (128)

$$dT=\frac{Fd_1}{ag}\,jRh_1e^{-u}du=Ae^{-u}du. \tag{130}$$

Integrating and determining the constant, we find

$$T = A(1 - e^{-u}) = A\left(1 - e^{-\frac{h}{h_1}}\right) = A\left(1 - e^{-\frac{r^2}{2Rh_1}}\right). \qquad (131)$$

Here

$$A = \frac{Fd_1}{ag} jR \cdot h_1. \qquad (132)$$

This expression determines the total work of atmospheric resistance.

For vertical motion we have /148

$$T = \frac{F(j-g)}{ag} d_1 h_1^2. \qquad (111)$$

During vertical motion of the projectile the work performed by atmospheric resistance will be less by a factor ((132) and (111))

$$\frac{j}{j-g} \frac{R}{h_1}. \qquad (133)$$

Here we let

$$j = 100;\ g = 10;\ h_1 = 8{,}000.$$

Then from (133) we obtain the value 883, i.e., the work during horizontal motion is almost 1,000 times greater than the work done by the resistance of the atmosphere during the vertical motion of the projectile. This is explained by the fact that the projectile, whose speed increases, must pass through very dense layers of the atmosphere. Therefore, the path which is close to the horizontal is very disadvantageous: the work of resistance will absorb a tremendous part of the rocket's force, and the latter will not achieve sufficient velocity. We have seen that the work of the vertical resistance of the air constitutes approximately 1/4,000 part of the kinetic energy of the projectile (when M_0 = 10 tons).

This means that horizontal resistance will absorb approximately 1/5 (22.2 percent). Table 11 shows that when the inclination is half a degree (0.56), the loss is somewhat less, approximately 15 percent (14.6). Here only 1/3 is due to the resistance, i.e., 5 percent. The value is so small because the acceleration according to Table 11 is 100 times less then the one we have assumed. In this case we have, therefore, losses due to the effect of gravity.

From (132) we see that T depends to a great extent on j, and that horizontal flights are advantageous when j is small. We can compute for various j the work performed by the resistance of the atmosphere during the horizontal motion of the projectile. Again we assume

$$F = 2,\ a = 50;$$

then (see 132)

$$T = 264{,}800. \tag{134}$$

The work performed by the rocket will be, from equations (41) and (38),

$$E_2 = 0.5 M_0 W^2 \left[\ln\left(1 + \frac{M_1'}{M_0}\right)\right]^2. \tag{135}$$

The work performed by the rocket to overcome Earth's gravity (11 kg) when $M_0 = 10$ constitutes approximately $64 \cdot 10^6$. This is greater than atmospheric resistance by a factor 240:j.

Let us prepare Table 12. /149

Table 12

Explosive force j	1	2	5	10	20	30	50	100
Losses in percent	0.42	0.83	2.1	4.2	8.3	12.5	20.8	41.7

Even if the acceleration is j = 5, i.e., half Earth's acceleration (g = 10), the losses are approximately 2 percent.

Ascent, Visit to the Planets and Descent to Earth

Let us assume that the rocket has ascended vertically to some altitude and lost its velocity there. Under the action of gravity it will fall back and achieve a substantial velocity and break up when it hits Earth, in spite of the braking action of the atmosphere. Even the braking action of the atmosphere may destroy the projectile or kill the organisms contained within it. However, if we imagine that after the rocket has risen, it retains a supply of explosives and uses these to slow down its descent in exactly the same order as this velocity was increased during the ascent from Earth, then the descent will be entirely safe and the projectile will come to a stop at the surface of the planet, i.e., it will return safely to Earth.

If, in order to achieve the ascent, a quantity of explosives must exceed the weight of the rocket by a factor K_1, then for safe descent we must also have a supply equal to the mass of the rocket multiplied by K_1. For the ascent alone the mass of the rocket with the explosives will be

$$M_0 + M_0 K_1 = M_0 (1 + K_1). \tag{136}$$

For safe descent the required additional supply of explosives, which are greater by a factor K_1 than this mass (136), will be

$$M_0 (1 + K_1) K_1. \tag{136$_1$}$$

With the weight of the rocket and weight of the initial supply (136), this gives us

$$M_0 (1 + K_1) K_1 + M_0 (1 + K_1) = M_0 (1 + K_1)^2. \tag{136$_2$}$$

The mass of a single supply will be

$$M_0 (1 + K_1)^2 - M_0 = M_0 [(1 + K_1)^2 - 1]. \tag{137}$$

If, for example, $M_0 = 1$, $K_1 = 9$, then the supply will be 99, i.e., its weight will be 99 times greater than that of the rocket with all its accessories (except explosives). It is questionable if this plentiful supply can be realized. The situation is even more difficult when we decide to take off from the surface of Earth and land on some foreign planet (which we may assume is situated in Earth's orbit), ascend from this planet and return home.

The situation is different when the altitude reached by the projectile is small and K_1 is a small fraction. In this case the supply will be approximately equal to

$$M_0 2K_1$$

(see (137)). This means that the supply is only doubled.

However, ascent to a low altitude is not of cosmic significance.

If we ascend from Earth and descend to a strange planet in Earth's orbit (no such planet exists), we would require a supply of

$$M_0\left[(1+K_1)(1+K_2)-1\right]. \tag{138}$$

Here K_2 designates the relative quantity of explosives required to descend to or ascend from a strange planet.

If we can replenish our supply of explosives on this planet and wish to leave the planet and return to Earth, we must take with us a supply of explosives equal to:

$$M_0\left[(1+K_1)^2(1+K_2)^2-1\right]. \tag{139}$$

If we assume that the mass and volume of the planet are the same as those of Earth, the required supply will be

$$M_0\left[(1+K_1)^4-1\right]. \tag{140}$$

Let us assume that in this case $K_1 = 9$ and $M_0 = 1$. Then the supply will be 9,999, i.e., entirely unrealizable. This corresponds approximately to Venus. A journey to Jupiter or other massive planets is even less feasible, since for them the value of K_2 is tremendous. On the other hand, travel to asteroids, specifically to small ones, is feasible since K_2 may be considered equal to 0. This path to any one of them (we again assume that they are in the orbit of Earth) and return to Earth requires the supply of fuel given by equation (137).

If we visit other planets and do not have the facility of replenishing our supplies on them, and if we then return to Earth, we must carry with us a total supply equal to

$$M_0 [(1+K_1)^2 \cdot (1+K_2)^2 \cdot (1+K_3)^2 \cdot (1+K_n)^2 - 1]. \tag{141}$$

If n is the number of planets (including Earth) and if they are equivalent to Earth, we obtain the following value for the supply of fuel

$$[(1+K_1)^{2n} - 1] \; M_0. \tag{142}$$

Apparently this successive visit to the planets is even less feasible.[1]

[1] At this point K. E. Tsiolkovskiy presents an excerpt from his article called "Cosmic Ship," which considers descent with braking against the atmosphere. We omit this excerpt since the article is published in its entirety. - Editor's Note.

Horizontal Motion of a Projectile in an Atmosphere of Uniform Density When Its Longitudinal Axis Is Inclined /151

We assume ((83) and earlier), that the rocket must move through the air as if it were on a runway, i.e., that the atmospheric resistance will prevent it from deviating from a path controlled by the explosives and the force of gravity. Now we shall confirm this.

Let us assume that the rocket moves horizontally with a velocity c, and that its longitudinal axis makes some angle ξ with the horizon. Then the vertical pressure R_y, on it, according to the well-known laws of the resistance of fluids, will be

$$R_y = \frac{d}{g} F_h K_1 \sin \xi c^2. \tag{143}$$

Here F_h is the horizontal projection of the rocket, while K_1 is the resistance coefficient.

If the rocket moves horizontally, then it does not drop and the pressure below it R_y is equal to the mass of the rocket M_0. From (143) we find

$$\sin \xi = \frac{M_0 g}{d F_h K_1 c^2}. \tag{144}$$

Let us assume, for example, that $M_0 = 1$; $g = 10$; $d = 0.0013$; $c = 100$; $F_h = 20$; $K_1 = 1$.

Now we compute

$$\sin \xi = 0.0385 \quad \text{and} \quad \xi = 2.2°.$$

When M_0 is 10 times greater, ξ will also be almost 10 times greater.

When c is 10 times greater, the inclination will decrease by the factor of 100, i.e., it becomes negligibly small.

We shall try to determine the work of atmospheric resistance during the accelerated and horizontal motion of the rocket. The spherical shape of Earth decreases this work. The horizontal pressure R_x due to the resistance of the air will be

$$R_x = R_y \sin \xi = M_0 \sin \xi = \frac{M_0^2 g}{dF_h K_1 c^2}. \tag{145}$$

Consequently, the element of work is

$$dT = R_x dl, \tag{146}$$

where l is the length of the travel path.

We may assume that d is constant and that only c is variable.

$$c = \sqrt{2jl}; \tag{147}$$

where j is the acceleration of the rocket. Now from (147), (146) and (145) we obtain /152

$$dT = \frac{M_0^2 g\, dl}{2dF_h K_1 jl}. \tag{148}$$

Integrating and finding the constant, we have

$$T = A \ln\left(\frac{l}{l_1}\right), \tag{149}$$

where

$$A = \frac{M_0^2 g}{2dF_h K_1 j}. \tag{150}$$

If we compute the work from the beginning of the path where the velocity was zero, this work then, theoretically, is infinite. It becomes small when the rocket has travelled a path l along a runway and has achieved some velocity. In a medium with uniform density the work is slower, but increases without a limit. Let us substitute in (150)

$$M_0=1;\ g=10;\ F_h=20;\ K_1=1;\ j=10.$$

Then A = 19.2 and

$$T=19.2\ln\left(\frac{l}{l_1}\right). \tag{151}$$

Let us assume that after a path of 10 km the projectile will fly a total of 1,000 km; then

$$T=19.2\ \ln 100=88.3.$$

If, however, the projectile initially travels 1 km, then T = 132.5.

Thus the work done to keep the projectile from falling is relatively insignificant.

We may express this work as a function of the velocity c achieved by the projectile. From (147) and (149) we have

$$l=\frac{c^2}{2j} \text{ and } T=A\ln\left(\frac{c^2}{c_1^2}\right). \tag{152}$$

Thus, if the rocket has started its flight with a velocity of 100 m/sec, while the terminal velocity is 10,000 m/sec, then

$$T=19.2\ \ln\ (100^2)=176.6.$$

This is already a cosmic velocity which almost frees the projectile from the force of Earth's gravity; the work performed is, nevertheless, quite insignificant. If the flight was started with a velocity of 10 m/sec, then

$$T=19.2\ \ln\ (1000^2)=265.$$

The difference in the work due to this turns out to be very small. /153
The corresponding path l is computed in accordance with (147).
Specifically

$$l=\frac{c^2}{2j}=5\cdot10^6 \text{ м}, \tag{147}$$

or 5,000 km. (We should remember that in these calculations we did not take into account the drag coefficient.) However, with a path this long (although it is first horizontal), the rocket substantially moves away from the surface of Earth, first enters the rarefied air and then vacuum. In dense air the work will be huge due to the strong inclination of the projectile, while in the more rarefied atmosphere even equilibrium is impossible, and it is particularly impossible in the vacuum. The work of equilibrium becomes a meaningless quantity.

It is possible to follow a constant layer of air until a velocity of 8 km/sec is reached, after which the centrifugal force completely eliminates gravity. The inclination is restored and the work expended in supporting gravity disappears. In general, the work during circular motion is much smaller than the computed value, due to the effect of centrifugal force. However, in this case we have other difficulties. When the projectile moves in a dense medium the work of the drag resistance of the atmosphere becomes too great, even when the projectile has a sharp form. In addition to this, after a velocity of 8 km/sec is obtained, it is still necessary to get out of the atmosphere following a tangential or ascending path, which again requires a lot of work. Our calculations at the present have shown only that the work of supporting the weight is very small, but we have not shown that the path along the air of uniform density is the most advantageous.

Horizontal Motion of the Projectile When its Longitudinal Axis is not Inclined

The projectile moves in the direction of the force of gravity.

The drop or, more precisely, the velocity of drop per sec will be

$$c_y=c\sin\xi=\frac{M_0 g}{dF_h K_1 c}. \tag{165}$$

Again we assume that the flight of the rocket is horizontal. By ξ we designate the small angle showing the deviation of the projectile from its horizontal movement due to gravity and air resistance. Let us assume for example that, $M_0 = 1$; $g = 10$; $d = 0.00037$ (at an altitude of 10 km); $F_h = 20$; $K_1 = 1$; $c = 2{,}260$; $h = 10{,}000$. Then $c_y = 0.6$, i.e., 60 cm/sec.

If the projectile moves along a tangent with respect to Earth, then, on the one hand it moves away from Earth with a definite velocity; on the other hand it falls and approaches the surface of Earth depending on its forward velocity and the density of the medium. The drop is given by equation (165). If we eliminate d and c from this equation /154
(see (97), (127), and (147)), we obtain

$$c_y = \frac{M_0 g e^{\frac{h}{h_1}}}{d_1 F_h K_1 \sqrt{2j} \sqrt[4]{Dh}}. \tag{166}$$

The velocity of fall during the movement along the tangent will be expressed in the following manner. We have

$$l = \frac{j}{2} t^2, \tag{167}$$

where t is the time and D is the diameter of Earth. We also have

$$h = l^2 : D.$$

Consequently,

$$h = \frac{j^2 t^4}{4D}.$$

Differentiating this expression, we have

$$\frac{dh}{dt}=\frac{j^2}{D}t^3=\sqrt[4]{\frac{64}{D}}\sqrt{j}\,h^{3/4}. \qquad (168)$$

Now we are able to present Table 13.

Table 13

Period of the rockets' flight in sec	10	20	50	100	200	400	1,000
Velocity in m/sec when j = 10	100	200	500	1,000	2,000	4,000	10,000
l is the length of the path, in km	0.5	2	12.5	50	200	800	5,000
Altitude $h = l^2:D$ (approximately), in m	0.02	0.32	12.3	197	3,150	50,400	1,970,000
dh/dt, ascent velocity in sec	0.008	0.064	0.554	4.43	35.5	283	4,430
Density of air d	-	-	-	0.0013	0.000878	close to 0	
Velocity of fall due to gravity and air resistance, m/sec	3.85	1.92	0.77	0.385	0.280	very great	
$d_1:d$	1	1	1	1	1.48	550	10^{109}

Flight takes place approximately along the tangent to Earth. In view of this the projectile moves away from the spherical surface (4th entry). Initially this separation is almost unnoticeable; after 10 sec, when the projectile has travelled 0.5 km, this separation is only 2 cm. The separation velocity (5th entry) after 10 sec is 8 mm/sec. However, after 50 sec, when over 12 km has been travelled and the projectile has risen to an altitude of 12 m, the separation velocity is greater than 0.5 m/sec (55 cm/sec). In this case it is slightly less than the velocity of fall (7th entry). After approximately 50 sec, the latter velocity becomes insignificant compared with the velocity of separation from the spherical surface. After 200 sec, when the projectile has reached an altitude of 3 km and has achieved a velocity of 2 km, having travelled 200 km along the tangent, the lift velocity exceeds the fall velocity. It is limited by the resistance of air by a factor of 127. /155

However, after this the velocity of fall increases, becomes comparable with the velocity of lift, and finally exceeds it because the atmosphere becomes rarefied. We need an infinite velocity in a vacuum to obtain pressure or resistance to the medium equal to the weight of the rocket. At that point the body will fall only under the action of the force of gravity. In short, at that time we can completely ignore the resistance of air (which does not exist in the vacuum).

Let us see what happens. For approximately 1 min the rocket deviates down from the horizon; after this the flight becomes parallel to Earth; then the rocket moves away from Earth's surface, and the flight path approaches more and more the tangent to Earth. Gravity virtually does not affect the projectile, and it moves as if it were on a runway. However, after approximately 4 min have elapsed (265 sec), the air is so rarefied that the runway effectively disappears and the projectile flies under the influence of Earth's gravity which begins to take over; at this time the ship has already reached an altitude of 10 km, has flown 351 km, and has achieved a velocity greater than 2 km/sec.

It would appear that some part of the atmosphere with greater density aids the path of the projectile, since over this distance it provides the projectile with a "runway," which decreases the amount of work if we disregard the drag of the projectile. We have provided for the acceleration of the rocket to be equal to Earth acceleration (10

m/sec^2). The increase in pressure j on the projectile will make the deviation from the tangent even less noticeable, i.e., will strenghten the "runway." The flight trajectory may be established precisely, but we shall not do this since we have already presented many equations. The inconvenience of this tangential flight with respect to Earth is that the flight must be started from some altitude: from towers, or steep mountains, since at the initial period the rocket will fall. When $j = 10$, as we can see from Table 13, the average fall velocity due to gravity and air resistance cannot exceed 4 m/sec, if the beginning of the flight is considered when its velocity is 100 m/sec. Thus, in 40-50 sec the projectile will drop much less than 200 m. It will probably be closer to 100 m. After this the flight will be parallel to the surface of Earth, and then it will begin to move away from Earth. Under moderate action ($j = 10$) of explosives, the flight must begin from a tower with an altitude of 100 m or from a mountain with the same altitude, but having a steep slope of 45°. When j is greater, the required altitude can be less and the slope can be less. This relationship is inversely proportional. If the projectile initially moves along the horizontal plane and achieves a velocity slightly greater than 500 m/sec, it will not be necessary to set off the explosion again, since its fall will not exceed its movement away from Earth. /156

Moving up into the Atmosphere along an Ascending Line

Tangential flight is advantageous because it permits us to use a small degree of exploding force j. From the technical standpoint, particularly in the case of initial experiments, this is an extremely valuable advantage. However, from the standpoint of economy of energy needed to overcome air resistance, the best flight must be inclined to the horizon. As the inclination increases, we must necessarily utilize a greater explosive force j, because this flight is similar to climbing a mountain.

We have already considered this earlier, (83), with respect to the resistance of air. Now we can add that we were correct in assuming a negligible deviation from the fall due to the resistance of the atmosphere.

We have seen that a sharp ascent is undesirable, particularly a vertical one.[1] Here we assume flight into the atmosphere with low inclination. It has many advantages. In the first place, the losses are equal to the losses encountered when ascending a hill, i.e., the energy losses decrease more. At a high altitude where the air can no longer serve as support, the action of the explosives may be normal to the radius of Earth; as we have shown before, there would then be no energy loss at all. In the second place, we can utilize a small explosion force j. In the third place, we can use mountains to provide sufficient initial velocity of the projectile; as we have seen, this is very useful since we can prevent its fall, particularly if the inclination of the path is sufficiently high. In the fourth place, a certain amount of inclination in the path radically decreases the expenditure of energy used to overcome the drag produced by the atmosphere (compared with tangential or horizontal flight). Finally, when the force of explosion is small, the rocket and all its parts need not be too massive. Protective measures to achieve the safety of man also will not be required.

During the inclined ascending motion of the rocket the distance h from the spherical surface of Earth depends on two factors - on the angle of inclination and on the spherical characteristics of the planet. The first is equal to /157

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[1]However, when the rocket flies with the most advantageous velocity and with the same acceleration acquired for this purpose, Oberth (Germany) comes to the conclusion that if the applied acceleration is infinite, then vertical ascent is most advantageous. See the book by Oberth entitled "Wege zur Raumschiffahrt." - Remark by Tsander.

$$h = l \sin y, \tag{169}$$

while the second is equal to

$$h_2 = l^2 : D. \tag{170}$$

We then have

$$h_1 + h_2 = l \sin y + \frac{l^2}{D} = l\left(\sin y + \frac{l}{D}\right). \tag{171}$$

The fall will be expressed by equations (165) and (166) which are known to us. The angle ξ in these should be interpreted as another angle giving the deviation entirely as a function of the resistance of the atmosphere and the forward motion of the flight. This angle ξ is generally extremely small.

During ascending motion, even though it be along a small angle of inclination y, the explosion force j cannot be arbitrarily small. Its minimum value is given by the equation

$$j = g \sin y. \tag{172}$$

In addition, the rocket will be standing on the top of the mountain (air). There will be no acceleration yet, but there will be a rapid fall. It is necessary and advantageous that j exceed this quantity substantially. We present the minimum j as a function of the angle of inclination y and the force of gravity g (Table 14).

Table 14

y in degrees	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, magnified by a factor of 10	1.75	3.49	5.23	6.98	8.72	10.5	12.2	13.9	15.6	17.4

We can see that j magnified by a factor of 10 even at 10° inclination is only 1.7 times greater than the acceleration due to Earth's gravity (10 m/sec^2). However, even at this inclination and at a smaller one, we can apparently limit ourselves to a much weaker explosive force, approximately down to 0.1 of the force of gravity. This has tremendous technical advantages since it makes the flight possible even at the present state of the engineering art.

In order to ascend by means of the inclined motion of the projectile, we have formulated equation (171).

The velocity of ascent (if we now neglect the spherical shape of Earth) will be

$$-c \sin \xi .$$

On the other hand, the rate of fall is given by equation (165). If we equate the fall to the rise, we find an equation from which we obtain /158

$$\sin \xi = \frac{M_0 g}{d F_h K_1 c^2} . \tag{173}$$

With this angle the initial velocity will be horizontal. If, for example, $M_0 = 1$; $g = 10$; $F_h = 20$; $K_1 = 1$; $c = 100$, then $\sin \xi = 0.0385$, while the angle $\xi = 2.2^{\circ}$. With a velocity of 200 m, the angle will be close to 0.5°.

It is quite possible to prevent the falling of the missile, even when the angle of inclination is very small, provided the initial velocity is sufficiently great. However, it may be much less, if the angle of inclination is greater. If the angle reaches a value of 8°, then a velocity of 50 m/sec is already sufficient.

Engine and Fuel Consumption

The Power of the Engine for a Rocket Weighing 1 Ton

In Table 15 we give the power of the engine for every ton of rocket for various velocities and accelerations; the power is expressed approximately in thousands of metric horsepowers (100 kgm/sec); the velocity of the rocket c_1 is given in km/sec for different periods of motion.

It turns out that the power of a 1 ton rocket with the least possible acceleration (and, of course, a small angle of inclination) varies from 100-11,000 metric hp.

If the rocket produces 100 kg of thrust on the engine, initially the power will be close to that of an aeroplane engine (100 metric hp), and only when it reaches extreme cosmic velocity will it increase by a factor of 110.

At first glance this is frightening, but we should not forget that we are dealing with a reactive (or rocket) engine.

Table 15

c_1, km/sec		0.1	0.2	0.3	0.5	1	2	5	8	11
	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
Acceleration j of rocket in m/sec^2 or explosive force	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

Consumption of Fuel for Different Values of Explosion Force: Terminal Velocity and Explosion Time as a Function of Fuel Supply

The problem consists of exploding a definite and constant quantity of explosives in the tube every second. We shall show by an example and in Table 16 that this quantity is not large at all. For example, for a 1 ton rocket which reaches a cosmic velocity of 8 km/sec, it is sufficient to have 4 tons of explosives. The period of explosion to obtain this velocity will be 8,000 sec, if the average value of the explosive force is equal to 1 (0.1 of the force of gravity). This means that in 1 sec 0.5 kg of explosives must be exploded, on the average. What do we have here that is not attainable? Even if the explosive force were 10 times greater (with a larger incline), it would be necessary to explode 5 kg per sec. This, too, is possible.

Table 16 gives us approximately the average quantity of explosives expended per sec for different values of explosion force j. The weight of the rocket is 1 ton. /159

Table 16

Supply of explosive material in tons	1	4	9	30
Terminal velocity, m/sec	3,465	8,045	11,515	17,170
Period of explosion in sec	3,465	8,045	11,515	17,170
Period 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
Quantity of explosives in kg/sec, j = 5	1.45	2.5	3.9	8.75
Quantity of explosives in kg/sec, j = 10	2.9	5	7.8	17.5

The second cosmic velocity is sufficient for us to become a satellite of Earth, of course, outside the atmosphere. The third cosmic velocity is sufficient to overcome Earth's gravity and to travel along Earth's orbit. In this case also the amount of explosives consumed per

sec is less than 1 kg. The last velocity is sufficient for us to escape permanently from our solar system and to float in the Milky Way with a velocity not less than that of a cannon shell. Even in this case, the amount of fuel consumed per sec is less than 2 kg. The explosion period lasts from 1-5 hours. All this happens when the explosive force j is 10 times less than Earth's force of gravity. When the force j is greater, the fuel consumption increases proportionately and the period of explosion decreases. The increase in the mass of the rocket is also /160
accompanied by a proportional increase in fuel consumption, while the period of explosion does not change. At first it seems odd that the work performed by the rocket engine increases progressively (with the velocity of the projectile), while the fuel consumption does not change. The fact is that the explosive, which has not yet been exploded, already has energy which increases as the speed of ship increases. Therefore, it releases it in greater quantity than that which is due to its potential chemical energy.

Conclusions

Based on the information presented we may make the following conclusions. It is more advantageous to initiate the flight on the top of mountains at the maximum possible altitude. The runway must be constructed on the mountains with an inclination of not more than 10-20°. The rocket is placed on an automobile which imparts to it a velocity of 40-100 m/sec. Then the projectile flies by itself in an ascending path, producing behind it the pressure of explosives. As the velocity of the projectile increases, its inclination decreases and the flight approaches the horizontal direction. However, when the projectile has left the atmosphere and is a certain distance away from all its traces, the flight becomes parallel to Earth's surface, i.e., it becomes circular. The acceleration j must have a minimum value, approximately from 1-10 m/sec^2. The fuel consumption to overcome air resistance will become minimum. The effective gravity will also be almost completely overcome (from the standpoint of energy loss). The first velocity is obtained by an automobile, aeroplane or some other device; these devices may operate on dry land, water or air. Flight in atmosphere not too rarefied may take place by means of fuel burned with oxygen obtained from the atmosphere. This will save the fuel supply by a factor of 9 (this is the ideal number, when only pure hydrogen is stored). If the rocket, while it is still in the air, has not achieved the cosmic velocity which separates it from gravity, then we can no longer use the atmospheric oxygen in the highly rarefied layers of the atmosphere.

Therefore, a reserve supply of liquid oxygen is released, or its unstable combination with other gases (for example, nitrogen). Then the velocity obtained is increased until it becomes equal to the cosmic velocity.

Preparatory Rocket on the Earth

Purpose of the Rocket. Runway. Engine. Air Resistance. Friction

We have seen that while the rocket is still on Earth it must attain a certain velocity so that it can fly horizontally or along an inclined ascending path. The greater the velocity it achieves on the runway, the better it is. It is desirable that the projectile not use its own supply of energy in the form of explosives. This is only possible when our rocket is placed in motion by an external force: by automobile, ship, locomotive, aeroplane, airship or by means of gas or an electromagnetic cannon, etc. Existing methods cannot produce a velocity greater than 100-200 m/sec, since neither the wheels nor propellers can turn fast enough without breaking down. The circumferential velocity may be brought up to 200 m/sec, but not more.[1] This velocity (720 km/hour) cannot, therefore, be produced by conventional means of transportation. Apparently this also is too much for the beginning. However, we shall strive to impart to our rocket the greatest possible preliminary velocity, so that it may conserve its fuel supply for future flight when it leaves its solid path. We can see that if a projectile is to attain a velocity greater than 200 m/sec, special devices will be necessary. Gas cannons and electromagnetic cannons must be rejected initially, since they are very expensive to construct, costing millions due to their great length. If the paths are short, the relative gravity (impulse) will kill and destroy. The simplest and cheapest approach is to use a rocket or a reactive device. We are trying to say that our cosmic rocket ship should be placed on another earth rocket and held by the latter. The earth rocket, which does not separate from the ground, will provide it with the necessary initial velocity. For the earth's rocket we must have a plane, rectilinear, inclined ascending path. /161

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[1]However, in engineering, for example, centrifugal superchargers for aircraft engines and high speed turbines have already achieved velocities up to 400 m/sec. - Remark by Tsander.

Aircraft propellers are not feasible or necessary. Their thrust is replaced by the back pressure of gases exploding in a tube. Wheels are unsuitable to reduce friction. The earth rocket must move like a sled.

The friction of solid bodies represents rather substantial resistance, even if lubrication is used. For example, the coefficient of friction for iron over dry cast iron or bronze (and vice versa) is approximately 0.2. This means that the projectile weighing 1 ton is placed into motion along a horizontal plane by a force not less than 0.2 tons, or 200 kg. This is the magnitude of friction for pressures which do not exceed 8-10 kg/cm^2 between the rubbing surfaces.

It is amazing that the coefficient of friction decreases by a factor of 4 or more as the velocity increases (within narrow experimental limits). Under ordinary pressure these limits are not violated, and with ample lubrication the coefficient of friction of the same bodies may decrease by a factor of 5-10. If the rubbing surfaces are wetted by water, friction decreases by a factor of 2. The coefficient of friction of metal against ice and snow (and vice versa) reaches a /162 value of 0.02, i.e., 10 times less than the friction of dry dissimilar metals, and it is thus comparable with the magnitude of friction when we have ample lubrication. If the rocket moves over ice or over a uniformly lubricated metallic runway, there are no insurmountable difficulties for rapid motion without wheels. If, for example, the projectile is subjected to gas pressure equal to its weight ($j = 10$), from 20-2 percent of the energy required to move the earth rocket is expended to overcome friction. When the acceleration is 5 m/sec^2 ($j = 5$), the consumption will be from 40-4 percent. If $j = 1$, then the consumption will be from 200-40 percent, which is unsuitable.

As a matter of fact, I know of a method for reducing the ground friction to 0, but I shall discuss this in another book.[1]

We begin to think of an earth rocket moving along ordinary, but smooth and strictly rectilinear rails, which are amply lubricated by grease, oil or ice protruding from the runners of the machine. Ice may only be used during the cold part of the year or on high mountains with temperatures below zero.

The shape of the earth rocket must be streamlined. The more elongated it is the easier it will be for it to penetrate the medium if we neglect the friction of air on the walls of the earth rocket. If its elongation is 100 or 200, i.e., when its length exceeds its maximum cross section by this amount, we may take into account only the friction.

[1] See my book "Air Resistance and a Fast Train." K., 1927.

In view of the very long path which, as we shall see, is necessary for the runway, the projectile itself may be quite long - there will be plenty of room.

Special calculations and considerations which we do not present here show that the magnitude of friction cannot exceed the number

$$\frac{dFV}{2g}, \tag{174}$$

no matter what the velocity of the rubbing surfaces. The equation shows that this limiting friction is proportional to the rubbing surface F, the density of the gas d and the velocity of its molecules V. This conclusion permits us to compare the gas at very high velocities with solid bodies, since in the latter case friction does not depend too much on the velocity of rubbing bodies. By transforming equation (174), it is easy to show that for "constant" gases and constant external pressure this limiting friction is proportional to the square root of the molecular weight of gas and inversely proportional to the square root of the gas temperature. This means, for example, that under atmospheric pressure heated hydrogen gives less friction than cold air, conversely, cold carbon dioxide gives more friction than heated air.

When the density of the gases is the same, the conclusion is exactly the opposite, i.e., hot gases with small molecular weight give a larger coefficient of friction. We shall discuss the limits. /163

From equation (174) the limiting friction for ordinary air along 1 m^2 is close to 0.011.

Other considerations of the magnitude of friction give us the following equation

$$R = \frac{slb}{2g} dc. \tag{175}$$

This shows that the coefficient of friction is proportional to the density of the gas d, to the velocity of the projectile, and to the thickness of the air which has adhered to 1 m^2 of the body moving with the velocity of 1 m/sec. Unfortunately this equation is valid only when the velocity of the projectile in m/sec is the same as the length of the projectile itself in m. Consequently, in this equation we must set $l = c$. Then we obtain

$$R = \frac{s}{2g} l^2 bd = \frac{s}{2g} c^2 bd. \tag{176}$$

We substitute here $2g = 20$; $b = 3$; $d = 0.0013$; in addition to this I know from personal experiments that $s = 0.01$ (1 cm). Then we find

$$R = 195 \cdot 10^{-8} \cdot c^2 = 195 \cdot 10^{-8}. \tag{177}$$

We also assume that the weight of the entire projectile in tons is given by the number 1. Then we prepare Table 17 for various accelerations j and various velocities of the projectile.

Table 17

Length, weight and velocity of earth rocket, in m, tons, and m/sec	1	10	100	500	1,000	1,500	2,000	3,000	5,000
Magnitude of friction, kg	0.002	0.2	20	500	2,000	4,500	8,000	18,000	50,000
Resistance with respect to pressure on the projectile in percent when j=10	0.0002	0.002	0.02	0.1	0.2	0.3	0.4	0.6	1
Resistance with respect to pressure on the projectile in percent when j=1	0.002	0.02	0.2	1	2	3	4	6	10
Resistance with respect to pressure on the projectile in percent when j=4	0.0005	0.005	0.05	0.25	0.5	0.75	1	1.5	2.5

We see that even when the velocity is 5 km/sec and the acceleration /164
of the earth rocket is 0.1 times its weight ($j = 1$), the losses do not exceed 10 percent. However, in this case we have a great inconvenience: the rocket must have a length of up to 5 km. With small velocities and a small projectile length, an insignificant percent of the work is absorbed. However, in this case a dull projectile will produce substantial resistance due to the work done to move the air apart.

The length of the earth rocket must not exceed 100 m, otherwise the rocket will have a large mass and will be very expensive. Also, the absolute work necessary to impart the velocity to it and overcome the air resistance would be too large. This means that we shall require a large supply of explosives, which will be quite expensive. If the rocket is shorter than shown in Table 17 by a factor c/l, then each particle of air will be subjected to displacement for shorter periods of time than is the case when the velocity of the projectile is numerically equal to its length.

The time will decrease by a factor (c/l).

The thickness l of the layer of air carried along will decrease, not proportionally, but approximately, by a factor $(1 + \ln (c/l))$. The resistance of air will decrease by the same factor. Instead of equation (176) we obtain a more accurate equation suitable for any arbitrary length of the earth rocket, specifically

$$R = \frac{sl}{2g} bdc : \left[1 + \ln \left(\frac{c}{l} \right) \right]. \qquad (178)$$

Let us assume that the length of the rocket is constant and is equal to 100 m. We also assume that the velocities are not the same. Then we obtain Table 18.

Table 18

c, м/sec	100	200	300	400	500	700	1000	2000	3000	4000
$\frac{c}{l}$	1	2	3	4	5	7	10	20	30	40
$\ln \left(\frac{c}{l} \right)$	0	0.69	1.10	1.39	1.61	1.95	2.30	3.00	3.40	3.69
$\left[\ln \left(\frac{c}{l} \right) + 1 \right]$	1	1.69	2.10	2.39	2.61	2.95	3.30	4.00	4.40	4.69

The last entry shows how the thickness of the adhering gas and the resistance due to friction decrease with change in length (second line).

Let us assume that in equation (178) s = 0.01; l = 100; b = 3. Then we find

$$R = 1.95 \cdot 10^{-6} c : \left[1 + \ln \left(\frac{c}{l} \right) \right]. \tag{179}$$

On this basis we can compile Table 19, showing the absolute and relative resistances for various explosion forces. /165

From this we can see that even with the smallest acceleration (j = 1) and an insignificant mass of the rocket (10 tons) friction absorbs not more than 17 percent.

Now let us solve the problem concerning the length of the runway for the earth rocket. Part of the runway will be used to accelerate the motion, while the other will be used to decelerate and eliminate it. Retro-explosion is not an economical way of destroying whatever velocity was achieved. This can be done quicker by using friction or air resistance, i.e., it can be done over a much shorter path-length. The lubrication may be discontinued, and plane surfaces installed perpendicular to the direction of motion. Their air resistance will quickly destroy the velocity of the earth rocket. To achieve braking, particularly if the cosmic rocket has already flown away, requires a much shorter path

Table 19

	c 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
Relative resistance percent	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

than for acceleration. The general picture is as follows. The earth rocket is accelerated together with the cosmic rocket. When the maximum velocity is achieved and the deceleration of the earth rocket begins, the cosmic rocket will leave the earth rocket due to inertia and will follow its own path due to its own explosion which has now started. The earth rocket which will be braked by air or by other means, will travel further along the runway, but will decrease its speed until it has stopped. We shall not consider the decelerating path of the runway, because it will be very short. In order for friction to be at a minimum, the cosmic rocket must constitute the front part of the earth rocket. Its nose will be in view, while its stern will be concealed in the earth rocket. When the motion of the latter begins to decelerate, the cosmic rocket will fly out of the earth rocket. This will cause a large aperture to open in the earth rocket, producing a /166
tremendous resistance and decelerating its motion very strongly. The earth rocket is very long, and the cosmic rocket will occupy only a very small portion of it with its stern. The remaining space will be filled with explosives and control equipment.

For compiling Table 20 (maximum velocities of the earth rocket), we have the equation

$$p=j-g\sin y. \tag{180}$$

Here we see the resultant p, acceleration due to the explosion force j, the acceleration due to Earth's gravity (10 m/sec^2), and the angle of inclination of the path with respect to the horizon. Furthermore,

$$c=\sqrt{2pl}=\sqrt{2(j-g\sin y)l}. \tag{181}$$

The pressure P of the explosives acting on the rocket is given by the equation

$$P=G_0\frac{j}{g}, \tag{182}$$

where G_0 is the weight of the rocket; pressure is expressed in conventional units.

Table 20*

Length of track, c, m/sec	1	2	5	10	50	100	200	300	500
$j=100$	447	632	1000	1420	3160	4470	6324	7746	10000
$j=50$	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	315	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

*The figures in this table have been corrected. - Editor's Note.

We assume that the runway is horizontal ($y = 0$). Maybe only a very small inclination will be required, which will slightly decrease the values of the velocities which we have presented, as well as the resistance of the air. /167

We obtain the period of motion of the earth rocket if we divide the velocity by the acceleration j. Thus, with a 500 km path, according to Table 20, it will be from 100-1,000 sec. When the path is 1 km long, the time will be from 4-1/2-45 sec. The time of deceleration may be quite short.

Gravity produced by acceleration, according to Table 20, varies from 0.1-10 times Earth's gravity. When it combines with the latter, it produces an apparent gravity in the rocket from 1-10 (approximately). The runway will be somewhere in the mountains at a high altitude with a possible length of 500 km (approximately 5° of earth's circumference), so that there is hope of achieving cosmic velocities. However, the high value of gravity will make it necessary to increase the strength of the rockets, and thus to increase their mass. Finally, the work done by the resistance of air will increase. It is sufficient to have an acceleration j which is equal to Earth's acceleration; we shall then be able to obtain a sufficient preliminary velocity up to 3,160 m/sec. A small, very useful inclination of the path by 10-20° will slightly decrease the preliminary velocity.

We can also compute the fuel supply for the earth rocket. If the empty earth rocket weighs 10 tons and the cosmic rocket with its charge weighs the same amount, both of them weigh 20 tons. From Table 6 we compute in tons the supply of explosives for the earth rocket, necessary to achieve various velocities. We shall assume that the velocity of the ejected material is 4 km/sec.

These velocities are quite sufficient, and the supply does not exceed 40 tons. We note that strong deceleration may kill a man controlling the earth rocket. Therefore, it is better if the latter is controlled automatically and does not carry any people. The passengers in the cosmic rocket during deceleration will not be attached to the earth rocket from which the cosmic rocket will have separated.

If the rocket has thus obtained an initial velocity without using its own supply, it may carry a smaller supply, or, if the supply is the same, it may obtain a greater cosmic velocity.

We had /168

$$dc = -W\frac{dM_1}{M_0 + M_1} \tag{34}$$

and

$$c = -W \ln (M_0 + M_1) + \text{const.} \tag{35}$$

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, m	2	4	6	8	10	12	14	16	18	20	30	40
c_1, m/sec	378	728	1048	1344	1620	1876	2116	2344	2568	2772	3660	4392

If the initial velocity of the rocket is equal to c_0, then $M_1 = M''_1$, i.e., the mass of the ejected material will be maximum (initially). Consequently

$$c_0 = -W \ln (M_0 + M'_1) + \text{const.} \tag{183}$$

Subtracting (183) from (35), we obtain

$$c - c_0 = W \ln \left(\frac{M_0 + M'_1}{M_0 + M_1} \right) \tag{184}$$

If $M_1 = 0$, we obtain the maximum velocity c_1. Consequently

$$c_1 = c_0 + W \ln \left(1 + \frac{M'_1}{M_0} \right). \tag{185}$$

Let us assume that the preliminary initial velocity of the rocket is equal to 3 km/sec and that we must have c = 8 km/sec. We assume that W is equal to 5 km/sec. According to Table 6 we find the relative supply of fuel for the cosmic rocket equal to $M''_1 : M_0 = 1.8$, whereas to obtain a velocity of 8 km/sec it is necessary to have a relative supply of 4 (Table 6). From (185) we obtain /169

$$\frac{M'_1}{M_0} = 1 - e^{\frac{c_1 - c_0}{W}}. \tag{186}$$

We make use of this equation to compile a comparison, Table 22.

Table 22 shows that the cosmic rocket with preliminary velocity is much less overloaded by explosives than the one without this velocity. For the cosmic velocities obtained above, which overcome the attraction of the sun (17 km/sec), it would be necessary to have a supply of explosives 30 times greater than the weight of the rocket. If the rocket, while still on land, has attained a velocity of 5 km/sec, the relative supply will be only 10 times the weight. The first cosmic velocity requires a 4-fold supply; but if the preliminary velocity is 3 km/sec, then the weight of the explosives will only be 0.8 of the rocket's weight.

Table 22

c_1, m/sec	8	11	17
$c_1 - 5$	3	6	12
$M''_1 : M_0$ (re (186))	0.8	2.31	10.0
$M'_1 : M_0$ (re 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 Rocket

The earth rocket is elongated for minimum resistance. The ratio of the length to the maximum cross section may reach a value of 50. Since the rocket does not leave the Earth and the sufficiently dense layers of the atmosphere, it need not be hermetically sealed. Its frame may be similar to the frame of an aeroplane. It contains a compartment for explosives which are pumped into the explosion tube and are ejected by the force of explosion from the rear. It also contains a pump driven by a gasoline engine (it is also possible to use a small part of the explosives for this; after operating the engine, they enter the explosion tube and perform the work of reaction).

Cosmic Rocket

A cosmic rocket must have a minimum mass and volume so that it will be easier to realize it. The ratio of its length to its maximum cross section should not be greater than 10. The maximum cross section is not less than 1-2 m. Its shape is also streamlined, but its shell is hermetically sealed, since the rocket will travel into space free of air where all the gas necessary for breathing could escape through openings.

The principal shell of the rocket must safely withstand a pressure of not less 0.2 atm, if it is filled with pure oxygen. Indeed, at sea level we obtain the largest amount of oxygen. Its partial pressure is approximately 0.2 atm. Its quantity is also the same. This means that from the physiological standpoint there is enough. However, a human being is able to withstand, or at least become adjusted to half this quantity of oxygen. On the mountains (5-6 km high) where the oxygen content is reduced by 1-1/2, a human being is still capable of living. Healthy people, although they may endanger their life, withstand an additional rarefaction by a factor of 2 (at an altitude of 10 km). In any case, 0.5 of the usual quantity of oxygen is sufficient. That means that there is enough oxygen when its pressure is 0.1 atm. /170

The rocket's shell must have a valve which opens to the outside, if the difference between internal and external pressure of the medium exceeds, for example, 0.2 atm. At sea level the absolute pressure in the rocket would be not greater than 1.2 atm, while in vacuum the pressure inside the projectile will not exceed 0.2. These apparently are the limits suitable for respiration. If we use a regulator to increase the external pressure on the valve up to 1 atm, the limits will be from 1-2 atm. The latter is suitable in the initial period of time as a supply for breathing. The internal gas pressure requires that we make the rocket in the form of a dirigible with round, circular cross sections. The same is useful for achieving the least air resistance. It also eliminates unnecessary internal reinforcements and partitions. A rocket which has been thoroughly inflated replaces a complex beam and has good resistance to flexure and to a general change in shape. However, since the rocket must glide (and, without wings it can do this only weakly), it is useful to connect several shells (rockets) having the shape of a body of revolution. The rockets are joined along their sides, and the places where they are joined must be strengthened by internal partitions. Such a complex rocket which resembles a wavy platter with several sharp tails and heads, or one large wing, will be able to glide more readily. The cosmic rocket must also undergo increased gravity. This requires that all its component parts be made much stronger than required to overcome conventional gravity. The individual containers for the explosive materials must be stronger. However, we have seen that the most advantageous flight is one with low inclination and with low acceleration rate ($j < 10$). In this case the change in gravity will be so small that all the calculations may be carried out assuming a conventional force of gravity.

We must also consider the condensation and expansion of the medium
surrounding the rapidly moving rocket. At the nose the air is compressed,
which makes it possible to make this part of the rocket shell weaker or
thinner; in the stern the atmosphere expands, which requires that the
stern part be made thicker or stronger. These forces act when the
rocket is in the atmosphere. In the vacuum they do not exist. Neverthe-
less, it is necessary to make the rear part more rugged, without weaken-
ing the forward part. This is very significant for the cosmic rocket
and less significant for the earth rocket with its substantial elonga- /171
tion. We have seen that the total longitudinal resistance to the air
constitutes a small part of the pressure exerted on the rocket by the
explosives. The pressure normal to the walls of the rocket is of the
same order of magnitude. Consequently, for average j it comprises a
quantity which does not exceed the force of normal gravity. Since there
is a large factor of safety in the strength of the rocket, these forces
as well as the forces of relative gravity may be neglected.

We assume that the principal parameter for a spindle-like rocket is the difference between the internal and external pressure. Table 23 shows the mass of the shell constructed from the strongest alloys of iron with a 4-fold factor of safety and the pressure difference of 1 atm (instead of the necessary 0.2 atm). This weight depends primarily on the volume of the shell and not on its shape and elongation, if we assume a spindle-type uniform shape.

Table 23

Volume of the rocket, m^3	5	10	15	20	30	40	50	100
Weight of internal gas having density of air, kg	6.5	13	19.5	26	39	52	65	130
Weight of shell, kg	33	65	98	130	195	260	325	650

It turns out that the weight of the shell is only 5 times greater than the weight of the air contained within, if it has a normal density (0.0013). At a pressure of 0.2 atm, the factor of safety will be 20, while at 0.1 atm, the factor of safety will be 40. It is sufficient to have 10 m^3 of space to accomodate one man. Then the oxygen supply is sufficient to provide for one man for a period of 10 days, if all the products of respiration are consumed within the rocket.

The maximum load which the rocket can carry as a function of its volume is expressed approximately in tons (first line, Table 23). This load for all of the volumes is approximately 154 times greater than the weight of the shell. As a matter of fact, for small rockets the shell will turn out to be impractically thin, so that it will be necessary to make it 2-3 times thicker in spite of the small volume. This will further increase the safety factor of small rockets. However, shells for small volumes in this case will represent a larger part of the maximum load lifting capacity (154), for example, 1, 2, 10 percent. For larger volumes the weight of the shell is less than 1 percent. We have already spoken of the external lamellar shell, which makes it possible to obtain 150° of heat and 250° of cold from the sun's rays in the ether. If it is a bright form it may prevent the rocket from heating during flight through the atmosphere, particularly if a cold gas liberated from the rocket passes between it and the hermetically sealed shell.

Explosives

Liquefied hydrogen has less potential energy, since it is cold and absorbs energy when it is transformed into a gas, so that its chemical action is weaker.[1] It is difficult to liquefy and store because it evaporates very quickly unless special measures are taken. The most useful explosives are liquid or easily liquefied hydrocarbons. The more volatile they are, the more hydrogen they contain and the more advantageous they are for this purpose. Oxygen in liquid form can be tolerated, particularly since it serves as a source of cooling the rocket (during the period of motion through the atmosphere it heats up) and the explosion tube. However, it is more rational to proceed as follows: to take the major supply of oxygen in the form of some endogenous compound, i.e., compounds which are synthesized with absorption of heat. When they are broken down, they again liberate heat and thus increase the energy of combustion. Another smaller part of oxygen may be taken in its pure and liquid form and may serve as a cooling agent and, later, for breathing and explosion. Only a small supply of this can be taken. Hermetically sealed liquid gases develop very high pressures and very heavy vessels are required to overcome this pressure. /172

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[1] However, as a whole, its heat-producing capacity is greater than that of hydrocarbons. - Remark by Tsander.

Therefore, if they are not to be this massive, they must have openings through which the resultant gas may escape freely. This way their low temperature can also be maintained. The action produced by the complex explosives is not quite as good as that of pure oxygen or hydrogen. The latter give an ejection velocity (products of combination or combustion) of 5 km/sec, while the complex fuels give a velocity of 4 km/sec. This means that the velocity of the rocket in the latter case will be decreased by the same factor, i.e., by 20 percent.

Some people have proposed using compressed gases in vessels or highly heated volatile liquids. This is entirely unsuitable for the following reason. Most accurate and numerous calculations which I have carried out show that the weight of vessels of the best form and material is at least 5 times greater than the weight of the compressed gas which replaces the combustible material. From this we can see that the ejected gas will always be 5-10 times less than the weight of the rocket. We have seen, however, (Table 6) that in order to obtain the lowest cosmic velocity, it is necessary that the combustible material, under the most advantageous conditions, exceed the mass of the rocket by a factor of 4. Although light gases are more advantageous, they also require heavy storage vessels. The same can be said of a highly heated gas. Water and other volatile liquids heated in moderation have certain advantages and therefore are more suitable for the initial experiments involving low altitude flights. My calculations have shown that compressed gases can be used to achieve an altitude of not more than 5 km, while superheated water can be used to achieve an altitude not above /173 60 km.

There is nothing that contains more energy or is more suitable among the explosives mentioned earlier.

How are these explosives to be set off and how are they to be stored? If we set off the explosion in the same way as in all the known old and new rockets, then the reactive pressure during explosion will be transmitted to the entire surface of the vessel (reservoir), which will require that the latter be very massive. The pressure produced by the explosives reaches a value of 5,000 atm. In this case calculations show that the weight of the storage tanks is at least 30 times greater than the weight of the explosives, if they have the density of water (actually one is less, which makes it worse). If this is so, the projectile will not reach an altitude in excess of 15 km.

However, we shall lose little, if by means of a moderate mixing of the combustible materials we lower their pressure to 100 atm, or by a factor of 50. In this case the supply of explosives may increase by the same factor and achieve a value of 1-2/3. However, this supply is also too small. A further decrease in the pressure of explosion is undesirable because of the atmospheric pressure and the low efficiency of utilizing the chemical energy. It is much more rational to keep the elements of explosion in a special way, without pressure, and to pump them into the explosion tube, i.e., a special chamber where the chemical combination of elements (combustion) takes place. To store them we may use conventional tanks or the partitioned rocket itself. The inconvenience here is that it is necessary to overcome the pressure of the explosion when pumping the substances into the chamber. However, if the pressure is not greater than 100 atm, the work of this supercharging is not too great.

In Table 24 we show this work for various cosmic velocities and different values of the explosion force. The weight of the rocket is assumed to be 1 ton and the pressure is assumed to be 100 atm.

We can see that for the smallest force of explosion $j = 1$ and for the lowest cosmic velocity of 8 km/sec, the work of pushing in or pumping in fuel is limited to 50 kg/m or half of a metric horsepower. For the greatest cosmic velocity and a 10-fold increase in the explosion force ($j = 10$), the work reaches the value of 17 metric hp.

Table 24

Velocity of the projectile in km/sec	8	11	17
Mass of explosives, in tons	4	8	30
Period of explosion in sec, when $j = 10$	800	1,100	1,700
Fuel consumption in kg/sec	5	11	17
Work of pumping, kilogram meter (kgm)	500	1,100	1,700
Period of explosion in sec, when $j = 1$	8,000	11,000	18,000
Fuel consumption in kg/sec	0.5	1.1	1.7
Work, kgm	50	110	170

All this can be achieved quite easily and may even be decreased when explosion takes place periodically, as we have already stated. It is clear that when the mass of the rocket is increased the work increases proportionately.

The figures which we have presented are approximate and average. The density of the explosives is assumed to be equal to unity.

We can also see from Table 24 that the work of pumping the explosives will not be overly heavy, even when the pressure of the explosives reaches a value of 1,000 atm. However, when the mass of the rocket is large and the pressure is high, it is economical to use periodic explosion and pumping. Then the amount of work required will be substantially reduced.

Components of the Rocket /174

Explosion Tube. Shape. Pressure. Weight. Cooling

The principal engine of the rocket is the explosion tube which, in its action, is similar to that of a cannon fired without a shell. We shall see below how much lighter the explosion tube is than the container which withstands its pressure. Table 24 shows that when the supply of explosives is 4 tons, the amount consumed per sec is 0.5 kg. The same amount of substance leaves the tube every second. This means that the tube is a vessel containing 0.5 kg of material at a pressure substantially less than the pressure in the vessel (where it is maximum and uniform). The vessel (tank) contains an amount of material greater by a factor of 8,000. It would follow then that its weight must be at least greater by the same factor. This is approximately the economy which my rocket represents, compared with those which are being used. The cylindrical shape of the tube turns out to be too long. A conic shape decreases this distance, and more so as the cone angle becomes greater. However, the greater the cone angle, the greater is the energy loss, since the movement of the gases is displaced sideways. Nevertheless, with an angle of 10° the loss is almost insignificant. However, even an angle this large is not necessary. The cone must be truncated. The combustible materials are pumped into the smaller base. They mix in the tube, explode, flow towards the wide open base in the cone and escape in a rarefied, cooled form with a velocity up to 5 km/sec. In /17
the cylindrical tube the useful pressure acts only on the round base of the cylinder into which the explosives are pumped; in a conic tube, on the other hand, the pressure is exerted on the entire inner surface of the cone.

Therefore, the base of a conic tube is much less than that of a cylindrical tube.

It is easy to derive an equation showing the ratio of the areas of the two cone bases:

$$F_{max} : F_{min} = \left(1 + \frac{l}{r} \operatorname{tg} \alpha\right)^2, \qquad (187)$$

where the following appear in order: the area of the large base and that of the small base, the length of the tube, the radius of the smaller base and the tangent of the cone angle.

If the rocket weighs 1 ton, has 5 tons of explosives and its acceleration $j = 10$, then the pressure of the gases in the tube must also be 5 tons. With a maximum gas pressure of 100 atm and with a cylindrical tube, the area of its base will be 50 cm^2, its diameter will be 8, and its radius 4 cm. Assuming its length to be 10 m and substituting various angles into equation (187) we find the values for the magnitude of the tube's divergence in Table 25.

Table 25

Angle in degrees	1	2	3	4	5	6	8	10
$F_{max}:F_{min}$	28.8	95.1	199	342	524	740	1296	2000
Ratio of diameters	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

We can see that it is sufficient to have a cone angle of 1° and in no case greater than 3-5°. The energy loss in this case will be entirely negligible. In spite of the conic shape of the tube a good utilization of the force of explosion requires as long a tube as possible, so that the gases transform their entire random motion (heat) into forward motion. In order to increase the length of the tube it is permissible to provide it with bends.

Engine for a Fuel Pump

The engine for a fuel pump, in view of its low power requirements, may be of the aeroplane type, except that in the rarefied layers and in vacuum it would have to consume stored oxygen. The exhaust must be directed into the general explosive tube or into a special tube parallel to the principal one. We must not ignore the small utilization of the energy of the hot products of combustion in the engines. We could utilize the entire supply of explosives in conventional engines (gasoline, gas) to obtain a tremendous amount of mechanical energy. We can see from Table 24 how large this energy can be. The minimum consumption of explosives according to Table 24 is 1/2 kg/sec. This quantity contains an energy (Table 1) of 1.37×10^6 kgm. If we utilize 30 percent of this, we obtain mechanical energy of 411,000 kgm/sec. This corresponds to continuous work of more than 4,000 metric hp. Having obtained this much mechanical energy, we make use of the products of combustion as a reactive material in the explosive tube. This would be particularly suitable in rarefied air and in vacuum. However, we have no need for such huge mechanical energy. In order to pump the explosives we require a very small amount of work (Table 24), from 1-100 hp. This is also quite impossible since the aeroplane engine of 4,000 metric hp weighs at least 4 tons. Its weight will absorb the entire lifting force of the rocket. I wish to state now that the mechanical work which we may obtain is at least 1,000 times greater than what we need. /176

We can expect some difficulty caused by the very high temperature of explosion at the very beginning of the tube. This temperature reaches a value of 2,000-3,000°C. The further we are from the beginning of the tube, the lower is the temperature of the flowing and expanding gases. At the very exit of the tube this temperature may be below 0 and in the ideal case may reach a value of -273°.

The tube must be made of a strong, heat-resistant and heat-conductive material. Then the heated part will transmit its heat to the adjoining cold parts. But this is insufficient. It is necessary to cool the hot parts of the tube continuously during the period of explosion. They may be surrounded by liquid oxygen which is required in any case for respiration, combustion in engines, and for cooling of the cabin. Therefore, the gas formed by the heating of the tube must be directed primarily to the supercharging engine. Nevertheless, a certain portion of the initial part of the tube will be damaged during the period of the explosion no matter how short it is.

The glowing part of the tube must therefore be made thicker than necessary to counteract the gas pressure. This pressure decreases as the gases move away from the beginning of the tube, expand and cool. Thus the thickness of the walls of the tube decreases towards the exit.

The weight of the tube is insignificant even at the maximum and uniform pressure along its entire length. If we assume a pressure of 100 atm, a 4-fold factor of safety, the best material, a tube length of 10 m and the tube diameter of 8 cm and a cylindrical shape, it is easy to show that the weight of the tube will be 32.5 kg. However, this quantity is obtained by assuming that the entire tube is of the same strength as at its origin where the pressure is many times greater than on its other parts. In other words, this is the limiting weight. /177

The weight of the fuel pump motor will be from 5-100 kg (Table 24).[1]

Control of the Rocket

The control system of the rocket is distinguished by the fact that it can operate not only in air but also in a vacuum. It consists of 3 rudders, all of which are placed in the neighborhood of the exit of the explosion tube. Since during its descent to Earth the rocket must glide like an aeroplane without explosion, these rudders cannot be inside the tube. The rocket must have the following: (1) a horizontal altitude rudder, (2) a direction rudder, and (3) a rudder for lateral stability. The first need not be described since they are identical to the control rudders of aeroplanes. However, they are also active in space because of the rapid flow of gases from the explosion tube. The deflection of the rudder produces the pressure of the stream on it and a corresponding change in the direction of the projectile. These rudders may have a very small surface, due to the high velocity of the gaseous stream; however, the rocket must glide in the atmosphere like an aeroplane, and therefore the area of the rudders will be the same as in the case of an aeroplane. The same can be said of the small wings for lateral stability. Placed at the sides of the missile frame, they will be operative only in the atmosphere. Therefore, in addition to the conventional ailerons of an aeroplane, they require another control surface which is operative in space. This is represented by a small plate ahead of the exit opening of the tube, which can rotate around an axis parallel to the axis of the tube of the rocket. As the plate is rotated, the gas flow from the tube also rotates; their vortex motion causes the projectile to rotate around its longitudinal axis in the desired direction.

If this rudder is outside the tube, it will also be effective in the atmosphere, like the ailerons of an aeroplane and independently of

[1]Assuming that the weight of the motor is 1 kg per power. - Editor's Remark.

combustion; however, it is so weak that it must be supplemented by ordinary ailerons. If the explosion tube is twisted, these twists must also be controlled.

The rocket must have transparent quartz windows so that appropriate observations may be made. The windows must not break from heat or vibration. Inside they must be covered with another transparent layer to offer protection from the fatal action of pure solar rays not made safe by Earth's atmosphere. A compass will hardly serve the purpose of determining the direction. For this purpose solar rays would be most /178 suitable, and when there are no windows or if the windows are closed, then rapidly rotating small disks would be suitable. During the short period of explosion and flight through the atmosphere they will operate without malfunction.

The Plan to Conquer Interplanetary Space

The General Plan

We may achieve the conquest of the solar system by means of readily available tactics. First, let us solve the simplest problem: to carry out an ether settlement close to Earth in the form of an earth satellite at a distance of 1,000-2,000 km from the surface of Earth and outside its atmosphere. In this case the relative supply of combustible material is quite accessible, since it does not exceed 4-10 (compared with the weight of the rocket). If, on the other hand, we make use of the initial velocity obtained on the surface of Earth, this supply will be quite insignificant (we shall speak of this later).

Having established ourselves firmly here, having obtained a reliable and safe base, and having become accustomed to life in ether (in the material vacuum), we would be able to change our velocity by simpler means, to move away from Earth and the sun and, in general, to travel where we wish. The fact is that as a satellite of Earth or the sun, we may use the smallest forces to increase or decrease our velocity and hence our cosmic position. As far as energy is concerned, there is plenty of it around in the form of permanent, continuous and active radiation of the sun. The support point or the support material may consist of the negative and, in particular, of the positive (helium atoms) electrons borrowed from solar radiation. This energy is plentiful, and it is not difficult to capture it in huge quantities. We may use conductors extended to a great distance from the rocket or other methods unknown today. We may even use the pressure of light by directing it with reflectors as required. Indeed, 1 kg of material with a surface area of 1 m^2 during a period of 1 year obtains a velocity increment, from solar rays, which is greater than 200 m/sec. Because apparent or relative gravity is absent, we could construct very large light mirrors and thereby obtain much larger increments in velocity and travel "free of charge" in the entire solar system.

In this manner we can reach asteroids, small planets, and descend to their surface which, because of their low gravity, will present no difficulties. Having reached these small heavenly bodies (from 400-10 km in diameter and less), we shall obtain a plentiful amount of support and structural material for cosmic travel and for housekeeping in the ether. This will open the path not only to all the planets of our sys- /179
tem, but also a path to other suns.

We have already stated that it would be possible to descend to Earth without using materials or energy. The establishment of the first economy close to Earth will require constant help from Earth. It will not be able to stand on its own feet immediately. Therefore constant contact with the planet will be necessary. Machines, materials, structures, food, and people will have to be obtained from the planet. Frequent turnover of workers will also be necessary in view of the unusual environment in the medium.

It is not necessary to use retro-explosion and thus to waste the supply of matter and energy to return to Earth. If, when we are close to the atmosphere, we use a weak explosion to move closer to it and finally touch its edge, we shall immediately lose velocity due to the resistance of air and will be sent to Earth in a spiral. The velocity will first increase due to the fall, then, when we enter a denser part of the atmosphere, it will begin to decrease. When it becomes insufficient for the centrifugal force to balance out the force of gravity, we can incline the longitudinal axis of the projectile and begin to glide. We can also increase the velocity by inclining the rocket downwards and increasing its fall. In other words, we treat the rocket like an aeroplane whose engine has been stopped. In both cases we must adapt the moment when the largest part of the velocity is lost to the moment when we touch land or water. The rocket, which loses large velocity at high altitudes, is quite safe because the air is extremely rarefied. We can even lose all of the velocity by orbiting many times around Earth: leave only 200-300 m/sec (depending on the density of the surrounding medium), and then proceed as with an aeroplane. Nevertheless, if the rocket does not have additional devices, landing takes place at a much higher velocity and may be quite risky. It should be performed over water rather than over land.

From what we have said, it is clear that the space ship must have some features of the aeroplane.

In view of the fact that it is advantageous to operate with a small acceleration j of the rocket, no special safety devices for the preservation of man against increased gravity are required; this increase is very small and a normal subject will be able to endure it even by standing up. Also, it last only several minutes and at the most, 2-3 hours. The products of respiration must be absorbed by alkalies and other substances which are well known to chemists. Similarly, all of the solid and liquid secretions of man must be decontaminated. I have already written a great deal concerning the procurement of oxygen and food in ether. There is no question that this can be achieved.

Conditions of Life in the Ether /180

1. It is impossible to exist very long in the rocket: the supply of oxygen for respiration and food will soon disappear, the products of respiration and digestion will contaminate the air. Special dwellings are required - safe, light, with desirable temperature, with regenerative oxygen, with constant flow of food, and with the conveniences for life and labor.

These dwellings and all equipment for them must be supplied from Earth by rockets in packaged form, they must be unpacked and assembled in ether when they arrive in place. The dwelling must be sealed for gases and vapors and must be permeable to light.

The materials must be nickel-plated steel, ordinary and quartz glass. The dwelling must consist of many compartments, isolated from each other and joined only by doors which close tightly. If any compartment is punctured or becomes permeable to gases, it will be possible to rescue oneself immediately to another and to repair the damaged compartment. The slightest leakage will produce a pressure drop which will be recorded by a sensitive manometer. At that time measures can be taken to repair the damage. Thus life in a vacuum may be made 100 percent safe.

Approximately 1/3 of the dwelling is open to sunlight. It penetrates all of the compartments due to the transparency of the partitions.

The entire surface of the dwelling is covered with a double layer of thin, movable shutters. If the side which is not illuminated by the sun is covered with bright shutters, while the transparent side is open to the rays of the sun, a maximum temperature of 150°C is achieved. If, on the other hand, the nontransparent side is covered with a movable dark layer, while the transparent side is covered with a brilliant surface like silver, a low temperature is obtained which, at great distances from Earth, will be 250° below 0. Close to the planet the temperature cannot be less than 100-150° below 0, since Earth produces a warming effect. By combing the shining shell with a dark shell in varying ratios, we may obtain any desired degree of heat: for adults, for children, for plants, for the bath, for the laundry, for sterilization, industrial purposes, etc.

Here is a description of a possible thermal system for various temperatures, although not necessarily the limiting ones which can be obtained. The opaque part of the dwelling is black on the outside. At a short distance from this surface there is a second surface, consisting of very shiny scale. The parts of this scale surface may rotate and become perpendicular to the surface, like the needles of a hedgehog. In this case low temperature is obtained. However, when this armor covers the black surface, a high degree of heat is obtained. The same scale may cover the transparent part of the dwelling. Then it will be possible to obtain low temperature. Depending on the purpose of the ether chambers, their construction may be quite diverse. The shiny scale may be moved to provide several layers and expose the more or less black surface of the dwelling, thereby producing the desired degree of heat. /181

Initially, there will be simple homes suitable for people as well as for plants. They will be filled with oxygen having a density of 1/5 of the atmosphere, with small quantities of carbon dioxide, nitrogen, and water vapor. They will also contain a small quantity of fertile and moist soil. This soil will be illuminated by the rays of the sun and will be seeded to produce edible roots and other plants. People will contaminate the air with their respiration and will eat the fruits, while the plants will purify the air and produce the fruits. Man will return in full measure that which he had stolen from the plants, in the form of fertilizer for the soil and the air. It will not be possible to do without the work of various types of bacteria.

We observe exactly the same cycle between animals and plants on our Earth, which is also isolated from other heavenly bodies like our rocket-dwelling.

Food provides man with 3,000 large calories per day. The same amount of heat is given by 0.5 kg of coal or flour or 3 kg of potatoes or 2 kg of meat. One square meter of surface illuminated by the normal rays of the sun in a vacuum at the same distance as Earth (from the sun) collects 43,000 calories every 24 hours, which corresponds to 10 kg of flour or 43 kg of potatoes (also bananas), or 30 kg of meat.

This means that theoretically a window with an area of 1 m^2 illuminated by the normal rays of the sun produces 14 times more energy than is required by man to live in a severe climate. Some plants utilize up to 10 percent of solar energy (such as the Burbank cactus), others utilize up to 5 percent (bananas, and edible roots). For man to exist, i.e., to obtain the necessary oxygen and food, it is therefore

sufficient to have 1 m^2 of solar rays, if the efficiency of utilization is 7 percent. It turns out that in order to satisfy the daily requirements of one strong man, a dwelling with a window of 1 m^2 and with suitable plants is sufficient. However, plants may be cultivated by selection and by artificial fertilization. It is possible that with time these plants under ideal ether conditions will give not a 5 or 10 percent yield, but rather a 50 percent yield. However, even existing plants properly selected will satisfy our needs.

Plants may feel quite comfortable in our dwellings. The temperature is most suitable for them, the quantity of carbon dioxide may be raised to 1 percent without harm to man, i.e., its concentration will be 30 times greater than on Earth, humidity may be controlled at will, /182 fertilization will be complete and suitable, light will be of proper direction and composition (for this purpose we may use glass of various colors and properties), and there will be complete elimination of pesticides, weeds and extraneous cultures by a preliminary purification of the soil at elevated temperatures.

However, the needs of various plants and people vary considerably. Each being requires a medium which is most suitable for him. In time this will also be true in the ether: certain plants will require certain types of accommodations with a specific type of soil, atmosphere, humidity, light and temperature; others will have different requirements. For mankind this requirement will differ even more. For various races, ages, and temperaments the accommodations will be different.

Initially we will have to put up with cohabitation (symbiosis) of plant life and mankind.

Gravity will not be experienced either by the plants or by the people. This may prove to be very advantageous for both. The plants will not require heavy trunks and branches which frequently break due to a surplus of fruit and which constitute a useless balast on trees, shrubs and even grasses. Gravity tends to hinder the upward movement of saps. A low gravity may, nevertheless, be quite useful to plants for holding the soil and water in one place. This low gravity is easy to achieve by rotation of the dwelling or the greenhouse. This low gravity will hardly be noticeable for plants and people: trunks will not bend, and people, as before, will be able to conduct flights in all directions, moving by inertia as necessary. The magnitude of the artificial gravity will depend on the angular velocity and radius of rotation. It will be approximately 1,000 times less than Earth's gravity, but there is nothing to prevent it from being 1,000 times more. No forces will be required to sustain the rotation of greenhouses or the dwelling. Objects rotate by themselves due to their inertia once they are placed in motion. The latter is eternal like the rotation of the planets.

The required temperature will make it possible for a man to exist without clothes and shoes. The abundance of heat will also limit the requirements of food.

Disinfection will destroy all contagious diseases and all the enemies of plants and of mankind. The absence of gravity eliminates the need for beds, chairs, tables, vehicles and forces for motion. Indeed, a small push is all that is required to move eternally, due to inertia.

Work of all types will be easier to carry out than on Earth. First, because the structures may be infinitely large even when the weakest materials are used --gravity will not destroy them since it does not exist. In the second place, under this environment man will be able to work in any position by merely securing his feet or other parts of his body -- there are no vertical or horizontal lines. There is no top or bottom. It is not possible to fall any place. Not even the most massive objects can crush a workman since they never fall, even without a support. All the component parts of the body, regardless of how large /183 they are, do not press on each other. All of the objects are displaced with the slightest force, regardless of their mass and dimension, only a short-term exertion is necessary, proportional to the mass of the object and the square of its velocity; after this the bodies move without stopping. When bodies are stopped the initial work used to place them in motion is recovered. Thus transportation will essentially cost nothing.

We should not forget that phenomena of inertia remain valid to the same degree as they are on Earth; impacts are just as strong as on the planet in the gravity medium. Forging is just as effective. If we fall between two masses which are moving with respect to each other we may be crushed --if they are sufficiently large or if they have a sufficiently high velocity. Presses, levers, crushers, hammers and all other machines operate effectively if their action is not based on the force of gravity.

It is not necessary to fight the weather, to combat slush, cold, fog, downpour, dampness, wind, hurricanes, darkness, heat, etc. Nor is it necessary to combat animals and plants. When one works outside the artificial medium, i.e., outside a dwelling, one cannot remain nude. In ether, in vacuum, workers and those who are out for pleasure must wear special protective clothing resembling the clothing worn by divers (diving helmet). These special suits like the sealed dwellings provide oxygen and absorb the products of human secretion. These suits are simplified versions of the closed quarters and are attached directly to the body. The only difference is that in this case the oxygen is not supplied by plants but is stored beforehand and is liberated gradually, like in the modern diving helmets. Special glasses protect against the fatal action of solar rays. These suits are not permeable by gases and are sufficiently flexible to hold the gas pressure without impeding the movement of the organs. Organic secretions are absorbed, the humidity inside the suit is controlled. The color of the suits must correspond to the desired temperature. In some suits it will be cold, in others it will be hot. In some cases it will be possible to fry, in others to freeze to death. The surface of the space suit may be of movable armor, just like the dwelling. Then the temperature may be varied at will.

Inside the dwellings, work is conducted exactly as it is on Earth; however, it is more convenient to work, since we are not impeded by gravity and its direction. We are not impeded by clothing, shoes, cold, heat, and Earth's normal dirt on clothing.

All of the structures, space suits, instruments, greenhouses or dwellings -- all of these must be constructed and tested beforehand on Earth. All of the initial work in ether will be limited to the assembly of ready-made parts. The first colonies must depend entirely on /184 their planet, especially since there are probably no suitable materials close to Earth (we can only capture a portion of the rarefied atmosphere, but this is insufficient). It would be good if the initial colonies did not have a shortage of oxygen and food. However, the beginning of the technology is possible even here. The colonies will require less aid when they settle in the belt of asteroids between Mars and Jupiter, where there should be no shortage of raw materials. Not only will the multitude of little planets be settled here, which will provide an unlimited quantity of materials and will not hinder us with their gravity, not only will we assume a solid position here, but we shall also get to the frightening space with solar energy, whose total quantity is 2,000 million times greater than that which is presently received by our planet. The temperature in the belt of asteroids may be brought up to 20°C or higher by a very simple method (the method described by me a long time ago in my manuscripts and the one patented by Markuze). With special methods and mirrors it may be raised to the temperature of the sun, and by means of electricity it can be raised even higher. However, nothing will prevent us from approaching the sun closer where its force is ten and hundreds of times greater than at Earth. The temperature is in our hands. We shall also find masses of matter between the orbits of the lower planets.

We have stated that the struggle with nature is virtually nonexistent. However, it is necessary to combat the pressure of gases, the fatal rays of the sun, the imperfect nature of man and of plants. It is inevitable that we shall have to fight for comfort, knowledge, and the perfection of mankind.[1]

The Program of Work to be Started in the Near Future

Now we shall discuss how we shall start work immediately to conquer the cosmos. It is customary to proceed from the known to the unknown, from the sewing needle to the sewing machine, from the knife to the meat cutter, from the flails to the crushers, from the carriage to the automobile, from the boat to the ship. In the same way we visualize going from the aeroplane to a reactive device for the conquest of the solar system. We have already stated that the rocket which flies initially in the air must have certain characteristics of an aeroplane. However, we have already shown that landing gears, propellers, the engine, the permeability of the cabin to gases, and the burdensome wings are unsuitable. All these things prevent the rocket from achieving a velocity greater than 200 m/sec or 720 km/hour. The aeroplane will not be suitable for the purpose of air transportation, but will gradually become suitable for cosmic travels. Does not the aeroplane even today, flying at an altitude of 12 km, overcome 70-80 percent of the entire atmosphere and approach the sphere of pure ether which surrounds Earth! Let us help the aeroplane to achieve more. Here are the rough steps for the development and transformation of the aircraft industry to achieve the above goals. /185

1. A rocket aeroplane is constructed with wings and conventional controls. However, the gasoline engine is replaced by an explosion tube, into which a low-power engine pumps explosives. The propeller is absent. There is a supply of explosives, and the cabin for the pilot is covered with something transparent to protect it from the wind, since the velocity of this device is much greater than that of an aeroplane. This device, due to the reactive effect of explosives, will move along a runway consisting of greased rails (if the velocity is low, the wheels may be retained). Then the device will rise into the air, achieve maximum velocity, lose its supply of explosives, and begin to glide like an ordinary aeroplane without an engine and land safely.

The quantity of explosives and the force of explosion will be increased gradually as well as the maximum velocity, flight distance and,

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[1]Following this, Tsiolkovskiy has a section entitled "The Development of Industry in Ether in the Widest Sense," which we have omitted. - Editor's Remark.

most important, the altitude of flight. Since the cabin for the pilot will not be sealed against the escape of gases, the height reached by this aeroplane will, of course, not be too great. It is sufficient to go up to 5 km. The purpose of these experiments is to learn how to control the aeroplane (at high speeds), how to control the explosion tube, and how to glide.

2. The wings of subsequent aeroplanes will be gradually decreased, while the power of the engine and the velocity will be increased. It will be necessary to attain initial preflight velocities by means of devices described earlier.

3. The frame of future aeroplanes will have to be sealed against the leakage of gases, filled with oxygen, and with devices which absorb carbon dioxide, ammonia, and other products of human elimination. The purpose of this aeroplane will be to reach any degree of atmospheric rarefaction. The altitude to be reached may be considerably in excess of 12 km. Due to the high velocity during descent, it would be safer to land on water. The hermetically sealed frame of the rocket will keep it afloat.

4. The rudders, which I have described, will be applied and will work well in the vacuum and in the highly rarefied air which will be penetrated by the rocket. An aeroplane without wings will also be launched and will consist of 2 or 3 sections, blown up with oxygen and hermetically sealed, which will glide very well. It will require a rather high initial velocity before it will take off into the air, and consequently will require a perfected runway for this purpose. The additional velocity will make it possible for this aeroplane to reach higher and higher altitudes. The centrifugal force may already produce its effect and decrease the work of motion.

5. The velocity will reach 8 km/sec, the centrifugal force will destroy gravity completely, and the rocket will go beyond the limits of the atmosphere. After it travels there for a period determined by the supply of oxygen and food, it will return to Earth in a spiral, braking /1 itself against the atmosphere and gliding without any explosions.

6. After this it will be possible to use a simple single frame. The flight beyond the atmosphere will be repeated. Reactive devices will move further and further away from Earth's atmosphere and will remain in ether for longer and longer periods of time. Nevertheless, they will always return since they will have a limited supply of food and oxygen.

7. Efforts will be made to eliminate carbon dioxide and other human eliminations by means of selected small plants, which will also

yield nourishment. This will require a great deal of work, progress will be slow, but success will be achieved.

8. Space suits will be developed to make it possible to leave the rocket and go into the ether with safety.

9. Special compartments to hold plants will be developed to obtain oxygen, food, and purified rocket air. All these devices will be packed and taken into ether by means of rockets and there unpacked and assembled. Man will become more independent of Earth, since he will obtain the means for life independently.

10. Extensive settlements will be established around Earth.

11. Solar energy will be utilized not only for nourishment and the comfort of life, but also for transportation over the entire solar system.

12. Colonies will be established in the belt of the asteroids and other points of the solar system where only small heavenly bodies exist.

13. Industry will be developed in space, and the number of colonies will be increased.

14. The population of the solar system will become one hundred thousand million times greater than the present population of Earth. A limit will be reached, after which it will be necessary to emigrate over the entire Milky Way.

15. The sun will start to die. The remaining population of the solar system will move to other suns to join their brothers who departed earlier.

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COSMIC SHIP

/18

(1924)

If a pressure acts on the base of a body, the body will not only rise but will continuously accelerate its motion. After a certain period of time it will attain a velocity which may be sufficient for permanent escape from Earth or even from the sun.

This is the basis for interplanetary and interstellar travel. In order for a projectile to escape Earth and travel along the orbit of Earth, it is sufficient to have a relative velocity of 11.2 km/sec, and to escape from the sun it is necessary to have a relative velocity of 16.5 km/sec.[1] In some cases it will be necessary to take advantage of the daily and annual motion of Earth; otherwise the required velocities will become enormous. To orbit eternally around Earth beyond its atmosphere, a velocity of not less than 8 km/sec is required. In this case our projectile will be similar to a small moon.

What are the means available to us to produce a pressure on the body several times its weight?

First of all, we think of a cannon with explosives (gunpowder, for example), with compressed gases, with overheated volatile liquids, electromagnetic cannons, etc.

However, in this case there are many insurmountable difficulties. Let us assume, for simplicity, that the gas pressure in a cannon is the same during the entire period of explosion. Let us assume that the projectile weighs 1 ton and that the gas pressure on it is equal to 2 tons. The acceleration will be twice as large as the acceleration due to Earth's gravity and, therefore, the projectile will appear twice as heavy. In other words, if we increase the pressure on the projectile by a certain factor, then the apparent gravity in the projectile will also be increased

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[1]All of the numbers and considerations presented here are based on calculations contained in my works.

by the same factor. In order for the cannon to produce a velocity sufficient to overcome Earth's attraction, it must have a length of approximately 3,000 km.

If the cannon is shorter, e.g., 60 km long, then the pressure required to achieve the desired velocity will be 100 times greater than the normal weight of the projectile with all its contents. In this case /188 the weight of the bodies contained within the projectile will also be increased by a factor of 100. It is doubtful that a living being can undergo such a gravity, even when the best safety measures are taken.

In a cannon 600 km long, the average apparent gravity increases by a factor of 10. This gravity is hardly tolerable for man even when he is submerged in a liquid of the same density as his average body density.

Let us clarify the role of the liquid as a safety device. Let us assume that you have been submerged into a liquid of the same density as the average density of your body, and that you are breathing through a tube with an opening to air. Your weight seems to disappear; it is equalized by the pressure of the liquid; you do not move up or move down and appear to be in equilibrium at any depth. Let us now assume that gravity is increased by a million times. As before, you will be in a state of equilibrium and will not feel this increased gravity. As before, it does not exist as far as you are concerned. Indeed, even though the gravity of your body has increased a million times, the pressure of the liquid has also increased by the same number. This means that the equilibrium is not violated.

Thus, the liquid would appear to safeguard a man from destruction under any increase in gravity. It is not in vain that nature uses the same approach when it wishes to preserve delicate organisms from the strong force of gravity and from shocks. For example, the fetus of an animal is developed in a liquid, and the brain of higher animals exists in exactly the same condition.

However, this would only be true if the body of a man were entirely homogeneous in its density. Unfortunately, this is not so. The bones are much denser than the muscles and the muscles, in turn, are much denser than the fat. As the force of gravity increases, a difference in pressure develops which under a sufficiently high force of gravity may destroy any organism. Only experimentation will determine the maximum relative gravity which may be endured by a man without detriment to his health. A 10-fold increase in the force of gravity is considered possible; however, in this case, the cannon must have a length of 600 km. When it is this long, it is necessary to place it horizontally. Its cost is prohibitive and it is doubtful that it can be realized. Also, in this case, the air resistance during horizontal flight and the tremendous initial velocity will destroy the major portion of the kinetic energy of the missile, and it will not reach its goal. Electromagnetic systems or other systems for a cannon will produce the same necessarily miserable results.

It is also possible to achieve velocity by supporting oneself on air like an aeroplane or an airship. However, the velocities which can be achieved in this manner are far from the required value. For example, the velocity of an aeroplane of 100 m/sec (360 km/hour) will constitute only 1/120 (less than 1 percent) of the velocity required for complete escape from Earth's gravity.

It is difficult to hope that a conventional unmodified aeroplane /189
could reach cosmic velocity. The velocity of aeroplanes will be limited to 100-200 m/sec (360-720 km/hour). However, aeroplanes may be transformed and may be powered in a different manner, not by means of propellers but by repelling air with special complex turbines. Apparently this method gives us unlimited velocity and an unlimited quantity of material for ejection (oxygen, obtained from the atmosphere). As a matter of fact, at sufficient altitudes (100-200 km) the oxygen will disappear completely and will be replaced by hydrogen. It is possible that this hydrogen could also be used as a fuel.

It is even simpler to put the aeroplane in motion by using explosives which have been stored; however, in this case, the aeroplane is transformed into a gigantic rocket. This approach is a little bit worse than the preceding one. Indeed, it would be necessary to store not only the fuel but also oxygen, whose weight is 8 times greater than the lightest fuel - hydrogen. This device compared to the preceding one will be overloaded by a factor of 9 with supplies of potential energy (in the form of explosives). Theoretically, at a certain altitude, there must be an explosive mixture consisting of oxygen, nitrogen, and hydrogen. It is true that this mixture is extremely rarefied, but its pressure may be raised by means of complex centrifugal pumps. Then the rocket need not have a large supply of fuel and may achieve very large velocities quite easily in the rarefied layers of the atmosphere.

Finally, there is a third and most attractive method of attaining high velocity. This method consists of transmitting energy to the projectile from Earth. The projectile itself need not carry a supply of any fuel material (i.e., in the form of explosives, fuel or energy). Energy will be transmitted from the planet in the form of a parallel beam of electromagnetic waves of shortwave length. Such rays may be directed in a parallel beam by means of a large parabolic mirror to a flying aeroplane, and there produce the work necessary to eject particles of air or of a stored "dead" material to achieve cosmic velocity while the projectile is still in the atmosphere.

This parallel beam of electric or even light (solar) rays must produce pressure in itself, which may also impart a sufficient velocity to the projectile. In this case, no supplies for ejection need to be carried.

The latter method would be the most perfect. Indeed, it would be possible to construct a power station on Earth of almost unlimited size; this power station would transmit energy to a flying machine which will not have to carry its own supply of special energy. It will contain only people and whatever is necessary for their life and its continuation during the voyage or during permanent life in ether. The problem of interplanetary communication would therefore become much simpler. /190

The pressure of solar light at the distance of Earth is not more than 0.0007 g per m^2. To produce a pressure of 10 tons (assuming that the projectile weighs only 1 ton), or 10 millions, we would need a mirror with an area of not less than 16 million m^2. Then the edge of a square parabolic reflector must be not less than 12.6 km. We cannot consider this to be realizable, particularly at the present time. In addition to this, the influx of rays would instantaneously fuse the most fire-resistant material of the space ship's construction. Also, how can we direct the flux of energy to the flying machine which is continuously changing its position? This method of obtaining velocity poses a series of difficult questions whose solution we shall leave for the future. However, the pressure of solar light, electromagnetic waves, electrons, and helium particles (alpha rays) could be applied, even today, in ether to a projectile which has already conquered Earth's gravity and requires only further cosmic displacement.

However, all this is still in the realm of fantasy.

At the present time it is more advantageous at high altitudes in the atmosphere to use rarefied air for ejection; the pressure of this air will have to be increased by complex centrifugal compressors. When the velocity of approximately 8 km/sec is achieved, the projectile will leave the atmosphere completely along a spiral path and will rotate around Earth like the moon. Beyond this point it will be easier to obtain cosmic velocities. We have indicated the value of velocities necessary to overcome Earth's gravity and the gravity of the planets and the sun. However, we have not computed the work which must be expended to achieve these velocities.

Simple integration shows that this work is equal to the one which is necessary to raise a projectile or any other body to a distance equal to one Earth radius, if we assume that gravity remains constant.

Therefore, if we have a mass of 1 ton, the total work performed by Earth's gravity when this mass is moved away to infinity is 6,367,000 ton-meters. The latter quantity expresses numerically the radius of Earth in meters.

Let us compare this energy with that which is presently under the command of man. A ton of hydrogen when it burns with oxygen releases 28,780 large calories, which corresponds to 12,300,000 ton-meters.

Therefore, if this energy could be converted into mechanical work, it would be almost twice as much as that required to free 1 ton of fuel from the forces of Earth's gravity. Petroleum gives up to 5,560,000 units of work, i.e., the energy of petroleum is only slightly insufficient to obtain the escape of a mass from Earth.

Of course, there is no oxygen in ether space and, therefore, we must take the oxygen with us in the rocket device. In general, we /191 must lift fuel, oxygen, and the ship itself with all the people and accessories.

A 1 ton mixture of hydrogen and oxygen, which forms water during reaction, liberates 1,600,000 ton-meters of work. This energy constitutes only a quarter of that work necessary for a complete surmounting of the force of gravity of only the products of combustion, i.e., of water. Gasoline and oxygen give 1,010,000 ton-meters per ton. This is less than 1/6 of the required energy.

The energy of radium and other similar substances is very great, but it is released so slowly that it is entirely unsuitable. Thus, a ton of radium in the course of 2,000 years liberates approximately 1 billion ton-meters, i.e., a million times greater than coal when it produces 1 ton of its products of combustion. A kg of radium produces approximately 130 calories per hour or 55,640 kg-meters, which constitutes approximately 15.5 kg-meters per sec. Consequently, under ideal conditions of exploitation, a kg of radium gives continuous work equal to that provided by a laborer. One ton of radium under these same conditions produces approximately 155 hp. Therefore, as far as its weight is concerned, radium is 5 times less productive than the aeroplane engine (the latter gives not less than 1 power per kg of weight).

It goes without saying that the necessary quantity of radium will not be found at the present time, and that its cost is enormous. No engine utilizing radium has been designed, and its ideal exploitation is impossible.

It is quite probable that electrons and ions can be used, i.e., cathode and especially anode rays.

The force of electricity is unlimited and can, therefore, produce a powerful flux of ionized helium to serve a space ship. However, we shall leave these dreams for a while and return to our prosaic explosives.

It would seem that the application of the most energetic explosives, under the most ideal conditions, will not make it possible to overcome even their own gravity. However, we shall show that explosives of sufficient quantities under certain conditions may impart an arbitrary velocity to space ships, and that in this manner cosmic travels may be achieved.

First, let us assume that there is no gravity. Let us further assume that we have two bodies of equal mass with a compressed spiral spring between them. The spring expands and both of the stationary bodies achieve equal velocities. Let us replace one of these bodies by an equivalent mass of compressed gas, whose motion is directed by a tube (nozzle) in one direction. We shall limit our discussions to a hollow sphere with the compressed gas inside, or a heated volatile /192
liquid inside the sphere. The gas will fly out in one direction, while the mass of the container will fly in the other. Instead of gas or vapor, we may use explosives to obtain the high velocity.

The velocity of ejected products of explosion may reach a value of 5 km/sec in vacuum, if the tube is sufficiently long. This means that our device (rocket), which has a mass equal to the mass of explosives, may achieve the same velocity.

Let us assume that the mass of explosives is 3 times greater than the mass of the rocket. We shall assume that the mass of the rocket is unity. The mass of explosives will then be equal to 3 (or $2^2 - 1 = 3$).

Let us first explode two units. The remaining 2 units of mass will obtain a velocity of 5 km/sec. After this we explode another unit. We obtain another increment of 5 km/sec. The projectile will achieve a velocity of 10 km/sec. Now let us imagine that the supply of explosives

of rocket constitutes 7 units of mass, i.e., ($2^3 - 1 = 7$). We explode 4 units. The remaining 4 units obtain a velocity of 5 km/sec. We explode 2 more units. The remaining units will achieve 5 more km/sec, i.e., a total of 10 km/sec. Finally we explode the third unit by itself. The empty rocket having a mass of unity will receive another 5 km/sec, and its total will be 15 km/sec. The supply of explosives compared with

the mass of the rocket will be of successive magnitudes: $2^4 - 1 = 15$;

$2^5 - 1 = 31$; $2^6 - 1 = 63$; ($2^n - 1$).

The corresponding velocities of the space ship will be 5 x 4 = 20; 5 x 5 = 25; 5 x 6 = 30; (5 x n) km/sec. Obviously the magnitude of the velocity will increase without limit, whereas to achieve interstellar flight we do not require a velocity greater than 16-17 km/sec.

Part of the work performed by the explosives is lost in the field of gravity. This part becomes smaller as the explosion becomes faster. When we have an instantaneous explosion, no energy will be lost. No losses will occur if the direction of the vector of reaction of the gases is normal to the force of gravity (to the vector), regardless of what the rate of explosion is.

When we have an instantaneous explosion, the relative gravity in the projectile will be infinitely high and will, therefore, kill all living things contained within the space ship. However, when the explosion on the rocket is directed in a horizontal direction, the rocket drops to the planet before achieving the necessary velocity. With a velocity of 8 km/sec, the centrifugal force becomes equal to the force of gravity; the projectile describes infinite circles.

In addition to this, during horizontal flight the path through the atmosphere is increased many times. Due to this, a substantial part of the work produced by the explosives is used up to resist air.

My calculations show that the optimum angle for the ascent of an interplanetary ship is between 20-30 degrees. In this case neither resistance of the atmosphere nor the relative gravity in a rocket are /193 very great, while the loss of energy produced by the explosives due to the forces of gravity is insignificant.

Thus a projectile of any mass apparently may attain a cosmic velocity with a relatively small supply of explosives.

It is necessary to apply the most energetic explosives and to explode them in a very strong, small container which we shall call the explosion chamber or at the beginning of an explosion tube (nozzle). The gas pressure will be felt only by this chamber and its extension - the explosion tube, where the products of explosion will flow, gradually expand and cool as the random motion of thermal energy is transformed into kinetic energy.

The tube and the explosion chamber have a very small volume. Therefore, their mass cannot be very large. It does not increase as the supply of explosives increases. The vessels (tanks) which contain the explosives are not under any pressure except the one due to the relative increase in their weight. Such vessels, particularly in the case of a multiple chamber device and a device with many explosion tubes, may weigh very little.

It will be necessary to pump the explosives continuously into the explosion chamber. Explosion in a medium with gravity must take place very rapidly; the quantity of explosives consumed per second will be very large and the pressure will be several thousand atm. It is clear that the work performed in pumping is not small. We note that we may use available materials as explosives, e.g., gunpowder, dynamite, etc., or we may use two or several different substances which are mixed in the explosion chamber and which give gaseous products during explosion. The latter is most practical in all respects. In the following discussion we shall assume that the rocket utilizes two or more substances which produce gaseous products during their reaction.

As my calculations have shown, when the cosmic rocket moves at an angle of 30° with respect to the horizon, gravity and atmospheric resistance absorb little energy. In rough calculations we shall neglect these losses and assume that the acceleration of the rocket is 30

m/sec^2. The relative gravity inside the rocket will be twice what it is on Earth. The following table shows approximately the time in seconds from the beginning of the rocket motion, the corresponding velocity in km/sec, the travel path, and the attained altitude in km. The fifth column shows the atmospheric density or the force of Earth's gravity.

By examining the table we obtain a picture of the rocket motion. Its motion is accelerated continuously. After 15 seconds, the velocity is 0.45 km/sec; however, the resistance of the atmosphere by this time has already decreased by half, since the rocket has reached an altitude of 5 km where the density of the air is half of what it is at sea level. /194

Five minutes later this density will decrease to 1/3, and the rocket will reach an altitude of 9 km with a velocity of 600 m/sec. The rocket has passed the troposphere in 30 sec from the beginning of the flight, and its velocity reaches a value of 0.9 km/sec. The resistance of the air is very small since the rocket is now at an altitude of 20 km where the density is 0.06, i.e., the air is 17 times thinner than on the ground. The rocket now continues its flight through the stratosphere. This is the region of falling stars, the place of their ignition and destruction, and of luminous clouds.

Approximately 1 min after the rocket has started its motion, an altitude of 80 km is reached. As it is lifted above 80 km, the rocket enters the secret region of Aurora Borealis.

In 150 sec or 2.5 min the rocket enters absolute vacuum in the region of the light-carrying ether, where the motion which it has achieved becomes eternal to the extent that the motion of heavenly bodies is eternal. First it is necessary to become established as Earth's satellite in the orbit of a small and close Earth's moon. From this point it will be easy to carry out further displacements and motions up to exit from the solar system and flight among the stars. The velocity of the rocket reaches a value of 4.5 km/sec and an altitude of 500 km from the surface of Earth. /195

Table

Time in sec	Velocity in km/sec	Distance in km	Altitude in km	Density of air	Time in sec	Velocity in km/sec	Distance in km	Altitude in km	Density of air
0	0	0	0	1	260	7.8	3,101	1,550	0.66
1	0.03	0.046	0.023	-	270	8.1	3,340	1,670	
2	0.06	0.183	0.91		280	8.4	3,596	1,798	0.61
3	0.09	0.413	0.26		290	8.7	3,858	1,929	
5	0.15	1.15	0.57		300	9.0	4,130	2,065	
7	0.21	2.25	1.12		320	9.6	4,700	2,350	
10	0.30	4.6	2.3		350	10.5	5,620	2,810	0.50
15	0.45	10.3	5.1	0.5	370	11.1	6,184	3,100	0.45
20	0.6	18.3	9.1	0.3	380	11.4	6,235	3,117	
30	0.9	41.3	20.6	0.06	390	11.7	6,287	3,143	
40	1.2	73.4	36.7	0.006	400	12.0	7,339	3,669	0.41
50	1.5	115	57.5		420	12.6	7,980	3,990	0.38
60	1.8	165	82.5	0.000020	450	13.5	9,290	4,645	
70	2.1	225	112		470	14.1	10,140	5,070	0.31
80	2.4	294	147		500	15.0	11,470	5,735	
90	2.7	371	185		520	15.6	12,460	6,230	0.26
100	3	459	230	0.000006	550	16.5	13,880	6,940	
120	3.6	660	330		570	17.1	14,900	7,450	0.21
150	4.5	1,030	515	0.000002	600	18.0	16,510	8,255	
170	5.1	1,330	660		620	18.6	17,600	8,800	0.18
200	6	1,830	915		650	19.5	19,380	9,690	
220	6.6	2,220	1,110		700	21.0	22,480	11,240	0.13
250	7.5	2,870	1,435						

However, this velocity of the projectile is not sufficient for it to become a reliable satellite of Earth. The rocket will travel 2 more min and a total of 270 sec from the beginning of its motion and, by means of an explosion, will achieve a velocity of 8 km/sec and an altitude of 1,700 km.

Here Earth's force of gravity is substantially reduced (approximately by 35 percent), and the rocket would rise much higher if its path were vertical all the time. Let us assume that the explosion continues: the table then shows us its future results. It shows the calculations for future explosions; in calculating the altitudes, the decrease in the force of gravity was not taken into account. However, the important factor is not the altitude reached but the velocity attained. This velocity makes it possible, after explosion has ceased in 370 sec, to escape completely from Earth and to fly along its annual orbit as its brother planet. If a further explosion takes place in the period of 550 sec (9 min) from the beginning of the flight, the velocity attained will be sufficient not only to reach any planet, but to escape completely from the gravitational force of the sun and float among other suns of the Milky Way (the direction of the rocket must, however, coincide with the annual motion of Earth).

This insignificant velocity overcomes the powerful solar gravitational attraction only because it is relative. The absolute velocity with respect to the sun, however, is quite large. We have utilized the motion of Earth, and it was Earth that gave us this power, having itself lost an entirely insignificant part of its velocity.

In our published works we have computed earlier that in order for a space ship to achieve the first cosmic velocity of 8 km, it must take a supply of the most active explosives which would exceed the weight of the rocket by a factor of 4. If a rocket with the people and with its other contents were to weigh 1 ton, the consumption of explosives would be 4 tons or 400 kg during a period of 270 sec. Their average consumption per sec would be 15 kg.

The pressure on the cosmic rocket[1], by arrangement, will be 3 times greater than the weight of the rocket with all its contents, including the material not yet exploded. Thus, if the acceleration is constant, then at the beginning of the flight, when the rocket weighs 5 tons, the pressure will be 15 tons (5 x 3). At the end of the explosion when the material has been used up and the rocket weighs only 1 ton, the pressure will be only 3 tons. This means that the consumption of explosives at the beginning of the flight is 5 times greater than at the end of the /196

[1] The reaction of the gases ejected from the nozzle or the thrust of the rocket. - Editor's Note.

flight. If we were to take the average consumption of 15 kg/sec, then the rocket would move more slowly at the beginning of its motion and more rapidly at the end of its motion. This would be useful in regard to decreasing losses due to the resistance of the atmosphere.

This would also simplify the explosion tube and the explosion chambers.

The work done by the explosives, i.e., by 4 tons of materials (if we consider the chemical energy of the combination of hydrogen and oxygen), will be 5,600,000 ton-meters. Consequently, 20,700 ton-meters will be liberated, in 1 sec, which corresponds to the work done by 207,000 metric hp. From this it is clear that the work performed by the explosion is tremendous and cannot be compared with the power of conventional engines.

At the same time, the entire weight of the explosion tube which performs this gigantic work is very insignificant: it only constitutes a part of 1 ton.

Can this be so? Indeed, it can. We can see the proof of this in the operation of artillery pieces. It is easy to compute that a gun which throws out a ton of cast iron with an insignificant velocity of 1,000 m per sec performs a work of 50,000 ton-meters during a period of 1/50 of a sec. This means, that in one sec this would represent 2,500,000 ton-meters or 25,000,000 metric hp. This is greater than the work of the explosion tube by a factor of 121. If such a cannon weighs 20 tons we find our explosive tube will weigh less than 200 kg which is achievable (as my calculations show).

We describe a cosmic rocket, designed by me in 1914.

The rudders for controlling direction and rotation are similar to those used on aeroplanes. They are placed outside, opposite the opening of the explosion tube. They operate in atmosphere and in vacuum. Their deflection and the corresponding deflection of the rocket in atmosphere takes place due to the resistance of the air or due to the pressure of the exhaust gases. A similar rudder, but separately installed, may be used to control rotation, i.e., it may cause the rocket to rotate in either direction whether rapidly or slowly and to stop the forced rotation of the rocket caused by improper explosion and air pressure. Its action depends on a helical beveling of the rudder plate, situated along the gas flow in the tube. The purpose of this is to stop any rotation of the rocket, which would be fatal to its passengers.

We shall discuss the sensations of the travelers who have left in a cosmic rocket to travel around Earth as a satellite. It is assumed that the rocket is comfortable and is performing its mission well.

The rocket contains several cases which have a human form and whose number is equal to that of the passengers. The people lie in these cases horizontally, with respect to the apparent gravity, and are covered with an insignificant quantity of water. Their hands are placed in the liquid but are free so that they can control the levers of various devices which are also placed in the water. The devices control the direction of motion of the rocket, the composition of its air, temperature, density, explosion, etc.

The travelers remain in this position for a period of 270 sec while explosion is taking place, and they are unable to observe very much. Their weight is substantially reduced by the water.

Let us now assume that the travelers are standing up or sitting in chairs and looking out through transparent windows and observing the quiet surroundings. Then, during these 270 seconds or 4-1/2 minutes, there are quite a few things to be noticed.

A high region in the mountains has been selected. The slope of the soil of approximately 20-30° with respect to the horizon has been found. The area has been leveled and tracks have been laid. The rocket stands on these tracks. The height of the region is 5-6 km, and the density of air is half of that at sea level; the rails are laid for a distance of 100 versts.

The rocket on the rails is in an inclined position, and the floor with attached seats is also inclined. The travelers have entered the rocket which has been hermetically closed. The explosion has started.

The rocket has started to roll along the track, the travelers have felt a shock and the horizon seemed to turn by 60°.

Gravity increased almost by a factor of 2.

The pressure on the rocket remained constant, but as the quantity of explosives decreased, the acceleration of the projectile increased. Due to this, gravity increased continuously from 1-4/5 at the beginning of the path to a value of 9 at the end of the path. This could be clearly seen by observing a spring balance.

Two minutes have elapsed, and the rocket has left the track and entered free flight. The travelers did not notice its motion, but they felt that the huge inverted horizon dropped, with all its mountains, lakes, and cities, to some point below and appeared to be moving away.[1]

[1] Following this, there is a description of various phenomena which are observed by the travelers in the rocket and in the surrounding space. Since this is a repetition of what has already been presented, we omit it at this point. - Editor's Remark.

The travelers, having reached a substantial distance from Earth, thought that they were in an absolute vacuum, but they were wrong: traces of the atmosphere were found even here.

Therefore, the rocket, subjected to some small resistance, traced a spiral with a very small pitch, which moved it continuously, but slowly towards Earth. There were so many revolutions around Earth that they could not even be counted. Nevertheless, return to Earth was inevitable. First, the velocity of the rocket increased and the centrifugal force balanced Earth's gravity, even though this gravity was increasing. /198

Then the velocity of the cosmic ship began to decrease, due to the increased resistance of the atmosphere. The passengers started to glide, lifting the nose of their rocket upwards by means of a rudder which operated like the rudder of an aeroplane. They now could not only decrease their fall, but they could even transform it into a lift as long as velocity was not lost. But this was unnecessary and might have ended with the loss of velocity and the destruction of the rocket, which would have become like a wingless aeroplane. The passengers continued to descend, but slowly, and approached closer and closer to Earth.

Indeed, the descent was more dangerous than one performed with an aeroplane, since the rocket had no wings and since a high velocity was required to balance gravity by the resistance of the air (with a slightly inclined motion), and to descend horizontally and not vertically. The passengers have flown into the ocean along a flat slope. The velocity was still very high, and they floated for a substantial distance before coming to a stop and before being picked up by a steamer passing by.

Only accurate calculations can give us the answers to questions concerning the cosmic ship. The calculations will also show the requirements which must be satisfied by the explosives, the properties of materials and the mechanisms suitable for flight and existence in ether.

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COSMIC ROCKET. EXPERIMENTAL PREPARATION /199

(1927)

Proposed Experimental Procedures

First, it is necessary to conduct stationary experiments without any noticeable displacement of the device. It is proposed to develop suitable construction and a control system for the explosion, the direction of the device, its stability, etc.

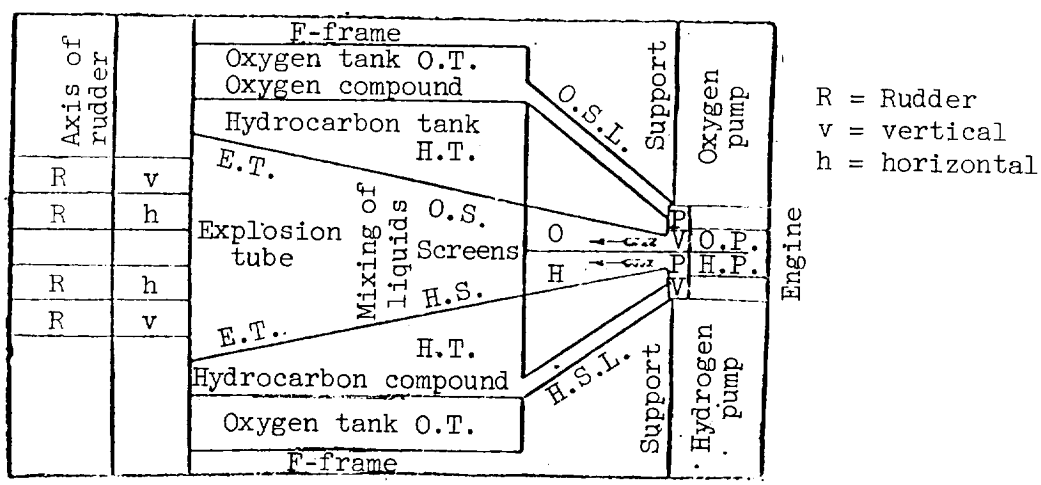

Figure 1

Figure 1 represents the proposed initial construction of the device. The figure is schematic (variable scale), i.e., dimensional proportionality is not maintained. In the future I shall attempt to come up with realistic dimensions.

We begin our description by going from right to left.

/200

K. E. Tsiolkovskiy at the bookcase in his room, 1927.

1. On the right we have a gasoline motor for pumping out or pumping in liquid air, oxygen or its endogenous compounds. The muffler should be removed and the products of combustion should be ejected in a direction opposite to that of the proposed travel. This will produce a slight increase in the reactive action of the rocket. As a matter of fact, this is not too important for experimental purposes.

2. O.P. and H.P. are two pumps which are driven by one engine. The first pumps oxygen into the explosive tube while the second pumps hydrogen. Their volumes must be such that we have complete combination of the explosives. In general, the volume of the oxygen cylinder is greater than the volume of the hydrogen cylinder. /201

Ultimate control may be achieved by varying the travel of one of the pistons. Control is of the utmost significance: if we have more oxygen than necessary, the explosion tube may start to burn; if we have less oxygen than necessary, we shall waste hydrogen.

Let us determine the ratio of the volumes of the pump cylinders when we use benzol, C_6H_6 and liquid oxygen, O_2. In the process of combustion we get water, H_2O and carbon dioxide, CO_2. For C_6 and in order to obtain CO_2, we require O_{12}, or 192 parts of oxygen by weight, while for H_6 we require O_3, or 48 parts. This is a total of 240 parts of oxygen. Benzol, on the other hand, has 78 parts. It would seem then that we would need 3.1 times more oxygen by weight. If the densities are approximately equal, the volume of oxygen will be 3 times greater than the volume of benzol. If we take compounds which contain more hydrogen, e.g., liquified ethylene, C_2H_4 or turpentine $C_{10}H_{16}$, this ratio will be greater, but it will change very little. For an oil-type gas C_2H_4, it will be 3.4. For turpentine it will be close to 3.2, if we assume that the density is the same. However, if we use liquid air, which contains a large amount of nitrogen, the volume of oxygen may increase by a factor of 5, and the ratio of the volumes of the cylinders may reach a value of 15. However, part of the nitrogen is usually removed; therefore, this ratio is much smaller and may reach a value of 4 to 5. The endogenous compounds of oxygen (for example, N_2O_5) also increase this ratio, but not too much. The latter compound increases the ratio of the oxygen compound to the hydrogen compound (gasoline) to a value of 4.2.

If we can find some way of injecting pure carbon powder (C equals 12), the quantity of oxygen O_2 will be only 2-3/4 times greater than that of carbon. If the carbon is in the form of diamond, the required volume of oxygen will be even less than that of carbon.

3. PV, PV are pump valves. One of the pumps has two oxygen valves, while the other has two hydrogen valves (i.e., valves which control the hydrogen compound). The valves are situated some distance from the point of explosion and, therefore, will not be damaged. In addition, the oxygen mixture is very cold and the hydrogen compound is even colder, so that the heat of explosion does not reach the valves and the pumps in any detrimental fashion. The valves leading to the explosion tube are automatically closed with a very strong force at the instant of explosion. Only when the pressure in the tube decreases and the products of explosion have been partially removed will the valves open
again to supply a new quantity of explosives to the tube (it would be /202
more accurate to call these the elements of explosion, since they do not explode independently like gunpowder or nitroglycerin and, therefore, are completely safe). We can see that the angular velocity of the engine cannot be greater than some value determined experimentally. It is for this reason that we require a discontinuous supply of fuel. If, e.g., it becomes necessary to decrease the rpm by a factor of 5 to achieve an economic operation of the engine, the transmission must acquire this value. However, the same thing can be accomplished by decreasing the volume of each pump by a factor of 5 or by decreasing the travel of the pistons by the same factor. The first approach is more advantageous. Then the variable supply or the variable movement of the pistons may become necessary only in the future when we decide to control the force of explosion.

4. O.S.L. and H.S.L. are the supply lines for oxygen and hydrogen. They connect the storage tanks and the pumps. Like the tanks they are not subjected to the pressure of explosion and, therefore, may be constructed of very thin material.

5. O.S. and H.S. are screens with oblique holes for the optimum mixing of the hydrocarbon and oxygen mixture. The initial part of the explosion tube is partitioned in half. The oxygen mixture is directed along one half and the hydrocarbon mixture along the other. At this point they are cold and cannot mix. Mixing and explosion take place beyond the screens, where a multiplicity of nonhomogeneous jets collide and mix. The tube inclined at this point causes them to react chemically or to explode. (For initial experiments it will be necessary to have an electric or some other glow plug, which is heated at the beginning of the experiments until the partition has become red hot.) The purpose of the partition is to protect the valves from the extreme heat, to cool the explosion tube slightly, and to decrease the force of explosion and its pressure on the base of the tube.

If the holes in the screen are too small and if there are too many of them, the explosion may take place too rapidly and the resulting shock may damage the tube. The number of holes and their dimensions must be determined experimentally by starting with large holes and decreasing their size and increasing their number as much as possible. Their direction and inclination is also varied until the best result is obtained.

6. E.T. is the explosion tube of conic shape. This form which expands towards the exit decreases the length of the tube. Its optimum divergence must be determined experimentally. If the angle is large, the length of the tube will be quite short; however, the explosives will be ejected sideways and used to a lesser degree.

The explosion tube must be made of strong material (even at high temperatures) which is heat-resistant and noncombustible; it is also desirable that it be a good conductor of heat. It would be easier to make the tube of two shells: the first, inner shell would be very strong and heat-resistant, the second would be less heat-resistant, but quite strong and a good conductor of heat. Then the heat from the /203 tremendous heating of the tube near the screen will be carried away faster by the external tube in both directions and will be useful to both sides of the tube: on the right, the cold, unmixed liquids will be heated while, on the left, the expanding and cooling gases will be heated. The heating will give them additional velocity, which is what we want. In addition, the tube will also be cooled by the liquids. The hydrogen compound cools the tube and is cooled itself by the mixture of liquid oxygen.

The results of the experiments will indicate the necessary changes in the materials, explosives and construction of the tube.

7. H.T. and O.T. are the internal hydrogen or hydrocarbon storage tank, which surrounds the hot surface of the explosion tube, and the external tank with liquid oxygen, respectively. The oxygen tank surrounds the hydrogen tank and cools it. The tanks must not be welded to the explosion tube since the latter is subjected to explosive shocks and will rupture the tanks if they are rigidly attached to its walls. Hermetic coupling is possible by the use of bellows.

8. The vertical and horizontal rudders are situated opposite the outlet of the explosion tube. Since the future device flies alternately in air and in vacuum and descends to Earth by gliding, the rudders must operate equally well in air and in vacuum. They must also function properly when the device is tied down to Earth during the initial tests. Before the experiment, the device must hang by means of a cable whose lower part is attached to its center of gravity to achieve neutral equilibrium. An appreciable inclination is not possible since the ground

11. Rotation of rocket by explosion,
with the rudder inclined

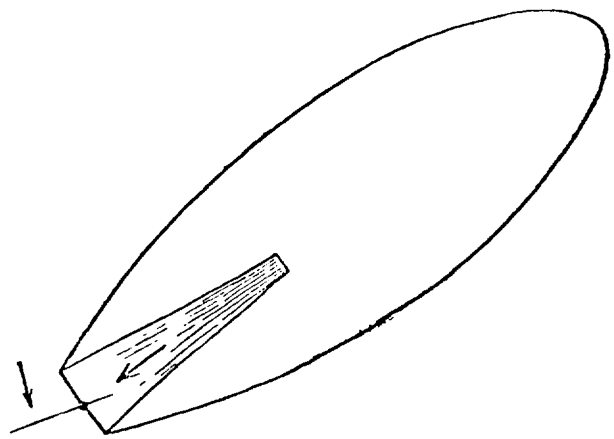

Figure 2. Sketch from K. E. Tsiolkovskiy's manuscript "Album of Cosmic Travels."

(soil or pavement) will be in the way. During the first experiments indoors (or outdoors), only the average reactive force or thrust should be measured. This thrust will be produced by a series of explosions which are almost blended. This is the thrust of the device or its tendency to move forward. Of course, in these experiments the device is fixed in such a manner that it cannot rotate; it produces tension only on the rear cable with the dynamometer. Subsequently, the effect of the rudders is tested. The device is secured so that it is free to rotate, and the rudders are manipulated to control its direction. Initially only the vertical rudder is tested. Although the projectile will be inclined slightly, we shall, nevertheless, be able to vary its position in the horizontal plane. Next the horizontal rudder is tested. The latter consists of two planes (somewhat like the split tail of certain birds) and of a double lever for manual control. In this fashion we attempt to direct the longitudinal axis of the rocket independently of the ground. For example, we may cause the projectile to assume a precisely horizontal position. The lateral stability is achieved by the mutual inclination of the components of the horizontal rudder, which is achieved by separating the levers of the double beam. There is nothing new here: the controls are the same as they are in an aeroplane. These same rudders (they may extend beyond the limits of the tube) are used both in a vacuum during explosion and when the aeroplane is gliding back to Earth.

9 and 10. The frame F and the support are described. The explosion tube at its narrow beginning must be particularly massive. Here it has a protruding section which bears on the cross beam of the frame. The support withstands a rapid series of powerful shocks. The large resulting pressure must be withstood by the cross beam and the frame. Therefore, the number of free oscillations of the cross beam must not be a

multiple of the number of revolutions of the engine or of the number of explosions. Otherwise oscillations will build up and even the strongest support will fail.

Explosion cannot be entirely uniform; due to the massive nature of the entire system and to the large number of explosions per second (up to 25), some average pressure will be obtained, which will be recorded by the dynamometer. It is advantageous for us that the force of explosion per unit mass of material consumed every second should have a maximum value. By performing a great many experiments we should be able to achieve economy, strength, and light weight for our device. Strength is achieved by using durable material, by selecting the optimum shape (or construction), by having adequate cooling, by having an expansive portion of the explosion tube and by decreasing the quantity of exploding matter and its force. The explosion chamber should be decreased /205 gradually, while the quantity of explosives used in each explosion should be increased.

Dimensions of the Pumps and of the Nozzle Tube.
Quantity of Fuel, Flow Rate, and Efficiency

If we assume that the weight of the projectile together with the explosives and the control mechanism is 1 ton, practical results will be achieved when the consumption of explosives reaches a value of 0.3 kg per second.[1]

The work expended on pumping will be less than a metric horsepower. From this we concede that the engine consumes fuel at a rate several hundred times less than the one for the explosion tube. Therefore, the reactive effect of the engine is almost imperceptible compared with that of the tube.

We shall carry out our calculations assuming a consumption rate of not .3 but 1 kg. In this manner we determine the total volume of the pump cylinders, assuming that the density of explosives is equal to unity, which is not too unrealistic.

If the engine makes 25 revolutions per second, each revolution must produce 40 cm^3. Therefore, the total volume of the two motors is equal to a cube whose side is 3.4 cm. Obviously, the pumps are very tiny. However, it is more rational to begin with a smaller quantity of explosives, e.g., with 0.1 kg.

[1] See the article "Investigation of Universal Space by Means of Reactive Devices."

The volume of this quantity will be equal to a cube with a side of 1.6 cm (16 mm). It is obvious that we can neglect the weight of the pumps entirely, particularly since they are not subjected to strong pressure.

Experiment will show whether the small force can inject the required amount of material into the explosion tube. The calculations in my notebook have been made under the assumption that the continous pressure is 100 atmospheres. However, when we have rapid mixing and a small explosion volume, it may reach a value of 3,000-5,000 atm. When a pressure of this magnitude is developed, the valves are automatically closed, the pump does not operate and the piston only compresses the liquid or a spring link and is compressed very little by the action of the crankshaft. However, this period of time is so short that the pump produces no effect. During this period the gases explode, the pressure in the tube and on the valves drops, and the pump begins to operate normally.

It is difficult to determine theoretically the best diameter for the beginning part of the explosion tube; however, it cannot be less than the approximate dimension of the pumps, i.e., the tube diameter will not be less than 2 to 5 cm. This means that the area will be from 4 to 16 cm^2. It is assumed that the maximum pressure on the base will be 3,000 atm, and will not exceed 12 to 48 tons. However, this pressure will only last for a very short period of time (during the shock). An average pressure of 1 ton is quite sufficient.

When these conditions are satisfied, flight become possible. When the tube is conic, we must add the additional pressure produced by the inclination of the tube walls. This means that the average pressure on the base may be less than 1 ton. /206

However, high pressure over a very short period of time is not desirable, because it requires massive construction of the explosion tube and of the valves, which increases the weight of the rocket. Therefore, the mixing must not be too thorough. Experiments must be started with screens which are not too small in order to prevent instantaneous explosion and the associated tremendous shocks, even though it is more advantageous to have a rapid explosion and greater pressure when we have an external atmosphere. In order to decrease the shocks which are destructive for the tube, we can make the latter more expansive and stronger than design calculations warrant.

The engine which pumps fuel and oxygen will be operating almost without a load, and the massive features of the tube will be required only for the short shocks. However, initially, we may neglect the required economy in weight. Subsequently it will be necessary to prolong the periods of pressure, so that they occupy at least half of the entire time or be of the same period as the weak or zero pressure. To do this, we must either increase the speed of the pumps or their volume. The first approach is more desirable, since it gives a more uniform pressure. Then the utilization of the massiveness of the tube will be greater, since the average reactive pressure will be increased proportionately. The work performed by the engine will not increase too much, since the pumping must coincide with the low pressure in the tube, which occurs after explosion. Only the motion of the piston will be more discontinuous, and the elasticity of the connecting link or the crankshaft must be increased.

In this case the strength of the tube will be utilized, because its action will be increased or because we shall obtain the larger average reactive pressure with the same weight of the tube. However, we can decrease the mass of the tube without increasing the reactive action by increasing the number of cycles of the pump and simultaneously decreasing its volume.

However, let us return to the initial experiments and to the initial modest numbers. The flow velocity in the pumps, when the cross section area varies from 2 to 8 cm^2, will be from 50 to 125 cm/sec (the volume of the pumps is from 4 to 40 cm^2). The revolutions of the engine will be 25 per sec.

When the gases leave the tube, they cannot have a pressure less than 1 atm. If we assume that expansion takes place by a factor of 1,300, then the absolute temperature of the gases which leave the explosion tube will be 625°, or 352° C.[1] This means that the gases which enter the atmosphere will still be quite hot, and the utilization of heat (its conversion into motion) will not be greater than 95 percent and actually will be much smaller, since the temperature of the ejected gases will apparently be much higher. Their velocity cannot exceed 3 to 4 km/sec. It is necessary to achieve the highest possible velocity, which can be done only when the tube has certain specific dimensions. It is safe to use a large base for the tube, but in this case maximum velocities cannot be achieved. /207

In thin layers of the atmosphere or in a vacuum the expansion may be quite great and will depend on the dimensions and shape of the tube. The temperature of the ejected products of combustion will be very low, its utilization will be very high, and the velocity will be maximum. However, we must start our flight in the atmosphere, and we can program for optimum flight in the vacuum only after we have achieved success in the atmosphere. For example, in the vacuum the maximum pressure of the

[1] See the article "Investigation of Universal Space by Means of Reactive Devices."

gases in the tube may be quite small without producing any disadvantages. This means that if we have reached the rarefied regions of the atmosphere by means of a massive tube, we may discard this tube and continue our flight by means of a tube which is lighter and which operates with smaller pressure. However, if we are to operate at a lower pressure we will have to redesign the tube: as we leave the atmosphere, we must make it wider and longer without changing the total weight, since in this case the walls will be thinner. It is impossible to make changes of this type during the flight and, therefore, the tube which has been adapted for air pressure must remain unchanged in space. It would be useful to extend it, i.e., to put a fitting on its end; this is possible and may be done in the future in the rarefied layers of the air outside the atmosphere.

There is another method of increasing the utilization of explosion energy; this is achieved by decreasing the fuel consumption in space. However, this can be done to a limited degree, depending on the initial force of explosion in the atmosphere. This force may turn out to be so small that there will be nothing to decrease. Nevertheless, as the speed of the rocket increases, the force of explosion in vacuum may be decreased almost to zero.

As we move away from the beginning part of the tube, the pressure of the gases (at 1 cm^2) decreases due to their expansion and the resulting cooling. The pressure and temperature distribution in the tube is similar to such a distribution in a vertical column of the atmosphere, although the two are not completely identical. Indeed, although the gases expand during the initial period of time, their temperature does not drop and is equal to the temperature of the dissociation of the products of combustion. This is due to the fact that, initially, only part of the elements combine chemically, while the other part is in a state of decomposition, because the high temperature (3,000-4,000° C) impedes chemical union. However, when all of the elements have combined, the gases will expand and cool, as in a column of atmosphere.

From this we can see that only the initial section of the explosion tube is subjected to a high pressure. We shall compute the weight of the tube and the thickness of its walls for one m of length, assuming the constant pressure of 3,000 atm, even though the average pressure, particularly with the first experiments, will be much less.

If the diameter of the tube is several times greater than the thickness of its walls, we may assume that the weight of the vessel is 6 times greater than that of the air compressed in the vessel. However, in this case, this law cannot be applied, because the thickness of the walls comprises a substantial part of the tube's diameter. However, if we design for a sufficiently high transverse strength, the longitudinal strength will be greater than required. /20

Let us carry out the calculations

$$\delta = R - r. \tag{1}$$

This expression contains the thickness of the tube walls and its external and internal radius.

Furthermore

$$q = 2(R - r)\frac{K_z}{S}. \tag{2}$$

This equation shows the strength of the tube's material over its unit length, the strength coefficient of the metal, and the desired factor of safety. The pressure produced by the gases over the same length will be

$$q_1 = 10^3 p 2r, \tag{3}$$

where p is the pressure in atmospheres. If we set this pressure equal to the resistance we obtain from (1), (2) and (3)

$$\frac{R-r}{r} = \frac{\delta}{r} = 10^3 p \frac{S}{K_z}. \tag{4}$$

Let us assume that $p = 3{,}000$; $S = 6$; $K_z = 60 \text{kg/mm}^2 = 6 \cdot 10^6 \text{ gm/cm}^2$;

now we find $\delta : r = 3$. This means that the thickness of the walls will be 3 times greater than the internal radius of the tube, or 1-1/2 times greater than its internal diameter. However, there are materials which are twice as strong, and because of the lower pressure it is possible to decrease the factor of safety also by 2. Then the thickness of the walls will be approximately 3/4 of the radius or 3/8 of the diameter.

The weight of the tube will be

$$G = \pi(R^2 - r^2)\gamma 100. \tag{5}$$

This is over a length of 100 cm; here γ is the density of the material. We assume that 2R varied from 2 to 4 cm.

From (5) and (4) we find that

$$G = \pi p \gamma r^2 \left(10^3 p \frac{S}{K_z} + 2 \right) 10^5 \frac{S}{K_z}. \qquad (6)$$

We have assumed that the internal diameter of the tube varies from 2 to 4 cm or that its radius varies from 1 to 2 cm. Therefore, equation (6) will give us a value from 37.7 to 150.7 kg for the weight of the tube, if we use conventional material and a large factor of safety. For a very strong material and a smaller factor of safety we shall have a weight of 5.2 to 20.7 kg. However, we do not actually need equation (6). Indeed, r varies from 1 to 2 cm; δ varies from 3 to 6 cm; R varies from 4 to 8 cm. Thus, according to equation (5), the weight of the entire tube will be 2,512 $(R^2 - r^2)$, or from 37.7 to 150.7 kg. In the same way we can obtain the weight of the tube, when the thickness is 3/8 of the internal radius. /209

What are the results of all this? The maximum weight of the tube does not exceed 151 kg, and this is true when we expand 1 kg of explosives per sec. This is more than sufficient to fly beyond the atmosphere, if the total weight of the rocket is 1 ton. The rest of the equipment weighs very little. The weight of the engine with pumps and tubes is not more than 10 kg. We assume that the weight of the frame of the tanks, of the rudder, and of the pilot is approximately 140 kg; the total weight will be approximately 300 kg. 700 kg will be left for the explosives, i.e., twice as much.

For the first experiments and even for flights into the stratosphere and into vacuum this may be sufficient; 700 pounds of explosives consisting of hydrogen and oxygen compounds will be sufficient to produce explosion over a period of 700-7,000 sec, or from 11.7 min to 1 hour 57 min.

Both the weight of the tube and the weight of the projectile may be less during the stationary experiments; it may be reduced to 100 kg.

Oxygen Endogenous Compounds or Mixtures

Initially we may utilize liquid air. The addition of nitrogen weakens the explosion and lowers the maximum temperature. In time the quantity of nitrogen should be gradually decreased. This will cause the temperature to rise slightly due to the phenomenon of dissociation. The cold liquid which enters the compartments of the explosion tube is very useful for cooling it. Liquid air is very inexpensive and apparently will be even less expensive in the future.

Its density is close to unity and the heat of vaporization is insignificant (65), its temperature is -194° C, and its specific heat is small. When we heat and evaporate air we lose very little energy, particularly since it is obtained from the overheated parts of the tube whose cooling is unavoidable.

The nitrogen anhydride N_2O_5 would be more suitable than liquid air. However, it is very expensive, chemically active, unstable and toxic. This compound has 3 times more oxygen than nitrogen. Also this is an endogenous compound which gives off heat when it breaks down. It would have to be heated, because at room temperature it is a solid. Perhaps the well-known physicists will recommend more suitable endogenous compounds of oxygen! However, the liquid air may be gradually replaced by oxygen from the atmosphere, which is better than N_2O_5 in all respects. In an open vessel its temperature is -182° C. Liquid oxygen obtained from the atmosphere is almost pure.

Hydrogen Compound /210

In general, hydrogen cannot be used, particularly in the initial stages. The reasons are as follows: high cost, low temperature, heat of vaporization, and difficulty of storing. It is more practical to use hydrocarbons with the largest possible relative quantity of hydrogen. Their energy of combustion is almost the same as that of the individual hydrogen and carbon. The products of combustion are vaporous or gaseous. The addition of carbon increases the combustion temperature due to the extreme difficulty of its dissociation.

However, hydrocarbons which have the largest percentage of hydrogen are gaseous such as, e.g., methane CH_4 or marsh gas. It is difficult to liquefy this gas and, initially, it will not be applicable, although its hydrogen content (by weight) is only 3 times smaller than its carbon content. Benzol, C_6H_6, is more suitable, although it has 12 times more carbon than hydrogen. Petroleum is more suitable and has a greater content of hydrogen. It should be cheaper than liquid air. Petroleum consists of a mixture of hydrocarbons. In the limiting hydrocarbon C_nH_{2n+2}, the hydrogen content is not less than 1/6 (by weight) and not more than 1/3. We repeat that all hydrocarbons from the standpoint of their chemical energy may be considered approximately as a mixture of hydrogen and carbon. Usually their density is less than unity. They all liberate volatile products and, therefore, are suitable for the rocket.

The maximum velocity of the products of combustion is decreased slightly if we replace hydrogen with hydrocarbons, approximately by 4 to 5 km/sec.[1] This occurs when we use oxygen containing a slight amount of nitrogen.

Combustion Temperature; Cooling the Mouth of the Rocket and the Temperature of the Gases at the Mouth

Initially it would be better to keep the temperatures down, so that it would be easier to find the material for the explosion tube. Thus, the mixture of nitrogen and oxygen is quite useful. The low temperature of liquid air and of the petroleum cooled by it is also useful, although it causes us to lose energy. However, nitrogen increases the combustion temperature of petroleum.[2] In this respect it would be desirable to use pure hydrogen, and possibly in time it will be used. Perhaps suitable endogenous compounds of hydrogen will be found. Monatomic hydrogen would be very desirable; if reports are correct, it liberates approximately 50,000 cal when 1 g is transformed into diatomic hydrogen H_2, i.e., almost 16 times more than 1 g of oxyhydrogen gas. From this we can see that there are practical sources of energy which are tens of /211
times more powerful than the known ones (such as oxyhydrogen gas, oxides of calcium).

In general, if we did not have artificial or natural cooling of the tube, its highest temperature could reach a value of 3,000° C. However, the gases, which have mixed, exploded and achieved a high temperature, move towards the exit of the tube, expand more and more and are cooled in this way: the tube converts the random thermal motion into the controlled mechanical motion of the jet. In vacuum the temperature of the ejected gases should reach absolute zero, since explosion is not limited by external pressure. In the atmosphere, however, if we have a sufficiently long conic tube the temperature will drop to 300-600° C. Therefore, the average temperature of the explosion tube cannot be very high: the heat from its red hot part moves very quickly toward its cold part. In addition, the tube is continuously cooled from the outside and the inside. Indeed, at its partitioned beginning two very cold liquids flow in: liquid air and petroleum cooled by it. The external walls of the tube are also cooled by the

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[1] See the article "Investigation of Universal Space." - Editor's Remark.

[2] Tsiolkovskiy incorrectly assumed that the combustion temperature of carbon is higher than that of hydrogen and that the dissociation of carbon is less than that of hydrogen. I have replaced the word "carbon" by the word "hydrogen" and have omitted a paragraph. - Remark by Tsander.

cold petroleum, which itself is cooled by the liquid air around it. We can see that only the central part of the gaseous column in the explosion tube may have a high temperature, while parts of it (products of combustion) attach themselves to the walls and have a moderate temperature, since they are cooled by the tube which is not very hot.

Materials for the Explosion Tube

Would it be possible for the tube to fuse and burn under these conditions? Or could only part of it burn - the part subjected to the high temperature? The burning of metal (i.e., its combination with oxygen and other substances) at the beginning of the tube is prevented by the low temperature of the liquid and the cold walls of the tube. The partition prevents a chemical process and consequently prevents the liberation of heat. Beyond the partition, mixing and combustion take place. Here the temperature must reach a maximum value. However, the oxygen is absorbed very rapidly by hydrogen and carbon and does not have an opportunity to react on the cool metal of the tube. When we have an excess of hydrogen, the mixture even has the property of deoxidizing the metal. The relatively low temperature of the tubes of the walls prevents it from fusing. It would be desirable to produce the mixing of the petroleum.

The safety of the explosion tube may be visualized by observing the welding of iron by means of an acetylene-oxygen flame. Its temperature is higher than the combustion temperature of our explosives because pure oxygen is used and the acetylene C_2H_2 contains a great deal of

carbon. When we have an excess of hydrogen (i.e., of its compound acetylene), iron does not burn and it is even deoxidized. It will not fuse when cooled by water from the opposite side. It is difficult to fuse large masses of metals, because they must be heated very thoroughly at first. /212

Nevertheless, we must find a material for the tube which is not only strong and heat-resistant, but which also has good thermal conductivity and a low chemical affinity for oxygen and other elements which enter into the composition of the explosives.

Many materials have a very high temperature of fusion. For example, tungsten melts at $3{,}200^{\circ}$ C. However, such metals are rare, expensive and difficult to process in large masses due, specifically, to their melting point. At the present time we must reject the use of such materials. It will be necessary to start with simple iron. Its temperature of fusion in pure form is $1{,}700^{\circ}$ C; that of steel is less (approximately $1{,}200$-$1{,}300^{\circ}$). However, because of its strength we shall have to use steel. To improve its strength we can alloy it with tungsten, chromium, nickel, manganese, cobalt, etc. Here we must solicit the aid of specialists.

It would be useful to cover the steel tube with a layer of metal which is a good conductor of heat, such as copper, aluminum, and other metals. However, these substances are usually not very strong or have a low melting point. Therefore this approach is not economical from the standpoint of weight. Possibly the metallurgists will provide a suitable material for this purpose. Until that time we shall have to do without coverings and be satisfied with the best quality steel and its thermal conductivity which apparently is sufficient for the initial experiments.

Even if the explosion tube were to burn slightly at its point of maximum temperature, no harm would be done. The thickness of its walls at this point has a maximum value.

Operation of the Entire Device

Let us consider the operation of the entire device, so that we can better judge the necessary properties of the various materials composing it.

We let a gasoline motor idle. Then, to decrease the mass of its fly wheel, it is desirable to make the engine with more than one cylinder, e.g., with two cylinders and double action.

We couple the motor with the double pump, which begins to pump cold liquids out of the tanks and forces them into the partitioned beginning of the tube. Explosions will start. (Actually a series of idle firings.) Part of the tube behind the partition will become very hot, and heat will propagate along the tube in both directions. Therefore, the liquids will turn into gases and vapors even before they reach the partitions.

Gaseous substances will explode through the screen and will be more or less dense. This will facilitate mixings, so that the screen may not be required. However, the beginning of the explosion tube, the valves and the pumps will have a low temperature and, therefore, will not be damaged. They can be made of conventional material. /213

Every cycle of the pump produces an explosion. The dense explosion wave will impart a severe shock to the tube and to the frame which is connected to the tube, and will propagate along the tube in the form of an expanding and cooling gaseous mass. Under atmospheric pressures the gas which reaches the end of the tube will not be very hot and will have a temperature of 300-600° C. In any case the metallic rudders will not be damaged by this temperature. In vacuum the temperature will be quite low, depending on the divergence of the tube and its length.

Frequent explosions (up to 25 per second) are blended into one and produce a thrust or motion of the device.

The success of the experiments on the test stand consists of the following:

1. The device must remain intact, and the explosion tube must not be completely destroyed after all of the explosives have been used up.

2. The mass of the device must have a minimum value.

3. The reactive pressure must have a maximum value consistent with the rate of fuel consumption and its property.

4. To achieve this, combustion must be as complete as possible.

5. The temperature of the gases that leave the tube must be as low as possible.

6. The device must rotate in accordance with the desires of the experimental operator, and it must retain the desired position.

7. The pumps must not be overdriven.

After stationary experiments have been successful the projectile should be placed on four wheels and propelled by reactive action along the airfield. Initially, it may be of normal size, but as its velocity increases its dimensions must also increase. It is possible that it will be necessary to remove the wheels and use a hydroplane on a quiet lake.

When we have four wheels we shall be able to achieve control with one vertical rudder for turning; if we have two wheels in line, we shall be able to use the turn rudder and the rudder for lateral stability; finally, when we have only one wheel, we shall be able to use all of the controls.

As the next step we can use the airport or the lake to start flights, without leaving the limits of the troposphere. To simplify this, our device should be equipped with aeroplane wings, and the rudders should be increased in size so that they can be used for gliding when explosion does not take place.

As a matter of fact, our works may lead us in an entirely different direction. They will provide us with a true path for our activities.

Provision for Safety /214

All of the experiments must we well thought through and conducted very carefully. The supply of explosives initially must be very small: approximately for 10 cycles of the piston, i.e., for 10 idle explosions. The pumps may be of the smallest size or the travel of their pistons may be reduced and actuated manually. After each experiment, i.e., after a small number of explosions, it will be necessary to examine the condition of the explosion tube, of the valves, of the frame and of the entire device. The number of explosions, therefore, should be increased very gradually.

Initially, we can make use of a short cylindrical explosion tube with a constant wall thickness; then we can use a similar one, which is longer and whose walls become thinner toward the exit. Later we can use a conic tube with a rapid thinning of the walls toward the end. When we use a tube of minimum weight (according to calculations), it is necessary to protect it with another tube in case of an explosion.

Cooling may be performed initially by means of water (cannons are cooled in this way); the supply of explosives must be stored separately, since their mixing may cause a dangerous explosion in the building. In our case they are contained in separate vessels and are not dangerous by themselves. The vessel with the liquid air must have an opening at the top for free evaporation. To keep this evaporation at a minimum, it is necessary to cover the vessel and protect it from penetration of external heat. In vacuum this is easy, while in the atmosphere special vessels will be required. As a matter of fact, the explosion lasts such a short time in the cosmic rocket that these precautions are unnecessary, since the losses even in the case of conventional tanks are very insignificant.

By increasing the number of explosions and the magnitude of each charge, we shall finally arrive at an engine and a projectile type more or less close to that shown on our drawing.

In essence we are dealing with a rapid series of very strong idle firings. Therefore, if the explosion tube is sufficiently strong or is protected, we do not encounter any danger in conducting our experiments. However, the experiments must guide us. We must not assume that there is anything absolutely correct in our theoretical considerations.

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COSMIC ROCKET TRAINS

/215

(1929)

Preface by the Author

I am already 72 years old. For a long time I have not worked with my hands and have not conducted any experiments.

Since the publication of my first work in 1903, practical work and the development of reactive devices have been going on in the West.

Initially, military applications were sought (Unge in Sweden and Krupp in Germany).

Then, since the time of my second work published in 1911-1912, general theoretical and experimental work has been carried on (Brickland, Goddard). At the same time Esno Peltri came out with his concepts.

However, since 1913, people in our own country have become interested in the problem of flight about the atmosphere, particularly after they realized that this problem was regarded seriously by the West.

Since the publication and extensive distribution of my article "Outside the Earth" (published separately in 1920) in the Journal "Priroda i Lyudi," 1918, Oberth became interested in astronavigation. His publications gave the German scientists and thinkers a fairly good impetus which led to the appearance of many new works and workers. Two of these (particularly Lademan) quite diligently translated and distributed many works.

Rocket automobiles, hydroplanes, sleds and even an aeroplane have appeared. None of these was perfect, but a great deal of bustle and clamor was produced, which was quite useful both from the standpoint of experiments as well as from the standpoint of arousing interest among societies, scientists and designers.

In the USSR, these ideas also became more widespread. The following personalities have emerged: Vetchinkin (lectures), Tsander and Rynin. The last, with his excellent works and his broad knowledge of the literature, was particularly responsible for the propagation of ideas on astronautics.

Not only abroad but also in our country institutes are being formed and societies organized, whose members are propagating new ideas with talent and success.

I send my best wishes to workers in astronautics both in the USSR and abroad. They will have to work for more than a decade. At the present time this work is thankless, risky and immeasurably difficult. /216
It will require not only a tremendous exertion of effort and ingenious talent, but also many sacrifices.

Most people consider astronautics a heretical idea and do not wish to listen to it. Others are skeptical and consider the idea impossible. The third group has too much confidence in it and considers it to be an easy problem which will soon be solved. However, the initial unavoidable failures confuse and discourage the weak and undermine public confidence.

Astronautics cannot be compared with flying in the atmosphere. The latter is a toy compared to the first.

Undoubtedly, success will be achieved, but the time of this achievement is completely unknown to me.

The thought that it can be easily solved is a temporary fallacy. Of course, it is useful, because it provides energy and courage. If all of the difficulties associated with this matter were known, those working with enthusiasm would fall back in horror.

And yet, the achievement will be quite excellent. The conquest of the solar system will not only give us energy and life, which will be two billion times greater than Earth's energy and life, but will give us spaciousness which will be even more abundant. We may say that man on Earth commands two dimensions, the third is limited, i.e., propagation up and down is impossible at this time. When the solar system is conquered, man will have three dimensions.

The absence of gravity, the active rays of the sun, and a desirable temperature, obtained in a structure only by means of solar rays, free travel in all directions, and knowledge of the universe--these are some of the assets which will follow the conquest of the solar system. I discuss some of these things in my work "Outside the Earth."

What Is a Rocket Train?

1. I visualize the rocket train as a combination of several identical reactive devices which move first along a runway, then in air, then in vacuum outside the atmosphere, and finally between the planets or the suns.

2. However, only part of this train is carried off into space. The remaining parts which do not achieve a sufficient velocity return to Earth.

3. A single rocket requires a great deal of fuel to achieve cosmic velocity. Thus, to achieve the first cosmic velocity of 8 km/sec, the weight of the fuel must be at least four times greater than the weight of the rocket with its other components. This makes it very difficult to construct a reactive device.

The train, on the other hand, makes it possible to achieve high cosmic velocities or to limit the relative fuel supply. /217

4. Initially, we shall solve this problem in its simplest form. We propose that all of the rockets be identical and that the fuel supply and the explosion force also be identical. In practice, of course, there will be some deviations. The rockets moving along the runway will be simpler than the ones moving in the atmosphere and will not require special features for the prolonged life of people in ether space.

Construction and Operation of the Train

5. The explosion starts on the first rocket in order to keep the entire train in tension rather than compression, because the former is easier to control. This also contributes to the stability of the train during the period of explosion. In this case it is possible to build a longer train and consequently achieve higher velocity with the same amount of fuel in each individual rocket car.

6. When the cars are shorter, we can have a greater number of them, if we maintain the same factor of safety, and the more cars we have, the greater will be the terminal velocity of the last car. We should therefore try to make the length of individual projectiles as short as possible. However, the diameter of a rocket device cannot be less than 1 m. Therefore, the length of a rocket car cannot be less than 10 m. If the elongation is less than this, air resistance will become too great. For rockets which return to Earth this may be

sufficient, but for a cosmic car we must have a diameter of not less than 3 m and a length of not less than 30 m. We conclude from this that the last cosmic car should be made as spacious as possible.

7. The construction of a cosmic rocket is very complicated and will become even more so with time. It is not our purpose at this time to go into all of the details. Our purpose is different: to show the advantages of a train, as far as terminal velocity is concerned, compared with a single rocket device. It is possible that a small rocket will unfold when it reaches ether space and become larger. However, we do not concern ourselves with this problem and assume that the dimensions of the rocket are 3 and 30 m.

8. The cross section of the rocket is 3 m and its length is 30 m, the thickness of the walls is 2 mm (a little thicker towards the ends). The density of the materials is 8. The average cross section area is 7 m^2, the surface area is 180 m^2, and the volume is 105 m^3. The rocket can contain 105 tons of water. A section of the shell 1 m in length has the same weight at any place, since at the ends where the diameter is smaller the thickness is greater. Specifically the weight is 0.15 tons. We assume that the weight of the people, tanks, pipes, and other devices will be the same: altogether we shall have 0.3 tons per meter of length. Therefore the entire shell of the rocket will weigh 4-1/2 tons. The internal contents will weigh the same, so that the total weight will be 9 tons. Of this total weight, 1 ton will be due to the weight of the passengers.

9. We shall assume that the weight of the fuel will be 27 tons, /218
i.e., 3 times greater than the weight of the rocket with its other contents. (The corresponding velocity for each if we use petroleum is equal to 5,520 m/sec.) In each rocket this supply will occupy a volume of 27 m^3 (if the density is equal to unity), i.e., approximately 1/4 of the rocket's volume. There will be 78 m^3 left for people and equipment. If we take 10 people, each will be provided with approximately 8 m^3. Oxygen in this volume, contained at the pressure of 2 atm, will provide for the respiration of 160 people for a period of 24 hours, or of 10 people for a period of 16 days, if, of course, we remove the products of respiration.

We wish to show that even this great supply of fuel does not overload the rocket.

10. Explosion places the train under tension and this is the reason why the thickness of the walls at the narrow places of the rocket

is greater: the rupture strength of each section of the rocket must be the same.

11. When the factor of safety is 5, the rocket will withstand an overpressure of 4 atm. However, since even in vacuum it is not greater than 2 atm, the factor of safety will be 10.

12. Since each of the rockets may have to glide, even the last cosmic one, during its return to Earth, each rocket is equipped with the necessary device for this purpose.

A single inflated shell which necessarily has the shape of a body of rotation will not glide very well. It is necessary to combine, e.g., 3 such surfaces. If they are inflated with air or oxygen to a pressure of approximately 2 atm they will represent a rather strong beam.

13. We cannot propose using wings due to their rather high cost.

14. Each rocket must be equipped with rudders to control direction, altitude, and to counteract rotation. These rudders must operate not only in the atmosphere, but also in vacuum.

15. The rudders are located in the rear part of each rocket. There are two pairs of rudders. They are followed by the explosion tubes, which are deflected slightly to the side. Otherwise, the ejected gases will exert pressure on the rear rocket.

There will be at least 4 explosion tubes. Their exits are placed along the circumference of the rocket at equal distances from each other. Explosion takes place in pulses. These pulses could damage the rocket. Therefore, it is desirable to make the number of tubes much greater than 4. The explosions will be more frequent and may be situated in such a way that their pressure on the rocket will be quite uniform.

Each pair of rudders is situated in a single plane (parallel to the longitudinal axis of the rocket); however, their deflection in this plane may not be the same. The rocket will start to rotate. From this we can see that any pair may be used to prevent the rotation of the rocket. In addition, each pair is used to control the direction of the /219
projector in a given plane. In general we obtain the desired direction in space and prevent rotation. The flow of exhaust gases is directed over these rudders. It is thus clear that they operate not only in air but in vacuum as well.

16. Small quartz windows give several solar spots inside the rocket, required for control purposes. The larger windows are closed from the outside with shutters. Subsequently, in the rarefied atmosphere or in vacuum, they are opened.

17. The nose of the projectile is occupied by people. Behind the people is the engine room (pumps and engines for pumps), and finally the stern part is occupied by the explosion tubes and the surrounding tanks with petroleum. The latter are surrounded by tanks with freely evaporating liquid oxygen.

18. The operation takes place in approximately the following manner. The train, which we shall assume has 5 rockets, slides along a runway for a distance of several hundred km and rises 4 to 8 km above sea level.[1] When the forward rocket has almost consumed its fuel, it will separate from the 4 rockets behind it, which continue their motion due to inertia. The forward rocket, however, moves away from the rockets behind it because its explosions, although weak, still continue. Its pilot directs it to the side, and it gradually descends to Earth and does not interfere with the movement of the remaining 4 joined rockets.

When the path is clear, the second rocket (which is now the leading rocket) starts its explosion. It follows the same pattern as the first; it separates from the remaining 3 rockets and first moves away from them, but subsequently descends to the planet because it does not achieve sufficient velocity.

The other rockets behave in the same way except for the last one, which leaves the limits of the atmosphere and acquires cosmic velocity. As a result of this, it either orbits around Earth as a satellite or moves further away towards other planets and even towards other suns.

Determining the Velocity and Other Characteristics of the Train

19. For a single rocket we have the following equation (see my work "Investigation of Universal Space by Means of Reactive Devices," equation (38))

$$\frac{c_1}{W} = \ln\left(1 + \frac{M_1'}{M_0}\right),$$

[1]The problem of a solid runway was considered in my work "Air Resistance," 1927.

which gives the ratio of the terminal velocity of the rocket c_1 to the ejection velocity W as a function of the ratio of the total ejected mass M'_1 or of the fuel to the mass of the rocket with all its contents ex- /220
cept the fuel components; ln is the natural logarithm.

20. This equation may be applied to a compound rocket, i.e., to a train consisting of reactive devices. c_1 will represent the increment V of the velocity of each train due to the explosion of materials in one rocket. The relative ejection velocity W will always remain the same, as well as the ejected mass M'_1. However, the mass of the rocket M_0 is not the mass of a single rocket, but that of the entire train, neglecting the mass of the explosives M'_1 of the forward rocket which propels the entire train with all its unused fuel.

21. Therefore in equation (19) we must replace the mass of the rocket M_0 with the mass of the train M_p in accordance with the equation

$$M_p=(M_0+M_1')\,n-M_1',$$

where n is the number of rockets. Obviously, this expression pertains not only to the total train consisting of a definite number of rockets n, but to any other special train (after several of the front rockets have departed), consisting only of a smaller number of rockets n'.

22. Now instead of equation (19), we obtain

$$\frac{V}{W}=\ln\left[1+\frac{M_1'}{(M_0+M_1')\,n-M_1'}\right].$$

23. For the first train which contains the maximum number n_1 of rockets we obtain

$$\frac{V_1}{W}=\ln\left[1+\frac{1}{[(M_0:M_1')+1]\,n_1-1}\right].$$

24. For the second train which has one rocket less we have

$$\frac{V_2}{W}=\ln\left[1+\frac{1}{[(M_0:M_1')+1]\,(n_1-1)-1}\right].$$

25. We do the same for the remaining rockets. In general for a train of order x we have

$$\frac{V_x}{W}=\ln\left[1+\frac{1}{[(M_0:M_1')+1]\,(n_1-x+1)-1}\right].$$

26. For example, for the last train x equals n_1. By substituting we get equation (19) for a single rocket.

27. The velocity of the first train is expressed by equation (23); the total velocity of the second is expressed by the sum of the velocities of the first train and the incremental velocity of the second. In general, the total velocity of a train of order x is expressed by the sum of incremental velocities (25) of the first x trains. The total velocity of the last rocket will be equal to the sum of the incremental velocities of all the trains, from the very complex one to the last one which consists of one rocket (of the order n_1). /221

28. From the general equation (25) we see that the incremental velocities of the trains are large when the number of remaining rockets is small. The minimum incremental velocity occurs when we have a complete train, and a maximum occurs when $x = n_1$, i.e., when only one

rocket remains. Incremental velocities increase rather slowly and, therefore, a large number of rockets is not particularly advantageous, i.e., there is only a slight increase in the total velocity of the last rocket.

Nevertheless, the increase in cosmic velocity would be infinite if we were not limited by the strength of materials used to fabricate the rockets.

29. We may simplify the calculations if we consider the train from the end, in the inverse order, i.e., consider the train with a single rocket to be number one, the next one number two, etc. Then the successive number will be y and we obtain

$$y + x = n_1 + 1.$$

30. If we use this equation to eliminate x from equation (25), we obtain

$$\frac{V}{W}=\ln\left[1+\frac{1}{[(M_0:M_1')+1]\,y-1}\right].$$

Thus, we have shown that if we number the trains from the end, the incremental velocity does not depend on the total number of rockets n_1 in the train, but only on the inverse order y.

31. We can now prepare a table which will show us the total velocity of each specific train and the maximum total velocity of the last train which consists of one rocket.

Order y of the train counting from the end									
1	2	3	4	5	6	7	8	9	10
Order from the beginning x									
10	9	8	7	6	5	4	3	2	1
Relative incremental velocity, 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 the last train (consisting of one rocket) which initially consisted of several rockets									
1.386	1.856	2.118	2.325	2.491	2.622	2.735	2.835	2.925	3.005

32. For example, if we have a train consisting of 4 rockets, the final relative velocity will be 2.325, i.e., it will be greater than the ejection velocity by this factor.

The velocities of partial trains (when we have 4 rockets) in the normal order may be determined from the second line. Beginning with the most complex one they will be: /222

$$0.207;\ 0.207 + 0.262 = 0.469;\ 0.469 + 0.470 = 0.939;$$
$$0.939 + 1.386 = 2.325.$$

When the train has 10 rockets, the total velocity of the last rocket will be 3.005. The velocities of partial trains of this train in order x may be determined from the second line by adding its numbers beginning at the right.

33. The true velocities may be determined if we know the velocity V and the ejection velocity, i.e., the velocity of the products of combustion which fly out of the explosion tube. We obtain the following table:

Number of rockets in the train									
1	2	3	4	5	6	7	8	9	10
Final velocity of the last train in km, 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
Same, but $W = 4$ km/sec									
5.56	7.49	8.49	9.28	9.96	10.48	10.92	11.32	11.68	12.00
Same, but $W = 5$ km/sec									
6.95	9.30	10.60	11.60	12.45	13.10	13.65	14.15	14.60	15.00

Even if we use petroleum and obtain an efficiency of 50 percent ($W = 3$) with 7-8 trains, we obtain cosmic velocity. When the efficiency is higher, cosmic velocity is achieved with two or three trains. To escape from Earth and reach the planets up to the asteroids, a train with 10 cars may be sufficient.

34. If in equation (30) the mass of the rocket M_0 is large compared with the mass of the ejected matter M'_1, or if the partial train contains many rockets, i.e., if y is large, the second term in equation (30) represents a small regular fraction of Z.

Then, approximately, we may write

$$\ln(1+Z) = Z - \frac{Z^2}{2} + \frac{Z^3}{3} - \frac{Z^4}{4} \ldots$$

The smaller the fraction Z, the smaller is the number of terms that we have to take.

35. Let us assume, for example, as before

$$M_0 : M_1' = {}^1/_3 \quad \text{and} \quad y = 6.$$

The first approximation according to (34) will give us 1/7 or 0.143. This is slightly greater than what is given in Table 31 (0.131). The second approximation will be 0.133, which is closer to the true value. If we take a train with 9 cars, then Z = 1/11 and the first approximation gives us Z = 0.91, which is almost in agreement with the value shown on the table. /223

36. Thus, beginning with the eleventh train, we may confidently assume that

$$\frac{V_y}{W} = Z = 1 : \left[\left(\frac{M_0}{M_1'} + 1\right)y - 1\right].$$

37. The sum of the incremental velocities of trains beyond the eleventh may be determined approximately from the end by integrating expression (36). We have

$$\frac{M_1'}{M_0 + M_1'} \ln\left[\left(\frac{M_0}{M_1'} + 1\right)y - 1\right] + \text{const.}$$

If const = 10, the sum of the incremental velocities is equal to zero. Consequently

$$\text{const} = -\frac{M_1'}{M_0 + M_1'} \ln\left[\left(\frac{M_0}{M_1'} + 1\right)10 - 1\right].$$

Therefore, for the sum of incremental velocities, we obtain

$$\frac{M_1'}{M_0 + M_1'} \ln\left[\frac{\left(\frac{M_0}{M_1'} + 1\right)y - 1}{\left(\frac{M_0}{M_1'} + 1\right)10 - 1}\right].$$

38. Assuming that y = 11 (eleventh train, i.e., the addition of 1 rocket to 10), we find the relative incremental velocity as 0.077 (table 31).

If we add 10 trains, y = 20, and the total incremental velocity of ten trains will be 0.55. When the ejection velocity is 4 km/sec, the absolute increment constitutes 2.2 km/sec.

If we add 90 rockets, y = 100, and the incremental velocity will be 1.78. The absolute increment (W = 4 km/sec) is equal to 7.12 km/sec. According to Table 33, 10 trains under the same conditions give us 12 km/sec. This means that 100 trains will give a velocity of 19.12 km/sec. This is more than is necessary to escape to other suns.

If the efficiency of fuel utilization is 50 percent (Table 33), we find that the velocity derived from 100 trains will be 9 + 5.34 = 14.34 km/sec.

39. If we have more than 100 rockets in the train, we may express the total incremental velocity by the equation (from 37)

$$\frac{M_1'}{M_0 + M_1'} \ln\left(\frac{y}{10}\right)$$

40. For example, for 1,000 trains the maximum relative velocity will be 3.454. If W = 4, the absolute increment produced by 990 rockets is equal to 13.82, while 1,000 rockets will give us 25.82 km/sec. /224

41. First, let us imagine a horizontal motion of all trains. The last rocket will have the maximum acceleration (velocity increase to 1 sec). However, in practice, it is more convenient to have the force of explosion remain constant. If this is so, then the acceleration of a single rocket will be weak at the beginning because its mass will be high or because its fuel has not been used up. Then, as the fuel is burned, the acceleration will become larger. In the case of our triple supply, the acceleration at the beginning will be 4 times smaller than at the end, when the entire explosive material has been used up.

42. When the explosion takes place normal to the direction of gravity, it is not advantageous to make use of large acceleration (on a solid track, in the air or in vacuum). In the first place, special safety measures will be required to safeguard the passengers from excessive gravity, in the second place, the rocket itself must be stronger and consequently more massive, and in the third place, the explosion tubes and other equipment must also be stronger and heavier.

43. Let us assume that the maximum acceleration of the train is 10 m/sec^2. The same acceleration (1 sec) is experienced on the surface of Earth by an object which falls freely. It is clear that this acceleration will exist in the last train consisting of one rocket and will occur at the end of the uniform explosion. We shall assume that the force of this explosion decreases proportionately to the decrease in the total mass of the rocket, so that acceleration will be constant and equal to 10 m/sec^2 during the entire period of time.

44. The mass of trains consisting of two or more rockets varies little and, therefore, the force of explosion in this case may be assumed to be constant as well as acceleration. It will be smaller in value when we have a great number of rockets in the train, so that some nonuniformity will not produce adverse effects.

45. The acceleration of the second train (from the end) will be twice as small, since its mass is twice as large. The acceleration of the ninth train will be 10 times smaller, since it contains 10 rockets of the same mass, etc.

It turns out that the tension of the horizontal train or its relative weight does not depend on the number of rockets. Indeed, even if we have 1,000 rockets, the tension due to the mass will be 1,000 times greater, but at the same time due to low acceleration it will be 1,000 times smaller. Obviously, the train consisting of any number of rockets will have the same tension as the one consisting of one rocket.

46. If the tension of a long train is greater than this, it is due to friction and air resistance. For the time being we neglect this effect.

47. An inclination of the path with respect to the horizon also increases the tension of the train proportionately to its length. If we follow a curved path which ascends gradually, such that the slope is /225 very small and is proportional to the acceleration of the train, this effect may be neglected.

48. Taking all these things into account, we compute the times, the velocities, the tracks and the ascents of the trains (Table 49).

It is very convenient to assume that the explosive part in each rocket operates in exactly the same manner. Then the explosion time will be the same for all rockets.

If we obtain the first cosmic velocity of 8,000 m/sec, when we are outside the atmosphere we can use light pressure or some other method which will make it easier for us to move away from Earth and to travel within the limits of the solar system, or even further away.

49. The train with five rockets.

	The number of the train in chronological order				
(1)	1	2	3	4	5
	The number of rockets in each train				
(2)	5	4	3	2	1
	Average acceleration in m/sec^2				
(3)	2	2.5	3.33	5	10
	(The explosion time is constant.) The relative increment in velocity of each train				
(4)	0.2	0.25	0.333	0.5	1.0
	The final relative velocity of each train				
(5)	0.2	0.45	0.783	1.283	2.283
	The absolute velocity of each train if the increment in velocity of the last rocket is assumed to be 55-20 m/sec[1]				
(6)	1,104	2,484	4,322	7,082	12,602
	The time of explosions in seconds is equal to				
(7)	1,104:2 = 552 = 5,520:10 = 552				
	It is the same for all rockets				
	The average velocity of each train in m/sec				
(8)	552	1,242	2,161	3,541	6,301
	The entire path traveled by each train in km (during explosion)				
(9)	288.14	685.58	1192.87	1954.63	3478.15

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[1]See "Investigation of Universal Space by Means of Reactive Devices."

The slope tangent

(10)	0.02	0.025	0.033	0.05	0.1

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The total vertical ascent of each train in km

(11)	5.76	17.1	39.6	97.7	347.8

The same if the slope is twice as small

(12)	2.88	8.5	19.8	48.8	173.9

The terminal velocity when 50 percent of the fuel is used up and when the velocity of a single rocket is equal to 3,900 m/sec

(13)	780	1,755	3,054	4,992	8,892

The length of the trains in meters

(14)	150	120	90	60	30

50. From the 6th entry we see that a train consisting of 5 rockets achieves a velocity sufficient for escape from Earth and even from its orbit. The next to the last train, consisting of 2 rockets, achieves almost the first cosmic velocity (8,000 m/sec). Thus, it lacks very little, which prevents it from traveling outside the atmosphere around Earth, together with the last rocket whose explosives have not been completely consumed. It is clear that it may be replaced by some other load. Here we see the possibility of making entire loaded trains into satellites of Earth, if the total number of rockets is sufficiently large.

51. From the 7th entry we see that the period of explosion in each train is equal to 552 sec, or 9.2 min. For 5 trains this is equal to 46 min. This means that in less than 1 hour everything will be finished, and the last rocket will become a roving body.

Our supply of explosives is 3 times greater than the weight of the rocket with its other contents, and therefore is equal to 27 tons. Consequently, 48.9 kg must explode every second. In order to produce uniform action, we must have a large number of explosion tubes. If each rocket has 40 explosion tubes and if the engine produces 30 revolutions per second or 30 pump cycles, each delivery will constitute 0.041 kg or 41 g. What can we compare this cannonade to? To 1,200 idle firings in 1 sec, each consisting of 41 g of a highly explosive substance. This firing lasts continuously in all of the rockets for a period of 46 minutes.

52. We have assumed that the cross section of the rocket is equal to 3 m. Initially we can do with 1 m. Then this entire horrifying picture is weakened by a factor of 27 (3^3). We have stated that in this case the last cosmic rocket may open up in a special way and become a spacious compartment for man. We shall speak of this elsewhere.

53. From the 9th entry we see that the path traveled by the trains /227
does not exceed the dimensions of Earth's sphere. However, the vertical ascent of each train (entry 11) is much smaller. Only the first train, which has traveled a distance of 288 km on Earth, rises to an altitude of 5-6 km. The second train must leave the solid runway very soon and fly in the air. The last rocket flies beyond the limits of the atmosphere before it has consumed its fuel. This is true when the maximum tangent of the angle of ascent (for the last train) is equal to 0.1, and the corresponding angle with the horizon is equal to 6^{o}. For the first train it is slightly greater than 1^{o}, for the second train it is slightly more than 2^{o}, etc.

54. When the slope is twice as small (entry 12), 2 trains can spend the period of their explosion on the solid runway. The height of Earth's mountains will still permit this. Then the solid runway will be approximately 600-700 km.

55. In entry 13 we have assumed a 50 percent utilization of the energy contained in the explosives. Even then, the last train will obtain a velocity substantially greater than the first cosmic velocity (8 km/sec). The rocket race in this case will be much shorter.

56. The maximum initial train has a length of 150 m. If initially we limit ourselves to dimensions which are 1/3 of this, a 5-rocket train will be 50 m.

57. We have already stated that the strength of the train does not depend on the number of rockets on the horizontal path. However, is the strength of the individual rocket sufficiently high?

The area of the cross section of the rocket's shell is the same

everywhere and is equal to 18,000 mm^2. The resistance to breakdown when we have a factor of safety of 6 will be not less than 180 tons. A rocket with all its contents (and fuel) has a mass of 36 tons. An acceleration of 10 m/sec^2 associated with ordinary gravity produces a relative gravity 1.4 times greater. However, the horizontal component will be equal only to Earth's component. Thus, the rocket is subjected to a tension which is equal to 36 tons. This destructive force is 5 times less than the force of resistance of the material. If, on the other hand, we use a rocket whose diameter and length is 3 times less, the breakdown force will be 15 times less than the reliable resistance.

58. Inclined motion increases this destructive influence. However, it is the same for all of the trains. For a single rocket the inclination is small and increases the stress only by a factor of 0.1. The inclination, e.g., of a 5-section rocket is 5 times less, so that in spite of the large mass the stress will be increased (in total) also by a factor of 0.1.

59. From this we can see that the rockets could be made much less massive, if it were not for the gaseous overpressure unavoidable in space. Nevertheless, it can be decreased by a factor of 4, because instead of 4 atm the overpressure may be limited to 1 atm. However, for small rockets the shell will be too thin to be of practical value.

60. In view of the excessive factor of safety for the strength of the train in tension, we propose another table for the trains consisting of one, two, three, four, and five rockets. However, we assume here that the force and velocity of explosion of the same mass of explosives is proportional to the mass of the train. Thus, the first train which may consist of five rockets is pulled with a force five times greater than that of a single rocket and, therefore, both trains have the same acceleration as well as all the individual trains of the same general train. It turns out that, in spite of the difference in the number of rockets of individual trains, we appear to have a single body moving with constant acceleration. However, the time of explosion, of course, is inversely proportional to the masses of the individual trains (because the stronger explosion ends sooner). /228

61. In all of the tables (see 62 and 63) we assume that the final total velocity of the last rocket is equal to the cosmic velocity of 8 km/sec. Incidentally, the tables answer the following question: what is the required incremental velocity for a single rocket? From the fifth entry of the table we see that these incremental velocities for various trains will be as follows:

Number of rockets in a train				
1	2	3	4	5
The required incremental velocity from a single rocket in km/sec				
8	5.3	4.4	3.8	3.5

We see that the incremental velocity is smaller when the number of rockets in the train is larger. For a five-car train it is only 3.5

km/sec, which is achieved when we have a relative fuel supply of 1 or 1.5.

From the tenth and sixteenth entries we see that the length of the tracks along the solid ground is much smaller in this case. Also, the entire take-off process is shorter: it lasts only 800 sec or 3.3 min, since acceleration does not change while explosion takes place.

62. The length of the rocket is 30 m.

One rocket	Two rockets		Three rockets		
Numbers of trains					
1	1	2	1	2	3
Number of rockets and relative force of explosion					
1	2	1	3	2	1
Relative time of explosion					/229
1	1	2	1	1.5	3
Relative period of the accelerated motion of each train					
1	1	3	1	2.5	5.5
Final velocity of each train in m/sec					
8,000	2,667	8,000	1,454	3,636	8,000
Velocity increment of each train in m/sec					
8,000	2,667	5,333	1,454	2,182	4,364
Period of motion of each train with the preceding ones in sec					
800	266.7	800	145.4	363.6	800.0
Period of motion of a single train in sec					
800	266.7	533.3	145.4	218.2	436.4
Average velocity of each train in m/sec					
4,000	1333.3	4,000	727.2	1818.2	4000.0

Path length of each train with the preceding ones in km					
3,200	355.5	3,200	105.7	661.1	3,200
Flight path of each train by itself in km					
3,200	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
Same			sin α = 0.25		
800	88.9	800	26.4	166.3	800.0
Same			sin of angle = 0.20		
640	77.1	640	211	132.2	640.0
Same			sin of angle = 0.15		
480	53.3	480	15.8	99.2	480.0
Same			sin of angle = 0.10		
320	35.5	320	10.6	66.1	320.0
Length of entire train in m					
30	60	30	90	60	30

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63. The length of the rocket is 30 m.

Four rockets				Five rockets				
Numbers 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
Relative explosion time of each train								
1	1.33	2	4	1	1.25	1.67	2.5	5
1	2	3	4	1	2	3	4	5

Relative acceleration period of each train								
1	2.33	4.33	8.33	1	2.25	3.92	6.42	11.42
Final velocity of each train in m/sec								
960.4	2237.7	4158.5	8,000	700.6	1576.3	2,746	4497.8	8,000
Velocity increment of each train in m/sec								
960.4	1277.3	1920.8	3841.5	701	876	1,170	1,752	3,502
Period of travel of each train with the preceding ones in sec								
96.0	223.8	415.8	800.0	70	158	275	450	800
Period of acceleration of one train in sec								
96.0	127.8	192.0	384.2	70	88	117	175	350
Average velocity of each train in m/sec								
480.2	1118.8	2079.2	4000.0	350	788	1,373	2,249	4,000
Length of track for each train with preceding ones in km /231								
46.08	250.43	864.45	3,200	24.50	124.50	377.57	1012.05	3,200
Flight path of each train individually in km								
46.1	204.3	614.02	2335.6	24.5	100.0	253.1	634.4	2188.0
Altitude reached						sin α = 0.3		
13.8	75.1	259.3	960.0	7.35	37.35	112.28	303.61	960
Same						sin α = 0.25		
11.5	62.6	216.1	800.0	6.1	31.1	94.4	253.0	800
Same						sin α = 0.20		
9.6	50.1	172.9	640.0	4.9	24.9	75.5	204.4	640
Same						sin α = 0.15		
6.9	37.5	129.7	480.0	3.67	18.6	56.7	151.8	480

Altitude reached				sin α = 0.1				
4.6	25.0	86.4	320.0	2.45	12.4	37.8	101.2	320
Length of entire train in m								
120	90	60	30	150	120	90	60	30

64. It should be recognized that the slope of the solid runway with respect to the horizon in this case must be very small but constant, e.g., 6°, in which case sin α will be equal to 0.1. The runway will be straight and not concave as is the case when we have a variable acceleration of individual trains.

65. If we have trains with two, three or four rockets, not only can we have a constant acceleration, but the period of explosion may also remain constant. However, in this case the fuel supply in each leading rocket must be proportional to the force of explosion or to the mass of each individual train. This means that the first rockets explode faster and for a longer period of time than indicated in Tables 62 and 63 in view of their high supply of fuel. In this case the individual trains also move like one body with a constant acceleration. On this basis we present the following table.

66. The length of the rocket is 30 m.

	Two rockets		Three rockets			Four rockets			
	Number of trains								
(1)	1	2	1	2	3	1	2	3	4
	Number of rockets in an individual train, relative force of explosion and fuel supply								
(2)	2	1	3	2	1	4	3	2	1
	Relative period of accelerated motion for each train /232								
(3)	1	1	1	1	1	1	1	1	1
	Relative total period of explosion for each train								
(4)	1	2	1	2	3	1	2	3	4
	Final velocity of each train in km/sec								
(5)	4	8	2.7	5.3	8	2	4	6	8

	Incremental velocity of each train in km/sec								
(6)	4	4	2.7	2.7	2.7	2	2	2	2
	Total period of motion for each train if acceleration is always equal to 10 m/sec^2								
(7)	400	800	267	533	800	200	400	600	800
	Period of motion of one train in sec								
(8)	400	400	267	267	267	200	200	200	200
	Average velocity of each train in km/sec								
(9)	2	4	1.33	2.67	4.00	1	2	3	4
	Total path length of each train, with the preceding ones, in km								
(10)	800	3,200	355.5	1,422	3,200	200	800	1,800	3,200
	Flight path of each train individually								
(11)	800	2,400	355.5	1066.5	1,778	200	600	1,000	2,200
	Total altitude achieved in km; sin α = 0.1; $\alpha = 6^{\circ}$								
(12)	80	320	35	142	320	20	80	180	3,200
	Length of trains in m								
(13)	60	30	90	60	30	120	90	60	30

67. In general the slope of the runway with respect to the horizon in this case may be constant, e.g., the tangent of the slope angle of 6° is equal to 0.1.

In this case even the first specific train can only travel part of the path along the solid ground. The remaining larger part of the path is in the atmosphere. /233

From the sixth entry we see that the incremental velocities are the same for specific trains with the same number of cars and decrease as the number of rockets in a train increases. For a four-rocket train the incremental velocity is only 2 km/sec, which corresponds to a relative fuel supply of 0.5-0.7 (with respect to the mass of the rocket without explosives).

The forward Earth trains may have a large mass of fuel because they may contain fewer people and less equipment since they return immediately to Earth.

68. Nevertheless, from the practical point of view it is desirable to have rockets which are constructed in the same manner and which have the same supply of fuel and the same constant force of explosion (see Section 4). They may consist of a large number of rockets, which increases the terminal velocity or which makes it possible for us to get away with a small supply of fuel in each individual rocket. In other words, even though reactive devices are not perfect, it is possible to achieve cosmic velocities.

69. We present a table for a train with 10 rockets. The period of explosion in each individual train is the same because each rocket is identical.

The length of each rocket is equal to 30 m. The rockets are identical in construction and have the same fuel supply.

Number of specific trains

(1)	1	2	3	4	5	6	7	8	9	10

Number of rockets in each specific train

(2)	10	9	8	7	6	5	4	3	2	1

(3) Explosion time is the same

Acceleration of each train in m/sec^2

(4)	1	1.111	1.250	1.429	1.667	2	2.5	3.333	5	10

(5) If we wish to achieve the first cosmic velocity of 8 km/sec, then the period of explosion will be 8,000 m/sec; 29.29 m/sec^2 = 273.1 sec (see below and section 70)

Incremental velocity of each train in m/sec

(6)	273	301	343	391	456	546	682	1,009	1,365	2,734

Final velocity of each train in m/sec

(7)	273	574	917	1,308	1,764	2,310	2,992	3,901	5,266	8,000

Average velocity of each train in m/sec

(8) 136 287 458 654 882 1,155 1,496 1,950 2,633 4,000

Path traveled by each train in km (see entries 3 and 5) /234

(9) 37.1 78.3 125.0 178.5 240.8 315.3 408.4 532.3 718.8 1092.4

Entire path traveled by each train with the preceding ones in km

(10) 37.1 115.4 240.4 418.9 659.7 975.0 1383.0 1915.7 2634.5 3726.9

Slope of the path of each specific train. The tangent of the angle (6°) of the latter is assumed to be equal to 0.1. The slope of the others is proportional to the acceleration

(11) 0.01 0.0111 0.0125 0.0143 0.0167 0.02 0.025 0.0333 0.05 0.1

Altitude reached by each train in km

(12) 0.371 0.870 1.562 2.553 4.021 6.306 10.21 17.72 35.94 109.24

Total altitude in km

(13) 0.371 1.241 2.803 5.356 9.377 15.683 25.89 43.61 79.55 188.79

Altitude with respect to the track (12 and 10)

(14) 0.01 .01090 .01179 .01278 0.0140 0.0161 0.0187 0.0227 0.0302 0.0508

Total period of explosion for each train in sec

(15) 273 546 819 1,092 1,365 1,638 1,911 2,184 2,457 2,730

70. If we designate the explosion period by x and require that the final rocket of the train reach the first cosmic velocity, then on the basis of the fourth entry we have

$$1x + 1.1x... + 1.25x... + 2x... + 5x + 10x = 29.39x = 8,000,$$

from which it follows that $x = 273.1$ sec.

71. The maximum incremental velocity which must be obtained by the last individual rocket will be only 2.7 km/sec, which corresponds to a relative fuel supply of 0.8 to 1. If the supply is greater, then the terminal velocity will also be greater. However, initially, this will not be necessary.

72. The first four trains may travel over solid ground which rises to an altitude of 6 km and has a total path length of 419 km (see the 13th and 10th entries). This is possible on Earth. The fifth train terminates its path in the atmosphere, and the remaining five trains start their path in the atmosphere. Due to the spherical shape of Earth, the ascent of the last trains is much greater than given in entry 12.

The length of the entire path over which explosion takes place reaches a value of 3,000 km.

73. The solid runway is concave (entry 14). Accurate calculations to determine this curvature yield equations which are too complicated (they contain second derivatives), and we shall not present them here so as not to obscure the principal points. We shall assume that the slope of the path is constant for each train. From elementary theory we have

$$r = L^2 : 2h,$$

where the symbols in their order indicate the following: radius of curvature, the traveled path and vertical ascent h. Entries 10 and 13 permit us to determine the radius of curvature for each section of the path. Thus, for the first, fifth and last, i.e., the tenth, we find in km: /235

$$r = 1,850,\ 23,220 \text{ and } 36,770.$$

From this we can see that the radii of curvature increase, which produces a decrease in the centrifugal force. However, at the same time, the centrifugal force increases due to the increase in the velocity of the trains (the true radii are greater and therefore the true centrifugal force is smaller).

74. We compute the centrifugal force for three cases. As we know, it is equal to

$$c_r = v^2 : r,$$

where c_r is the centrifugal force, v is the velocity and r is the radius of curvature of the path. From this equation we obtain (entry 7 and Section 73)

$$c_r = 0.04,\ 1.34 \text{ and } 1.74.$$

With respect to Earth's gravity (10 m/sec^2 acceleration), this constitutes 0.004 to 0.17. But let us not forget that only the fourth train can move along the solid path and develop a centrifugal force. The remaining trains move in the atmosphere and there the centrifugal force may not exist at all: in general it depends on us, i.e., on the method of control. For the fourth train r = 16,360 and c = 1.05, i.e., the force which presses the train towards the path is not greater than 1/10 of the train's weight (actually, it is even smaller).

75. Let us consider the relative force of gravity developed inside the train during its motion. The centrifugal force presses the train against the runway, first very insignificantly and then with greater force; however, the maximum of this force does not reach 0.1 of Earth's gravity. We shall neglect this force. The second force normal to it depends on the acceleration of the train. Its maximum value is equal to Earth's acceleration (10 m/sec^2). We can no longer neglect this quantity. The resultant of the two forces gives us an acceleration which is approximately equal to 14 m/sec^2; this is 1.4 times greater than Earth's acceleration. A person weighing 75 kg will weigh not more than 105 kg inside the train. It is easy to withstand this increase in gravity for a period of several minutes, even standing up. Gravity will increase slowly, varying from 1-1.4 of its normal value. The slope of this relative gravity with respect to the vertical line also increases gradually from 0-45°. The horizontal surface of Earth appears to incline more and more as acceleration is increased, and at the end of acceleration it appears to the passengers that the train is moving up a mountain at an angle of 45°. During the initial stages of the motion this mountain is almost horizontal, then becomes steeper and steeper, and at the end of the solid path it becomes almost vertical. The picture is frightening and astonishing. Friction and air resistance decrease the acceleration slightly and, therefore, decrease the additional gravity. /236

76. When the train leaves the solid runway and moves into the air, the phenomenon becomes more complicated.

In the atmosphere the effect would be the same as when the resultant explosive force is directed along the longitudinal, slightly inclined axis of the rocket. Then, as the latter falls, it will experience air resistance equal to its weight. Air will put pressure on it, just like the solid runway. However, the rocket which flies along the inclined path with its nose up will not fall to Earth, since it will rise faster than it falls.

77. Descent to Earth due to its gravity will be slow at first and then accelerated; then a velocity will be reached at which the air pressure is comparable to the weight of the rocket. At this point the vertical fall velocity will become constant and not too great, compared with the continuously increasing velocity of ascent of the rocket.

78. A rocket which undergoes parallel tripling or quadrupling will produce, on 3 m^2 of its horizontal projection, a force of gravity approximately equal to 0.9 tons at the beginning of the explosion. (For a rocket with a diameter of 1 m, it will be 9 times less.) For an area of 1 m^2 we shall have 0.3 tons (see 8). The air pressure on 1 m^2 of the horizontal projection of the projectile will also be the same. We may use this as a basis for forming an equation which will give us the necessary conclusions.

79. Let us assume that the resultant force of explosion is horizontal. Then the incident stream will be directed at some angle with respect to the rocket (if we assume that the latter is plane), and the tangent of this angle will be equal to

$$c_h = c,$$

where c_h is the constant velocity of fall of the rocket due to its gravity and c is the variable velocity of the rocket's forward motion.

80. The pressure of the air stream on a surface normal to it with an area of 1 m^2 will be not less than

$$(d:2g)c^2,$$

where d is the density of the air, g is the acceleration due to Earth's gravity, and c is the velocity of the stream.

The stream exerts a strong force on the inclined plate (proportional to twice the tangent of the angle). Consequently the pressure on each m^2 of the rocket's base is given by

$$(d:g)cc_h.$$

81. We must equate the magnitude of this pressure to the weight G_1 of the rocket, corresponding to 1 m^2 of its base (0.3 tons or 300 kg). Consequently,

$$G_1 = (d:g)cc_h.$$

From this it follows that /237

$$\frac{c_h}{c} = (gG_1):(dc^2).$$

From this we can see that the relative velocity of fall, or the angle of fall (tangent), will decrease very rapidly as the forward velocity of the rocket increases. However, it increases when the density of the air decreases, i.e., when the rocket gains altitude.

82. Let us compute the tangent of this angle for various velocities of the rocket and various air densities.

If, for example, d = 0.0012, G_1 = 0.3 tons, g = 10 m/sec^2, c = 1,000 m/sec, the slope will be 0.0025. Even at an altitude of 8-10 km where the density of the air is four times less, the slope will be 0.01. If the velocity of the rocket is twice as small (500 m/sec), the slope will be 0.04. Even this slope is 2.5 times less than the value assumed by us (0.1) for the slope of the rocket's axis with respect to the horizon (when it leaves the solid runway). This means that under these conditions the rocket also will not fall, but will rise rapidly, moving away from the surface of Earth, particularly since the latter has a spherical shape.

83. However, as time passes the rarefaction of air increases more rapidly than the square of the forward velocity of the rocket. Therefore, a time will be reached when the weight of the rocket will not be balanced by the resistance of the atmosphere, the relative vertical component of gravity will decrease, and beyond the limits of the atmosphere in the vacuum it will disappear. Then only gravity due to the accelerated forward motion of the rocket will remain and will be equal to 10

m/sec^2. It will produce an apparent gravity whose magnitude will be equal to Earth's gravity, but whose direction will be almost perpendicular to Earth's gravity. Then Earth will appear as a vertical wall, and we will be moving parallel to it.

However, this, too, lasts only a few minutes: explosion ceases and all traces of gravity vanish.

84. If, in the last equation, we let the tangent of the angle be equal to 0.1 and c = 1,000 m/sec, we find d = 0.00003, i.e., we can fly to an altitude where the air density is very small (0.00003 or 40 times less than at sea level), and still not fall when the velocity is 1,000 m/sec. This velocity still does not develop the centrifugal force which is equal to the force of gravity of Earth and, therefore, does not give us a circular orbit where we neither approach Earth nor move away from it. Only when the velocity of 8 km/sec is achieved, will the orbit be circular and permanent (this will be true only outside the atmosphere).

Various Train Systems

85. We shall describe our trains as they are used in various systems. We have four cases.

A. The construction of the rockets is almost identical. They all have the same supply of fuel; however, explosion becomes greater as the mass of the train is increased. In view of this, the acceleration for all individual trains will be the same; however, the period of explosion will be inversely proportional to the mass of the train (Sections 62 and 63). /238

B. The supply of explosives and the force of explosion increases as the mass of the individual train increases. Due to this, the acceleration and the explosion time are the same for all trains (see Section 66).

C. The fuel supply is proportional to the mass of the individual train, but the force of explosion is constant. In this case the period of explosion for each train becomes larger as its mass becomes greater. The acceleration is inversely proportional to the mass of the individual train. We have not considered this case.

D. All of the rockets are identical with respect to the fuel supply and the nature of the explosion. The greater the mass of the individual train, the lower is its acceleration. The period of explosion is the same for all trains (see Section 49).

86. System A is inconvenient because it requires a strong or rapid explosion in the first rocket, and consequently makes the firing mechanism too complicated and too heavy. Due to this, the tension in the first long trains will be tremendous. The entire system is subject to failure, and, therefore, a multirocket train cannot be used. The incremental velocity of each train is the same as in system D. The advantages are the decreased length of the solid runway and the decrease of explosion time, but these are not very important (Sections 62 and 63).

87. System B, like the preceding system A, requires an increase in the mass and the volume of the rocket, when we increase the number of elements in the train. The fuel and the more complex equipment require additional space. In this case, we can not use too many rockets in the train: it will break down due to high acceleration. The advantages are in the velocity increase, since the incremental velocity is the same for all trains. This means that the terminal velocity is proportional to the number of rockets in the train. If, e.g., the incremental velocity of a single rocket is 8 km/sec, the train of system B, consisting of two rockets, will reach a velocity of 16 km/sec, which is almost enough to move among other suns. If we can obtain a velocity of 2 km/sec from each rocket, a train with four rockets will impart the first cosmic velocity of 8 km/sec to the last rocket (see Section 66).

88. System C is more practical because in this case for long trains the acceleration will be lower, as in system B and we may, therefore, use many rockets for each train. The firing mechanisms in the rockets themselves are almost identical. However, since the quantity of fuel is proportional to the mass of the individual train, the forward rockets must be larger in order to contain a larger mass of fuel. This is the disadvantage. However, we have seen that we have enough space in our rockets, and a train consisting of two or three rockets is, therefore, possible even without a change in the volume of the devices. The other advantage consists of the fact that the incremental velocities do not decrease as the number of rockets is increased, as in system B. Indeed, even though the acceleration in a long massive train is less, /239 the period of explosion due to the large supply of fuel is also greater by the same factor. Therefore, the final incremental velocities in all of the individual trains are the same, which is a considerable advantage. The increase in the time and the length of the solid runway (compared with systems A and D) is insignificant.

89. Although we have not considered this case, we can obtain the magnitude of incremental velocities by making use of Table 66. This system C deserves our most undivided attention. If, e.g., by using a single rocket we could achieve a velocity of only 1 km/sec (the velocity achieved by a cannon may be greater), which requires a relative supply of 0.2 to 0.3, then 17 trains would be enough to achieve the maximum cosmic velocity necessary to reach all our planets (but not descend to

them) and to travel in the Milky Way. The fuel supply in the rockets beginning with the first will not be more than

5.1 4.8 4.5 4.2... 1.2 0.9 0.6 0.3

Such supplies are within our reach. The last cosmic rocket will be almost empty, i.e., without fuel.

Such are the prospects of using trains and such is the manner in which they can make it easier for us to achieve cosmic velocities!

90. We have discussed system D sufficiently (see Section 49). Its advantages are that the elements of the train are identical (except for the last cosmic rocket).

Having dispatched the last rocket on a cosmic voyage, all of the other rockets of any of the systems fly a rather prolonged path in the atmosphere, glide and descend to land or water, and may be used again for the same purpose. The same train in the same path may dispatch a million devices for space travel. The only thing required is a continuous expenditure of funds to obtain the fuel made from inexpensive petroleum products and endogenous compounds of oxygen.

The disadvantage of system D is the small incremental velocity. However, if the series in Section 89 is replaced by equal members, e.g., with a value of 5.1, then system C will be transformed into system D and the terminal velocity will increase substantially.

91. The problem of materials for combustion, the construction of the explosion tube, of the shell and of the other parts of the rocket cannot be solved at this time. Therefore, I assume for the present that the explosives will consist of petroleum products and liquid oxygen or its endogenous compounds, and that the rocket will be made from various known types of steel: chrome steel, beryllium steel, etc.

Of course, there is much to be gained by using monatomic hydrogen and ozone for the explosives. However, we do not know whether these materials are sufficiently stable or that they can be utilized in a /240
convenient form. This problem must be solved by chemists specifically concerned with these substances.

If good results are possible with oxygen, petroleum and steel, then the results will be even better when we use more advantageous materials.

The Temperature of a Cosmic Rocket

Even among scientists there are contradictions and obscure ideas concerning the temperature of bodies in ether, e.g., the temperature of the rocket.

It is claimed that space has a temperature. Such claims are impossible: they have no meaning because we do not have a clear understanding of ether. We can speak only of the temperature of gases, liquids, and solid bodies which are placed in space.

If we can assume that some body in space is not surrounded by any other bodies, e.g., suns, planets, comets, and small bodies, then this body will only lose heat because it cannot exchange it with other bodies. It is quite probable that the temperature of such a body will reach absolute 0, i.e., it will be -273° C: the motion of molecules will stop, but this does not mean that the motion of their parts and, particularly, the motion of protons and electrons will cease. It is also doubtful that the motion of molecules and atoms will cease completely.

However, we shall not become deeply involved in this problem. We need a simple concept concerning the temperature of bodies in space. It is quite probable that this temperature is close to -273° C. This is the temperature we have when we are far away from the suns, when they appear like stars, since in this case the heat obtained from them can be neglected. It is very difficult to doubt this (although in this matter, too, the conclusions of the scientists are contradictory). Indeed, at the present time, there is factual data to show that the temperature of the planets far from the sun is very low, even though they are heated by solar rays. If they were to move even further away from the sun, so that all of the suns would appear to them as stars, this temperature undoubtedly would reach absolute 0 (273° below 0° C).

Planets also contain their own heat, they combat cooling, they have a large supply of heat and of its sources.

However, small bodies such as asteroids (if they are removed from warm or heated bodies), rapidly reach a degree of absolute cold.

Therefore, a cosmic rocket, situated at a great distance from the sun between stars which hardly twinkle, will apparently be in a critical state. Its temperature will very rapidly reach -273° C.

However, it may contain a source of heat inside it, or it may be protected by a series of shells to such a degree that the heat losses will be replenished artificially, even during a period lasting for thousands of years. /241

We shall not consider this question at the present time. We turn to the projectile situated at the same distance from the sun as Earth. This does not in any way prevent it from being outside Earth in its orbit, at hundreds of millions of km away from Earth, where the latter appears like a small star similar to Venus.

Our rocket will lose heat only by radiation, because there is no air and no other material medium around it. However, it will also receive heat from the sun and, therefore, its temperature will drop only as long as the loss of heat, due to radiation, is not equal to the influx of heat from the sun.

Therefore, we must have some idea concerning the quantity of influx and outflux, and solve the problem concerning the magnitude of the equilibrium constant temperature of the body.

The magnitude of the heat influx, of course, depends on the energy of solar rays. We shall assume that this energy is constant. However, it may not be absorbed by our body, if the body is covered on the solar side with one or several shining shells which reflect this heat completely. Thus, no matter how great the energy of solar rays, it may not be absorbed by our rocket due to its construction and due to the properties of its surface.

The situation will be different if we have black surfaces which absorb solar heat almost completely.

Thus, the influx of heat may vary from 0 to some maximum value which depends on the energy of the rays. If heat were not lost by radiation, our rocket would heat up and reach the temperature of the sun.

Now let us consider the loss of heat.

Every surface of a body loses heat; however, some lose more than others. Also, this loss increases very rapidly (as the fourth power) with increase in the absolute temperature of the body. Of course, the losses also increase when the surface area is increased (for example, that of the projectile). All these considerations and calculations lead to the following conclusions. If we have a structure which faces the sun with one side with a dark absorbing surface, and a shining surface on the other side, it may have a temperature whose upper limit is not less than 150° C.

Here is a practical example. We have a spherical closed vessel containing gas. One third of its surface facing the sun is covered with /242
glasses, which transmit the radiant energy quite well. This radiant energy falls on a dark surface inside the sphere which absorbs the rays of the sun quite readily. The remaining two thirds of the surface are

prevented from losing heat by one or several bright surfaces. The temperature of the gas inside the sphere reaches a value up to 150° C.

The same sphere facing the sun with its bright surface achieves an internal temperature which is close to -273° C. The temperature variation is greater than 400° C.

The same sphere, facing the sun with its side so that only part of the transparent surface receives the solar rays, has a temperature intermediate between -273° and +150° C.

By rotating the sphere we obtain any desired temperature between these two limits, e.g., the temperatures of all climates, all altitudes and all periods of the year on Earth.

If our projectile were to rotate quite rapidly so that its transparent side would periodically face the sun, it would establish an average temperature (according to calculations) close to 27° C. This is almost twice as high as the average temperature of our rotating planet--Earth.

However, the latter does not absorb a large part of the solar rays, but reflects it back into space. Fifty percent of Earth's atmosphere is always covered with clouds. The brilliant surface of these clouds serves as a perfect reflector for solar light. This is why the average temperature of Earth is close to 15° C.

In general, the temperature of the planet is a conditional matter and is very complex. It is not our purpose to consider this matter at this time. My manuscripts contain many concepts and calculations relative to the temperature of a planet. In my published works, however, I have only presented the results of these calculations.

It would seem that now the question concerning the temperature of the cosmic rocket is sufficiently clear.

However, it is possible to construct a space vehicle such that its temperature will be expressed not by hundreds of degrees, but by thousands of degrees. To achieve this, it would be necessary to reduce the heat losses further and not decrease the influx of heat from the sun.

If we were to decrease the area of the windows in our sphere and increase the area of the shiny surface, then the heat losses would decrease, but so would the influx of heat from the sun. However, there is a way out of this bewitched circle. We may leave a very small, transparent opening in the sphere and admit any quantity of solar energy by means of a collecting lens or a spherical mirror. The opening in the sphere, in this case, must coincide with the focal image of the sun. In this way the heat losses will reach a minimum without any decrease in the influx of solar energy.

What will happen? The quantity of heat in the sphere will increase until its rate of admission is equal to its loss rate. This will definitely take place, because the heat losses increase with temperature. The temperature inside the sphere may reach a value of 1,000° or more.

Even if our projectile were to move away beyond the limits of the solar system where Saturn rotates with its rings, where Uranus and Neptune travel, even there the cosmic rocket could obtain heat from the sun sufficient to sustain life.

It is also possible to obtain very low temperatures, in spite of the most powerful rays of the sun. This will make it possible for our rocket device to travel close to the sun, not only where Mercury rotates and is cooked by the solar rays, but even closer.

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REACTIVE ENGINE

/244

(1929)

I have been concerned with reactive devices since 1895. And only now, after working for 34 years, I have come to a very simple conclusion in regard to their system. These devices have been invented a long time ago and require only insignificant additions.

Explosion (internal combustion or thermal) engines are also reactive engines. However, the reaction of the exhaust gases is not utilized at the present time: The gases are exhausted in a useless manner in all directions and without a conic nozzle.

The reason for this is quite rational: their action is quite weak due to the small quantity of burnt fuel. Their action is also weak due to the low velocity of the moving devices and due to the fact that expansion and utilization of the heat of the products of combustion is hindered by atmospheric pressure.

All of this changes when we use the aeroplane in rarefied regions of the atmosphere, when the aeroplane has a high forward velocity, and when we use conic tubes directed one way--backwards. The exhaust gases will escape through these.

Let us see how much material is ejected. Let us assume that we have an engine with 1,000 metric horsepower (100 kgm each).[1] Let us assume that the engine consumes 0.5 kg of fuel per hour for each hp. For 1,000 hp this will require 500 kg. If the fuel is hydrogen, atmospheric oxygen will be 8 times greater, i.e., 4,000 kg. However, oxygen in the atmosphere constitutes only 1/5, so that the mass of the required air will be 20,000 kg. We neglect the hydrogen. Over 20,000 kg are ejected each hour, and each second 5.6 kg of vapors and gases are ejected.

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[1] 1 metric horsepower = 75 kgm/sec. This unit is not used in modern engineering. - Editor's Note.

This is a very large quantity. Not only can we not neglect it, but it is also sufficient to obtain tremendous velocities.

In my "Investigations 1926" I presented Table 24 for a cosmic rocket weighing 1 ton. This rocket reaches the first cosmic velocity of 8 km/sec when the fuel supply (together with oxygen) is 4 tons. The fuel itself will weigh from 1/2-1 ton (if we do not take a supply of oxygen with us). The cosmic rocket ejects 5 kg of products of combustion every second, i.e., even less than our engine. /245

It is true, of course, that due to the large quantity of nitrogen in the atmosphere, the velocity of the ejected products of combustion will not reach 3 kg/sec. This means that we shall not achieve cosmic velocities in this case, but will approach them very closely.

The rocket weighs 1 ton. Is this mass enough for it to have an engine of 1,000 hp? At the present time engines are made twice as light as they were a short time ago. Let us assume that an engine of 1,000 hp weighs 50 kg. This is particularly possible since the engine need not be perfect: it may only produce 200 hp instead of 1,000 hp, or even less; it is only necessary that it consume a large quantity of material. The more material it burns, the better it is, because it is not work that we need so much as the explosion and ejection of gases.

Let us also draw attention to the fact that we are taking the fuel supply to be 4 tons. If, however, we can use part of the oxygen in the air, it will be sufficient to take along 1 ton of fuel. This means that we shall economize by 3 tons. Such a mass may serve its purpose for the most diverse objectives, e.g., for increasing the supply of hydrogen compounds (and the achievement of cosmic velocity), for increasing the number of passengers, for improving and strengthening the structure, etc.

What is the problem, how can we carry out the flight, how can we perfect it and get close to flying beyond the atmosphere?

Let us imagine the aeroplane I described with the smallest possible dimensions. Its engine at first is concerned more with the operation of propellers and less with the reaction of ejected gases. However, as altitude is reached and the velocity increases, the work done by the propellers decreases, while the work performed by the combustion of fuel increases. This is possible because any engine may operate even in the idling state, i.e., without any results. The work performed by the propeller is gradually replaced by the reactive work. Finally, the propeller is removed or rotates without developing thrust, or is completely stopped with its blades feathered.

However, we shall use the engine first to pump air and then, in the rarefied layers of the atmosphere or in vacuum (where this pumping isn't possible), to force the supply of explosives into the explosion tube in order to achieve cosmic velocities.

If we have 10 engines, each with 10 cylinders which produce 30 revolutions per sec, we shall have 3,000 bangs per sec and a reactive pressure up to 5 tons. This is true if we use 100 tubes. Each one will be provided with a pressure of 10-50 kg.

Published in the pamphlet "Cosmic Rocket Trains," Kaluga, 1929; published for the second time in the pamphlet "The New Airplane," Kaluga, 1929.

THE NEW AIRPLANE

/246

(1929)

Preface

My first work devoted to the airplane was published in the journal "Nauka i Zhizn'" in 1895. Before that time no one published such a detailed theory of the airplane with such concrete conclusions, which have only recently been justified. A special printing of this work was given extensive dissemination. Incidentally, a copy was sent to the Secretary of the French Academy of Sciences.

A short period after this, the Frenchman Ader constructed his "avion," which was followed by more successful experiments, until the Wright brothers in 1903 solved this problem practically in the most brilliant manner. I wrote a few more things about the airplane in the journal called "Vozdukhoplavatel'", and my thoughts about it would not leave me. Sometimes I began carrying out calculations. However, matters were progressing quite well without any efforts on my part, so that to me my work appeared superfluous.

The significance of the wing shape was clarified experimentally and by means of calculations in 1891, 1896, 1898, 1899, and 1903. All of the information was published in well-known journals. Only recently, when I had come to new and comforting conclusions, did I decide to share them with the reader.

In spite of everything, the future airships will always have a certain advantage over the airplane as the cheapest means of transporting the most inexpensive cargo. Indeed, the future airship will transport them using the wind like a sailing vessel or like the flow of a river. The airplane will not have these advantages because it cannot be low-powered like the airship. Gliders will be of no significance as a means of transportation.

1. Let us imagine the surface of a revolution in the form of a spindle strongly inflated with air or oxygen. Its diameter is not less than 2 m and its length not more than 20 m.

A parallel series of such spindles is attached along the edges and forms a wavy square plate with projections to the rear and in front (see Figure 1).

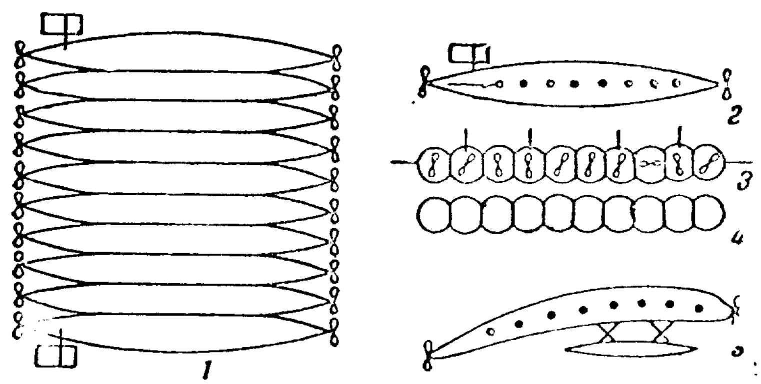

Figure 1

The area of the plate is not less than 400 m^2 (20 x 20). In front and behind, each sharp end has a propeller. The diameter of the propeller is not less than 1 m, and there are at least 10-20 propellers.

Along the sides at the stern are two large rudders for controlling the altitude as well as lateral stability. On the top of the projectile and also at the stern, there is one rudder (or several) for controlling direction. /247

The engines drive the propellers.

2. When the airplane takes off from water, it must be placed on special floats in a slightly inclined position. When it has achieved sufficient velocity and has become airborne, the floats are detached and the airplane flies without them. Descent may be accomplished directly on water since the shells are watertight. The takeoff from the airport is carried out in the same manner, but the floats are replaced by landing gears which remain on the ground when the airplane has taken off. However, a descent in this case also requires a large water surface. It can be achieved without water, if we have a level field or a flat surface covered with snow. It is not advantageous to carry the landing gear or the floats on the airplane--this will be discontinued soon.

3. And so this is the principal construction of a new airplane without a fuselage. The advantages may be clarified only by means of calculations. However, even now we can enumerate the more obvious advantages.

4. Since the shell is impervious to air, a constant pressure is obtained inside the airplane and consequently it is safe to fly in the rarefied layers of the atmosphere. In this case it is necessary to pump air into the cabins, so that it may be burned by the engines. However, pumping is also necessary in conventional airplanes at high altitudes.

5. The strength of the entire device is due to the internal excess pressure, and the weight therefore remains at a minimum.

6. Minimum weight and maximum strength are also achieved by the uniform distribution of people and loads.

7. The low air resistance due to the absence of the framework, struts, wheels, floats, wings, bracing wires, angle braces, etc. is responsible for the high speeds. /248

7_1. For the same reason we have economy in weight.

8. The construction is very simple and the entire structure therefore very inexpensive.

9. We have the possibility of constructing large load-carrying airplanes, suitable for 100 or more passengers. The distribution of various propellers and engines is very convenient and provides total safety. A simultaneous breakdown of even 5 engines is entirely safe and has almost no effect on the speed of the flight. It is possible to use propellers of small diameter with high rpm engines, which makes them more powerful.

10. The device may be elongated and expanded without increasing its height. When it is expanded, the work decreases; when it is contracted, the work increases. The previous calculations were made for a square wing.

11. We may lengthen and widen the apparatus without increasing its height. With widening, its work is decreased (the oblong form of the wing is transverse), while for narrowing it is increased (the oblong form is longitudinal). We will perform the following calculations for a square wing.

12. The low-power requirements of each engine result in mimimum weight, interchangeability, low cost, and simplicity.

13. There is a great deal of space and comfort.

14. It will be possible to fly at high altitudes where the air is rarefied and, therefore, to have large forward velocity.

15. It will be possible to achieve gradual transition into a cosmic reactive ship. Other advantages will be clarified by calculations, which will confirm what we have already stated.

16. It is inconvenient to have a continuous pumping of air into the airplane, but, generally speaking, this is unavoidable if the engine is still delivering full power in the rarefied air, and if the airplane is designed to fly at high altitudes, as is now the custom.

Velocity of Flight and Other Characteristics

17. Let us start our calculations. I warn the reader that they are all very approximate.

Unless otherwise stated, the basic units are as follows: second, meter and its products--ton, ton-meter, etc., are implied.

Let us imagine a cutout between two transverse parallel sections of the same spindle with a length of 1 m. We shall assume this cutout to be a round cylinder with diameter D (average cross section).

18. The circumference U of this cross section as well as the surface area F will be

$$U = F = \pi D.$$

19. The weight of the shell G_1 will be given by the /249

$$G_1 = \pi D \cdot \delta \cdot \gamma,$$

where δ and γ are the thickness of the shell and the specific weight of its material, respectively.

20. The area of its horizontal projection is $F_h = D$.

21. The load q_1 of one shell per unit area of the projection is obtained from (19) and (20).

$$q_1 = G_1 : F_h = \pi \cdot \delta \cdot \gamma.$$

22. However, this load is incomplete. This load is only due to the weight of the shell. The load is increased further by the weight of the engines and the control elements q_2, of the fuel with tanks q_3, of people and cargo q_4, and of the safety factor q_5. The total load q will be equal to

$$q = q_1 + q_2 + q_3 + q_4 + q_5.$$

23. If, for simplicity, we assume for the present that all of the loads are identical, we find from (21) and (22)

$$q = 5q_1 = 5\pi\delta\gamma.$$

24. The resistance to the breakdown of the shell Q must be equal to the excess pressure P of the gas inside the shell. Therefore we write

$$Q = \delta 2K_z : S = PF_h = PD,$$

where K_z is the temporary resistance to failure, S is the safety factor and P is the overpressure of the gas on a unit area.

25. Equation (24) makes it possible for us to compute the thickness of the shell and, consequently, its weight and loading. The total load will also be known. Thus from (23) and (24) we obtain

$$\delta = PDS : 2K_z$$

and

$$q = 5q_1 = 5\pi\gamma P \frac{DS}{2K_z}.$$

We have assumed that the individual loads on 1 m^2 of the projection are equal to 1/5 of the total load (22).

26. In general the surface of the entire airplane represents a single plane wing. We assume the most undesirable conditions. Thus, we could impart a slight curvature to this wing so that the lift force would be doubled. However, we make our calculations assuming that the wing is flat.

27. Furthermore, the pressure on the plane P_n, which is normal to the flow, is assumed to be given by equation

$$P_n = (c^2 : 2g)\, d,$$

where c is the flow velocity, g is the acceleration due to Earth's gravity, and d is the density of air. This equation gives us a value of the pressure which is 1-1/2 times smaller than the real value. This is also disadvantageous. /250

28. To compute the pressure on a plane, inclined with respect to the flow, we utilize the equation of Langley, since this equation is very close to mine and is entirely justified on the basis of my experiments. According to Langley, the pressure on an inclined plane may be obtained by multiplying the magnitude of the pressure of the normal stream by $2 \sin y : (1 + \sin^2 y)$.

However, during the efficient flight of an airplane, its angle of attack with respect to the horizon y is very small, so that we may multiply the normal pressure simply by twice the sine of this angle. The error will be insignificant.

29. On the basis of condition (26) we then obtain a pressure which is actually much greater, particularly if we impart a slight curvature to our airplane. Specifically, the lift P_v of a plane inclined slightly to the horizon and having an area of 1 m^2 will be (26) and (28)

$$P_v = (c^2 : g)\, d \sin y.$$

The error will be quite small. With an angle of 10° it will be not more than 3 percent. It is insignificant for the plane, compared with the decreased lift of the air, according to conditions (26) and (27).

30. The uniform horizontal flight of an airplane requires that the total load q be equal to the lift force P_v. Therefore, from (25) and (29) we obtain

$$c=\sqrt{5\pi\cdot g\cdot\gamma PSD:2d\sin yK_z}.$$

Here the velocity is expressed independently of the weight of the shell and of the weight of the airplane and its pilots. It is only assumed that it must be equal to its total lift force produced by the pressure of the incident flow on the wing. The lift force may be very small and the entire airplane must also be small, which is not achievable in practice. Conversely, the airplane may be very large, which also cannot be achieved. This velocity is therefore of little interest to us. From the equation we see that it must increase when we have a decrease in the excess pressure, the desired strength and dimension D, and that it decreases when we have an increase in the density of the air, the angle of attack of the wing, and in the strength of the material.

31. Now we must consider the significance of the energy (or the power of the engine) and the resistance of air due to friction and inertia.

Let us imagine that our airplane has a length l, a width b, and a height D. It is required to determine its total resistance when it moves in the air and to determine its specific resistance, i.e., for 1 m^2 of the horizontal projection.

I make use of my work "The Resistance of Air and the Fast Train," 1927. In that work equation (31) determines the total resistance of a surface which is an ellipsoid of rotation. We shall not concern ourselves with the meaning of the constants in this equation and will only replace them by numbers. In addition to this we shall divide the total resistance by the magnitude of the horizontal projection. We may set its area equal to l·D·0.75, where l and D are the diameter and the length of the ellipsoid, respectively. /251

32. Then, instead of equation (31) of this work which gives the total resistance, we obtain the specific resistance, i.e., for 1 m^2 of a projection

33.

$$P_{h1}=d:c^2(A:X^2+B:XD),$$

where A = 0.0212, B = 0.00134, X is the elongation of the shape or the ratio of the length to its height, while ξ is a special coefficient of friction (equation ([illegible]), "Resistance," 1927), which depends on the ratio l:c. It is determined by means of calculations utilizing equation ([illegible]) and the tables in the same work.

34. Determining A and B we have assumed that[1]: π = 3.14; g = 9.8; the coefficient of resistance of the sphere Ksh = 0.4; the shape coefficient Kf = 1; the coefficient of a plane plate Kpl = 1; the coefficient for the convergence of the surface at the ends Kes = 0.75, and the thickness of the surface layer Tsl = [illegible]. The significance of these constants is sufficiently explained in my work "The Resistance of Air," 1927.

35. To make the calculations more convenient we make the following substitution in equation (33)

$$A:X^2+B:XD=C.$$

Then

$$P_{h1}=d\xi c^2C.$$

36. This is the specific resistance due to friction and inertia, when the airplane flies in a completely horizontal direction. To obtain lift it is necessary to have an angle of attack. Therefore, an additional horizontal resistance P_{h2} is obtained due to the angle of attack of the airplane. This is the horizontal component of the lift force P_v or of the normal pressure on the wing. It is equal to (see 29)

$$P_{h2}=P_v\sin y=(c^2:g)\,d\sin^2 y.$$

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[1] Here we have retained the symbols used in the work "The Resistance of Air and the Fast Train," 1927. We should point out that the derivation of equations by Tsiolkovskiy is very different from the accepted practice in modern aerodynamics. - Editor's Remark.

37. In order to determine the required work which must be done by the airplane, we multiply the sum of all the horizontal resistances (34) and (35) by the velocity of motion. However, because a propeller is used, the work done by the airplane will be greater than the ideal work by a factor a.

38. Thus, we obtain the amount of work done by the airplane every second from (35), (36) and (37)

$$(P_{h1}+P_{h2})\,ac=adc^3(\xi C+\sin^2 y:g)=L_1.$$

The last letter designates the magnitude of the specific power of the engine, i.e., the amount of work which it does every second for every 1 m^2 of the horizontal projection of the airplane.

39. On the other hand, the power L_1 is determined by the magnitude /259 of the lift force: the greater it is, the more mass we can provide for the engine and, consequently, the more powerful it will be. In (23) we have assumed that the masses of the five loads are the same and that they are equal to the mass of the shell. Then the weight of the engine will be given by the weight of the shell, or by one-fifth of the total load (see 25). If we know the weights of the engines, their energy E, and the work performed by their unit weight in 1 sec (specific work), it is easy to find an expression for their power. Thus, by means of (25) we find

$$L_1=0.5\pi EP\gamma DS:K_z.$$

40. The basic equations are as follows: equation (25) gives the total load on 1 m^2 of the projection as a function of the weight of the shell. Equation (29) gives the same thing, but gives the lift force as a function of the velocity of the forward motion. Equation (38) gives the specific power which depends on the velocity of horizontal motion and the angle of attack. Equation (39) also gives the power for 1 m^2 of the projection as a function of the weight of the engines, which is assumed to be equal to the weight of the shell, or to 0.2 of the total lift force. Equations (32), (33) and (36) are auxiliary equations.

All of the seven equations pertain to 1 m^2 of the horizontal projection of the airplane. We cannot do without equation (25), because the shell must be sufficiently massive for high altitude flight and because it must have a certain amount of strength.

For horizontal flight the total load q must be equal to the lift force P_v. This makes it possible to eliminate the specific loading or the specific lift force from equations (25) and (29).

In the same way, the specific power L_1 depends on the drag (38), and it also depends on the specific weight of the engines (39), which makes it possible to eliminate the specific power L_1. Thus we obtain

41.

$$2.5\pi\gamma PD\frac{S}{K_z} = \frac{c^2}{g}\cdot d\sin y$$

and

42.

$$adc^3\left(\xi C + \frac{\sin^2 y}{g}\right) = 0.5\pi E\gamma\cdot P\cdot D\,\frac{S}{K_z}.$$

By eliminating the density D of the air from the equation we obtain by means of (41)

43.

$$c = E\sin y : \left[5ag\left(\xi C + \frac{\sin^2 y}{g}\right)\right].$$

From this we can see that the velocity of the airplane is proportional to the specific energy of its engine. Thus, if the weight were to decrease by a factor of 10, while the power remained constant, the independent horizontal velocity would increase by the same factor.

44. However, let us not forget that the density of the medium in this case satisfies equation (41). Therefore, we have /253

$$d = 2.5\pi\gamma\cdot PDSg : (K_z\sin y c^2).$$

Consequently this density must decrease, because the square of the velocity increases. If, for example, the velocity increases by a factor of 10, the airplane must rise to an altitude where the density of the medium is 100 times less than at a lower altitude, where it flew with an anergy 10 times less. However, it is difficult to obtain energy from the engines at high altitudes, unless the rarefied air is condensed or we use a supply of liquid oxygen. It is remarkable that the velocity does not depend on the weight of the shell or on its properties.

45. Let us remember that ξ itself depends on the ratio of the velocity to the length of the airplane (equation (20) in "Resistance"). Therefore, we determine the velocity approximately. As a matter of fact, ξ varies very little. From equation (20) or from the tables in "Resistance" we find, if we assume that the length l of the airplane is 20 meters.

velocity	100	200	300	400
ξ	2.5	3.4	3.7	4.2.

Hence the corrections are not difficult, since the calculations are approximate.

Let us now turn our attention to C. Equation (35) gives the variation in C as a function of the dimensions D and the elongation X of the airplane. Consequently, the magnitude of the velocity depends also on its elongation.

However, let us determine the velocity C itself. Let us assume that $l = 20$; $D = 2$; $\pi = 3.14$; $E = 100$ (1 metric hp per 1 kg of the engine's weight); $a = 1.5$; $\sin y = 0.1$ (6° inclination with respect to the horizon); $g = 10$, and $X = 10$. From these data we find $\xi = 2.5$ (see 45). Assuming beforehand a velocity of 100 m/sec, $C = 0.000088$ and $c = 109$ m/sec (393 km/hour).

This is the first approximate value. However, we have proposed a priori a velocity of 100 m/sec, whereas it has turned out to be approximately 109. Therefore ξ will not be 2.5, but will be slightly larger, which will produce a very small increase in the velocity we established.

46. Let us also compute the corresponding density of the air using equation (44). Let us assume that $\gamma = 8$; $P = 10$; $D = 2$; $S = 10$; $g = 10$; $K_z = 10^5$ (100 kg per 1 mm^2 of the section), and $c = 109$. Then we find the density of the medium to be slightly less than 0.0011. This means that we can ascend to an altitude which does not exceed 2 km.

47. On the basis of equation (44) we prepare a table.

Velocity, in m/sec	109	545	1,090	2,180
Ratio of densities of medium	1	1:25	1:100	1:400

48. However, the variation in the velocity as the function of the angle of attack of the airplane (sin y) is not entirely clear. The function /254

$$\sin y : (\xi C + \sin^2 y : g)$$

has a maximum at which we obtain the greatest velocity. By taking the derivative, setting it equal to zero, and determining the slope sin y, corresponding to its maximum, from the resulting equation, we obtain

$$\sin y = \sqrt{\xi C g}.$$

49. Substituting this slope sin y into equation (43), we find

$$c = \frac{E}{10a\sqrt{\xi C g}} = \frac{E}{10a \sin y}.$$

50. Let us assume that $C = 0.000088$; $= 2.5$; $g = 10$. Now from (48) we obtain

$\sin y = 0.047$ (the angle is equal to $2^{0}40'$).

51. Assuming also that E = 100 (a conventional aircraft engine) and that a = 1.5, we compute c = 141.8 m/sec, or 511 km/hour. This is the maximum velocity achieved when the angle of attack of the airplane is almost 3^{0} with respect to the horizon. We cannot obtain a greater velocity by using a smaller or greater angle of attack.

52. If we always maintain the optimum angle of attack, then, to compute the density of the medium from (44) and (49), we obtain

$$d = 250\pi \cdot \gamma \cdot PD \frac{a^2}{E^2} \frac{S}{K_z} \sqrt{\xi \cdot C \cdot g^3}.$$

From this we can see that if we were to obtain the maximum energy from the engines, it would be necessary to fly in the highly rarefied layers of the atmosphere because, according to the equation, the density of the medium must decrease very rapidly as the power of the engines is increased.

53. Let us determine sin y from equation (41); we find

$$\sin y = A \cdot D : (c^2 \cdot d),$$

where

$$A = 2{,}5\pi\gamma P g (S : K_z).$$

54. Now eliminating sin y from equation (42) and solving this equation with respect to the density of the medium d, we obtain

$$d = \frac{A \cdot E \cdot D}{10g \cdot \xi \cdot C \cdot a \cdot c^2} \left(1 \pm \sqrt{1 - \frac{100g \cdot \xi \cdot C \cdot a^2 \cdot c^2}{E^2}}\right).$$

55. From this we can see that

$$c < E : (10 \cdot a \sqrt{\xi \cdot C \cdot g}),$$

i.e., the velocity cannot be greater than a definite value. Assuming the previous conditions, we compute /255

55.

$$c \leqslant 141{,}8.$$

We obtain the same maximum velocity which we obtained earlier (49).

55_1. The velocity of conventional airplanes cannot, therefore, be increased in the rarefied regions of the atmosphere, unless the specific energy of the engines is also increased. Therefore, it would seem that the conventional aircraft engine is not suitable for achieving high velocities.

55_2. The necessary rarefaction of the air for this maximum velocity will be given by equation (54) in the following form

$$d = A \cdot E \cdot D : (10g \cdot \xi \cdot C \cdot a \cdot c^3).$$

If we eliminate the velocity C and A by means of equations (54) and (55), we obtain equation (52).

56. What is the work performed by the airplane? The specific work is given by equation (38) or (39). Under conditions (45) and (46) we compute L_1 equals 2.5 ton-meters or 25 metric hp for each m^2 of the horizontal projection. For the entire projection (20 x 20), we obtain 10,000 metric hp.

57. The total load can be obtained from equation (25)

$$q = 5q_1 = 0.125m = 125 \text{ kg}.$$

Every type of load (0.2) will constitute 0.025 tons or 25 kg.

58. A man weighing 75 kg will require 3 m^2 of the projection, i.e., 75 metric hp. Since the entire projection consists of 400 m^2, the airplane may contain 133 persons.

59. The volume corresponding to 1 m^2 of the projection will be $0.75 \cdot 2 = 1.5$ m^3. Consequently, for each man there will be approximately 4.5 m^3. The area of the floor, which is equal to 3 m^2, may give us even more than we require.

61. The specific work of the engine which we have obtained for each person--75 metric hp--is too great and not economical (although a velocity of 511 km/hour more than compensates for the expenditure of energy). Can we decrease it? To do this we must first express the work of the engine corresponding not to 1 unit of area of the horizontal projection, but to 1 unit of the lift force and to 1 unit of the velocity of forward motion. Indeed, if we move 10 times faster and lift a load 10 times greater, why not expend a quantity of work which is 100 times greater? The reduction in time due to the velocity of motion is another advantage which we shall not consider here (in view of its uncertainty).

62. From equations (39), (55) and (25) we obtain /256

$$L_1 : (c \cdot q) = 2a\sqrt{\xi \cdot C \cdot g}.$$

Here we divide the power (39) by the maximum velocity (55) and the total load (25).

63. From this we can see that the power required to produce a unit displacement of unit load does not depend on the energy of the engine nor on the velocity, but only on the form and size of the airplane. It is almost constant.

64. Equation (62) shows the amount of work done every second in ton-meters, when 1 ton of airplane is displaced by a distance of 1 meter along the path. However, the passengers occupy only one-fifth of the weight or 200 kg. Therefore, we obtain the work performed in displacing two people (with their baggage) for a distance of 1 meter along the path.

65. Let us assume condition (46). Then from (62) we find 0.047 ton-meters or 47 kgm for each ton of airplane and 1 meter of the path. This is for two people; for one (100 kg), we obtain 24. Normally a conventional airplane traveling at the velocity of 40 m/sec (144 km/hour) uses 40 metric hp per person. Over 1 meter of path, 1 metric hp will be required. In our case we have four times less. However, we shall also save a tremendous amount of time!

66. How long can our airplane fly without descending under conditions (46)? We see that in this case the velocity is 551 km/hour. The total load is equal to 125 kg, while the individual load (for example, of the engine) is 25 kg (1 m^2 of the horizontal projection). The corresponding power will be 25 metric hp (56). 25 metric hp will require a fuel equal to 0.2 × 25 = 5 kg. This means that our gasoline will last us for 5 hours of flight. During this time the airplane will travel 2,555 km. However, we have shown that the lift force of our airplane will actually be at least two times greater, i.e., we will be able to add another 75 kg of fuel. This will make it possible for the airplane to fly 30 hours without landing, or a distance of 15,338 kilometers, which is sufficient to cross the ocean.

67. The velocity of the airplane depends on the velocity of the propeller along its periphery (and not on the number of revolutions per second, which becomes greater as the dimension of the propeller becomes smaller), which does not in any way depend on the size of the propeller (its diameter), but only on the strength of the material and its distribution in the propeller blade. It is desirable to make the

base of the propeller blade very heavy. In any case, this peripheral velocity will not be greater than [illegible] m/sec; otherwise, there will be no material that will withstand the centrifugal force, and the propeller blade will fail. The velocity of the airplane, when the blades of the propeller are inclined at the optimum angle of 45° with respect to incident flow, will not be greater than [illegible] m/sec or [illegible] km/hour, which is very far from cosmic velocities.

68. Consequently, if we wish to achieve cosmic velocities by flying in the rarefied layers of the atmosphere, the propeller is not suitable (in addition to the normal weakness of the engines).

In addition to these obstacles there are others no less serious. This is the question concerning oxygen. Air may be compressed, i.e., it may be pumped into the cabin of the airplane. However, when air is compressed by a factor of 6, its absolute temperature increases by a factor of 2. Here is the table: /257

Number of times rarefied air is compressed:	1	6	36	216	1,296	7,776
Absolute temperature of compressed air:	200	400	800	1,600	3,200	6,400
Temperature, ° C	-73	127	527	1,327	2,927	6,127

69. The temperature of the compressed gas reaches a value of 6,000° C. Here a tremendous amount of work is used which is partially returned if, without lowering the high temperature, we drive the compressed air into the engine.

Compression by a factor of 36 is still possible (during high compression, chemical reaction and liberation of heat is retarded). Here the temperature will be approximately 527° C.

70. For an airplane this is also good, i.e., 3,066 km/hour. However, compression to this degree has not been achieved in practice; it may be achieved in the future.

71. However, what do we do beyond this point? How can we obtain even greater velocity, for which neither the propeller nor the compression in the engines is applicable? We must give up conventional engines and propellers.

We can take supplies of oxygen in liquid form with us and explode the fuels with them, ejecting the products of explosion through a tube,[1] and utilize the recoil to produce motion.

However, on one hand, it is very uneconomical to load an airplane with the weight of oxygen previously obtained from the atmosphere. On the other hand, the velocity of the airplane is not important enough to utilize the recoil action for propulsion.

For 1 unit mass of fuel consisting of pure carbon we require a quantity of oxygen whose weight is 2.7 times greater (32:12). The mass of the fuel supply containing the same amount of energy increases by a factor of 3.7. If the utilization of the fuel were greater by the same factor, we could get used to this inconvenience, particularly since we gain a great deal in the velocity of motion.

72. In a rarefied atmosphere the utilization of heat may be brought up to a value of 50-100 percent (in the motion of the ejected gaseous matter). The utilization of the fuel to produce rocket motion with a velocity of 1 to 2 km/sec will be hardly greater than its utilization in conventional engines.

To obtain complete utilization of the rocket it is necessary that the velocity of the ejected matter at each instant of time be equal to /258 the velocity of motion of the airplane.[2]

73. As a result of this, the construction of a flying machine having a high velocity is very complicated. First, it uses the conventional engine and a propeller. Then the propeller is removed or idles while the engines pump air into the rear, isolated compartment, from which it is ejected with a velocity equal to the velocity of the device. Since this velocity of the airplane increases initially, the velocity of the air ejected to the rear must also increase. When it reaches a value of 1 km/sec or greater, the same engines pump the elements of explosion into the explosion tube, such that these elements are ejected into the rarefied atmosphere with a velocity of 3-5 km/sec.

74. At this point the centrifugal force produced by the motion of the airplane around Earth becomes quite substantial, decreases its weight and the work it has to do for displacement. This work becomes equal to 0 when the airplane attains the first cosmic velocity and moves beyond the limits of the atmosphere.

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[1] See the article "A Rocket Into Cosmic Space."
[2] See "Investigation of Universal Space by Means of Reactive Devices," 1926.

75. A propeller can give an airplane a much higher velocity than is realized. Its peripheral velocity, of course, cannot be greater than 500 m/sec, but the blades of the propeller may be directed almost parallel to the incident flow or parallel to the motion of the airplane (with an angle of attack from 20-40°). At first its work will be almost useless. However, when the airplane achieves a high velocity, the propeller under certain known conditions will begin to operate more efficiently. The work performed by any propeller is not efficient at the beginning of motion when the airplane has not yet achieved a constant velocity. It would be well if the blades of the propeller could change their angle of attack gradually, by means of automatic or manual control, and decrease this angle of attack as the speed of the airplane is increased.

Although the work performed during the small angle of attack of the blades is very uneconomical, there is no way out of it. However, we do not recommend this construction and the small angle of attack for the blades.

76. It would be simpler to use some method to impart a substantial velocity to an airplane and then to turn on the air pumps, which by means of conventional engines would condense and pump the air into a special chamber. From this chamber the air would be forced out through special tubes to the outside beyond the stern of the ship. It is easy to control the ejection of the gases in accordance with the velocity obtained by the airplane.

77. The velocity of the gas ejected into the rarefied space from the opening is rather similar and depends little on the degree of its compression. However, this is only true for constant temperature. But the temperature is not constant and may reach a value of several thousand degrees (no matter how rarefied and cold the initial gas is). If we require a low ejection velocity (when the velocity of the pro- /259
jectile is low), we compress and pump the air in a moderate manner. Then its velocity during ejection may be even less than 500 m/sec. However, if we require a large velocity for the ejected air, the pumping is accelerated, the air is strongly compressed and heated, and the velocity increases. The velocity of highly compressed and heated air (up to several thousand degrees) may reach a value of 2 km/sec and higher (proportional to the square root of the elasticity of the gas or its absolute temperature).

Let us not forget that we compress a gas which is highly rarefied (for example, by a factor of 1,000), and its condensation will produce a pressure of only 1 atmosphere, that it is cold initially but will heat substantially, due to compression, and that it will be ejected with a velocity which will be greater when this heating is greater.

78. Engines may operate with a constant force, and the ejection velocity of the compressed air may be controlled by valves. When the exit nozzle is small there will be more air in the reservoir, it will be more compressed and hotter, and the velocity of its ejection from the tube will be greater.

79. It is only necessary to isolate the air chamber from heat losses. If the compressed air is cooled, the ejection velocity will be difficult to increase and, in addition, there will be a useless expenditure of energy (energy which is transformed into heat and dissipated in space).

80. When the airplane has to reach even higher velocities, it becomes efficient to burn the fuel directly with the supply of oxygen.

81. Any thermal engine is also a reactive engine, if the exhaust gases are directed into a conic tube and are ejected in the direction opposite to that of the ship's travel. However, since only a small quantity is ejected, the velocity of the ship is small, so that utilization of this auxiliary energy will be very weak; for example, in an automobile or a conventional airplane it is not used and the gases are ejected into spcae without any special devices.

In our high-speed airplane at high altitudes we cannot neglect this. However, the force of this reaction will not be sufficient in view of the small quantity of explosives in the engines.

The engines may pump air and produce an air reaction; the exhaust gases will also produce a gaseous reaction.

The air rocket will utilize approximately 20 percent of the heat of combustion. The remaining 80 percent will be utilized by the exhaust gases. In view of the small velocity of the airplane, only 10 to 20 percent of this energy will be used to impart motion to the projectile.

Nevertheless, it turns out that the utilization of the gases ejected into rarefied space may double the work performed by the engines. /260

82. We note that the air to be pumped must be removed by the pumps from the space directly in front of the ship, and must be released from the stern. Then the air ahead of the projectile will become rarefied, while behind the projectile it will become condensed. This will move the airplane faster.

83. A complex construction of the aircraft engines make the airplane heavy and quite unsuitable. Therefore, we propose several types of airplanes. They will all be capable of carrying large loads--not less than 133 persons, and of dimensions not less than 20 m long, 20 m

wide, 2 m high. The power of their engines will be not less than 10,000 metric hp (as a matter of fact, the airplane may be narrowed by a factor of 2, and the specific work will then increase by a factor of 1.4).

However, we must not forget that the total true lift force of the airplane or of a load per 1 m^2 is greater by a factor of at least 2 than the value computed by equations (26) and (27).

This excess force may be utilized in various ways: it may increase the number of passengers by 6, and it may be used to increase the fuel supply which will permit the airplane to fly one-fourth of Earth's circumference without landing. Part of the excess lift may be used to increase the factor of safety of the airplane (25). The utilization efficiency may also be of a different order.

Types of Airplanes Suitable for Various Flight Velocities

Let us return to types of airplanes.

84. A. An airplane for flight into the troposphere not exceeding an altitude of 3-4 km. The excess pressure of half an atmosphere is required only to give the shell necessary strength and rigidity. The engines and the propellers are of the conventional type, the velocity if 500 km/hour, the flight from Europe to America takes longer than 12-15 hours. The number of passengers, of minimum size (20 x 20), varies from 133 to 798. Each passenger will require from 75 to 12 metric hp.

85. B. An airplane for flight to high altitudes where the human being already suffers from rarefaction of air and where the velocity of the airplane may be much higher. The engines are conventional, but the propeller blades have a small angle of attack. Part of the work done by the engine is used to compress the air for the engines, while the second part is used for air reaction. Here the operation of the propellers is inefficient, but the velocity of the airplane is greater by a factor of 2.

86. C. The propeller is removed. The engines are used exclusively to compress air for the purpose of air reaction. The exhaust gases are also utilized. The velocity and altitude of flight are higher than in the preceding type.

87. D. The velocity and altitude of flight are very high. The engines are low-powered and are used only to pump petroleum and oxygen compounds into the conic explosion tube.

88. E. The velocity is even greater. The high velocity elimini- /261
nates air resistance, while the high velocity and the centrifugal force

counteract Earth's gravity. Here the motion of the projectile becomes permanent, because no expenditure of energy is necessary.

89. The last three types require a substantial initial velocity which may be imparted to them by auxiliary trains which ascend a mountain.[1]

90. With the new system of engines it is possible to achieve higher altitudes, rarefied layers of the atmosphere and greater velocities. The cost of traveling a unit path will not be low, but there will be a tremendous saving of time. This is the main advantage of these airplanes. In the future they will serve for transition to astronavigation.

91. There is no necessity for giving the horizontal projection of the airplane a square form. It may be narrow, consisting of 3-5 inflated surfaces of revolution. However, in this case the specific work of the engine will be greater, due to longitudinal elongation. With this inverse elongation equal to 2, the work will increase by some 30 percent (see "Resistance," 1903).

92. When the airplane moves with the velocity of 300-400 m/sec at the equator in the direction of the rotation of Earth, the centrifugal force will decrease the weight of the airplane by approximately 1 percent.

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[1]See the article "Rocket Cosmic Trains."

THE REACTIVE AIRPLANE /262

(1930)

1. The reactive airplane differs from a conventional airplane by not having a propeller.

The action of the propeller is replaced by the recoil (reaction) of the products of combustion in ordinary aircraft engines. However, the latter require some transformation and addition since they consume a great deal of fuel and produce a relatively small amount of work, for example, ten times less than what is available in the form of thermal energy. Furthermore, they have a large number of revolutions per second and therefore have large valve openings. In addition, as we can see from the table, compression of even the very cold air at high altitudes is accompanied by heating.

The compression factor of some constant gas or mixture (air)					
1	6	36	216	1,296	7,800
Absolute relative temperature					
1	2	4	8	16	32
Absolute temperature					
+273	546	1,092	2,184	4,368	8,736
Same, in $^{\circ}C$					
0	273	819	1,911	4,095	8,463
Absolute temperature					
+200	400	800	1,600	3,200	6,400
Same, in $^{\circ}C$					
-73	+127	+527	1,327	2,927	6,127

From the last line we can see that even when the temperature of the gas is -73° C, its compression by a factor of 36 requires cooling.

To achieve this we use the tremendous expansion of the products of combustion in a rarefied atmosphere; this is also associated with strong cooling. Therefore, the air, heated by compression, is first passed into a shell which surrounds the tail end of the tube with the expanding products of combustion.[1] Only then does this compressed and cooled air serve to cool the working cylinders and then to burn in them. /263

2. The airplane acquires increased speed in the rarefied layers of the atmosphere only when the work performed by the engine is proportional to the velocity of the airplane.

The following table illustrates this.

Relative density of air at high altitudes				
1	1:4	1:9	1:16	1:25
Approximate flight altitude above sea level in km (at 0° C)				
0	11.1	17.6	22.1	25.7
Relative forward velocity of the airplane				
1	2	3	4	5
Required relative energy of the engines				
1	2	3	4	5

This capability (to produce work proportional to the velocity of the projectile) can only be done by a reactive engine. We want to transform the conventional aircraft engine into such a reaction engine in order to increase the velocity of the airplane in the rarefied layers of the atmosphere. No other solution is possible. We arrive at this conclusion if we neglect the work of compression of the incident air stream needed to burn the fuel.

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[1]To decrease the amount of work required to compress the gases, it is best to cool the air between each of the two stages of the compressor by passing the corresponding tubes to the tail part of the nozzles. - Remark by Tsander.

However, at high altitudes it is necessary to compress the rarefied air for use in the engines. It is for this purpose that the principal part of the ordinary mechanical work of the engine will be used. Therefore, we cannot entirely eliminate these engines.[1]

The engine makes a large number of revolutions and operates almost without a load, doing relatively little work: it is not efficient. However, we do not require much work because the work of compressing the cold rarefied atmospheric air is rather small, and the energy of the engines is more than adequate for this purpose. The principal purpose of the engine is to provide a reactive action of the ejected products of combustion; in this case the propeller is eliminated.

Let us indicate the magnitude of this work. Since the compressible air is cooled by the tail sections of the reactive tube, its temperature is assumed to be constant. In this case we determine the work performed to produce compression by means of the equation.[2] /264

$$L = P_1 \cdot V_1 \cdot \ln\left(\frac{V_1}{V}\right).$$

Here P_1 and V_1 are the initial pressure and volume, respectively, while V is the final small volume (after compression). Let us assume that the air is rarefied by a factor of 1,000. In this case its pressure will also be 1,000 times smaller. Our purpose is to compress this huge volume by a factor of 1,000 in order to reduce it to the initial small volume. In doing this we perform a certain amount of work. We can see that the product $P_1 \cdot V_1$ remains constant, no matter which rarefied layer of the air we consider. This means that the work of compression depends only on the logarithm of compression $V_1 : V$. The product $P_1 \cdot V_1$ is equal to 10.3 ton-meters at 0° C. By using the above equation it is easy to prepare a table showing the work performed to obtain 1 m^3 of compressed air of normal density. Specifically, we have:

[1]However, air may also be compressed dynamically, by using a stream method in air reactive engines. - Remarks by Tsander.

[2]Here and in the future we refer to the article "Pressure on a Plane."

Rarefaction of the air or the required compression

1	6	36	216	1,296	7,800

The work done to obtain 1 m^3 of air of normal density (0.00129) at 0 temperature in ton-meters (approximately):

0	18	36	54	72	90

For benzol we need approximately 11 m^3 of normal air for 1 unit of fuel mass (kg).[1] To obtain this from air which is rarefied by a factor of 7,800 we require $90 \cdot 11 = 990$ ton-meters. One kg of benzol will give us not less than 4 hp per hour. This is equivalent to a work of $(75 \cdot 3{,}600 \cdot 4)$ equal to 1,080,000 kgm or 1,080 ton-meters. It turns out that this is slightly greater than required for compression.

As we see from the table, when the compression is less, the amount of work required is also less. However, the amount of work required if we do not cool the air is much larger. Here we can make use of equation (39), indeed:

$$L = BP_1V_1[1-(V_1:V)]^{1:B}.$$

From (44) we take: B = 2.48 and 1:B = 0.403. Let us assume that $V_1:V = 7{,}800$. Then we compute

$$L = P_1V_1 34.7 = 358 \text{ ton-meters},$$

i.e., it will be three times greater than the preceding (90 ton-meters). It is four times greater than the one developed by the engines. In practice we should take the average work, which will be 5 times less than that performed by the engines.[2] The computed work refers to /265

[1]The entire calculation carried out by Tsiolkovskiy is for 1 m^3 of compressed air. - Editor's Remark.

[2]This constitutes 1,080:5 = 216 ton-meters for 1 kg of benzol or

216:11 = 19.6 ton-meters for 1 m^3 of normal air. Approximately this quantity of work is required to produce a 6-fold compression at constant temperature. If cooling is not accomplished, the degree of compression is even less. From the table in Section 2 air at an altitude of 11.1 km is rarefied by a factor of 4, while at an altitude of 17.6 km it is rarefied by a factor of 9. - Remark by Tsander.

compression in space. Atmospheric pressure aids in the compression and therefore the real work is less, particularly in the lower layers of the atmosphere and during small compression.

The airplane does not remain very long in the lower layers of the atmosphere. But even then the work of the engines is useful, and will be used for the air-cooling of operating cylinders, and even for the compression of air to increase the combustion of gasoline, to increase the power of the engines and the force of the exploding gases.

Indeed, the equations and the tables may be used to establish the compression of normal air (near sea level), and to increase the energy of the engines (but their walls will have to be made stronger).

From equations (14_1) and (39) we see that the work of compression in this case increases proportionately, since P_1 increases. However, the work performed by the engines increases by the same factor. Since the factor of safety for the operating cylinders is always excessively large (so that we do not have very thin walls), it is quite advantageous to compress the air even in the lower layers of the atmosphere.

3. In developing the theory of such airplanes we must deal with the compression and expansion of gases, with their thermal conductivity, i.e., heat of combustion, with the velocity of the ejected matter, with their reaction, with air resistance, with compressors and their operation, and with many other things.

Therefore we must again refer to our published work "Pressure on a Plane," 1930.

4. To be specific in our consideration of the fuel, we take three types of fuels: hydrogen, carbon, and benzol. To burn them, we use pure oxygen, ordinary air or nitrogen anhydride N_2O_5.

This does not mean that we consider these materials to be the best for the engines, but simply that other materials have not been investigated to date, and their practical application has not been demonstrated.[1]

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[1]At the present time alcohol and gasoline were tested in Germany, while petroleum was tested in France. - Remark by Tsander.

For example, monatomic hydrogen H liberates 16 times more energy than the same mass of oxyhydrogen gas when it forms a diatomic hydrogen H_2 ("Cosmic Rocket," 1927).

However, we cannot propose a fuel not tested in practice. For example, it is not known whether monatomic hydrogen H can be liquefied and whether this liquid is safe from the standpoint of explosion. The same can be said of other materials proposed by various authors, for example, ozone O_3 and light metals (for example, aluminum, lithium, calcium, etc.). /266

The idea of ejecting part of the airplane or converting it into fuel is also impractical at this time.

5. Below we present a table which shows the relative weight of materials which participate in combustion.

Name of fuel	Hydrogen	Carbon	Benzol
Formula of the fuel	H_2	C	C_6H_6
Relative weight of the particle (of the molecule)	2	12	78
Products of combustion	water	carbon dioxide	water and carbon dioxide
Formula for the products of combustion	H_2O	CO_2	H_2O and CO_2
Relative weight of oxygen O_2 necessary for combustion	16	32	240
Same, using N_2O_5	21.6	43.2	324
Relative weight of the products of combustion in case of oxygen	18	44	318
Same, for N_2O_5	23.6	55.2	402
Weight of the fuel considered as unity	1	1	1
Then the weight of the oxygen will be	8	2.67	3.33
Then the weight of the products of combustion will be (for oxygen)	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 products of combustion for N_2O_5 will be	11.8	4.6	5.5

6. If we burn air in our airplane, we must indicate the quantitative ratio of its components.

For this purpose we propose the following table.

Name	Air	O_2 Oxygen	N_2 and remaining components
Composition of the air by weight	100	23.6[1]	76.4
Same, by volume	100	21.3	78.7

[1]The handbooks for oxygen give slightly lower figures: 23.1 percent by weight or 20.9 percent by volume. - Remark by Tsander.

From this we find the following weight ratios of the component parts of the air: $N_2\ O_2 = 3.24$; $O_2{:}N_2 = 0.309$; $O_2{:}\text{air} = 0.236$; /267 $\text{air}{:}O_2 = 4.24$; this means that oxygen constitutes 0.31 by weight of nitrogen and 0.236 by weight of the entire air.

For the volumetric ratios we obtain $N_2{:}O_2 = 3.69$; $O_2{:}N_2 = 0.271$; $O_2{:}\text{air} = 0.213$; $\text{air}{:}O_2 = 4.70$.

7. Now we can give the quantity of air by weight and volume for 1 unit weight (kg) of fuel.

Equation of the fuel	H_2	C	H_6C_6
Weight of fuel	1	1	1
Required quantity of oxygen	8	2.67	3.33
Weight of the products of combustion obtained with oxygen	9	3.67	4.33
Required quantity of air	33.9	11.3	14.13
Weight of the products of combustion in the case of air	34.9	12.3	15.13
Required volume of air (density of 0.0013), m^3	26.1	8.7	10.9

8. However, we must also know the required amount of oxygen, air, and nitrogen on hydride for each metric hp (100 kgm). We propose, therefore, the following table.

9. We shall derive and explain this table. When atmospheric oxygen is used, it is very convenient to store hydrogen. The weight of this fuel for the same work will be three times less than that of gasoline (3 and 12). It is unfortunate that at the present time liquid hydrogen is difficult to handle. Liquid methane (CH_4) is also very useful.

In the case of stored liquid hydrogen the difference in the supplies or in the explosives is not very large (7). In this case there is not much advantage in replacing gasoline with hydrogen. The same is true if we use N_2O_5. When the total weight of the equipped airplane is 1 ton, even the hourly supply of fuel does not appear to be very excessive (12_1).

For hydrogen it is particularly small.

The ejection velocity per second under optimum conditions is given in 13 and 14: when combustion is complete, there is no heat loss, if the tubes are long and conic and the products of combustion expand into vacuum. When we utilize air, it is clear that the mass of the products of explosion will be almost four times greater (7 and 8) than in the case of pure oxygen. In this case the ejection velocity will therefore be twice as small. However, we shall not be overloaded with the supply of oxygen, but, we cannot do without these supplies in a vacuum or in a highly rarefied atmosphere. The supply of N_2O_5 is slightly more ad- /269

vantageous compared to oxygen.

The acceleration of the rocket, whose mass is 1 ton when air resistance is neglected, is given in 15 and 16. It turns out that it is more advantageous to utilize air because it gives higher acceleration, to say nothing of the loading effect of liquid oxygen. We obtained these values after we found out how much greater the weight of the rocket (1,000 kg) was than the weight of mass ejected per second. We then divided the velocity of ejected matter per second by the number obtained. (From the well-known laws stating that when a force acts between two masses, the large one obtains a velocity which is smaller by the ratio of the large mass to the small.) It is clear that as the fuel is burned, the acceleration of the projectile will increase. We have presented the lowest acceleration.

The recoil or thrust in kg is expressed in 17 and 18.

Entries 19 and 20 give the velocity of the rocket after 1 hour has elapsed, without taking into account the resistance of the medium. When air is used this velocity reaches the first cosmic velocity in value.

1	Formula of the fuel	H_2	C	C_6H_6	/268
2	Quantity of heat per unit mass of fuel..	34,180	8,080	11,500	
3	Thermal ratio..........................	2.97	0.709	1	
4	Amount of fuel required for 1 metric hp per hour, kg.......................	0.0842	0.353	0.25[1]	
5	Amount of oxygen required for 1 hp (100 km/sec) per hour......................	0.674	0.942	0.833	
6	Amount of air required per hour for 1 hp, kg...............................	2.498	3.994	3.532	
6_1	Amount of N_2O_5 required per hour for 1 hp, kg..............................	0.910	1.272	1.125	
7	Weight of ejected matter per hour when combustion takes place with oxygen.....	0.758	1.295	1.083	
8	Same, when combustion takes place with air, kg..............................	2.584	4.347	3.782	
8_1	Same, when N_2O_5 is used................	0.994	1.625	1.375	
9	Weight of ejected matter when oxygen is used for 1,000 hp per hour............	.758	1,295	1,083	
10	Same, per second......................	0.21	0.36	0.30	
11	Same, when combustion takes place in air, kg..............................	0.72	1.21	1.05	
12	Same, when N_2O_5 is used................	0.275	0.450	0.380	
12_1	Hourly supply of fuel for 1,000 hp, kg..	84	353	250	
13	Velocity of ejected matter per second when oxygen is used ("A Rocket Into Cosmic Space," 1926) m/sec............	5,650	4,290	4,450	
14	Same, using air........................	2,743	2,082	2,160	
14_1	Same, using N_2O_5	4,900	3,840	3,900	
15	Acceleration of a 1 ton rocket per second when oxygen is used, m/sec^2........	1.19	1.54	1.33	

	Formula of the fuel	H_2	C	C_6H_6
16	Acceleration of a 1 ton rocket per second when air is used m/sec^2............	1.97	2.52	2.27
16_1	Same, when N_2O_5 is used.................	1.35	1.75	1.48
17	Pressure (recoil) on the rocket when oxygen is used, kg.....................	119	154	133
18	Same, when air is used, kg..............	197	252	227
18_1	Same, when N_2O_5 is used.................	135	175	148
19	Velocity of the rocket after 1 hour of flight when oxygen is used, in vacuum, m/sec..................................	4,284	5,544	4,788
20	Same, when air is used (see 15, 16, and 12)...............................	7,092	9,072	8,172
21	Period of time, in seconds, necessary to achieve velocity of 8,000 m/sec, when oxygen is used...................	6,720	5,200	6,010
22	Same, in hours..........................	1.87	1.44	1.67
23	Corresponding quantity of fuel, kg (see 12)..............................	154	508	418
24	Number of seconds required to obtain a velocity of 8,000 m/sec, when air is used (see 18)......................	4,061	3,175	3,524
25	Same, in hours..........................	1.13	0.88	0.98
26	Corresponding quantity of fuel..........	94.9	310.6	245.0
27	Volume of the air used for 1,000 hp per hour, m^3. Air density = 0.0013........	1,921	3,079	2,717
28	Same, for period of 1 second............	0.53	0.35	0.75

[1]We assume that the metric hp is equal to 100 kgm/sec. Then we find that the author has taken an efficiency of approximately 30 percent: for H_2 we have 29.4 percent; for C we have 29.6 percent, and for C_6H_6 we have 30.7 percent. - Remark by Tsander.

However, we might now ask the question as to whether it is possible to have an engine with 1,000 hp, when the entire system weighs 1,000 kg The gasoline fuel alone uses up 250 kg (12_1). Under the present state

of engine developments an engine of 1,000 hp will weigh not less than 500 kg. The fact is that our engine need only produce 100 to 200 hp (see Section 2), if only it could burn as much fuel as a 1,000 horsepower engine. Here the important thing is not the work, but combustion and reaction. Such an engine may weigh much less, for example, 100 or 200 kg. Then we shall have enough left for the remaining part of the structure.

Entry 23 shows the value of the fuel supply alone, when we use oxygen to achieve a velocity of 8 km/sec (in vacuum). Even when oxygen is not stored, this value is quite large, and when oxygen is stored, the value becomes impossible when the rocket weighs 1 ton. On the other hand, the required fuel supply when we utilize air for the same purpose is quite feasible.

The next question is whether a conventional airplane, weighing 1,000 kg, can take off with the value of the reactive thrust found in entries 17 and 18? If we assume that we have a conventional airplane with 100 hp and weighing 1 ton and having a velocity of 40 m/sec, we find that its thrust is 125 kg. We assume that the efficiency of the propeller is 0.67. When we use oxygen, the thrust of a reactive airplane is close to 125 kg (17), so that in this case also the airplane will take off and fly without a propeller (with a velocity of 40 m/sec). However, when we use air (18), the thrust is almost twice as large. According to my theory ("Airplane," 1895 and 1929), an airplane with a thrust of 125 kg may fly with a velocity twice as great to an altitude of 12 km, where the air is rarefied by a factor of 4.

10. We have in mind uniform and horizontal motion of the airplane. We do not consider the amount of work required for the airplane to reach its altitude or the work required to reach a constant velocity of motion. This can be ignored only when the velocities do not exceed /270
500 m/sec and when the altitude is not greater than 30 km.

Under these conditions the natural condensation of air in the forward tube is quite insufficient, and we cannot therefore eliminate some form of compressor.

11. Let us assume that we have achieved a velocity of 100 m/sec at sea level. We have done this by using our reactive engine. At an altitude of approximately 12 km where the air is rarefied by a factor of 4, the velocity of the airplane with the same engine will be twice as large. How is this possible? Do we not have the same engine? The fact is that the reactive engine develops power proportional to the

velocity of motion of the projectile. Indeed, its thrust or reaction does not change at any velocity. For example, if the reaction is 250 kg. there is nothing to decrease it at higher or lower velocities of the airplane. If this is so, the amount of work performed each second will be proportional to the velocity of the airplane. If its velocity increases by a factor of 5 and the thrust remains constant, the work will also increase by a factor of 5. When the velocity is 0, the power of the engine in spite of the tremendous reaction will also be equal to 0. We are speaking, of course, of the utilized work: as the velocity increases, the utilization of the energy of combustion also increases.

12. The amount of work required to travel a unit distance of path at various altitudes remains unchanged (see "The New Airplane"). It does not depend on the velocity of the projectile at various altitudes. This means that the power or work per unit time is proportional to the velocity of the airplane. However, this is only true for conventional propellers. When we have a reactive motor, the power remains the same. Consequently, the consumption of fuel per unit distance of path will be smaller when the velocity is larger.

13. Let us consider an example. We have discovered that an airplane weighing 1 ton must burn at least as much fuel as is required for 1,000 metric hp. At sea level it will have a velocity of 100 m/sec. Under these conditions it will consume 5 times more fuel than a conventional airplane with a propeller.

Therefore, our reactive airplane is less efficient than the conventional airplane by a factor of 5. Now, however, let us assume that it is flying at twice the velocity in the atmosphere, where the density is 4 times less. Here it will be less efficient only by a factor of 2.5. If we go higher, where the air is 25 times thinner, it flies 5 times faster and is now as efficient as an airplane with a propeller. At an altitude where the medium is 100 times thinner, its velocity is 10 times greater, but it is more efficient than a conventional airplane by a factor of 2.

With very high velocities the phenomenon becomes so complicated, our conclusions are not sufficiently accurate since we have neglected the fact that oxygen is taken from the atmosphere (see "Resistance of /271 the Air," 1927).

14. What are we after and what are we trying to achieve, if the efficiency of operation is not much better? The fact is that we obtain a velocity which is impossible for an airplane with a propeller.

When we have high velocities, we inevitably reach high altitudes. Also in this case we obtain a noticeable centrifugal force which decreases the necessary work and lifts us upwards. At a velocity of 8 km/sec this work is reduced to 0, and we depart beyond the limits of the atmosphere.

15. A large projectile velocity also has an application on Earth, even though the efficiency is not very great.

We have seen that under the assumed conditions flight cannot take place for more than 1 hour. Here are the distances which are covered by the projectile at various altitudes with different forward velocities of flight.

Relative density of the rarefied layers of the atmosphere					
1	1:4	1:9	1:16	1:25	1:100
Approximate flight altitude, km					
0	11.1	17.6	22.1	25.7	36.8
Velocity in m/sec					
100	200	300	400	500	1,000
Velocity in km/hour					
360	720	1,080	1,440	1,800	3,600

The last entry shows the hourly race. Apparently it is not sufficient for practical purposes. However, in the first place the altitude of the velocity may be much greater, in the second place, the supply by weight and the energy of the fuel may be increased further. Then the distance traveled will be sufficient for flying across an ocean.

16. In this article we have hardly considered the relative ascending acceleration of the projectile and the attainment of cosmic velocities, which free it from the resistance of the atmosphere. We have spoken of transportation on Earth and have only hinted about transportation in space: there will be a transition to this airplane. The era of propeller airplanes will be followed by an era of reactive airplanes or airplanes of the stratosphere.

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ROCKETPLANE

/272

(1930)

1. The rocketplane is similar to a conventional airplane. However, its wings are small compared with those of the conventional airplane, and it does not have a propeller. The rocketplane has a very powerful engine which ejects the products of combustion through special conic tubes to the rear towards the stern of the projectile. As a result we obtain recoil or thrust, which is responsible for the accelerated ascending motion of the rocketplane.

2. If it were to move horizontally, its velocity would increase only to a small magnitude; however, it has an ascending motion, whereby the air becomes more and more rarefied and its resistance decreases. Therefore, accelerated motion takes place during the entire period of time when the engine is in operation.

3. When the fuel has been consumed or the engine has been turned off, it may have achieved an altitude and a rarefied region of the atmosphere, so that its velocity permits it to fly beyond the atmosphere, due to its inertia, and to move in the vacuum.

4. In this case, depending on the magnitude and direction of its velocity, it may:

(a) again return to the atmosphere and by losing its velocity by friction descend to Earth;

(b) orbit indefinitely in the vacuum around Earth like a moon or comet;

(c) escape from Earth and orbit around the sun like a planet;

(d) escape from the sun and travel among the stars, i.e., among other suns.

5. If the operation of the engine can be extended, all those results may be varied in any desired manner.

6. The principal parts of our rocketplane are as follows:

(a) a frame having the form of a spindle and containing people, machines, fuel supply, etc.;

(b) small, fixed, elongated plane wings;

(c) a direction rudder behind and above the frame;

(d) two horizontal rudders behind and on the sides which control lateral stability and also serve as altitude rudders;

(e) several modified aircraft engines with conic tubes for ejecting the products of combustion towards the stern;

(f) an air compressor to increase the power of the engine and produce the mandatory compression of the air at high altitudes; it is driven by an engine;

(g) a device for cooling the compressed air which feeds the operating cylinders;

(h) a compartment for the fuel (gasoline);

(i) humidity absorbers, absorbers of carbon dioxide, ammonia gas and other liberated substances harmful to mankind. /273

7. The frame. Since the projectile is designed to achieve altitudes where man cannot breathe, the device must be hermetically sealed so that not even the slightest amount of gas leaks outside. The inside pressure will be maintained at a constant value.

However, in this case it will be much greater than the external pressure of the rarefied atmosphere at high altitudes. From this we can see that the excess inside pressure is unavoidable for a high altitude airplane. We may also have this excess pressure at sea level. For this purpose it is only necessary to pump some of the external air into the frame or to turn on a jet of oxygen from the internal supply.

8. Excess pressure lends a certain amount of rigidity to a thin shell, giving it resistance against flexure and other deformations.

Nevertheless, the device must have a certain amount of rigidity even without excess pressure, i.e., before it is filled with oxygen or air. To achieve this, it is desirable to give the transverse cross sections a wavy form. The ridges of the shell will move along its length. Due to pressure the waves expand and the rigidity decreases; however, in this case the device is still rigid because it is inflated.

9. It is desirable to make the device as large as possible; however, we must start with the smallest possible. The diameter of the transverse section of the frame cannot be less than 2 m; otherwise the movement of man will be too confined.

Elongation should also be as large as possible; however, initially we may use a moderate value, for example 10. Then the length of the frame will be 20 m.

10. The volume W will be given by the equation

$$W=0.5\,l\frac{\pi d^2}{4},$$

where d is the maximum diameter and l is the length of the frame.

Since $l = \lambda d$, where λ is the elongation or the ratio of the length to the diameter, we have

$$W=\frac{\pi}{2}d^3\lambda.$$

11. Let us assume that d = 2 m; $\lambda = 10$. We obtain W = 31.4 m^3.

12. We can also express the surface F as:

$$F = 0.75\ l\pi d = 0.75\ \pi\lambda d^2.$$

13. If d = 2 m and $\lambda = 10$, then F = 94.2 m^2.

14. If the frame is filled with pure oxygen, the pressure will be entirely sufficient (even for a sick and weak man) and will have a magni- /274
of 0.5 atmospheres. This will be its value on Earth. During ascent it may become greater than atmospheric pressure, but then part of the gas may be released. During descent it will again be necessary to increase the inside pressure, otherwise, the shell will be crumpled by the atmospheric pressure.

What will be the thickness of the shell under these conditions? If it is of constant thickness, the maximum stresses are developed at the wide parts of the central cross section. Circumferential stresses are greater than longitudinal stresses. On this basis we write: $\delta=\frac{npd}{2k_z}$, where p is the excess pressure per unit area; δ is the thickness of the shell; k_z is the coefficient of strength of the material; and n is the factor of safety.

15. From this equation we see that the thickness of the shell will increase when the diameter is increased, when the safety factor is increased, when the overpressure is increased, and when the resistance of the material is decreased.

16. Let us assume that: $p = 0.5\ kg/cm^2$; $n = 10$; $k_z = 10^4\ kg/cm^2$.

Then we find $\delta = 0.5$ mm. If we increase the factor of safety by two, i.e., if we make $n = 20$, then $\delta = 1$ mm. If we use chromium steel the thickness of the shell will be quite suitable. If it has a wavy form it will retain its shape quite well without too much excessive pressure.

17. One m^2 of this shell will weigh approximately 8 kg. The entire shell will weigh 752 kg.

18. One-third of the volume of the frame may be occupied by fuel, the same volume may be occupied by machines, equipments for removing human secretions, and other required devices. One-third of the space is used to house man. This space will be approximately 10 m^3. For 2 or 3 travelers this is sufficient.

19. The total volume occupied by fuel and equipment will not be greater than 15 m^3. The remaining 15 m^3 will be occupied by gaseous oxygen. Its weight will be 9.75 kg when rarefied by a factor of 2. This will be enough for 1 man to breathe over a period of 10 days, 2 men for 5 days or 3 men for 3 days. At the same time, the entire trip may be completed in 1 hour. We may also inflate the shell with air which can be used for breathing, although in this case the time of use will decrease 5 times, i.e., the amount of oxygen will be enough for only 6 days in the case of 1 man, and 2 days in the case of 3 men (of course, in this case we must not exhaust our air at high altitudes and we must absorb human exhalations).

20. The fuel will occupy 10 m^3. Even when its density is 0.5 we may assume that the weight of the fuel is equal to 5 tons.

21. For an engine with 1,000 metric hp it is entirely sufficient to have a chamber with a volume of 10 m^3. It may weigh 1,000 kg or 1 ton.

22. We have a special engine. It must burn as much fuel as possible even if it only produces the same power. We do not require a great deal of work. Actually this work is used principally to compress the air for the operating cylinders. We require a large quantity of exhaust gases or products of combustion to produce the thrust. /275

23. How can we increase fuel consumption? To do this we may:

(a) increase the number of revolutions of the shaft (at the expense of fuel economy);

(b) have a preliminary compression of the air which feeds the operating cylinders.

24. An increase in the number of revolutions will require an increase in the valve openings and, in general, is associated with a very uneconomical operation of the engine; this does not justify the additional expenditure of fuel. However, in this case too we are not concerned with economy. For example, the fuel may be burned at 10 times the rate, while the work may increase only by a factor of 2. This will be enough to compress the air feeding the cylinders.

25. Its compression even at sea level may not increase the revolutions of the engine, but it will increase its work and the quantity of fuel burned each second.

As we shall see, the work of compression is not very large. The compressor, the increase in the thickness of the cylinder walls, and the massiveness of other parts will, of course, increase the weight of the motor, but it will not increase its volume. We may assume that the weight of the engine will be 5 tons. We hope to increase its power to 5,000 metric hp and to increase the amount of fuel consumed, not by a factor of 5, but by a factor of 20, i.e., based on the quantity of fuel it could give 20,000 metric hp, but will actually only produce 5,000 or less. The economy of operation will be reduced by a factor of 4, or even more.

26. Now we can state the approximate weight of the entire projectile: frame, rudders and wings--1 ton; fuel--5 tons; engines and equipment--5 tons, and people, various devices and small items--1 ton. We have a total of 12 tons.

27. The thrust which produces the motion of the projectile will be 4 to 5 tons, which is sufficient (see my "Reactive Airplane") for the accelerated ascending motion of the airplane.

28. I shall base the subsequent discussions on what I have published in my works of 1930, "Pressure on a Plane" and "Reactive Airplane;" also my works of 1895 and 1929, entitled "Airplane" and "The New Airplane."

29. The compression of the gas may take place without heat losses and without its absorption from the outside. In this case the gas will heat more when it is more compressed, its elasticity will increase, and the work of compression will become quite large. The degree of heating does not depend on the density of the gas or on its nature (if the latter is constant). For this purpose we present Table 1.[1]

The temperature refers to the compression of gas at 0 temperature. At low temperatures of high altitudes the air is heated less by compression, specifically, it is proportional to the initial absolute temperature.

In Table 1 we see that compression by a factor of 4 increases the temperature only by 204° C. However, at high altitudes where the air is several thousand times thinner, it must be compressed several thousand times more. Thus, when it is compressed by a factor of 10,000, the temperature reaches a value of 10,901° C. This is the temperature of the hot surfaces of the sun. /277

31. We would be in a very hopeless situation without sources of cooling in our flying device. The cooling system consists of the stern part of the tube through which the products of combustion are rejected. Due to their expansion, particularly in a rarefied atmosphere, they have a very low temperature and serve to cool the compressed air.

32. Without this cooling the work of compression is greater in a vacuum than in a medium of equal pressure, because in the latter case the external atmosphere itself aids in the compression process. This is particularly noticeable at low densities.

However, we shall not stop to consider this, since we burn the air when it is cooled. In our case the compressed air enters a special jacket covering the stern parts of the exhaust tube, where it can cool even below the atmospheric temperature, since the temperature of expanding products of combustion may reach a value of -273° C at the limit.

34. In Table 2 we assume that the temperature of the air is constant and remains at 0° C. The atmospheric pressure is assumed to be

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[1]The table corresponds to the adibatic compression (K = 1.4). - Editor's Remark.

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
Temperature in °C									
0	87.9	152.1	204.2	249.2	288.8	324.9	357.9	387.9	417.4
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
Temperature in °C									
540.0	639.9	801.8	934.2	1047.5	1148.2	1239.4	1323.2	1400.5	1463.4
Compression									
150	200	300	400	500	600	700	800	900	1,000
Ratio of absolute temperatures									
7.532	8.459	9.959	11.18	12.24	13.17	14.01	14.79	15.51	16.18
Temperature in °C									
1,783	2,036	2,444	2,779	3,068	3,322	3,552	3,765	3,961	4,144
Compression									
1,500	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000

Table 1 (continued)

Ratio of absolute temperatures									
19.05	21.40	25.19	28.29	30.95	33.30	35.44	37.40	39.22	40.93
Temperature in °C									
4,928	5,569	6,604	7,450	8,176	8,818	9,402	9,937	10,434	10,901

Table 2

Compression									
1	2	3	4	5	6	7	8	9	10
Work in ton-meters for compressing 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 of 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 a vacuum									
24.70	25.60	26.42	27.18	27.89	28.56	29.18	29.77	30.32	30.86
Work in 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
Work in a vacuum									
30.91	31.78	32.58	33.32	34.01	34.66	35.26	35.84	36.38	37.89

Table 2 (continued)

Work at atmospheric pressure /278									
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 a vacuum									
38.07	39.12	40.07	40.94	41.74	42.49	43.18	43.82	44.48	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 a vacuum									
46.05	47.88	49.42	50.75	51.93	52.98	53.94	54.81	55.61	56.35
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	1,000	1,500	2,000
Work in a vacuum									
57.04	59.92	62.15	63.97	65.51	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									
3,000	5,000	10,000	50,000	100,000	500,000	1,000,000	5,000,000	10.10^6	10^9

Table 2 (continued)

Work in a vacuum			
92.10	115.13	138.16	207.24
Work at atmospheric pressure			
82.10	105.13	128.16	197.24

10 tons per m^2. Table 2 gives us the amount of the work required to compress 1 m^3. This is applied, first of all, to increase the power of the engines while still at sea level. Here the pressure of the medium helps, and the work of compression is not very large. For an engine of /279 1,000 metric hp we require 0.75 m^3 of air per sec.

If we supply air with twice the density, the work performed by the engines will double. We shall then obtain 2,000 metric hp. Will this excess power pay for the work done in compressing the air? The work shown in Table 2 for 1 m^3 of air must be doubled, since we must obtain 1 m^3 of compressed air rather than 0.5 m^3. This means that the work will be 4 ton-meters. To obtain 0.75 m^3, we would require 3 ton-meters, i.e., 30 metric hp, whereas we have achieved an increase of 1,000 hp. Obviously the compression of the air is advantageous.

36. However, it is not as advantageous as this when compression is very great. This can be seen in Table 3.

From the last entry we see that the excess of power is much greater than the amount of power absorbed for compression. In a conventional airplane this absorption will be from 3-12 percent. For our purposes this is necessary and advantageous, since the mechanical work will undoubtedly be much larger than necessary and the thrust will increase proportionately to the burned material and will not depend at all on the fuel economy, as it does in a conventional airplane.

37. Now let us consider the rarefied air at high altitudes.

For rarefied layers of the atmosphere we may neglect the auxiliary force produced by the pressure of the external medium. Table 2 shows both works. The greater the compression, the less do the two vary.

Table 3

Compression								
2	3	4	5	6	7	8	9	10
Work obtained for 1 m^3 of compressed gas in ton-meters								
4	14.4	26	42.0	60	79.1	100.0	121.5	145
Same, for 0.75 m^3 of air								
3	10.8	19.5	31.5	45	59.3	75	91.1	108.7
Same, in metric hp								
30	108	195	315	460	593	750	911	1,087
Excess work of engine by compression of air in metric hp								
1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000
Percentage of work absorbed (due to excess) by work of compression								
3	5.4	6.5	7.9	9	9.9	10.7	11.4	12.1

Let us assume that at a high altitude the air is thinner by a factor of 100. To obtain 1 m^3 of air under ordinary pressure, we compress a volume of 100 m^3 by a factor of 100. On the one hand, the work increases by a factor of 100; on the other hand, it decreases by the same factor, because the pressure at the high altitude is 100 times less. /280
The work, therefore, remains constant.

The figures in the table refer to the work necessary to obtain 1 m^3 of air regardless of the degree of its rarefaction, provided the temperature remains the same (0° C). We see from the table that even when compression takes place by one million times and 1 m^3 of ordinary air is obtained, the energy consumed is 128 ton-meters. This means that to obtain 0.75 m^3 of ordinary air we require 96 ton-meters or 960 metric hp. However, in this case the work done by the engine is not sufficient.

If the front nose part of the flying projectile has an opening with a tube leading to the engines, the air in the tube is compressed and may be used to feed the operating cylinders without special compression. However, this is only possible at extremely high velocities which are of the order of 1 km/sec and higher. At lower velocities we have to use a compressor. Nevertheless, we should not ignore the compression of air produced by the motion of the projectile.

38. We have determined that the thrust produced by the ejected gases is 4-5 tons. Is this pressure sufficient, compared with the resistance of the air at various altitudes? To solve this question we must specify the density of the air at various altitudes, which specifies the resistance, and the resistance of our projectile when it has a specific velocity and a specific shape. If the resistance turns out to be negligible compared with the value of the thrust, then, in the first place, we shall simplify the problem of the motion of the rocket, and, in the second place, its motion will be accelerated and will achieve the high velocities we desire.

39. I refer to my works "Resistance of Air," (1927), "Aerostat" and "Airplane," (1906-1908), and "Pressure on a Plane," (1930).

40. If the velocity of the body is very high and the body is not elongated, the air in front of the body is compressed and the resistance becomes extremely large. Table 4 shows the variation in the elongation (the ratio of the bodies' length to the diameter of its maximum cross section) of a body of proper shape as a function of its forward velocity.

It would be even better if the elongation at the indicated velocities were greater than specified in the table.

41. The equations and calculations in the above references can also be used to prepare Table 5.

Table 4

Elongation of a moving body	1 (sphere)	2	3	4	5	6	7	8	9	10	15	20
Maximum velocity in 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

Table 5

Elongation		5	10	20	30
Length		10	20	40	60
		Ratio of resistance of the body to resistance of a plate and reciprocal value of this ratio			
Velocity 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
	500	0.00488	0.00298	0.00273	0.00283
		205	336	366	353
	700	0.00464	0.00260	0.00244	0.00256
		216	385	410	391
	1,000	0.00439	0.00248	0.00226	0.00230
		228	403	442	435

In Table 5 we have computed the resistances of bodies having a cross section diameter of 2 m with respect to the resistance of a plane plate with a surface equal in area to the maximum cross section of the body, as a function of the body's velocity and its elongation. Thus, when the elongation is 10 and the length is 20 m, the resistance of the body compared with the resistance of the plate decreases by a factor of 47 when the velocity is 10 m/sec.

42. To find the absolute pressure of the flow incident on the body, we must determine the resistance of air to the motion of the transverse plane of the body at the same velocities and then divide the result by the efficiency of the shape K_{sh}. When the diameter is 2 m the resist- /282

ance of this circular area is given by the expression

$$Q = 0.306\ K_{sh}\ \Delta V^2\ \text{kg}$$

where Δ is the density of the medium with respect to its density at sea level.

For example, if the efficiency of the shape, the velocity, and relative density are equal to unity, the resistance will be 0.306 kg (when the diameter is 2 m).

43. Now, by using Column 3 in Table 5 we may compute the resistance encountered by our body at sea level for various velocities (specifically Table 6).

Table 6

Velocity of device in m/sec							
10	50	100	200	300	500	700	1,000
Efficiency of shape							
47	152	236	269	299	336	385	403
Air resistance in kg							
0.646	5.03	12.91	45.53	92.25	228.00	390.04	758.90
Same, in percent, referred to reaction pressure of 4000 kg							
0.016	0.13	0.32	1.1	2.3	5.7	9.8	19

From Table 6 it is clear that even with a velocity of 1,000 m/sec and with dense air at the sea level its resistance is only 19 percent of the reactive pressure. However, before the projectile attains a velocity of 1,000 m/sec, it will reach a high altitude where the resistance of the medium is close to zero due to its rarefaction.

44. To confirm this further, let us prepare a table showing the densities of the air for various altitudes above sea level. The value of this density is affected by the decrease in temperature with altitude. Let us assume that this decrease is 5° C for each km of ascent. We further assume that the temperature at sea level is 0° C and the atmospheric

pressure at sea level is 10.33 tons per 1 m^2. On the basis of these data we compute the density up to an altitude of 18 km. The decrease in temperature may be assumed to take place to an altitude of 15 km. Above this the decrease in temperature ceases.

45. For altitudes above 15 km, for the stratosphere we assume that the temperature is constant and has a value of -75°.[1] /283

46. At an altitude of 15 km the density and resistance have already decreased by a factor of 6, and at an altitude of 30 km they have decreased by a factor of 80, while at an altitude of 33 km they have decreased by a factor of 135. Above this altitude the pressure is insignificant. Thus, at an altitude of 58 km the pressure has decreased by a factor of 10,000 times.

We see that during the ascending motion of the reactive airplane, which consumes a tremendous quantity of fuel and develops a thrust of 4-5 tons, the air resistance may be neglected. This simplified the initial calculations of the motion of the airplane, specifically the velocities in the horizontal and vertical direction, the corresponding density of the medium, its resistance, required work, etc.

47. Initially, the airplane, due to its own reaction or due to an external force, moves up a mountain with a definite slope. Then, having assumed sufficient velocity, it takes off from the mountain and moves into the atmosphere. The inclination of the frame may remain the same. The airplane will also move upwards. However, at the same time it may fall, due to its weight: the reaction will tend to lift it, while its

[1] On the basis of the approximate values presented here, Tsiolkovskiy computes and presents two tables which show the variation in density with altitude. Because in the international standard atmosphere other initial data are assumed, we omit these two tables as of no specific interest. - Editor's Remark.

weight will tend to drop it. However, the drop is prevented by air resistance,[1] particularly since the velocity of the frame is very high. Before the solid runway is left the velocity must be such that the drop is less than the lift, otherwise the projectile may fall to the ground or into the sea. It would be best if the drop were much less, compared with the lift. Then the projectile would move in the atmosphere as if it were on a track.

48. Let us determine the conditions for such motion. According to Langley, the pressure on a slightly inclined plate is obtained if the pressure of the normal flow on it is multiplied by 2 sin α.[2] I have derived theoretically ("The Pressure of a Plane," 1891), that this pressure is also proportional to $\sqrt{\frac{a}{b}}$, where a is the side of the rectangle situated normal to the flow, while b is its other side. As applied to our device, the role of a is played by the diameter d; it is less than d, i.e., than the length l. In addition, we have an elongated body of revolution rather than a plane. Because it is a body of revolution, the side pressure[3] exhibited by the medium on it will decrease, as in the case of a round cylinder. The coefficient of resistance of the latter may be assumed to be equal to $K_2 = 0.6$ (according to various experiments). The constriction of our body (spindle or bird) towards the ends will produce a decrease in the ratio b/a, but we shall assume that it is equal to the elongation l/d of the device and in this manner obtain the resistance; this is less than its true value: the fall will be greater than its computed value. /284

Thus the relative coefficient of resistance of our spindle inclined at a small angle with respect to the horizon will be:

49. $K_1 = 2 \sin \alpha \sqrt{\frac{d}{l}} K_2$. Here $\sin \alpha$ specifies the sin of the inclination angle of the longitudinal axis of the body with respect to the horizon.

If this slightly inclined body moves under the action of its thrust (directed along its length) with a velocity V_1 and falls in the same air due to its gravity with a velocity V_2, then

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[1]That is, the lift force. - Editor's Remark.
[2]α is the angle of attack; this equation is not accurate. - Editor's Remark.
[3]That is, the lift force. - Editor's Remark.

50. $\sin \alpha = V_2/V_1$ and the coefficient of resistance will be

51.

$$K_1 = 2K_2 \frac{V_2}{V_1}\sqrt{\frac{d}{l}}.$$

We may assume that the area S of the longitudinal section of the device is given by

52. $S = 0.75\ dl$. The pressure Q of the normal flow on the plane may be equal to

53.

$$Q = K_3 S \gamma \frac{V_1^2}{2g}.$$

Here K_3 is the longitudinal coefficient for the plane, which is close to 1.5, while γ is the specific weight of the air. We must multiply the magnitude of the pressure Q by the coefficient K_1. We obtain the value of the vertical pressure on our projectile.

54.

$$P = \frac{0.75}{g}\gamma K_3 K_2 V_1 V_2 d^2 \sqrt{\frac{l}{d}}.$$

55. Let us assume that $\gamma = 0.0013$ tons/m^3, $d = 2$ m, $l = 20$ m. We find $P = 0.0111\ V_1V_2$; this is the pressure on our projectile as a function of its fall velocity V_2.

For a uniform fall of the projectile the pressure due to the resistance of the medium is equal to the weight of the projectile G, i.e., $0.00111\ V_1V_2 = G$, from which

56.

$$V_2 = 901 \frac{G}{V_1}.$$

57. If the projectile were to fall due to gravity, it would climb due to inclined motion (with its nose upwards). The velocity of this fall would be equal to $V_1 \sin \alpha$. When the 2 velocities (of fall and ascent) are in equilibrium, the projectile will move horizontally. This will take place when the following equation is satisfied. /285

58.

$$V_1 \sin \alpha = 901 \frac{G}{V_1}.$$

From this we find

59.

$$V_1 = \sqrt{\frac{901\, G}{\sin \alpha}}.$$

60. We see that G = 12 tons.

Let us assume for an example that $\sin \alpha = 0.1$. Then we obtain $V_1 = 329$ m/sec. The projectile takes off from the mountain after it has achieved this velocity, and it will fly horizontally.

61. What must be the length and altitude of the mountain in this case? When the thrust is 4 tons, the acceleration of the projectile j is equal to

$$j = g\,\frac{4}{12} = \frac{g}{3}.$$

The distance L traveled until a velocity of 329 m/sec is achieved will be $L = \frac{V_1^2}{2j}$ = 5,412 m, i.e., approximately 5 km. We obtain the altitude of the mountain if we multiply the inclined path which has been traveled by $\sin \alpha$. It is equal to 541 m, i.e., approximately 0.5 km. This is entirely feasible.

63. With the velocity specified above the projectile will leave the solid runway and will not drop. If the velocity is greater it will

begin to ascend. Ascending motion is desirable. To achieve this, it is necessary that the ratio of the velocity of fall V_2 to the velocity of ascent $V_1 \sin \alpha$ be very small. However, this ratio which we designate by m is equal to

$$m = \frac{V_2}{V_1 \sin \alpha} = \frac{901 G}{V_1^2 \sin \alpha}.$$

From this it follows that

64.

$$V_1 = \sqrt{\frac{901 G}{m \sin \alpha}}.$$

65. Let us assume that G = 12 tons, $\sin \alpha = 0.1$ and prepare a table:

m	1	$\frac{1}{4}$	$\frac{1}{9}$	$\frac{1}{16}$	$\frac{1}{25}$
V_1 m/sec	329	658	987	1,316	1,645

When the velocity is 1 km/sec, the drop will be almost unnoticeable. Nevertheless, the velocity is quite substantial, and the altitudes of the mountains necessary to construct the inclined path will be very high; specifically, they will be: /286

H, km 0.54 2.16 4.95 8.80 13.75.

66. To decrease the fall and to decrease the length of the solid runway, we utilize the thin, narrow, almost flat wings which we have mentioned, but whose action we have neglected.

In any case, a mountain with a height of 5 km is entirely sufficient to achieve velocities at which the projectile will move without support.

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SEMI-REACTIVE STRATOPLANE /287

(1932)

Introduction

In the lower layers of the atmosphere the airplane cannot reach high speeds. If we wish to increase its speed by a factor of 2, 3, or 4, the power of the engine will have to be increased by a factor of 8, 27, and 64, respectively, without changing the weight of the entire airplane. This is difficult for many reasons. For example, the strength of the engine would be inadequate, the propeller would fail due to rapid rotation, the airplane itself would be unable to withstand the pressure of the incident flow, etc.

It is easier to achieve high speeds at high altitudes in the rarefied air. Accurate calculations show that when the rarefaction of the medium reaches values of 4, 9, 16, 25, the velocity of the airplane may be increased by a factor of 2, 3, 4, 5; however, it is necessary that the power of the engine also increase by a factor of 2, 3, 4, 5 and not by 8, 27, 64, 125, as is necessary in the lower part of the atmosphere with constant air density.

Although at high altitudes the air is sufficiently cold, it is too rarefied to cool the engine sufficiently.

The shortage of oxygen at high altitudes and the low atmospheric pressure require sealing the cabin of the airplane hermetically. Then the pressure on the human being will not decrease, and he will not become weak or suffocate.

At the same time, it is more difficult to increase the horsepower of the engine at high altitudes, because the air which feeds the operating cylinders must previously be compressed. This increases the weight of the engine and consequently the weight of the entire airplane. However, the increase in the weight may be partially compensated by using the recoil (reaction) of the exhaust gases.

My reflections and calculations have convinced me at this time that the type of high-altitude airplane described below is the one most feasible.

Short Description

1. Figure 1 shows a diagram of the almost identical frames of proper shape. One of these contains a pilot and is hermetically sealed, so that respiration at high altitudes is as easy as at low altitudes. Another frame contains the fuel. The middle frame contains the propeller, engine, compressor, cooler, etc. /288

The middle frame will be described further, using the sketches. Above the frames there is a large wing to connect the frames. To the rear there are two wings to control the altitude and the lateral stability. Finally, there is a direction rudder which is placed behind on the top of the middle frame.

2. Figure 2 shows the longitudinal cross section of the frame. The size of the opening on its forward part 1 may be controlled within certain limits (see also Figure 3). It is never completely closed. The rear part of the frame 9 is constructed in the same manner. During the motion of the airplane the incident flow enters the frame aided by the propeller 2, which is driven by an oil or a gasoline engine 3. The latter is cooled by the flow of air. In the drawing the flow of pure air is designated by single arrows. The products of combustion move from the engine along many tubes 3 and are collected in an annular, gradually diverging space.

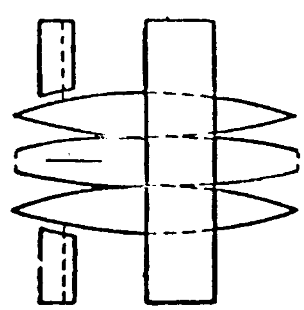

Figure 1

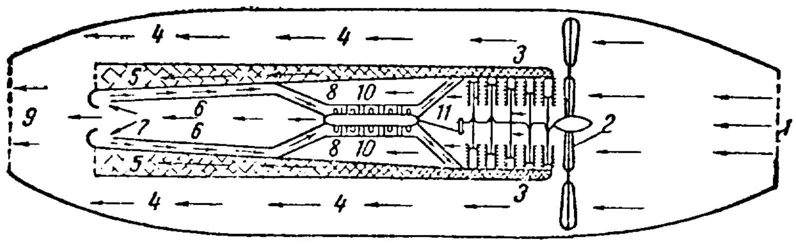

Figure 2

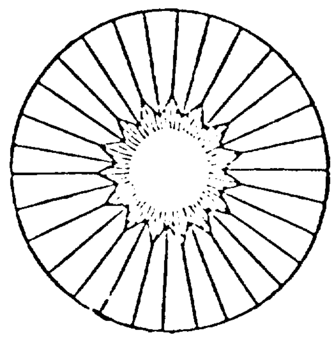

Figure 3

Here they undergo substantial expansion; heat is converted into motion, and they attain high velocity and a low temperature which may reach a value of -250°.[1] This provides us with a very good cooler 5. The tubes with the products of reaction are the shaded parts in the Figure 2. /289

[1]This low temperature is obtained when the initial temperature is 2,400° absolute (the temperature of gasoline combustion in air), when the products of combustion expand adiabatically to such an extent that their pressure decreases approximately by a factor of $17 \cdot 10^6$. Even with very high initial pressures, the final pressures in this case are very low. Actually, the resistance caused by the friction of gases along the walls and the internal friction is associated with the liberation of heat and the drop in pressure. Therefore, the gases at the end of the nozzle will be substantially warmer and their velocity will be decreased; it is possible to have a secondary increase of pressure inside the tube, which is then followed by the final pressure drop with a lower exit velocity. It is possible to select the most advantageous total length of the tube for a given angle of divergence. In this case the temperature will be greater than -250° C. - Remark by Tsander.

The direction of the products of reaction is designated by double arrows.

The airplane moves due to the thrust developed by the propeller and the recoil produced by the products of combustion. This entire mass of gases escapes at high velocity from the rear, variable opening of the middle frame.

The annular space 5 of the cooler adjoins a similar space, also between two cylinders. A flow of pure air enters this space through the annular opening 7, changing its direction toward the rear. This air is substantially cooled by the cooler 5 and moves through a series of tubes 8 into compressor 10, which is driven by an engine 3 through a gear box and Hooke's link 11. The pure, compressed and heated air from the compressor is directed along several tubes to the engine to mix with the gasoline and feed the operating cylinders.[1]

As the velocity of the airplane increases, the openings in front and in back of the middle frame are made smaller. Figure 3 shows the design of the variable opening. The surface at the end of the frame consists of rectangular plates which form creases or a wavy star at the opening. There are other ways of constructing this variable orifice.

Now we list all the things achieved by this machine.

3. The hermetically sealed cabin containing the pilot and the passengers makes it possible to fly in the most rarefied layers of the atmosphere.

4. The propeller always rotates with a safe, constant velocity (150-300 m/sec peripheral velocity) in spite of the very high velocity of the airplane. The fact is that when its velocity increases by a certain factor, the area of the openings in front and to the rear decreases by the same factor. Let us assume, for example, that when we have a maximum opening the velocity of the airplane is 100 m/sec. If the velocity of the projectile increases by a factor of 9 (900 m/sec), the area of the opening will also gradually decrease by a factor of 9 and the border by a factor of 3. Consequently, the quantity of air which enters the middle frame will always be the same under this action, thereby producing a constant flow velocity in the wide part of the case and /290

[1]It is better to cool the air between the stages of the compressor and inject relatively cold air into the cylinders: this increases the volumetric factor of the cylinders, i.e., the power of an engine of given size, and decreases the work required to compress the air. - Remark by Tsander.

also a constant velocity of the propeller, even though the velocity of the airplane and the velocity of the incident air may vary over a wide range. We shall clarify this later.

5. The thrust of the airplane is produced not only by the propeller, but also by the recoil of the products of combustion.

6. When the stratoplane flies at a high altitude the atmosphere becomes thinner and the gaseous products of combustion expand so that their temperature becomes lower. This increases the cooling of the air which feeds the engine, and the action of the compressor is increased so that it operates properly both in the dense and in the rarefied atmosphere.

The theory of the gas compressor is described in my special published article.[1]

7. Initially the stratoplane travels over tracks, over snow or water (it is also a stable hydroplane). Having achieved a velocity of 100 m/sec, it flies up along an inclined path. In the lower layers of the atmosphere it would have reached the limiting velocity of approximately 200 m/sec in a very short period of time. However, in its steep ascent it encounters more rarefied layers of the atmosphere and its velocity therefore continues to increase: first slowly and then more rapidly at the higher altitudes where the air is extremely thin.

8. We should note that the work performed by the engine tends to increase rather than decrease, due to the low temperature of the cooler and due to the strong cooling of the air which enters the compressor (the air may even become liquefied).

9. The drawings are presented in schematic form. To achieve better understanding of the construction and operation of the projectile, all secondary details had been eliminated; for example, the reinforcements are not shown nor the mechanism for the construction of the input and output vents (for the air).

10. If the velocity of the stratoplane is to exceed by several factors the magnitude which can be withstood by the conventional propeller without enclosure, it is more practical to make this enclosure smooth, of proper shape, but with equal openings in front and back.

If, for example, the maximum velocity of the projectile is to be nine times greater than the conventional velocity, the opening must also have an area which is nine times smaller.

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[1] "The Compressor of Gases," 36 pp., Kaluga, 1931.

Thus, we can design stratoplanes which will fly at twice the velocity, three times the velocity, etc.

In order not to expend unnecessary work on the motion at the beginning of flight, the case may be provided with special longitudinal openings which close gradually; these should be above the case in front and below the case in back. This construction will increase the lift force.

Air Compressor /291

11. The conventional propeller cannot be used for high altitude, high-speed flight, because it breaks down at a definite peripheral velocity, regardless of its size. Similarly, the blades of our fan cannot exceed a certain peripheral velocity. The rpm of the engine will be larger when the diameter of the propeller is smaller; however, the peripheral velocity cannot exceed a limit which depends on the strength of the material used to construct the propeller.

12. The fan-compressor is shown in Figure 2 (10). At the rear where the flow exists we must add a conic surface which can be compressed at the apex. Its opening at the apex may constrict or expand under the control of the operator. This surface may change from a cone with a barely noticeable opening to a cylinder.

13. The fan-compressor (Figures 2 and 3) consists of a round cylindrical tube which contains another rotating, closed cylinder with air blades secured on its surface (these blades are similar to the blades of the propeller or have the shape of Archimedes' spiral). A stationary blade is placed between each two rings with longitudinal blades, parallel to the axis of the cylinders. It may be extended in an eccentric manner in the large cylinder and attached to it. The purpose of these blades is to prevent the possible rotation of air in the compressor. The diameter of the internal rotating cylinder is approximately half as large as that of the external stationary cylinder.

14. When the axis rotates with a total expansion of the end cone (cylinder), the air encounters almost no resistance and moves along almost without compression. However, when the exit opening (Figure 3) is constricted, the gas passing through is compressed more strongly at its exit.

This action is best understood if we imagine that the exit opening is completely closed. There will be no flow, but the air will be compressed, more so toward the end of the tube.

15. In this case each pair of blades compresses it by a certain amount. Let us assume that the first blade increases the pressure and

compresses the air by 1.1. Then the second blade, together with the first, increases this pressure by a factor $(1.1)^2$, the third, with the first and second, by a factor $(1.1)^3$, the tenth by $(1.1)^{10}$, etc.

We see that the limiting pressure and compression in the tube increases with the number of compressor stages. It is not the same in any one tube and is expressed by a series of numbers: (1.1)... $(1.1)^3$... $(1.1)^{10}$. The last number expresses the pressure in the tube after the tenth compressor stage.

In addition, the temperature increases due to compression, which distorts these conclusions by causing the pressure to decrease due to a decrease in the density of heated air.

16. If we open the hole slightly, flow will take place; however, /292
the pressure will immediately become weaker. The wider the opening in the cone (Figure 3), the faster will be the flow, but pressure and compression will decrease (the phenomenon is considerably more complex).

There is an average external resistance during which the action of flow is most advantageous.

18. Let us assume that the axis is covered with a cylinder whose diameter is two times smaller than the diameter of the tube. The compressor blades are situated around a small cylinder, and the air stream passes in the annular space between the two cylinders. This passage constitutes 0.75 of the cross section area of the large cylinder. The small cylinder is terminated with streamlined surfaces at both ends.

19. Figure 2 shows the longitudinal cross section of compressor 10. In this illustration we can see partitions. These are attached to the large cylinder but do not touch the small cylinder. The purpose of the partitions is to assure that no rotating streams are formed in the tube. These would destroy or weaken the gas pressure and its forward motion.

20. It is desirable that the partitions have the lowest possible resistance and the lowest possible weight. For this purpose both ends of each partition are secured to the large cylinder.

Design of the Compressor

21. Let us determine the maximum velocity u along the circumference of a rotating body. Let us assume that this body is a cylindrical rod, or a cylinder in general, which is perpendicular to the axis of rotation (like the spokes of a wheel).

A maximum circumferential velocity will be obtained when the maximum stress in the cylinder (y axis) due to the centrifugal force is equal to the strength of the material. On this basis we write the following equation

$$\frac{u^2 l}{lg}\gamma 0.5=\frac{K_z}{S},.$$

where l is the length of the cylinder, g is the acceleration due to gravity, γ is the specific weight of the material, K_z is the resistance of the material to breakdown, and S is the factor of safety. Coefficient 0.5 is obtained by means of simple integration. Therefore

$$u=\sqrt{\frac{2gK_z}{\gamma S}}.$$

We can see that the maximum circumferential velocity of the cylinder does not depend in any way on its thickness or its length. It is clear that the number of revolutions of the rod per sec can be greater when its length l is smaller. However, the velocity u is proportional to the square root of the strength of the material and inversely proportional to the factor of safety S and the density of the material (see the equation). /293

22. The rod may be tapered toward the end like a cone, like a wedge or like a body having the same resistance at all points. This will increase the circumferential velocity. However, we expect to use blades in the compressor stage, and therefore it is not convenient to decrease the cross section area toward the end. Since the cylinder is flattened into a blade, it becomes thinner toward the end.

23. What will be the condensation of the air produced by the blade of the fan?

The shape of the blade is part of Archimedes' spiral. We shall use only the upper half of the rod.

If the inclination of the upper part of the blade with respect to the circumference of its rotation is designated by tan α, the inclination of its lower part will be (2 tan α). The maximum velocity of the airflow in the cylindrical pipe normal to the circumference will be $v = u \tan \alpha$. This velocity due to the properties of Archimedes' spiral will be the same for all of the blades or for a definite cross section of the tube.

24. This flow of air along the tube may produce a maximum pressure P, which is not less than

$$P = \frac{(u \operatorname{tg} \alpha)^2 d}{2g}.$$

25. Here may be eliminated by equation (21). Then we obtain

$$P = \operatorname{tg}^2\alpha\, [K_z : (\gamma S)\}\, d.$$

We are particularly interested in this maximum pressure. It increases with the specific strength of the material ($K_z S$), with the density of the medium d and the tangent of the angle of inclination of the blades (as the square of this tangent).

A large factor of safety S is not desirable.

26. The tangent of the angle of the upper part must not be greater than 1. Then the angle of the blade with respect to the circumference will be 45° and of its lower part will be 64.5°. Let us assume further that in equation (25) $K_z = 2 \cdot 10^6$ kg/cm^2 of the section (we can assume this to be so only for selected and tested types of chromium steel or other similar steels); $\gamma = 8$; S = 4 (not less); d = 0.0012 kg/∂m^3. Now we use equation (25) to compute P = 75 kg/∂m^2 or 0.75 atm. Equation (21) will also give the corresponding velocity along the circumference of the blades, specifically, u = 353.5 m/sec.

27. It would be more practical to let tan $\alpha = 0.5$. Then P = 19 kg/∂m^2 or 0.19 atm, while u = 353.5 (the same).

28. A cylindrical tube with several stages on one axis will produce the following maximum pressures for different numbers of stages. We may assume a value of 1.2 for the pressure increase, assuming that the temperature is constant or that there is artificial cooling of the tube and of the air.

29. To be even more practical, let us make the following substitutions in equation (25)

$\tan \alpha = 0.5$; $K_z = 10^6$; $\gamma = 8$; $S = 5$; $d = 0.0012$.

Then P = 7.5 kg/∂m², or 0.075 atm. From equation (21) u = 223.6 m/sec.

Number of stages	1	2	3	4	5	6	7	8
Compression, in atm	1.2	1.44	1.73	2.07	2.48	2.99	3.59	4.28
Number of stages	10	12	14	16	18	20	22	24
Approximate compression, in atm	6.75	8.94	12.9	18.3	26.3	37.8	54.4	79.9

/294

30. On the basis of this we obtain the following table.

Number of stages	2	4	6	8	10	14	18	20
Approximate pressure, in atm	1.15	1.32	1.52	1.74	2.00	2.64	3.48	4
Number of stages	30	40	50	60	70	80	90	100
Pressure, in atm	8	16	32	64	128	256	512	1,024

31. For a stratoplane flying at high altitudes in very thin layers of the atmosphere we require large compression and the maximum number of stages, as well as a huge volume of air for combustion.

Let us assume condition (26). Specifically, u = 353.5 m/sec, compression = 1.75 (for each stage).

Number of stages	1	2	3	4	5	6	7	8	9	10
Compression, in atm	1.7	2.9	4.9	8.4	14.3	24.0	40.8	70.5	117.6	204.5

Number of stages	12	14	16	18	20	22	24	26
Pressure, in atm	591	1,714	4,960	14,380	41,470	120,000	$348 \cdot 10^3$	10^6

Of course, in all these tables we obtain the maximum limiting pressure. High condensation is applicable only for the case of highly rarefied air in the uppermost layers of the atmosphere. /295

32. This compressor may give us any optimum pressure (up to a point where the gases are liquefied or very high temperatures are reached) and any quantity of air. The efficiency of the engine depends on the design of the compressor, pressure, and flight velocity.

Low efficiency is compensated by the simplicity of construction, absence of lubrication, compactness, possibility of high temperature, light weight, and low cost of the compressor. It can be applied to fans, blast furnaces, and other types of furnaces and devices where a great deal of air is required at high pressure and high temperature. It can also be applied to stratoplanes, to reactive ships, to vehicles and fast trains (see for example "Zeppelin on the Tracks" and my wheelless train). It transforms mechanical energy into heat and may be used to lift fluids and also as a turbine.

Propeller

33. Now let us describe the propeller. It differs from the compressor by having a cone in front as well as one behind The number of its blades is indefinite and we may even limit ourselves to one blade (Figure 2).

When the input is fully opened, the relative velocity of the stream with respect to the tube is c + w, i.e., the velocity of the projectile c plus the relative (in relation to the propeller) velocity of the exhaust w from the action of the air propeller. However, since the velocity of the projectile c may be very large, the relative velocity of the flow in the tube of the propeller is also large, whereas the latter cannot exceed the limit given by equation (21)

$$v=\sqrt{\frac{2gK_z}{\gamma S}}.$$

This velocity is quite definite. We determine its maximum value to be 353 m/sec. This means that the projectile cannot have a large velocity, because the air blades inside the tube would break down due to centrifugal force.

34. What should we do? Does this mean that we cannot have high velocities for the projectile? However, we have a way out of this

dead end. Let us start with the experiment (Figure 4). I have constructed the external part (case) of my propeller without blades.

The blades in this tube, which is widened substantially at the center, were placed in four locations: in the middle, at the inlet, at the outlet and to the side of the inlet--outside the tube. Both openings were of the same size and the blades were identical. /296

With this device I moved uniformly or stood still near the half-opened door of a warm room. In the latter case there was a very regular flow from the warm room into a cold room above the door.

All of the deflectors were identical. Therefore, the observed identical deviation of the end deflectors pointed to the same force or flow velocity. However, the middle deflector moved very little. This pointed to a small flow velocity in the expanded portion of the tube.

35. What is it that we observed? Let us assume that a tube of this type is moving with the projectile in the direction of its longitudinal axis. The incident flow enters the inlet with the velocity of the projectile, then is weakened substantially in the wide part of the tube, but leaves the outlet with the same velocity with which it entered. This is what our experiment confirms.

36. If we decrease the area of the end openings proportionately to the increase in velocity of the airplane, the relative velocity in the expanded part of the tube will remain constant, regardless of the increase in velocity of the projectile. Indeed, if, for example, the velocity of the airplane increases by a factor of 10, while the end openings decrease by the same factor, the volume of air entering the propeller will be the same. Since the average area of the tube's cross section is also constant, the flow velocity in this section will remain unchanged.

37. Thus the air screw will operate safely at any velocity of the airplane, since the velocity of the surrounding medium will not increase even with an increase in the velocity of the airplane.

When the propeller is absent, the relative velocity of the medium at the input and output will be approximately equal to the velocity of the airplane. However, the action of the operating propeller increases this velocity by some magnitude dependent on the power of the engine.

Thus, the output flow obtains some excess velocity above that of the stratoplane.

38. When the airplane flies, the openings must be closed gradually as the airplane accelerates. Thus, if the velocity of the projectile

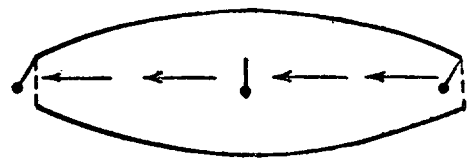

Figure 4

increases by a factor of 25, the area of both openings must be decreased by a factor of 25 and their diameter by a factor of 5.

39. In this case we must be guided by the acceleration indicator: it is necessary to change the size of the opening until the acceleration of the projectile has reached the maximum value. The acceleration of any body is recorded accurately by a simple special device (accelerometer). Our setup makes it possible for us to use the air propeller at any velocity of the airplane since our blade always rotates with the same velocity, even though the velocity of the projectile varies. /297

We determined the maximum velocity of the flow at the midsection of the tube to be 353 m/sec. A smaller velocity, for example, 210, would be safer. Initially this velocity is not obtained. However, the velocity of the projectile increases gradually and reaches a value which we shall assume to be 200 m/sec. The ejection velocity will be assumed to be 10 m/sec. Later, when the tube has a cylindrical form, i.e., when the holes of the propeller tube are fully opened, the velocity of the flow and the rotation of the blades should not increase. Therefore, as the velocity of the projectile increases, we decrease the end openings proportionally to the increase in the velocity of the device.

Let us express this by means of a table:

Velocity of the projectile, m/sec	100	200	400	900	1,600	2,500
Relative area of the end sections of the tube	1	1	1/2	2/9	2/16	2/25
Relative diameter of openings	1	1	0.707	0.471	0.354	0.284

The velocity of the flow in the wide part of the tube will always be 10 m/sec; the inflow and the outflow, which are approximately equal, will have the corresponding values:

110, 210, 420, 945, 1,680, 2,625

Of course, the openings may be closed more than indicated (but this is not advantageous), but they cannot be increased above the norm because the propeller would break down.

When the inlet and outlet are fully opened we can travel only with a velocity up to 100 m/sec. Beyond this point it is absolutely necessary to increase the size of the openings. If this decrease is greater than required the propeller will remain intact, if the decrease is less than indicated by the table, the propeller will fail.

In order to achieve medium altitudes, our stratoplane must have not less than 1,000 metric hp, when the total weight is 1 ton. Consequently, the engine must be lighter than the conventional aircraft engine. It must develop not less than 2-4 metric hp for each kilogram of its weight. The trend is in this direction, and there are already engines in existence which produce 2 hp for 1 kg of engine weight (this refers to the state-of-the-art in 1930).

Acceleration of the Stratoplane /298

51. The air enters at the nose of the airplane and is ejected backwards, thereby obtaining some true velocity v or the ejection velocity. This velocity is absolute. The relative velocity of the outgoing flow v_0 will be (if we do not consider the change in density)

$v_0 = c + v$, where c is the velocity of the stratoplane.

52. The acceleration of the projectile, if we neglect the resistance of the medium for the time being, will be proportional to the mass ejected per second M_s and its velocity v. The velocity v is actually the excess velocity produced by the action of the propeller compared with the velocity of the projectile itself.

The momentum must remain unchanged. Therefore, after one sec we find: $Mj + M_s = 0$, from which $j = (-M_s/M)v$. The minus sign shows that the acceleration of the airplane j is opposite to the acceleration of the ejected matter. We may take a plus sign here because we are not interested in the direction of the projectile. In the equations M is the mass of the airplane.

53. The velocity of ejected matter v depends on the construction and operation of the propeller, while the fuel consumption by weight per sec G_s depends on the same factors and on the density of air and dimensions of the tube. Due to the limited strength of the materials,

the maximum relative velocity in the wide part of the tube is constant. Therefore, we always have

$$G_s = dF(c+v).$$

Consequently, G_s depends only on the density of the medium and the diameter of the tube, because the relative velocity of the flow in the center part of the tube is constant.

54. The density of the medium depends primarily on the flight altitude; the cross section F of the wide part of the tube (where the blades rotate) depends on its diameter D and the cross section of the axial shaft.

In place of the axial shaft there may be another obstruction for the motion of the flow, for example, internal engines, pipe work, etc.). Assuming that it is equal to half of the diameter of the tube we obtain

$$F = \frac{\pi D^2}{4} \frac{3}{4},$$

where

$$\frac{3\pi}{16} = 0.59.$$

55. The relative velocity of the flow at the point where the blades are located is given by equation (see 21 and 23)

$$c+v = \sqrt{\frac{2gK_z}{\gamma_m S}} \operatorname{tg} \alpha,$$

where γ_m is the specific weight of the material.

56. Now from equations (53), (54) and (55) we obtain /299

$$G_s = \frac{3\pi}{16} D^2 \sqrt{\frac{2gK_z}{\gamma_m S}} \operatorname{tg} \alpha \, \gamma,$$

where γ is the specific weight of the medium.

Density of the Air

57. We express the density of the air d as a function of its rarefaction p[1] and its density d_0 at sea level

$$\gamma = \gamma_0 : \frac{\gamma_0}{\gamma} = \gamma_0 : p.$$

58. From equation (52) we find

$$j = \frac{3\pi}{16} \frac{D^2}{G} \sqrt{\frac{2gK_z}{\gamma_m S}} \operatorname{tg} \alpha \gamma_0 \frac{v}{p},$$

where G is the weight of the stratoplane.

This means that at high altitudes in the rarefied medium the acceleration will be less, if the velocity v does not increase proportionately to the rarefaction of the air. We can see that the preservation of the constant acceleration requires increased work by the engine at high altitudes.

59. Let us compute the acceleration j. Let us assume that D = 2m; G = 1 ton; tan $\alpha = 1$; $\gamma_0 = 0.0013$ ton/m^3; $\gamma_m = 8$ ton/m^3; $k_z = 2.5 \cdot 10^6$; S = 5. Then we find j = 3.43 v/p. For example, when p = 1 (sea level) and v = 1, j = 3.43 m/sec^2, i.e., it is 3 times less than the acceleration due to gravity.

Operation of the Propeller

60. Now let us consider the minimum required work of the engine. It consists of two parts:

[1] $p = 1/\Delta$, where $\Delta = \rho/\rho_0$. - Editor's Remark.

(1) the work performed to move the mass of air L_1 pushed backwards by the propeller, and

(2) the work required to accelerate the projectile L_2. We determine the former first. It is equal to

$$L_1 = G_s \frac{v^2}{2g}.$$

61. From (56) and (57) we find

$$L_1 = \frac{3\pi}{16} D^2 \sqrt{\frac{2gk_z}{\gamma_\text{ж} S}} \operatorname{tg} \alpha \frac{\gamma_0}{p} \frac{v^2}{2g}.$$

62. Let us assume that

$$\frac{3\pi}{16} \frac{\gamma_0}{2g} \sqrt{\frac{2gk_z}{\gamma_\text{ж} S}} = \text{const.}$$

63. Based on the data of Section 59, the constant is equal to 0.0422 and then /300

$$L_1 = D^2 \cdot \operatorname{tg} \alpha \cdot \frac{v^2}{p} \text{ const.}$$

64. From (61) and (58), by eliminating p, we obtain

$$L_1 = \frac{G}{2g} vj.$$

65. Now let us determine the work performed every second to accelerate the projectile. We obtain it from the equation

$$L_2 = \frac{G}{2g}(c + \Delta c)^2 - \frac{G}{2g} c^2 = \frac{G}{2g}(2c\Delta c + \Delta c^2).$$

Here the increment of the projectile Δc is numerically equal to j.

66. However, since j is not very large compared with c, because the projectile achieves a large velocity while it is still on Earth, we obtain, approximately,

$$L_2 = \frac{G}{g} cj.$$

67. The total work L will be

$$L = \frac{G}{2g} vj + \frac{G}{g} cj = \frac{G}{2g} j(v + 2c).$$

We see that the work done every second, or the power, is proportional to G and j. We also see that the work L_1 is insignificant compared with L_2, particularly when the velocity of the projectile is high.

68. Let us not forget that work depends on the rarefaction of the medium and is given by equation (58) when j remains constant. From this equation we find

$$v = \frac{16}{3\pi\gamma_0} \sqrt{\frac{\gamma_M S}{2gk_2} \frac{G}{D^2} \frac{jp}{\operatorname{tg} \alpha}}.$$

69. On the basis of (62)

$$v = C \frac{G}{D^2} \frac{jp}{\operatorname{tg} \alpha},$$

where C = 1.185; see equation (63).

70. Let us assume: G = 1 ton; tan α = 1; D = 2 m. Then

$$v = 0.296 \cdot jp.$$

71. Now we eliminate v from equation (67) by means of equation (69). We find

$$L=\frac{G}{2g}\,j\left(C\,\frac{G}{\operatorname{tg}\alpha}\,\frac{jp}{D^2}+2c\right).$$

We can see that L of the engine is generally variable even with j constant. It increases with the velocity of the projectile and the rarefaction of the medium, i.e., with the ascent of the airplane into the rarefied layers of the atmosphere.[1] /301

Reaction of the Engine's Exhaust

83. In addition to the action of the propeller, we also have the reaction of the exhaust gases which are ejected through special conic tubes at the stern of the airplane. This recoil is computed, approximately, in my work "Reactive Airplane," 1930. When the latter weighs 1 ton and when the combustion of gasoline and air corresponds to 1,000 metric hp, the recoil reaches a value of 227 kg. The acceleration of the projectile resulting from this will be 2.27. We know the mechanical work of the engine may be much less than 1,000 hp. It may be, for example, 500 or 100 hp. The recoil does not decrease as a result of this and may even increase.

84. However, in our case acceleration due to reaction will be more than 2.27 m/sec^2. Indeed, we assume that the weight of the equipped airplane is 24 tons, and that the horsepower of the engine is 10,000 metric hp, while the power produced by the burning of the fuel is 40,000. The thrust will be 9.08 tons. Therefore, the acceleration of a mass of 24 tons will be equal to the acceleration due to Earth's gravity, multiplied by the ratio (9.08:24), i.e., by 0.38. We obtain approximately 3.8 m/sec^2 and not 2.27. However, this calculation is made under the assumption that the velocity of the stratoplane does not exceed 1,000 m/sec. Now we present equations which are more accurate and which are applicable for the cosmic velocities of the projectile.

85. We compute the reactive action of the exhaust gases in the following manner. Let us assume that an incident particle of air containing oxygen and nitrogen is stopped by the projectile. Its reactive action will be detrimental, negative, and equal to mc, where m designates the mass of the exhaust gas per sec and where c is the velocity of the projectile.

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[1]Sections 72-82 are missing in the manuscript. - Editor's Note.

86. Then we may impart some velocity x in the opposite direction to the ejected material by using the energy of stoppage $mc^2/2$ and the chemical energy of combustion, whose relative velocity is w and whose energy is $mw^2/2$.

87. We determine this velocity from the equation

$$\frac{mc^2}{2}+\frac{mw^2}{2}=\frac{mx^2}{2}.$$

From this we find

$$x=\sqrt{c^2+w^2}.$$

88. The useful reaction will be

$$m\sqrt{c^2+w^2}.$$

89. The total reaction of the ejected matter will be /302

$$-mc+m\sqrt{c^2+w^2}.$$

Here we have not considered the fact that the fuel is carried in the projectile and is not taken from the atmosphere. This situation produces only a positive effect, because it increases the recoil. In addition, the mass of the fuel is small compared with the mass of the exhaust gases. The weight of the gasoline comprises 1/15 of the ejected matter, while the hydrogen comprises 1/30. This means that the error will be quite insignificant. Also, by using the equation we obtain a smaller reaction compared with its real value.

90. From the well-known laws we may write

$$Mj=-mc+m\sqrt{c^2+w^2}.$$

By means of this equation we may determine the acceleration of the projectile with mass equal to M.

91. We obtain

$$j=\frac{m}{M}(\sqrt{c^2+w^2}-c).$$

92. During the initial motion of the stratoplane the velocity c is insignificant. Therefore, we may simplify equation (91)

$$j=\frac{m}{M}\left[w\left(1+\frac{c^2}{2w^2}\right)-c\right].$$

94. When the velocity of the projectile is less than 500 m/sec, we may even use the equation j = m (w-c)/M and equation j = mw/M. In general we can see from equation (92) that when the velocity of the projectile is smaller, the value of j given by equation (94) is more accurate.

95. If, on the other hand, c is large compared with the velocity of the exhaust gases, then we may write

$$j=\frac{m}{M}\left[c\left(1+\frac{w^2}{2c^2}\right)-c\right]=\frac{m}{M}\left(\frac{w^2}{2c}\right).$$

98. We may use the exact equation (91) directly, expressing it in the form

$$j=\frac{m}{M}\left(c\sqrt{1+\frac{w^2}{c^2}}-1\right).$$

99. Let us assume for gasoline and air m = 42 kg per 40,000 metric hp; M = 24,000 kg; w = 2,000 m/sec. We obtain

$$j=0.00175\left(c\sqrt{1+\frac{2000^2}{c^2}}-1\right).$$

100. By making use of these equations we prepare the table: /303

c, km	0	0.5	1	2	3	4	6	8	10	12
j, m/sec^2 =	3.50	3.73	2.16	1.45	1.05	0.826	0.567	0.430	0.346	0.289

Elongation of the Frame

103. Let us consider the design for a stratoplane. In my work "Pressure" of 1930 I showed that if the velocity of any projectile in the air becomes great, no matter how correct its shape is, a time is reached when the air in front of the device is compressed by a large factor and the projectile appears to press against the wall. Further motion becomes impossible.

Motion is possible and is economical when the compression of the medium in front of the nose is insignificant.

In the same article I showed that for a sphere this phenomenon occurs at a velocity which exceeds 300 m/sec.

104. When the body has a smooth shape with any elongation,[1] there will be a limiting velocity which cannot be exceeded. Otherwise, we will hit a wall produced by the strong compression of the medium.

In this case the increase in the temperature of the compressed gas may reach many thousands of degrees, which is entirely unsuitable for the projectile.

105. On the basis of my article referred to above, we prepare a table showing the elongations necessary for different velocities to prevent high compression of the medium and the resulting dangerous overheating.

Below we show the velocities of the stratoplane in km/sec and the corresponding limiting elongations.

Velocity, km/sec	0.5	1	1.5	2	3	4	5	6	7	8	9	10
Elongation	2.5	5	7.5	10	15	20	25	30	35	40	45	50

These elongations may be larger but in no case must they be smaller. Therefore, for example, if our rocketplane is to achieve a velocity of 500 m/sec, the elongation of its proper shape must not be less than

[1]The ratio of the length to the maximum diameter. - Editor's Remark.

2.5. If, on the other hand, we desire to fly with a velocity of 10 km/sec, its elongation must be greater than 50. Thus, when the diameter of the projectile is 2 m, its length must be 100 m.

Thickness of the Wings

106. Although we anticipate small wings, they also must satisfy certain conditions to prevent formation of the air "wall" and its dangerous overheating.

On the average, the wings must be plane and their thickness, or the ratio of the maximum thickness to the depth, must be twice as small as the elongation of the projectile's frame. We present a table. /304

Velocity	0.5	1	1.5	2	3	4	5	6	7	8	9	10
Relative thickness	$\frac{1}{5}$	$\frac{1}{10}$	$\frac{1}{15}$	$\frac{1}{20}$	$\frac{1}{30}$	$\frac{1}{40}$	$\frac{1}{50}$	$\frac{1}{60}$	$\frac{1}{70}$	$\frac{1}{80}$	$\frac{1}{90}$	$\frac{1}{100}$

It would be better to make them thinner.

107. This condition will correct itself, since the length of the projectile becomes greater as the velocity increases. When its length is great, the depth of the wings may be larger and their relative thickness may be less at the maximum height of the profile.

Thus, if we hope to achieve a velocity of 2 km/sec, the elongation of the frame will be 10 and its length will be 20 m, when its diameter is 2 m. If the depth of the wings is 1/4 of the length of the frame, this will be 5 m, while the thickness will be 20 times less, i.e., 0.25 m or 25 cm.

The auxiliary braces and struts may be left out because of the small span of the wings. If they do exist, the form of their transverse cross section must satisfy the same condition as the wings. The section of the rudders must also satisfy the same law.

Shape of the Projectile. Rudders

108. In view of the fact that sufficient elongation eliminates the compression of the medium, the shape of the frame at the stern part of the projectile must also be smooth like that of a bird, fish or ship. We have seen that we require a special propeller contained within a case or a closed longitudinal enclosure. This enclosure also has the form of a bird, although its ends are more or less open. It is inconvenient to place it in a second frame, because the latter would have to be too large. Therefore we place the case with the propeller between

two bodies of the same shape. These contain the people, fuel, and various other equipment. All of the three frames are identical and are parallel. They are joined at their edges and are attached to the short wings.

This arrangement increases the lift force of the projectile and produces a very small increase in the drag.

The two side frames are hermetically sealed and do not permit the escape of gas, even when the external pressure is lowered.

The one or two direction rudders are situated to the rear over the frame. The rudders for altitude control are also behind, but are on the sides. There are two of them. They also serve to control lateral stability. There is a similar system of small rudders placed in front of the rear opening of the middle frame from which the gases are /305
ejected, i.e., air and products of combustion. This system is operational in the vacuum or in a highly rarefied medium. As a matter of fact, it is also functional in the air. Initially we can dispense with the second system.

Dimensions, Areas, Surfaces, and Volumes

109. It is necessary to take the smallest possible dimensions. For the initial experiments, which will probably be unsuccessful, this is particularly important.

The limiting diameter of the cross section of each frame must not be less than 1 m. On the other hand, initially it is not necessary to have this dimension greater than 2 m. In the first case, man may fit himself into the projectile and control it in a sitting position. In the second case, the tallest pilot will be able to stand up and move freely in this position.

Later we shall present a table for dimensions, values, and surfaces based on the following approximate equations which pertain to one of the frames.

110. The volume $V = (\pi D^2/4)l\ 0.5$ where D is the maximum diameter, while l is the length of the frame.

111. Since $l = \lambda D$, where λ is the elongation of the frame, we find from (110)

$$V = \frac{\pi}{8} D^3 \lambda.$$

112. The surface of one frame will be

$$S_0 = \pi D l 0{,}75 = 0{,}75 \pi \lambda D^2.$$

113. The area of the maximum cross section will be

$$S = 0{,}25\ \pi D^2.$$

114. The same longitudinal area along the long axis of the frame will be

$$S_1 = 0{,}75\ \lambda D^2.$$

115. Let us assume that the elongation of the frame is equal to 5. Then, for a projectile velocity less than 1 km/sec, we obtain the following table:

D	1.0	1.2	1.4	1.6	1.8	2.0	
l	5	6	7	8	9	10	
S	0.785	1.131	1.529	2.011	2.545	3.142	
S_1	3.75	5.40	7.35	9.60	12.15	15.00	
S_0	11.78	16.97	22.94	30.17	38.18	47.13	
V	1.96	3.39	5.38	8.03	11.4	15.7	
3 S	2.355	3.394	4.587	6.033	7.635	9.426	/306
3 S_1	11.25	16.20	22.05	28.80	36.45	45.00	
3 S_0	35.34	50.91	68.82	90.51	114.54	141.39	
2 V	3.92	6.78	10.76	16.06	22.8	31.4	
$\frac{2}{3}$ V	1.30	2.26	3.59	5.35	7.60	10.47	

(Continued)

D	1.0	1.2	1.4	1.6	1.8	2.0

For velocities of the projectile less than 2 km/sec, when $\lambda = 10$

l	10	12	14	16	18	20
S_1	7.50	10.8	14.7	19.2	24.3	30.0
S_0	23.6	34.0	45.9	60.3	76.4	94.3
V	3.92	6.78	10.76	16.06	22.8	31.4
$3\ S_1$	22.5	32.4	44.1	57.6	72.9	90.0
$3\ S_0$	70.8	102.0	137.7	180.9	229.2	282.9
2 V	7.84	13.56	21.52	32.12	45.6	62.8
$\frac{2}{3}$ V	2.61	4.52	7.17	10.71	15.2	20.9

We shall limit ourselves to these tables, since they are easy to prepare for high velocities and large elongations.

Limiting Supply of Fuel, Engine

116. We use the volume of the two side frames to store the fuel and the equipment, and to house the people. If we assume that the volumes of the first, second, and third cases are the same, we can see from the above table that this third of the volume is 1.3 to 20.9 m3. If we assume that the fuel density is 0.5, we find that we can store from 0.65 to 10.45 tons of it. The weight of the equipment and of the instruments would be approximately the same, and we could have from 1 to 20 people.

Compartment for the Engine

117. The engine is placed in the central part of the propeller case, close to the longitudinal axis of the case which is always open and air-cooled.

Engine /307

118. At the present time explosive engines are most suitable for our purpose because they are the lightest. However, there are many types. We select one having the following characteristics:

(1) with air-cooling in order to achieve economy in weight;

(2) with the smallest possible operating cylinders to produce the best cooling and maximum energy;

(3) a star arrangement of cylinders to produce the best cooling and economy of mass for the cranks;

(4) with 4-cycle operation, for simplicity;

(5) without rotation with a movable axis;

(6) with a compressor so that we can fly into rarefied layers of the atmosphere and increase the energy and power of the engines as we gain altitude;

(7) without mufflers, but rather with the freest exit of gases from the cylinders, so that we can more conveniently use the reaction of the exhaust.

Fuel

119. For our fuel we select the lightest gasoline or liquid hydrogen because it mixes readily with air. We also select the highest rpm for the axis of the engine. In addition, we increase the energy and mass of the ejected products of combustion (the reactive action of the exhaust). Perhaps initially it will be necessary to use a mixture of gasoline and hydrogen.

120. The energy contained in 1 ton of gasoline is equal to 4,922,000 ton-meters. The energy of a metric hp per hour (100 kgm/sec) will be 360 ton-meters. The minimum specific quantity of gasoline per metric hp per will be

$$360:4,922,000 = 0.0000732 \text{ tons} = 0.0732 \text{ kg}.$$

In practice we shall require 0.25 kg per hour for 1 metric hp. The utilization efficiency of the heat will be 0.0732:0.23 = 0.293, i.e., approximately 29 percent. However, our projectile also uses the exhaust gases since, when these are expanded and cooled, they produce high velocity and large reactive pressure. Part of their energy is transformed into the motion of the projectile.

121. Liquid hydrogen gives almost three times more energy than gasoline and mixes very quickly with air, and therefore produces a high rpm of the axis and great energy.

Utilizing the Oxygen of the Air

122. To simplify the problem, we use the oxygen of the atmosphere. Pure stored oxygen tends to overload our airplane, particularly in relation to the mass of hydrogen. The required supply of oxygen is eight times greater than that of hydrogen.

123. For 1,000 metric hp we require 0.75 m^3 of air per sec (when the density is equal to 0.0013).

Maximum Power /308

124. What is the hp rating of an engine which we can place into the propeller tube or into the middle frame of the projectile? The volume of the middle frame varies from 2-16 m^3. However, the engine can only occupy the central part of the tube close to its axis. The volume of this part is not more than 0.25 of the entire volume or 0.5-4 m^3. This will be enough to accommodate an engine of 1,000-8,000 metric hp.

Of course, if we use condensed air, the power produced by the same volume of the engine may increase by a factor of several times.

Excess Pressure and the Thickness of the Shell[1]

129. Excess pressure is necessary to provide rigidity of the shell. At high altitudes it is unavoidable, since atmospheric pressure approaches zero; the air or oxygen is necessary for respiration and therefore must not escape from the shell.

At sea level we may assume that excess pressure is equal to 1/2 atm. The air inside the frame will be 1.5 times denser than outside. During rapid ascent to a high altitude this density must be retained, so that the excess pressure must reach a value of 1.5 atm. It may be decreased only very gradually. If we replace the air with pure oxygen, the excess pressure in the vacuum may approach a value equal to half of the atmospheric pressure. However, the entire flight may end so quickly that it

[1]This Section is identical to Sections 14-16 of Tsiolkovskiy's article "Rocketplane." Therefore we shall retain those statements not contained in the indicated article. - Editor's Remark.

is not worth bothering about decreasing the pressure. Also, when we descend, we must again build up the air pressure so that the frame is not crumbled by atmospheric pressure. In other words, during the initial short flights the internal pressure should remain constant. The excess pressure will increase during ascent, and the design of the shell's thickness must be based on the higher pressure at this time.

When the thickness of the shell is sufficiently great and its waves are longitudinal, it is sufficient for the internal pressure to be equal to 1 atm. Thus, at the sea level the excess pressure will be zero and as the altitude is gained, it will increase and strain the shell, giving it rigidity.

130. Under these conditions when D = 2 m and the factor of safety is equal to 5, our calculations show us tnat the thickness of the shell made of chromium steel must be 1 mm. If it has a corrugated form and is not subjected to excess pressure, it will retain its form quite well. Of course, only part of the shell may be covered with corrugations. Approximately 1/3 of it must remain smooth. This is the part that will have doors and windows.

131. 1 m^2 of this shell will weigh approximately 8 kg.

The average thickness of the case holding the propeller will also be 1 mm.

132. For small dimensions we shall decrease the thickness proportionately, while the factor of safety will remain the same. /309

General Table

133. We can now tabulate the weights of the various parts of the flying projectile when its dimensions vary, its total weight, power fuel supply, number of people in the cabin, etc.

1. D, diameter of maximum cross section of each frame

	1.0	1.2	1.4	1.6	1.8	2.0
2. D^2 =	1.000	1.44	1.96	2.56	3.24	4.00
3. D^3 =	1.000	1.728	2.744	4.096	5.832	8.000

4. Thickness of shell in mm

	0.5	0.6	0.7	0.8	0.9	1.0

5. Weight of 1 m^2 when specific weight is 8 kg

4.0	4.8	5.6	6.4	7.2	8.0

6. Weight of 3 frames

0.142	0.246	0.389	0.582	0.828	1.136

7. Weight of wings, rudders, braces, etc. (0.5 of the frames' weight)

0.071	0.123	0.195	0.291	0.414	0.568

8. Weight of 3 frames with wings, etc.

0.213	0.368	0.584	0.873	1.242	1.704

9. Volume occupied by engine in propeller tube

0.245	0.424	0.671	1.004	1.428	1.960

10. Power of engine

245	424	671	1,004	1,428	1,960

11. Weight of engine in tons

0.245	0.424	0.671	1.004	1.428	1.960

12. Number of people in projectile

1	2	3	4	6	8

13. Weight of people with baggage and equipment

0.200	0.346	0.548	0.820	1.166	1.600

14. Weight of fuel

0.650	1.124	1.781	2.665	3.790	5.200

15. Total weight of projectile

1.308	2.263	3.584	5.363	7.626	10.464

16. Horizontal projection of projectile /310

11.25	16.20	22.05	28.80	36.45	45.00

17. Same, with wings

25	36	49	64	81	100

18. Load per m^2 of projection in kg

52	63	73	84	95	105

19. Number of metric hp for 1 m^2 of projection

9.8	11.8	13.7	15.7	17.6	19.6

(Here we do not consider reaction of exhaust gases)

2 Weight of gasoline for 1 hour operation; for 1 metric hp we obtain 0.25 kg

0.0613	0.108	0.168	0.251	0.357	0.490

21. This will be enough for 10.6 hours of accelerated flight

22. Approximate volume occupied in two frames by air or oxygen

2.6	4.52	7.18	10.70	15.20	20.94

23. Amount of air allocated to each person

2.6	2.26	2.39	3.57	2.53	2.62

134. We do not assume any conditions which cannot be realized today. The horsepower of the motor is not excessive: from 245-1,960 metric hp. To permit free travel in the frame it is sufficient to have dimension of 1.8 m and therefore 1,000-1,400 metric hp. We do not take into account the reactive work done by the exhaust gases; this is usually neglected, although at high velocities it may even exceed the work done by the engine.

135. The acceleration as a function of the ejection velocity v produced by the propeller and the rarefaction of the atmosphere p is expressed by the equation (58). From equation (71) or from the approximate equation $j = Lg/Gc$ we find the acceleration as the function of the work performed by the motor L.

The latter equation is applicable when the projectile has traveled over the solid or liquid runway and has achieved a velocity of approximately 100 m/sec.

136. The acceleration and the reaction of exhaust gases is given by equation (91) or by the identical equation (98).

137. As we see, both accelerations are applicable. The total acceleration will be

$$j_p = \frac{gL}{Gc} + \frac{m}{M}\left(c\sqrt{H\frac{w^2}{c^2} - 1}\right).$$

138. From the General Table for D = 1.8 we find L = 142.8 ton- /311
meters and G = 7.63 tons. Also we know from "Reactive Airplane" that

m = 0.0015 and w = 2,000 m/sec.

Let us further assume that c = 100 m/sec. Now, by means of (137) we compute j_p = 2.248.

139. For c, which is less than 1,000 m/sec and greater than 100 m/sec, we may use the following equation instead of (137)

$$j_p = \frac{gL}{Gc} + \frac{m}{M}w.$$

140. From this equation we see that the first term, which depends on the propeller, decreases very rapidly as c increases, while the second term, which depends on the reaction, remains constant. On the basis of (139) we prepare the following table

c =	100	200	300	400	500
j_p =	2.248	1.310	0.998	0.842	0.748

141. Beyond this point the acceleration will decrease even more, so that it will be insufficient for operation in the medium with gravity even at small velocities during inclined motion. According to Table 140, we use only 1/7 of the weight of the equipped airplane for the engine. We could make the engine heavier, but there is another solution. By compressing the air which is fed to the operating cylinders and by increasing the rpm, we may increase the power of the engine and the mass of the ejected gases. For example, let us increase the mass of the burning gasoline (or hydrogen) by a factor of 6 and the power of the engine by a factor of 2. Then the first term will increase by a factor of 2, and the second term will increase by the factor of 6.

In this case instead of Table 140 we obtain

c =	100	200	300	400	500	600	700
j_p =	5.99	4.11	3.49	3.17	2.99	2.36	2.77

142. At high velocities the first term of equation (139) becomes very small, and only reactive action remains. At high velocities it is expressed by equation (95)

$$j = \frac{m}{M} \frac{w^2}{2c}.$$

Let us assume, for example, that $m = 0.009$; $M = 7.63$; $w = 2{,}000$; $c = 8{,}000$. Then $j = 0.305$. This means that the acceleration due to reaction at cosmic velocities is very small. However, it may be sufficient, because at high velocities the centrifugal force decreases the weight /312 of the projectile, eliminates or even exceeds it.

143. As the fuel is consumed, the mass of the projectile decreases causing an increase in acceleration j. Finally, as the velocity c of the projectile increases, we may compress the air which enters the operating cylinder more and more, and thus increase the velocity of the projectile. Of course, there are practical limits to this.

Part of this article, specifically Sections 1-39, was published as a separate brochure at Kaluga in 1932. This part was also contained in "Selected Works," Part II, 1934. The remaining part of the article is published from the manuscript dated 1931.

N 65-36889

REACTIVE MOTION

/313

(1932)

Reactive motion is the one which is produced by the recoil of firearms.

It would seem strange that this clumsy force, which pushes back the cannon when it is fired, would be considered as a form of propulsion in the rarefied layers of the atmosphere (in the stratosphere) as well as for very high-speed travel between the planets and the stars.

I have shown that an explosive may be used to impart any velocity to a device in which it is exploded.

When the weight of an equipped rocket increases in geometric progression, the velocity of the rocket also increases without a limit, but in the arithmetic progression.

The true terminal velocity of the projectile depends on the velocity of the gases ejected from the nozzle and on the quantity of fuel supply (for example, gun powder).

Experiments conducted by Goddard and others show that the velocity of the gases ejected from the nozzle may reach a value of 3 or more km/sec. Theory shows that in the vacuum, when we have a sufficiently long conic tube and use the most powerful explosives, this velocity may reach a value of 5-6 km/sec.

The velocity of a rocket having a value of 8 km/sec is sufficient to escape permanently from the atmosphere of Earth and to orbit around Earth as a satellite. A velocity of 12 km/sec is sufficient to become a small planet along Earth's orbit. Finally, a velocity of 16 km/sec may be enough to overcome the attractive force of all the planets and the sun. Then the projectile will move away permanently from our solar system and will fly in the Milky Way (in the Galaxy) among other stars and planets. This will take place when the supply of explosives exceeds the weight of the rocket by only a factor of 15.

The question is whether such supplies of fuel are feasible. Even in the record-breaking airplanes the mass of fuel does not exceed the weight of the device.

The following conditions must be satisfied, if the weight of fuel and oxygen is 15 times greater than the weight of the rocket:

1. The elements of explosion (petroleum and oxygen) must not produce pressure on the vessels which contain them.

2. They must be dense, so that they do not occupy too much space. In this respect liquid hydrogen is not suitable, because it is 14 times lighter than water. /314

3. The acceleration of the projectile must not be more than 10 m/sec^2, otherwise the relative gravity produced by the explosion will make it necessary for all parts of the projectile to be strong and massive. For this reason it is desirable to have the projectile move along an inclined path.

Conditions for safety, light weight, and proper operation of the rocket consist of the following:

1. The elements of explosion must be separate and combined gradually to produce the reactive pressure.

2. We must use a conic tube such that batches of explosives mix and explode in its narrow section.

3. We must use piston pumps to pump the explosives.

4. We must use periodic pumping. This consists of a series of idle firings, which take place 50-100 per sec. After each firing the nozzle is freed of the gases, so that a very small force is required to force a new charge into it. If we needed continuous explosion (combustion), the pumps and the prime mover for the pumps would have to be very powerful.

Flight in the rarefied atmosphere (stratosphere) and then in the vacuum requires the following means for preserving the life of the pilot and the passengers:

1. A hermetically sealed frame similar to the one used by Piccard (he ascended to an altitude of 16 km, where the air was 6 times thinner than at sea level).

2. The compartment must be supplied with oxygen. The daily supply of oxygen per man does not exceed 1 kg.

3. Alkalies and other substances for absorbing the products exhaled and secreted by man.

4. Food supply. For prolonged stay outside the atmosphere we can use specially selected plants which provide oxygen and food. To do this we must have transparent windows and solar light. Solar light is sufficient, since there are no clouds or fog or air beyond the atmosphere.

5. We must control the internal temperature of the rocket by varying the amount of solar light absorbed by the surface of the projectile. In addition to the strong, impermeable shell of the device, a second shell must be placed on it which has the form of fish scales and can be adjusted to produce a shiny or black surface on the exterior of the projectile.

6. Protective cooling of the surface of the frame against heat during flight through the atmosphere. For this purpose we also use a shiny movable scale.

Cosmic velocities (8-16 km/sec) are impossible in the lower layers /315
of the atmosphere, because they are immediately lost due to the tremendous resistance of the atmosphere.

However, the reactive device achieves cosmic velocity gradually. It is very advantageous to have an inclined, ascending accelerated flight. In this case flat wings are useful. In the lower layers of the atmosphere the velocity is small, while in the rarefied medium it achieves a value of 1-2 km/sec. However, at these altitudes the high velocity does not encounter great resistance, because the air is extremely thin. Furthermore, this velocity does not produce great heating of the projectile's surface, because the air is very thin and cold. To protect the rocket from excessive heating, apparently it is sufficient to have one heat-insulating layer, for example, powder or cork. The second shell is particularly suitable due to its lightness.

We give a schematic drawing of this device in its simplest form, indicating various components (Fig. 1).

1. Plane wings. With small span they will not be heavy, and even though their length along the projectile may be considerable, they will not be very thick. At low velocities they will not operate too well, but they will become more effective as the velocity increases. Their form must be almost flat.

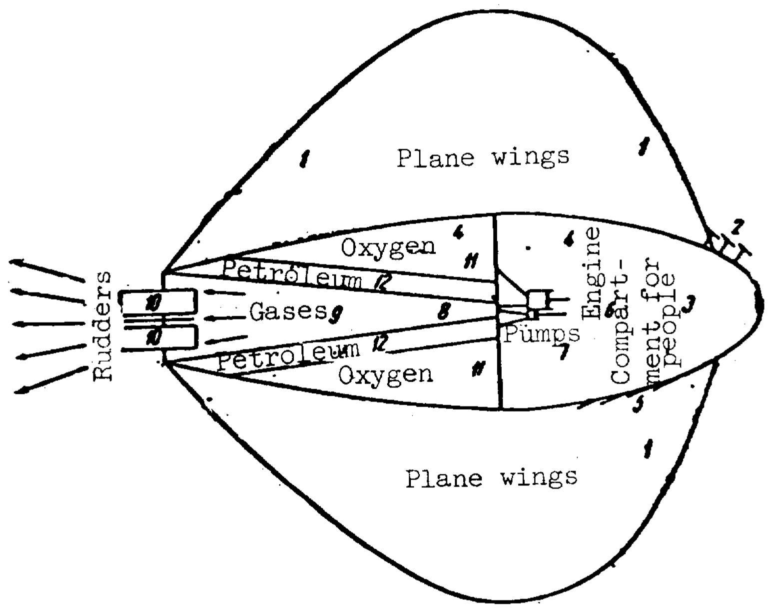


Figure 1

2. A part of the movable, shiny scale. When the scale assumes a position normal to the surface of the rocket, it exposes a black surface of the projectile, and the temperature will be lower. If, on the other hand, it is parallel to the frame, the heat loss will be less and the temperature will be higher. To obtain a high temperature, the parts of windows facing the solar light must not be covered by the scale. /316
During flight through the atmosphere the scale must be closed, and it is then impossible to control the temperature (Fig. 2).

3. A compartment for people.

4. A hermetically sealed rocket frame which can withstand the pressure of at least 1 atm.

5. Therefore, it is convenient to have a movable scale (like a fan). /31

6. A place for a small engine.

7. Pumps for pumping oxygen and oil.

8. A place to mix the elements of explosion (carburetor).

9. A conic tube. The expanded and cold gases are ejected from the opening with a relative velocity of 3-6 km/sec. This velocity is constant for each device.

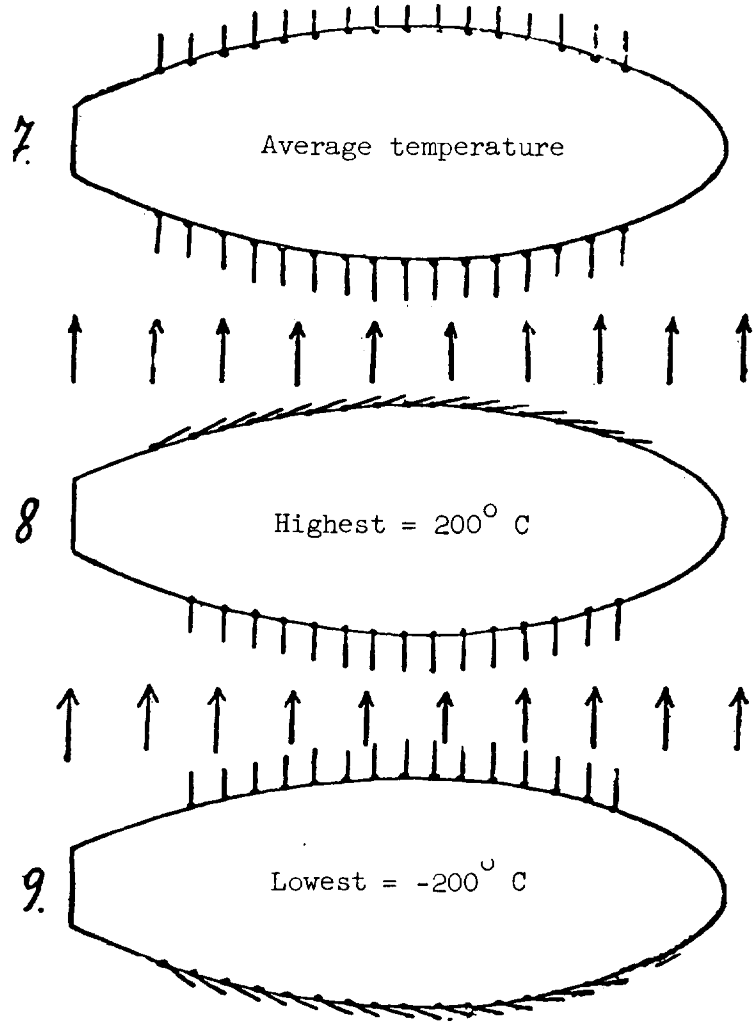


Figure 2. Drawing from the manuscript of K. E. Tsiolkovskiy's "Album for Cosmic Travels"

10. There are two vertical and two horizontal rudders. These are rudders for controlling direction and stability. The rudders operate in vacuum due to the stream of ejected products of combustion.

11. Liquid oxygen.

12. Petroleum.

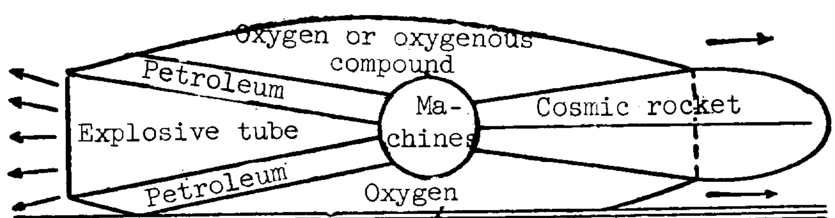
The construction of such a purely reactive device is extremely simple: an impermeable, extremely elongated surface with a cover which produces thermal insulation and regulates the temperature; a conic tube with a carburetor where liquid oxygen and petroleum are mixed; the tube is cooled by petroleum, while the heated petroleum is cooled by oxygen; special tanks are eliminated (we have only partitions); two tiny pumps, and a very weak engine (Fig. 3).

The virtue of this device is its extreme simplicity and lightness. Its disadvantage is that it must carry oxygen with it.

Initially, the flight of the device may be limited to the lower layers of the atmosphere (stratosphere), then it can fly beyond the atmosphere, and finally it can undertake cosmic flights. /318

Return to Earth, as shown by me and Homann, may be carried out without expending any explosives: first we shall have spiral motion in the thin layers of the atmosphere, then, in the denser regions, a gradual decrease in cosmic velocity, and finally we shall glide down to descend to the ground or water like the conventional airplane (Fig. 4).

3. <u>Earth rocket containing cosmic rockets.</u>
Velocity of earth rocket 20 times greater than that of the Earth's gravitation, i.e., 200 m can be tolerated by man only in water.



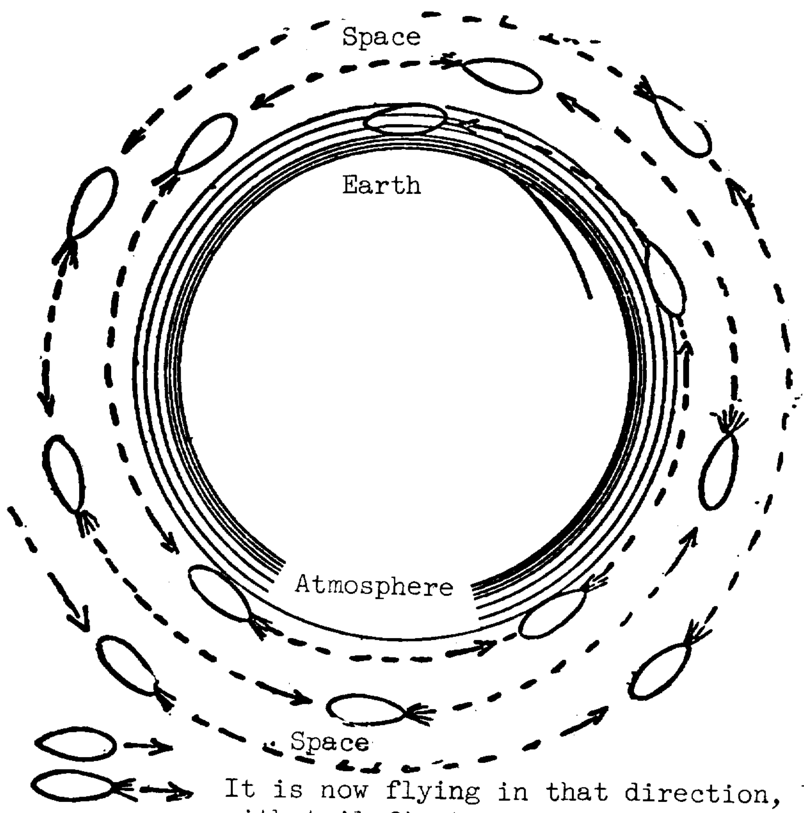
Earth rocket elevation in mountains. Km

Seconds	1	2	3	4	5	10	15	20	25	30
Velocity	0.2	0.4	0.6	0.8	1	2	3	4	5	6
Path	0.1	0.4	0.9	1.6	2.5	10	22.5	40	62.5	90
Altitude	0.01	0.04	0.09	0.16	0.25	1	2.25	4	6.25	9
Rarefaction						1.11		1.53	2	2.45

Altitude 10 15 20 25 30 35 40 45 50 55 60 65 70 75
Rarefaction 1,72 3,12 6,10 14,4 35,7 80,6 190,5 430,4 2519 13720 48700

Figure 3. Drawing showing the earth's (auxiliary) rocket with a cosmic rocket contained within it. (From the "Album of Cosmic Travels.") The drawings and inscriptions were made by K. E. Tsiolkovskiy

48. Food and oxygen supplies spent. Plan of return to Earth. Rocket turned nose last, and retroblast begun.



It is now flying in that direction, but with tail first, where gases are exploding

49. Landing on Earth. Meeting.

Figure 4. Sketch from the manuscript of K. E. Tsiolkovskiy's "Album of Cosmic Travels"

These purely reactive devices are extremely promising. Why is it that the results obtained in Europe and in America have given us so little? The most successful flight of a rocket, built by Ridel (1931) near Berlin, achieved an altitude of only 1.5 km. The other practical results are even worse. /319

The Goddard and Swan rockets with wings also produced insignificant results. For example, the reactive glider of Swan which weighed 80 kg ascended to an altitude of only 60 m.

These poor results are due partially to inadequate funds and partially to errors made by the investigators. I have already pointed out these errors in my book "To the Astronauts."

However, from the standpoint of achieving very high velocities, high-altitude airplanes or stratoplanes are of interest in addition to the rocket. These are conventional airplanes which are equipped with:

1. Unusually light and powerful engines;

2. a compressor of air;

3. a propeller with sharply inclined blades;

4. multiple coolers and radiators.

The flight of such a stratoplane is possible only in the atmosphere. Their construction is very complicated, and their mass is necessarily high.

According to my calculations ("Airplane," 1895), which have been confirmed by the most recent investigations (for example, by Corvin-Krukovskiy, see the book by Rynin "Super Aviation and Super Artillery," 1929, pp. 51-53), it follows that the velocity of the stratoplanes, when other conditions are equal, is proportional to the square root of the rarefaction of the medium, and the power must increase proportionately to the velocity of flight.

Therefore, to double the velocity, it is necessary to increase the power of the engine by a factor of 2, which produces an increase in weight, or to make the engine twice as light for the same power. The latter is the only solution. Perhaps in time engines will be designed weighing 200 g per hp. Then the forward horizontal velocity will be increased by a factor of 5. If, for example, for engines of conventional weight it reaches a value of 200 m/sec (720 km/hour), for lighter ones it will then be 1,000 m/sec (3,600 km/hour).

With airplanes of this type it will be possible to fly over the Atlantic Ocean in 2-3 hours. This will have to be done at a high altitude where the air is 25 times thinner than at sea level.

It is reported in journals that the well-known builder Farman is quite occupied with high-altitude airplanes. He hopes that at an altitude of 6 km the velocity of the stratoplane will double, while at an altitude of 12 km it will increase by a factor of 4. At an altitude of 6 km the atmosphere is rarefied by a factor of 2, while at an altitude of 12 km it is rarefied by a factor of 4. Consequently, in the latter case the velocity may only double compared with the record velocity, and it can do this only if the specific weight of the motor is reduced by a factor of 2, or its power is increased by a factor of 2. However, doubling of the velocity is difficult to expect, due to the complexity of the airplane and the associated increase in its weight. /320

It has been reported that in England, in 1932, a flight across the Atlantic Ocean is expected, at an altitude of 16 km with a velocity of 1,250 km/hour (347 m/sec). At an altitude of 16 km the air is rarefied by a factor of 6. This means that the velocity may be increased by a factor of 2.5. However, in this case, too, if the weight of the engine is to remain the same, it must deliver 2.5 times more power. If the record velocity for long distance flight is 100 m/sec (360 km/hour), it will be possible to achieve a velocity of 250 m/sec and not 347 m/sec. Consequently, this, too, is still a dream. We do not take into account here the increase in the weight of the airplane due to various complications associated with the rarefied atmosphere. However, there is no doubt that all these things are possible.

In my work "Semireactive Stratoplane" I propose semireactive stratoplanes. They are also quite complicated, but will achieve the required success much faster than airplanes, although they will never reach cosmic velocities.

Astronautics is only a goal, and a rather remote one. It is very attractive if we remember the possibility of using solar energy, which is 2,000 million times greater than that received by our planet.

Before achieving this goal we must go through a series of stages. The first stage is to perfect the conventional airplane and to double or triple its velocity at an altitude of 12-18 km, where the air is 4-9 times thinner. Then we shall obtain a velocity of 200-300 m/sec. Flight across the Atlantic Ocean will be reduced to 8-10 hours (see my "New Airplane," 1929). After this, a semireactive stratoplane will appear. Its velocity may be much higher, for example, up to 1,000 m/sec. It will fly at an altitude of 23-24 km, where the atmosphere is 100 times thinner than at the surface of the ocean. Flight from America to Europe will last from 2-3 hours.

However, there will be no economic advantage. Theory shows that for one unit of traveled path the fuel consumption is the same. Furthermore, such devices are very complicated and expensive. Therefore, the fare will be extremely high. However, the time of travel would be reduced when an altitude of 24 km is reached.

However, this will not be a complete conquest of the stratosphere. A purely reactive device, due to its extreme simplicity and its supply of oxygen, permits even higher penetration. It is difficult to predict what maximum velocity will be attained in practice. However, when the velocity is greater than 1 km/sec, centrifugal force will begin to show its influence and will lighten the rocket. If the velocity reaches 8 km/sec, the projectile will lose all of its weight and will be carried away beyond the limits of the atmosphere. This is when Earth's atmosphere will be conquered and Earth's gravity overcome. Then the rocket during its spiral ascent will fly through the vacuum like a small moon close to Earth. /321

However, it is doubtful that we can expect the achievement of the first cosmic velocity without some auxiliary means.

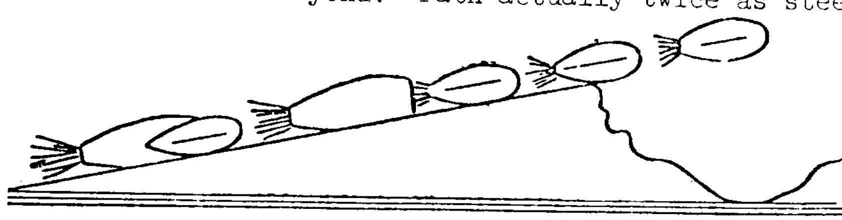
The auxiliary means consist of the following:

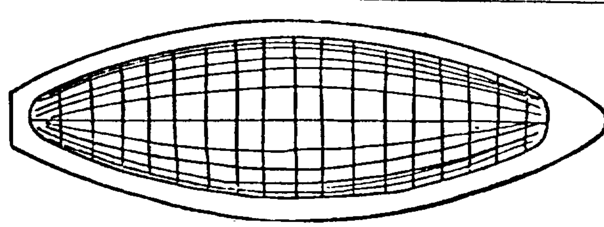
1. Preliminary acceleration of the rocket along a specially designed, solid, ascending path (Fig. 5) where the rocket does not expend its fuel, but uses the energy obtained from special installations situated along the sides of the runway (for example, like a streetcar).

2. A multi-rocket train flying into the atmosphere, where only one of the component rockets achieves a maximum velocity and flies beyond the atmosphere, while the other rockets return to Earth (see my article "Cosmic Rocket Trains," 1929).

3. Transmission of energy to a flying rocket from Earth by means of real or virtual wires (for example, the flux of radiant energy).

5. Earth rocket path in mountains, but cosmic rocket in mountains and beyond. Path actually twice as steep.

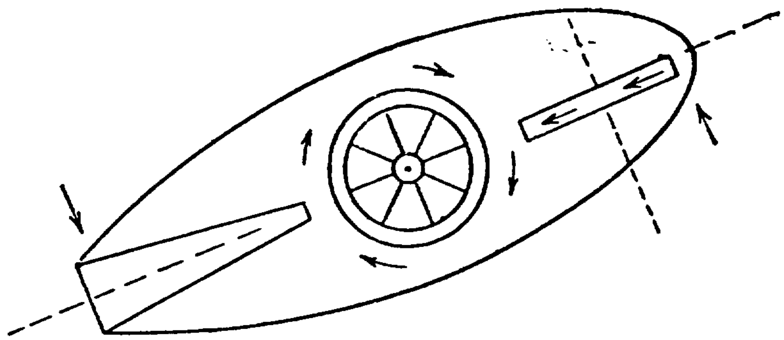




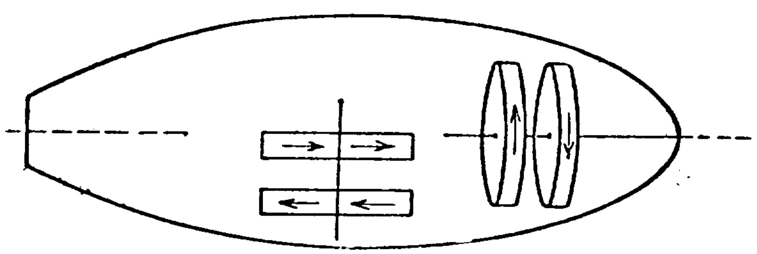
6. Form of the final rocket without fins.

Figure 5. Sketch from the manuscript of K. E. Tsiolkovskiy's "Album of Cosmic Travels"

Swing and rotation of the rocket with rotation of the disk. Direction obtained.



13. Construction of the rocket with its immovability and rapid rotation of two pairs of disks



(Test on water or a pendant.)

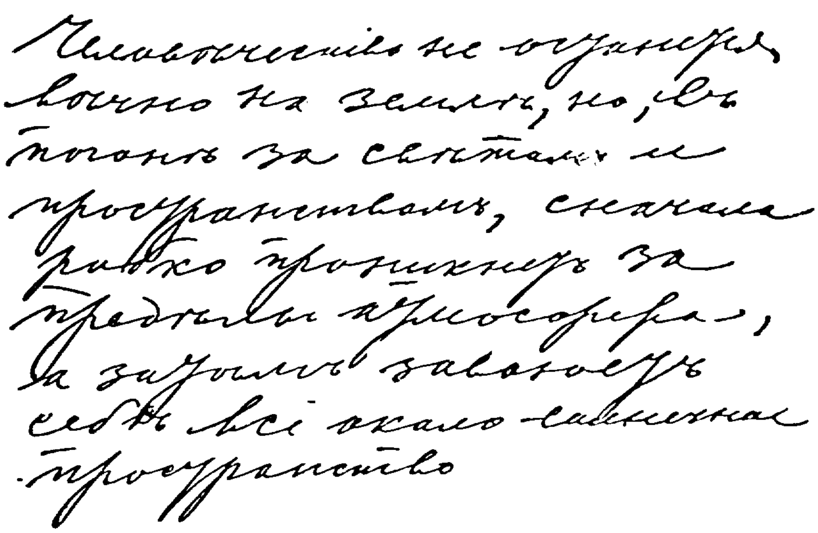
Figure 6. Sketch from the manuscript of K. E. Tsiolkovskiy's "Album of Cosmic Travels"

Having achieved the maximum possible velocity, the rocket continues to increase it by means of its own energy, i.e., by the explosion of its fuel supply.

The benefits to be gained by mankind in overcoming gravity and conquering the solar system are described in my book "The Goals of Astronautics," 1929.

The command of solar energy which now escapes into space does not constitute the conquest of the moon and of the planets. Even descent to the moon for many reasons presents a complex and difficult problem. /323
As far as the large planets are concerned, we cannot even think about this at the present time.

The asteroids are quite accessible, as are heavenly bodies of even smaller dimensions. They will be the first to be reached by astronauts.


Человѣчество не останется
вѣчно на землѣ, но, въ
погонѣ за свѣтомъ и
пространствомъ, сначала
робко проникнетъ за
предѣлы атмосферы,
а затѣмъ завоюетъ
себѣ все околосолнечное
пространство

Inscription on the memorial on the grave of K. E. Tsiolkovskiy at Kaluga. (A facsimile of the letter written by K. E. Tsiolkovskiy to B. N. Vorob'yev, 1911.) (Mankind will not always remain on Earth, but in the pursuit of the sun and space, will first timidly reach the limits of the atmosphere, and then will conquer for himself all the space near the sun.)

When will all this take place?

Not a single wise man can predict the time. Even if we take into account the madly rapid progress in science and technology of our day, apparently we shall have to wait a decade, if not a century.

The rapid growth of progress is an unknown quantity. It is possible that the time will be much shorter, although we feel otherwise.

Published in the journal "V boy za tekhnikum," No. 15-16, August 1932, under the title "The Theory of Reactive Motion." We have retained the title of the manuscript. - Editor's Note.

FUEL FOR THE ROCKET

/324

(1932-1933)

In essence there is no sharp boundary between the processes of explosion and simple combustion. Both represent a more or less rapid chemical reaction. Combustion is slow reaction, while explosion is rapid combustion.

We may regard smoldering, rusting, and slow oxidation or, in general, any slow chemical reaction in the same way. In other words, the difference between all these phenomena is purely quantitative.

We note that the energy of explosives per unit mass is much less than the energy released by one mass of fuel. In the economic sense, combustible materials are more advantageous than explosive materials, because the latter are much more expensive, and it is much more difficult to use them.

At the present time no one knows how to do this economically. All of the experiments with rocket automobiles, hydroplanes, sleds, and gliders are of significance only as study and preparation for the stratoplane and the astroplane.

What then are the advantages of explosives? The advantages are great, but they do not include economy.

Indeed, explosives release a tremendous amount of energy in a very short period of time because the chemical combination of the mixed elements of combustion takes place instantaneously.

Let us assume that 1 kg of carbon is burned every second, while the explosive material burns at a rate of several tons per second. If, as usually happens, volatile products are obtained, they may achieve a velocity of several km per sec. Their energy of motion may be used by a turbine, but a practical solution of this question is not sufficiently advanced. We believe, however, that the future of rocket engines will be quite remarkable.

We base our conclusions on the fact that the volatile products of explosion expand in the artificial or natural vacuum (outside the atmosphere) and convert all of their energy into motion. Therefore, the efficiency of converting heat into motion may be higher than anywhere else. In addition, we have very rapid combustion and a substantial quantity of energy liberated every second.

The energy of explosives is used today for firearms and to destroy solid masses (for example, granite rocks). In a small fraction of a second they impart high velocity to the cannon shell and develop several million hp (on the average). In the same small fraction of a second they produce a tremendous amount of work in shattering stone masses. /325

The rocket devices of direct action (rockets) may also impart tremendous power to projectiles and vehicles, when their velocity is several km per sec. However, this velocity is impossible in the lower layers of the atmosphere because of air resistance. It is only in the rarefied regions of the atmosphere that this velocity and high efficiency is possible.

In conjunction with this, I should like to repudiate the widely held misconception that cosmic velocity is possible in the upper rarefied layers of the atmosphere, if we use the common energy of engines. Back in 1895, in my published works, I found that the power consumed by an engine with constant weight in the optimum rarefied layer is proportional to the velocity of the airplane. For example,

Density of atmosphere. . . .	1	1/4	1/9	1/16	1/25
Velocity	1	2	3	4	5
Required power	1	2	3	4	5

Here the velocity of horizontal flight when we fly over the surface of Earth is assumed to be unity; the power of the engine in this case is also assumed to be unity. If the atmospheric density remains constant, this power is proportional to the cube of the velocity, i.e., this power increases as the ratio of the numbers 1, 8, 27, 64, etc. This was confirmed 35 years later by the American scientist Corvin-Krukovskiy.

The difficulties of flying into the stratosphere are great, but they can be overcome by making use of precisely the monstrous power of combustible substances.

Engines and Explosion

Actually, in any fuel we have continuous combustion-explosion, particularly when we use atomizers. However, in conventional steam engines or turbines this explosion is not used directly. Only the heat obtained in this manner is used. When we have a cheap fuel such as peat or coal, with undesirable impurities, and when we are not concerned about the weight of the machine, this becomes quite economical. However, in the locomotive the fuel is much purer, more expensive, and less economical. There are some efforts to employ explosion engines (benzol and Diesel engines) or electric engines.

Internal combustion engines are another case. Here the force of /326
explosion is used, and these engines should therefore be called explosion engines. Their advantage is that they produce such a tremendous amount of energy and use the fuel so efficiently, that its supply can be quite small. Their disadvantage is that the fuel must be purer and is, consequently, more expensive. In both cases the free oxygen of the atmosphere is used.

Reactive automobiles, hydroplanes, sleds, airplanes, stratoplanes, and astroplanes use stored oxygen with another element required for combustion. The purpose is to obtain a tremendous amount of energy in a very short period of time. Here we have two approaches.

1. The oxygen element or its substitute may be mixed with the fuel beforehand (for example, with gunpowder). Until now only ready-made explosives have been used for flight propulsion of people.

The advantage of this approach is as follows. There is an arbitrarily rapid release of energy and simplicity in the construction of the engine. There are many more disadvantages; specifically, there is danger of the entire supply exploding (the catastrophy of Tilling and others), and overloading of the device by the weight of the oxygen compound or of the liquid oxygen. Another disadvantage is overloading due to the weight of the tubes which are filled with explosives and which sustain a tremendous pressure produced by the escaping, compressed products of combustion (the tube must therefore be strong and heavy) at low velocities in the lower layers of the atmosphere. Others are low efficiency of utilized chemical energy and the high cost of explosives.

2. In the second approach the oxygen compound is separated from the combustible material. The two components are mixed gradually, as in the aircraft engine, except that the oxygen is taken directly from the atmosphere. There is no danger of a total explosion. The overloading produced by the heavy tubes is the same, but the other disadvantages are absent.

Why will it be necessary for us to store oxygen? At very high altitudes, in the extremely rarefied atmosphere or, in general, beyond the atmosphere in the vacuum, we require a supply of oxygen compounds because it is practically impossible to extract oxygen from the atmosphere and in the vacuum oxygen does not exist.

There we can achieve large velocities and high efficiency for the utilization of chemical energy. The disadvantages which remain are as follows: we have overloading due to the weight of the oxygen, and oxygen or its compounds are very expensive. However, the elements of explosion may consist of cheap petroleum (combustible material) and liquid oxygen or its compounds, for example, liquid nitrogen anhydride. This is not so expensive. The separation of the elements of explosion is already achieved in practice in cases of small flying devices (without people). Matters are apparently progressing. However, these devices have their shortcomings which have been pointed out by me in the journal "Samolet" (1932). It is for these reasons that the results are extremely poor.

Selecting the Elements of Explosion /327

Here we presuppose the attainment of very high rarefied layers of the atmosphere, where it is very difficult to extract oxygen.

The elements of explosion for the rocket engine must have the following properties:

1. They must liberate a maximum amount of work per unit of their mass when they burn.

2. During their combination they must produce gases or volatile liquids which turn into vapor by heating.

3. They must generate as low a temperature as possible during the combustion, so that they do not burn or fuse the combustion chamber.

4. They must occupy a small volume, i.e., have as large a density as possible.

5. They must be liquid and easily mixed. The use of powders is very complicated.

6. They may be gaseous, but must have high critical temperature and low critical pressure, so that they can be used in liquefied form. The liquefaction of gases is undesirable in general, due to the low temperature and because they absorb heat when they are heated. Their use is also associated with losses by evaporation and danger of explosion. The expensive, chemically unstable products difficult to obtain are also unsuitable.

We shall present some examples. Hydrogen and nitrogen, for example, satisfy all the conditions except those indicated in Sections 4 and 6. Indeed, liquid hydrogen is 14 times lighter than water (its density is 0.07), and therefore it is inconvenient because it occupies a large volume. Also, the critical temperature of hydrogen is equal to -234°, while that of oxygen is equal to -119°. Carbon by itself is not suitable because of its solid state. Silicon, aluminum, calcium, and other substances are not suitable, not only because they are solids, but because they produce nonvolatile products when they react with oxygen. Ozone is not suitable because it is expensive and chemically unstable. Its boiling temperature is -106° C. Most of the simple and complex bodies are not suitable because they release very little energy per unit mass of their products.

What are the suitable substances? They are those which satisfy the following conditions.

1. Simple or complex substances which do not become liquid under ordinary temperature or under a temperature which is not too low, and whose density is not too far from the density of water. Thus, we can accept the liquefied gases, but only those which have low critical temperatures.

2. Substances which liberate the maximum amount of work per unit of the resulting products. These are certain weakly exogenous compounds and, particularly, endogenous compounds (the latter do not absorb heat during decomposition, but rather liberate heat and therefore are particularly useful). /328

3. Inexpensive and chemically stable substances.

4. Substances which produce volatile products during combustion· gases or vapors.

The most energetic components of an explosion which yield volatile products are hydrogen and oxygen.

When water vapor is formed, 3,233 cal are liberated for each kg. The burning of light metals such as lithium, aluminum, and magnesium is also the same, as well as silicon and boron which give from 3,400-5,100 cal, i.e., substantially more. However, these materials are unsuitable because the products are not volatile.

However, hydrogen and oxygen stored individually are not convenient at the present time. It is best to replace them with their weak compounds with other elements.

Thus, in place of hydrogen, we have hydrogen compounds and in place of oxygen, we have oxygen compounds. The most convenient compounds for burning in oxygen are hydrocarbons. Both hydrogen and carbon, when they unite with oxygen, produce volatile products. Hydrogen, when combined with oxygen, produces more energy per unit mass of the products than carbon. Specifically, hydrogen produces from 3,233 (vapor) to 3,833 cal (water), while carbon produces 2,136 cal. (All subsequent numbers are expressed in terms of small cal per g or per mol of substance.) Therefore, hydrocarbons liberate more energy during combustion when the percentage of hydrogen is higher.

Such are the limiting hydrocarbons. Of these the simplest is methane, CH_4, or marsh gas. It contains the maximum percent of hydrogen (25 percent). However, we must bear in mind that most of these compounds are exogenous, i.e., when they are formed, heat is liberated. When these compounds burn in oxygen they must first be broken down into H_2 and O_2, which causes the inverse absorption of heat. In addition, liquefied methane has a very low boiling temperature (-82° C) and therefore is inconvenient.

However, let us compute its energy of explosion. One part of C requires 2 parts of O_2. In this case every gram molecule (mol) liberates 94,000 cal. Four parts of H require 2 parts of O. In this case for 36 g, 116,000 cal is liberated. For 80 g, a total of 210,000 cal is liberated. However, the initial breakdown of CH_4 requires 18,500 cal for 16 g (mol). This leaves 191,500 cal for 80 g. For 1 g of the products we obtain 2,394 cal.

Among the hydrocarbons there is one which contains a smaller percent of hydrogen (12.2 percent), but which is formed with absorption of heat (endogenous compound). This compound is ethylene (C_2H_4). We find it to be more suitable. Indeed, 2 parts of C require 4 parts of O. For 89 g, the liberated heat is 188,000 cal, and 4 parts of H require 2 parts of O. For 36 g, 116,000 cal is liberated (vapor). This means that for 124 g we get 304,000 cal. However, when C_2H_4 breaks down, the heat absorbed earlier, amounting to 15,400 cal per 28 g (mol), is liberated. We obtain, therefore, a total of 319,400 cal. This is for 124 g. For 1 g of the products we obtain 2,576 cal. This is slightly greater than what we obtained from methane. Ethylene is easily liquefied, because its critical temperature is 10° above 0, while its critical pressure is 52 atm. Ethylene is obtained quite easily from ethyl alcohol or ether by passing the latter through clay bowls heated to 300-400° C. It turns out that ethylene is better than marsh gas (methane). /329

Now let us consider benzol, C_6H_6. Because it is a dense liquid, it is more suitable for a vacuum. However, it contains only 8 percent hydrogen. What is its energy per unit mass of the products when it combines chemically with oxygen? During its formation it liberates only 102,000 cal per mol (gram molecule or 78 g). Nevertheless, let us carry out the calculations. C_6 requires O_2 and H_6 requires O_3. This means that for 318 g of the products a heat of 738,000 cal is liberated. If we subtract from this the absorption of heat caused by the breakdown of C_6H_6, we obtain 727,800 cal. This is for 318 g. For 1 g of the products we obtain 2,289 cal. This is slightly less than what we obtained from ethylene, but we have a liquid at room temperature with very insignificant vapor pressure.

Acetylene, C_2H_2, which has the same percent composition as the gas, is not convenient to use. Also, this is an exogenous compound which liberates a much greater quantity of heat during its formation than benzol, approximately greater by a factor of 18. This means that it absorbs more during combustion. In addition, when the quantity of carbon in the hydrocarbon is increased, the dissociation temperature becomes higher and, consequently, the temperature of combustion becomes higher. The best substance is liquid hydrogen; however, it is difficult to obtain and to store, and it occupies a very large volume.

We present data on the heat of combustion of alcohol, ether, and turpentine.

Methyl alcohol. . . .	CH_4O	2,123 cal
Ethyl alcohol	C_2H_6	2,327 "
Ether	CH_4O_{16}	2,512 "
Turpentine.	$C_{10}H_{16}$	2,527 "

Here we have shown the number of calories liberated per unit of the products of combustion. We can see that we cannot neglect these fuels either.

In our calculations we have assumed a liquefied oxygen. This is highly inconvenient. Ozone, on the other hand, is chemically unstable and unobtainable in practice. Therefore we turn to oxygen compounds.

The oxygen compounds of nitrogen are very interesting. We list those most suitable for our purpose. The endogenous, gaseous compound N_2O

is not suitable, because it contains a very large percent of nitrogen. The same is true of the endogenous compound NO. The third compound, NO_2, is a stable liquid. Its formation (synthesis) is accompanied by insignificant liberation of heat. It is sufficiently stable chemically /330
(up to 500° C) and is very dense (1.49), which makes it quite suitable. It is a strong oxidizer; however, if the reservoir tubes, valves, etc. are plated with gold, platinum, indium, or other noncorrosive substances or alloys, its corrosive action can be controlled.

The fifth compound, nitrogen anhydride, (N_2O_5), contains a slightly smaller amount of nitrogen, but it is inconvenient because of its chemical instability.

Let us consider NO_2. This compound can replace oxygen, but it is overloaded with nitrogen. This decreases the ejection velocity of the products of combustion because their mass is increased. We have considered benzol. Its gram molecule is 78. We have seen that 78 g of this substance requires 240 g of oxygen for complete combustion. The weight of the products when combustion takes place in pure oxygen is equal to 318 g. However, in place of oxygen we have NO_2. Here we have an additional 105 g of nitrogen. Therefore, the products will be 423. This quantity is greater by a factor 423:318 = 1.331. Because of the increase of the mass of the products of combustion, their ejection velocity decreases by a factor 1.15, i.e., it constitutes 87 percent. For example, instead of 6,000 m/sec the velocity will be 5,220 m/sec. The energy of explosion for 1 g of the products will be 1,721 cal.

Perhaps we shall be asked whether nitroglycerin pyroxylin and simpler substances give a larger amount of energy. This is not so. The energy they release is much smaller, as we can see from the following table. The table shows the heat of formation of several substances for 1 g of products in small cal. Let us select the most powerful explosive substances.

Aluminum with ammonium nitrate	1,480	cal
Smoking powder and smokeless powder. . . from 720 to	960	cal
Nitroglycerin powder . . . to	1,195	"
Nitroglycerin	1,475	"
Dinitrobenzene with nitric acid	1,480	"
Picric acid	750	"
Mercury fulminate	350	"

These ready explosives cannot be used because of the danger of sudden explosion of the entire mass, in addition to the fact that their energy is very low.

Summary

1. Hydrogen is unsuitable because of its low density and storage difficulties when in liquid form.

2. Liquefied methane, CH_4, with liquid oxygen produces 2,394 cal and is inconvenient due to the low boiling temperature.

3. Ethylene, C_2H_4, with O_2 produces 2,576 cal.

This mixture is more suitable because ethylene has a critical temperature equal to 10° C.

4. Benzol, C_6H_6, with oxygen produces 2,289 cal. The amount of energy is low, but it is convenient that benzol is a liquid at room temperature. Mixtures of liquid hydrocarbons with a high boiling temperature are also suitable (kerosene and others), particularly because they are inexpensive (petroleum). /331

5. The use of liquid oxygen presents some inconvenience because of difficulties in storing it.

6. The most suitable replacement for oxygen is nitrogen anhydride, NO_2. This is a chemically stable liquid denser than water. When it is mixed with benzol, 1,721 cal are liberated per unit of the products.

These two liquids are most suitable for the rocket. However, the components of the machines must be protected from the oxidizing influence of NO_2. This energy (1,421 cal) is not great, but is larger than the energy of the best gunpowder and of the most dangerous explosives (nitroglycerin). Also, the latter is expensive and dangerous in exploitation.

7. Alcohol and sulfuric ether are also suitable. We present the relationship between the heat of combustion and the corresponding velocity of the products of combustion under ideal conditions, i.e., in a vacuum with very long nozzles:

Heat b in cal	1,000	1,500	2,000	2,500	3,000
Ejection velocity in m/sec. . .	2,900	3,600	4,200	4,600	5,100

When we use ether we obtain a velocity of 4,630 m/sec. In this last case, when we have horizontal motion along the tracks, or the ground gravity and the resistance of the medium are absent, we obtain the following velocities of the projectile for various ratios of the fuel weight to the weight of the projectile with all its contents except the fuel and the oxygen.

Ratio of the fuel's weight to the weight of the structure. . . .	1	2	3	4	5
Maximum velocity in m/sec. . . .	3,500	5,000	6,500	7,700	8,600
Ratio of the fuel's weight to the weight of the structure. . . .	6	7	8	9	10
Maximum velocity in m/sec. . . .	9,500	10,100	10,700	11,100	11,300

This means that when we have a 5 to 1 ratio, we can become the satellite of Earth, and when we have a 10 to 1 ratio, we can become a satellite of the sun. The projectile will be separated from Earth and will move in the orbit of our planet.

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STEAM-GAS TURBINE ENGINE

/332

(1933-1934)

Introduction

Ships contain the heaviest engines. In railroads these engines are lighter. In automobiles, hydroplanes, sleds, and airships the engines must be even lighter, and finally on high altitude flying machines the engines must be unusual, having high power, low weight, and small volume. The last do not exist today.

The specific weight of the motor is the weight corresponding to 1 metric hp. (1 metric hp is equal to 4/3 of a conventional hp or 100 kgm). The specific weight of the engine in a locomotive is 100 kg, in an automobile it is 4 kg, and in an airplane it is 1 kg.

We should like to have an engine with a specific weight of 0.2 kg or less. The light weight of such an engine makes it possible to use it in flying machines which would have the extremely large power necessary to fly at high altitudes.

The same light weight or even a lighter weight is required for high altitude airplanes or stratoplanes.

The specific volume of the engine is also very important, i.e., the volume which corresponds to one unit of its power. Flying machines have little space, and therefore the portability of the engine is quite necessary. It is understood that an engine of this type need not have boilers and coolers.

Engines using cylinders are also unsuitable, because they are heavy and cannot withstand the high temperatures which are unavoidable for lightweight and high-power engines. The use of cylinders and lubrication must be avoided. Complexity of design must be avoided for the sake of economy.

Light engines must be powered by the oxygen of the atmosphere, since a supply of oxygen carried aboard, particularly its compounds with nitrogen, load down the flying machine. Furthermore, the pure oxygen produces a temperature which is too high and which cannot be endured by the structural materials: alloys of iron, with small quantities of other metals. The fuel must release as much heat as possible and must have maximum density. The first condition is satisfied by hydrogen, while the second is satisfied by the dense products of petroleum. Initially, we shall have to use petroleum, and then it will be necessary to use hydrogen. The principal shortcoming of the latter is its small specific weight, even in liquid form (0.07 of water). /333

My engine consists of four principal parts (see Figure 1): air compressor 1, a small carburetor tank 2, turbine 3, and a pump, shown in the figure, to pump the fuel into the tank. The compressor pumps air into tank 2 under very high pressure. The higher this pressure is compared with the pressure of the surrounding atmosphere, the better will be the efficiency for the use of the heat of combustion. The greater the absolute value of the pressure, the smaller will be the specific volume and the specific weight of the engine. Therefore, the most portable machine will be the one operating with compressed air at sea level.

However, extremely large compression of air is prevented by the very large amount of work that has to be done, and principally by the high temperature generated. For example, when compression takes place to 10 atm, the associated heating produces a temperature of 418° C. This is not too great, if we take into the account the cooling of the

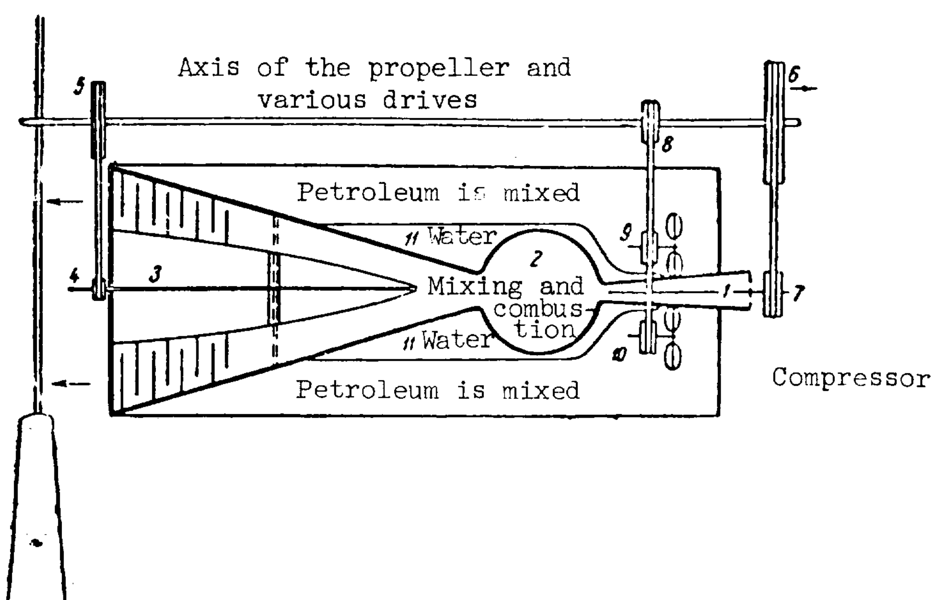

Figure 1

compressed air. As far as the work of compression is concerned, it is returned when the products of combustion expand.

A compression of approximately 10, regardless of the rarefaction or density of the atmosphere, always produces the same increase in temperature, specifically from 0-418° C (the absolute temperature increases by a factor of 2.53).

In the carburetor the air is mixed with finely atomized petroleum. Incomplete combustion takes place in the carburetor. Combustion continues beyond the carburetor in the conic tube placed between the carburetor /334
and the operating turbine. Here the products of combustion expand, are cooled, and achieve high velocity and afterburning.

The products of combustion are cooled by expansion, more so, when the surrounding atmosphere is rarefied.

Having become substantially cooler, they drive the multistage turbine.

The force of the gases acts simultaneously almost on the entire surface of the disks.

Airships use the exhaust gases to heat and change the lift force. At the same time water vapor is formed in the pressure tube; the liquid which is formed flows away and goes to work. There is no vacuum in the pressure tube. The gases exit into the atmosphere. Stratoplanes use exhaust gases substantially cooler than in the preceding case to obtain recoil (reaction).

The high temperature of the small chamber-carburetor requires cooling. Cooling is produced by the petroleum surrounding it. The latter is continuously mixed and transfers the heat from the very hot chamber to the cool parts of the machine, where the turbine operates and where the relatively cold gases exit. It is possible to have a special jacket filled with water, which is placed close to the carburetor and which adjoins the very hot parts of the conic tube. When the water in this jacket is heated and the pressure reaches the value of 10 atm and the temperature is close to +179° C, the steam which is formed bursts into the carburetor and increases the steam-gas flow and the work performed by the turbine. Jacket 11 with the water is also surrounded by petroleum 9 and 10. The latter is circulated by a special drive with rotating paddles. The water cools the carburetor and the tube, the petroleum cools the water and is itself cooled by the walls of the petroleum tank, which are cooled by the atmosphere. It would be possible to try and do without the water. The petroleum may be cooled by spraying it into the airstream and then collecting it again. This is simpler than cooling it with air bubbles or air tubes.

The engine is put into operation in the following manner. First an auxiliary engine is used to actuate air compressor 1 and the petroleum pump. In this manner carburetor 2 and turbine 3 will begin to operate. Then the auxiliary motor, not shown in the drawing, is turned off. The air compressor and the pump are put into the operation by a special transmission 4, 5, 6, and 7 by the turbine.

If we eliminate the water jacket 11, the fuel, i.e., the petroleum, will surround carburetor 2, air compressor 1 and turbine 3. Cooling of the last is necessary, because the compressor is excessively heated by the compressed air; the carburetor becomes even hotter; also the origin of the conic tube is heated where the sprayed petroleum burns. /335
The expanded end of the turbine is not heated very much, and when the engine is used at high altitudes it may even be cold, because the ejected gases expand considerably. The hot walls of the carburetor and the origin of the conic tube transfer their heat to the cold sections, since metal is a very good conductor of heat. A uniform temperature in the petroleum tank is sustained by the artificial mixing of petroleum 8 and 9. In the lower layers of the atmosphere it will be necessary to use additional cooling of the petroleum by means of external air. The most economical method of achieving this is to spray the petroleum in the cold airstream. Of course, in this case the air will carry away some of the fuel. However, we must select the fuel which would not produce any vapors at moderate temperatures. This cooling atmospheric air which carries away petroleum vapors may be directed into the air compressor. Then the petroleum will not be lost. It is only necessary that the boiling temperature of the petroleum be high, so that not too much fuel vapor is carried away and so that there is no explosion in the compressor. The ribs on the beams create excess weight and cannot be used on powerful engines which must also be light. The tubes which pass through the tank with petroleum are penetrated by the air and are not as heavy and therefore more accessible as coolers.

In general, this is the description of our engine. The purpose of this device is to produce light weight, high power, simplicity of construction and, consequently, low cost. Engines of this type are particularly advantageous at high altitudes, where the reaction of the exhaust gases may be effectively used.

The use of atmospheric oxygen is possible only up to a certain altitude where the air is not too thin. Otherwise difficulties will be encountered when we try to compress it. Indeed, if, for example, the air which is substantially rarefied is compressed by a factor of 1,000, its temperature will reach a value of 4,000°. It is doubtful that cooling by petroleum will be adequate. In this case the cone of the compressor will require thin ribs. As a matter of fact, this role may be played by diaphragms welded to the shell of the compressor.[1] The diaphragms must be made from a material which is the best conductor of heat.

What is the substance of the operation of the engine proposed by me?

Let us assume that in a period of 1 sec we force 1 m^3 of air into the chamber. The pressure in the chamber will increase continuously if we do not have an outlet[2] through which the gases flow to the turbine. The smaller this opening, the greater is the pressure in the chamber. We shall make the size of our openings so that the pressure in the chamber is always 10 atm. The mass of air entering must be equal to the mass of air leaving. The mass of air flowing in is 1 m^3, and when /336 combustion takes place we have essentially the same mass, but at a temperature of approximately 1,638° C. This increases the volume of the air (at the same pressure) by a factor of 7. The annexation of hydrogen which enters into the composition of the fuel and the splitting of the oxygen increase the volume of the products of combustion even more. The volume of the air will be greater not by a factor of 7, but by a factor of approximately 10. Thus 10 m^3 of gas must be withdrawn every second through the exit opening of the chamber (at a pressure of 10 atm and temperature of 1,638° C).

This is how heat is transformed into the rapid mechanical motion of gas molecules. However, it is far from complete and combustion is far from complete. Both phenomena continue in cone 3. The gas which has been compressed to 10 atm may expand by a factor of 10. Greater expansion is impeded by atmospheric resistance.

Expansion will be accompanied by a drop in temperature and afterburning. If the latter did not take place, the temperature would have decreased by a factor of 2.53, i.e., it would have been 487° C. However, due to the continuation of combustion it will be much higher, approximately 1,000° C.

We can see that for more efficient use of energy we must have much greater compression, for example, a compression of 100.

The purpose of the compressor is clear: the operation of the engine is impossible without it. The compressor is particularly necessary at high altitudes.

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[1] See the article by K. E. Tsiolkovskiy "Compressor of Gases," Kaluga, 1931. - Editor's Remark.

[2] The critical cross section of the nozzle. - Editor's Remark.

It is desirable to use a turbine compressor, since in this case we obtain a very large quantity of air and have no lubrication problems and may thus achieve a high degree of compression, which is particularly advantageous when the surrounding atmosphere is very dense, for example, in the case of airships.

The narrow outlet from the chamber is necessary, otherwise the overpressure of gases will not be developed in it. The latter is necessary to convert the thermal energy into the rapid mechanical motion of the products of combustion.

However, their combustion and expansion does not end at the opening: the gas leaves the opening in a heated and compressed state. It continues to expand and cool as it travels through the funnel. This increases the velocity of the flow further and converts more heat into motion. The cone-shaped funnel is necessary to reduce the length of the entire device.

At the limits, when there is no external pressure and the tube is sufficiently long, the products of combustion are cooled almost to absolute zero, and all of the heat is converted into the forward motion of the gases. It is utilized by means of multistage turbine 3. The funnel is useful for the simultaneous exploitation of all the turbine blades, which reduces its weight.

Various parts of the engine have different temperatures, from 2,000-3,000° to 0. This makes it possible to obtain the average temperature which is not very high and which the materials can withstand: the surrounding fuel is mixed, cools the heated parts of the engine /33
and heats the cold parts.

What are the advantages of this engine compared with the lightest aircraft engines? They are simplicity of construction, absence of pistons, small specific volume and great energy, low cost of materials and of the fuel. Unfortunately, it is doubtful that a power of less than 1,000 metric hp would be advantageous. For low power these engines are not efficient. In this case aircraft engines would be better (it is assumed that the engine operates at sea level).

The operation is very efficient and the compression and atmospheric pressure are low. But the work performed by the engine will also decrease. Thus, with a compression of 5, the work of compression for a 1,000 hp motor will be approximately 292 metric hp. If we reduce this by 2, the work will be equal to 80 metric hp. This is not very much, even for an engine of 500 metric hp.

We give the approximate volume of the carburetor and other parts of the engine, starting with the compressor. Since for a power output of 1,000 metric hp the carburetor is subjected to 2 m^3 of compressed air every second, it is sufficient for its volume to be 0.5 m^3. The remaining components occupy three times this volume. The volume of the principal parts of the motor is 2 m^3. If we assume that, on the average, all of the vessels can withstand an excess pressure of 10 atm, the weight will be approximately 30 kg, if we use an acceptable factor of safety. The disks of the turbine and the compressor do not weigh less. If we take into account all of the other components, we obtain a weight of 100 kg for a 1,000 metric hp engine. This will correspond to 0.1 kg per hp. This is the specific weight of the engine. It is 10 times less than the specific weight of the aircraft engine.

The greater the engine, the more efficient it is, since the detrimental heating of the walls will be less because the great heat of the gases will be further removed.

I wish to note that in my published articles I proved on many occasions that the velocity in the rarefied regions of the atmosphere will be proportional to the square root of the rarefaction of this air, if we satisfy the condition that the power of the engine, with its weight unchanged, be proportional to the forward velocity of the flying device.

If this condition is to be satisfied, we must compress the rarefied air to a density greater than its density at sea level.

Velocity in m/sec	200	300	400	500	600
Necessary rarefaction factor.	4	9	16	25	36
Altitude in km.	12	17	21	23	25
Natural compression of air.	1.37	2.19	4.41	8.1	25
Required compression.	4	9	16	25	36
Less by a factor.	2.9	4.1	4.7	3.1	2.24
Velocity in m/sec	700	800	846	1,000	2,000 /338
Required rarefaction factor	49	64	71.6	100	400
Altitude in km.	27	29	29	31	39
Natural compression of air.	51.5	99	138	316	9,330
Required compression.	49	64	71.6	100	400
Greater by a factor	1.05	1.56	1.9	3.16	23.3

The first entry of this table shows the velocity of the stratoplane, the second shows the required rarefaction of the medium to achieve this velocity, and the third entry shows the corresponding flight altitude above sea level. The fourth entry shows the natural compression of the air due to the pressure of the incident flow, and the fifth entry shows the required compression of the medium to bring it up to the density which it has at sea level. From the sixth entry we see that the natural compression is insufficient, and it shows by what factor it is less than the required value. This is how matters stand up to a velocity of 700 m/sec. At velocities higher than this, the compression of the medium produced by the incident flow will be greater than at sea level. Only the increase in temperature will pose a problem. For a velocity of 700 m/sec, it is no longer applicable, unless we do something to lower it.

Thus we encounter three difficulties. The first is to figure out a way of increasing the power of the engine proportionately to the velocity of the stratoplane. Of course, we could increase the hp by increasing the weight of the entire engine and keep the flight weight of the stratoplane unchanged. For example, the total weight of the stratoplane may be 1,000 kg. The power required for normal velocity is of the order of 50-100 hp, and the weight of the engine is not less than 50 kg. If we could increase the weight of the engine to 500 kg, the velocity would increase by a factor of 10. A certain difficulty is associated with the necessity of having compressors for the rarefied air. We could do without these only when the velocity is greater than 700 m/sec. The third difficulty is associated with the excessive rise in the temperature of air due to its compression.

These difficulties prevent us from realizing the high altitude airplane at the present time. To these we must add the necessity for having a hermetically sealed cabin or special clothing to protect the passengers from the rarefied medium.

All of these calculations and considerations are approximate. Experiments and more detailed analyses will produce more accurate conclusions, which apparently will be more modest.

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PROJECTILES WHICH ACHIEVE COSMIC VELOCITIES ON LAND OR ON WATER /339

(1933)

1. These projectiles have a substantial advantage over those which must achieve this velocity at a high altitude without being coupled to installations on Earth, specifically:

(a) they may utilize electrical energy which they obtain from the outside (i.e., from installations on Earth similar to those which power streetcars);

(b) in horizontal cannons we may also use the elasticity of gases heated electrically;

(c) these installations may be used continuously to dispatch many projectiles beyond the atmosphere;

(d) if a projectile is to move in the tube, we may create a vacuum in it; the long path of the projectile will, of course, be horizontal or slightly inclined and will rest on the ground and not rise vertically like a tower;

(e) the projectiles are dispatched without a large supply of fuel.

The principal advantage is that any amount of energy can be imparted to the projectile, which can then reach cosmic velocities.

2. Devices of this type have many shortcomings compared with reactive devices. The latter represent the first stage, while the first represent the later stage of development.

Here are some of the shortcomings:

(a) it is necessary to have a special path (runway, tube), which is up to 1,000 km long and obviously very expensive;

(b) it is necessary to have supplementary sources of energy such as, for example, generators of electric current, compressors, etc.;

(c) the projectiles must be 40-400 m long or even longer, of proper streamlined shape, otherwise it will be impossible to achieve cosmic velocities;

(d) the projectile acquires cosmic velocity while it is still in dense layers of the atmosphere, and it is therefore subject to great resistance of the medium.

In general, obstacles are associated with the complexity, size, and high cost of these installations. However, they are possible. It is necessary that people become convinced of the possibility of achieving cosmic velocities and of the advantages of existing beyond the atmosphere outside Earth. /340

3. High velocities are possible only if the projectile which moves or flies along Earth is extremely long. We make use of my work "Pressure on the Plane," 1930. We present a part of one of the tables:

Velocity, km/sec						
1.2	1.5	1.8	2.4	3	4.5	6
Corresponding minimum elongations of projectiles						
4	5	6	8	10	15	20

Let us assume that with an elongation of 4 we can achieve a velocity of only 1 km/sec. Then we obtain a slightly different table:

Velocity, 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 we increase the elongation by a factor of approximately 2, we shall have only friction, and resistance due to inertia may be neglected as rather small.

In this case the resistance due to friction Q_q per unit volume of the projectile will be given by the equation (see my "Resistance of Air," 1927, equation (56))

$$\frac{Q_q}{V} = a\,\frac{F\gamma v^2}{xD^2}.$$

Here x is the elongation of the projectile, D is the diameter of the maximum cross section, γ is the density of air, and v is the velocity of the projectile.

5. F is variable and is given by following equation

$$F = 1 : \left[1 + \ln\left(\frac{v}{l}\right)\right],$$

where l is the length of the projectile, or xD (see equation (19) "Resistance").

7.

$$a = 0.00225.$$

8. Let us assume that v = 1,000 m/sec; D = 4 m; γ = 0.0013; /341
x = 100; l = xD = 400; F = 0.5211 (see "Resistance," Table 21). Then we compute

$$Q_q/V = 0.000093 \text{ tons}.$$

Consequently, with a velocity of 1 km/sec in the densest layers of the atmosphere, the resistance of 1 m^3 of the projectile will be approximately 0.1 kg.

9. On the basis of the above equations we prepared a table for the specific resistances, (i.e., the resistance of 1 m^3) in kg for various velocities 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
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. In order to obtain the amount of work done per sec, it is necessary to multiply the specific resistance by the velocity

$$L_s = \frac{Q_q}{V} \cdot v.$$

We obtain the specific work in metric hp (if we divide by 100).

11. The total power of the projectile is huge, because it is proportional to the volume

$$N = \left(\frac{Q_q}{V}\right) v V = Q_q v.$$

12. From equation (33) of "Resistance" we obtain

$$N = a_1 F D v^3.$$

14.

$$a_1 = 0.00000156.$$

Thus we determine the total power of the projectile (under conditions of Section 8).

16. We present a table which gives the velocity in km/sec, the resistance of the medium per 1 m^3 of the projectile's volume in kg, the work performed per sec in metric hp, the resistance of the entire projectile Q_q in tons and the total power per sec of the entire projectile N in metric hp.

v	1	2	3	4	5	/34
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	15,060	42,670	92,870	170,680	
v	7	8	9	10	11	
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	1,140	1,478	

The power is expressed in metric hp, but for a velocity greater than 6 km/sec it is expressed in thousands of metric hp. Thus, for a velocity of 12 km/sec, the power must reach almost 2 million metric hp, while the resistance will reach a value of 16 tons.

17. This power may be reduced, if we decrease the dimension of the projectile. Let us assume that the average density of the projectile is equal to 0.2 and its volume is equal to 2,680 m^3. Then the mass of the projectile will be 521.6 tons. With an acceleration of 100 m/sec^2 the pressure will be 5,216 tons. This means that with the velocity of 12 km/sec the resistance of the medium is 326 times less.

18. It is interesting to compute how much of the total work is used to overcome the resistance of the air. Of course, we shall not take into account the work used to overcome inertia and to achieve a high velocity.

19. If we consider only friction we have

$$Q_q = A_1 F D v^2.$$

20. Or $Q_q = A_2 v^2$, where $A_2 = A_1 FD$.

21. The differential of the work performed to overcome friction will be $dL = A_2 v^2 dx$, where x is the length of the path.

22. However, $dx = vdt$, where t is the time measured from the beginning of motion, while v equals jt. We assume that the acceleration j of the projectile is constant.

23. Then $dL = A_2 v^3 dt = A_2 j^3 t^3 dt$.

24. Integrating, we obtain

$$L = \frac{A_2}{4} j^3 t^4.$$

or, on the basis of (22),

$$L = \frac{A_2 v^4}{4j}.$$

25. We can see that in order to achieve the same velocity, it is more advantageous to use a high acceleration j. However, the magnitude of the acceleration has its limits because great acceleration may prove /343 fatal not only to the pilot but also to the objects in the projectile. Less acceleration is unsuitable, since the path will be too long and too expensive. If the human being is in a horizontal position in water, we may assume that the acceleration can be 100 m/sec^2. It will produce 10 times the force of gravity.

26. Let us assume the old conditions (see Section 8) and a velocity of 12 km/sec. To simplify our calculations we express equation (24) in the form

$$L = A_2 v^2 \frac{v}{4j}.$$

On the basis of equations (12) and (20) we find

$$L = N \frac{v}{4j}.$$

27. However, N is known from Table 16. If we take its value for v = 12 km/sec and an acceleration of 100 m/sec^2, we compute L = 5,775,000 ton-meters.

28. A power of 1 metric force per sec for a 24 hour period gives us 86,400 metric hp or 8,640 ton-meters.

The work obtained in Section 27 is liberated by a power of 1 metric hp over a period of 670 days, or by a machine of 670 hp in a period of 1 day, or by a machine of 1,000 hp in a period of 16 hours.

29. It is best to compare this work with the work of inertia of the projectile. It is equal to

$$L_i = \frac{v^2}{2g} G.$$

30. The weight, on the other hand, depends on the volume of the projectile and its average density.

32. Let us compare this work of inertia with the work performed by the resistance of the medium (12). We obtain

$$\frac{L_i}{N}=\frac{G}{2ga_1FDv}.$$

33. The table in Section 9 shows the values of F for various velocities, when the length of the projectile is 400 m.

34. Using the conditions in Section 8 and the velocity of 1 km/sec and a projectile density of 0.2, we compute the ratio from the equation in Section 32. We obtain 8,400, i.e., the work done to overcome resistance is quite insignificant.

Even at a velocity of 12 km/sec it will be 703 times less than the work of inertia. For large DX and large projectile density it will be even smaller.

Why are we then afraid of the resistance of the atmosphere? It is dangerous and relatively large only for bodies of small elongations such as the airplane, the airship and, more so, the automobile and the ordinary train.

However, this is not all. We launch a long body of smooth shape with the velocity of 8-12 km/sec. Will not this velocity be absorbed by resistance during the flight of the projectile through the atmosphere?

We shall now consider this. /344

We prove the following theorem: the work performed in cutting through the entire atmosphere during the vertical motion of the projectile with a constant velocity is equal to the one obtained if the atmosphere is considered to be of constant density, for example, equal to the density at sea level if the mass of the atmosphere is the same.

This density is equal to 0.00129. With this constant density and the known mass of the atmosphere its altitude will be approximately 7,800 m.

Indeed, whether any part of the atmosphere is rarefied or condensed, the work performed by the projectile traveling through it will remain the same. Let us assume, for example, that the atmosphere becomes rarefied by a factor of 100 at some place. The resistance will be 100 times less, and the work will decrease by a factor of 100. However, the work will also increase by a factor of 100 because the rarefied path will be 100 times longer. Thus it will remain unchanged.

35. We may assume in practice that the velocity in the atmosphere will be constant because the resistance of the medium, as we shall see, is quite insignificant compared with the supply of the active force of the rocket (or its kinetic energy). The force of Earth's gravity has much more effect on reducing the magnitude of the velocity. However, even this force is insignificant over the extent of the total atmosphere (20-40 km) in view of the initial cosmic velocity of the projectile.

36. Due to the small inclination of the motion of the rocket with respect to the horizon along a solid runway, the path may not be vertical: it lies along the mountains, whose total inclination is quite small. This means that the further motion of the rocket must also be inclined. If we assume that the path of the rocket along a small section of Earth is horizontal, we can present the second theorem: The work of penetrating the atmosphere during the inclined motion of the projectile is inversely proportional to the sin of the angle between the path and the horizon.

37. From these two theorems it is easy to determine the work absorbed by the atmosphere. We even obtain a large quantity because the velocity is decreased during the ascent; the real work of overcoming the atmosphere is much less.

To obtain this work it is sufficient to multiply the resistance given by Table 16 by 7,800 m. For example, if the velocity is 12 km/sec we obtain 124,800 ton-meters.

The quantity 7,800 is obtained by dividing the atmospheric pressure at sea level by the density of air at the same level.

38. Let us find the general equation for the resistance of the entire atmosphere (see equation (33), "Resistance")

$$L_a = \frac{x A_1 F v^2 D}{4 \sin y} 7800.$$

39. Let us compare it with the work performed by air resistance when we travel along the solid runway (24). We obtain

$$\frac{L_a}{L} = \frac{7800 \pi j}{v^2 \sin y}.$$

Thus, the average resistance in the entire atmosphere is smaller when the initial take off velocity of the projectile from the runway v /34 is larger and when the inclination with respect to the horizon y is larger. This ratio increases as the projectile is accelerated along the runway j.

40. Let us assume, for example, that $j = 100$ m/sec^2; $v = 12,000$ m/sec; $\sin y = 0.1$. Then the ratio is 0.1717 or 1:5.8. This means that the work performed when cutting through the atmosphere is almost six times less than the work performed to overcome friction along the runway.

41. Needless to say, this work is much less not only with respect to the kinetic energy of the rocket, but also with respect to the work performed to lift the rocket. The latter is equal to the weight multiplied by the height H of the atmosphere, which in this case must be taken as 30 km. The work performed to lift the rocket is equal to

$$L_{lift} = GH.$$

Comparing this work with (38), we find

$$\frac{L_{lift}}{L_a} = \frac{GH4 \sin y}{\pi A_1 F v^2 D 7,800} .$$

42. However, H = 7,800. Then we obtain

$$\frac{L_{lift}}{L_a} = \frac{G \sin y}{\pi A_1 F v^2 D} .$$

This means that the relative magnitude of the work of gravity increases as the velocity decreases, and increases as the slope and the dimensions of the ship increase.

43. Let us assume the conditions of Section 8 and make use of Table 9. We assume that the density of the projectile is 0.2, that $\sin y = 0.1$, and $v = 12,000$ m/sec. Then from the equation we see that the work of gravity in spite of the small slope and the large velocity is 45.16 times greater than the work required to penetrate the atmosphere when we move freely in it.

44. In view of the rather low resistance of the air and correspondingly low work we can decrease the elongation of the projectile by a factor of 2. It is also possible to increase its dimension by the same factor. Then $D = 2$ m, $x = 50$, and $l = 100$ m.

This is much more feasible as far as the energy consumption and cost are concerned. Things will be even better, if we can achieve the maximum velocity of 8 km/sec. Then we can decrease the elongation and dimensions by 2 and make $D = 1$ m; $x = 25$, and $l = 50$ m. In this case the diameter is small; however, our main concern is to displace the mass and fly through the atmosphere. Beyond the atmosphere we may construct a dwelling of desired dimensions. Up there the dimensions are of no significance, since there is no resistance of the medium.

45 Now we find the necessary length for the solid runway. High acceleration of the projectile is impossible because man will be crushed. Low accelerations are also undesirable, because the solid runway will be too long and there will not be enough room for it on land; besides, its cost will be too high. /346

46. Assuming a constant acceleration j of the projectile, we find the length of the path $x = v^2/2j$. From this we see that the length of the path will decrease as velocity decreases and acceleration increases. Based on our preceding remarks we can neglect the resistance of air, and the work necessary to obtain definite velocity is the same, regardless of acceleration.

It is not known what maximum acceleration man can endure if he lies submerged in water. However, we can assume that this acceleration will not be less than 100 m/sec^2 or 10 times greater than the acceleration due to Earth's gravity. Then, for various velocities we obtain the following path length in km:

v in km/sec	5	6	7	8	9	10	11	12
x in km	125	180	245	320	405	500	605	720

When the acceleration is twice as large ($j = 200$ m/sec^2)

x in km	62.5	90	122.5	160	202.5	225	302.5	360

At the highest velocity of 8 km/sec the path will be from 320 to 160 km. If we ascend 5 km up a smooth mountain, the inclination will be from 1:64 to 1:32. The sin at the angle will be from 0.0156 to 0.0313, and the angle itself will be from 1 to 2°.

47. We need not concern ourselves with resistance of the medium, but the large relative weight of the train requires that it be of unusual strength, which should be proportional to the acceleration j. From this point of view it would be more desirable to make the path longer.

The best method of transmitting energy is by means of the electric current. But how is the electrical energy to be converted into mechanical energy? Of the known electrical motors none are suitable because of their weight. By using electric current it is easy to obtain a high temperature and a chemical decomposition of materials. This can be used in thermal engines, but these motors are very heavy. It is possible to use a reactive engine and electricity to heat gases which have become cold by expansion. But here the advantage is not very great. The heated temperature cannot be very high, because the tubes conducting the gas may fuse. First of all, it is necessary to find heat-resistant materials and methods of their fabrication.

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K. E. Tsiolkovskiy in the last years of his life

MAXIMUM VELOCITY OF A ROCKET /348

(1935)

Chapter X of "Principles of Gas Machine Construction"

A. Relation Between the Velocity of the Rocket and the Mass of the Explosives

1. We shall use the simplest equations of my article "Investigations," 1926, (with gravity and resistance of the medium absent). These equations are approximate and can be applied in the following cases:

a) when action takes place outside the gravitational field and in a vacuum;

b) when the device moves along a horizontal path and its form is extremely elongated and optimized;

c) when flight takes place in the atmosphere in a direction which is almost horizontal; the device deviates very little from the horizon because of its high speed and because it has wings.

We shall also apply these equations when the projectile moves at a slight inclination with respect to the horizon--when it moves in the air.

2. We have $v = v_1 \ln\left(\frac{M_1+M_2}{M_1+M}\right)$, where v is the velocity of the rocket, M_1 is its total mass except for the explosives, v_1 is the relative velocity of the ejected matter (this remains constant), M_2 is the total mass of explosives, and M is the mass of unburned explosives not yet ejected. It is clear that v and M are variable quantities.

3. Let us assume that M = 0, i.e., that the entire supply of explosives has burned; then we obtain the maximum velocity of the rocket:

$$v_0 = v_1 \ln\left(1 + \frac{M_2}{M_1}\right).$$

4. On the basis of this equation we prepare Table 4[1] which shows the maximum velocities of the rocket as a function of the total expended supply of explosives and the relative velocity of the ejected matter. The first column shows the entire expended mass of explosives with respect to the mass of the rocket (without explosives), the next six columns give the velocity of the rocket in m/sec when the relative velocity of the ejected matter is 1, 2, 3, 4, 5, and 6 km/sec. Theory shows /349 that the energy of explosives currently available to man cannot produce a velocity of the products of explosion greater than 6 km/sec. Finally, the last column shows in percent the part of the total energy of explosion converted to the motion of the rocket. As we can see, this percentage is very small. As the relative quantity of explosives increases, it also increases. It reaches a maximum value when the supply is 4, achieving in this case an efficiency of almost 65 percent, and then begins to drop to 0.

When the supply is between 0.7 and 30, the efficiency is quite respectable and is greater than 40 percent.

The absolute velocities of the rocket reach cosmic values which are sufficient not only to escape from Earth, but to escape from our sun and move among the suns of the Milky Way.

5. However, in practice the ejection velocity of 5-6 km/sec has not /350 been achieved so far, and we cannot take these large supplies of explosives required to attain cosmic velocities--at least not for escape from the sun and to travel among the stars of the Milky Way.

What are the velocities that can be achieved with modest means, and how do we find a method of achieving cosmic velocities?

6. It is impossible to utilize completely the thermal energy of an explosion; the ejected products cannot be cooled (by expansion) to absolute 0, and therefore it is impossible to convert all of the heat into kinetic motion of gases. The infinite expansion of gases and vapors is

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[1]The numbers of the tables correspond to the numbers of the sections. - Editor's Remark.

Table 4. Velocity of Rocket

Ratio of ejected mass to mass of rocket	Velocity of rocket (when thermal energy of chemical combination is transformed completely into motion of gases) in m/sec. Velocity of ejected matter in km/sec: 1	2	3	4	5	6	Efficiency
0.1	94.5	189	283.5	378	472.5	567	8.9
0.2	182.0	364	546	728	910	1,092	16.5
0.3	262	524	786	1,048	1,310	1,572	22.9
0.4	336	672	1,008	1,344	1,680	2,016	28.2
0.5	405	810	1,215	1,620	2,025	2,430	32.8
0.6	469	938	1,407	1,876	2,345	2,814	36.7
0.7	529	1,058	1,587	2,116	2,645	3,174	40.0
0.8	586	1,172	1,758	2,344	2,930	3,516	42.9
0.9	642	1,284	1,926	2,508	3,210	3,852	45.8
1.0	693	1,386	2,079	2,772	3,465	4,158	48.0
1.2	788	1,576	2,364	3,152	3,940	4,728	51.8
1.5	915	1,830	2,745	3,660	4,575	5,490	55.8
2.0	1,098	2,186	3,294	4,392	5,490	6,588	60.3
2.5	1,253	2,506	3,759	5,012	6,265	7,518	62.0
3	1,380	2,760	4,140	5,520	6,900	8,280	63.5
4	1,609	3,218	4,827	6,436	8,045	9,654	64.7
5	1,792	3,584	5,376	7,168	8,960	10,752	64.1
6	1,946	3,892	5,888	7,784	9,730	11,676	63.0
7	2,079	4,158	6,237	8,316	10,395	12,474	61.7
8	2,197	4,394	6,591	8,788	10,985	13,182	60.5
9	2,303	4,606	6,909	9,212	11,515	13,818	58.9
10	2,398	4,796	7,194	9,592	11,990	14,388	57.6
15	2,773	5,546	8,319	11,092	13,865	16,638	51.2
20	3,044	6,088	9,132	12,176	15,220	18,264	46.3
30	3,434	6,848	10,302	13,736	17,170	20,604	39.3
40	3,714	7,428	11,142	15,856	18,570	22,284	34.4
50	4,480	8,960	13,440	17,920	22,400	26,880	31.6
100	5,256	10,512	15,768	21,040	26,280	31,536	21.0
193	6,007.6	12,015.2	18,022.8	24,032	30,038	36,045.6	14.4
	infinity			infinity			zero

prevented by the external pressure of the medium (for example, of the atmosphere), as well as the liquefaction and solidification of the products of combustion. The ideal utilization of chemical energy is also prevented by the limited dimensions of the tube.[1] For this reason the velocity of ejected matter will be less than computed in Table 4.

7. The next table expresses this

50 percent	60 percent	70 percent	80 percent	90 percent	100 percent
0.707	0.775	0.837	0.894	0.949	1.000

The first line shows the utilization of the heat of combustion in percent, or the value of its relative transformation into kinetic energy (the motion of ejected matter), the second line shows the decrease in the velocity of the rocket proportional to the decrease in the velocity of the ejected matter. If the thermal or mechanical work is decreased, for example, by a factor of 9, then the velocity decreases by a factor of 3. The values in Table 4 must be multiplied by one of the fractions of the second line to obtain the true maximum velocity of a rocket compatible with the percent utilization of the heat of explosion.

8. Let us use this to prepare a new table, assuming that the efficiency of heat utilization is 70 percent and that the relative velocity of the products is 4 km/sec. The latter, of course, depends on the type of explosives.

9. In Table 9 the first line shows the velocity of the products of explosion (from 2 to 4 km/sec), the second line shows the utilization of heat and percent, and the subsequent lines show the final velocity of the rocket after the entire supply of explosives has been expended. The first column of the table shows the supply of explosives with respect to the weight of the rocket. As we can see, the practical velocity is hardly sufficient to become a close satellite of Earth.

However, we shall show other approaches for obtaining much higher velocities of the rocket. This approach consists of starting our trip by several similar and modest (from the standpoint of velocity) rockets. /351
All of these, except the last one, expend only half of their initial supply of explosives and transmit the remaining half to each other. Only the last rocket reaches maximum velocity. The other projectiles, after giving up their supply, glide down to Earth.

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[1] I.e., of the nozzle. - Editor's Remark.

Table 9. Table of Velocities for Various Uses of Heat of Combustion and Total Expenditure of Explosives

Relative supply of explosives	Velocity of products, 2,000 m/sec			Velocity of products, 3,000 m/sec			Velocity of products, 4,000 m/sec		
	Percent use of heat			Percent use of heat			Percent use of heat		
	50	60	70	50	60	70	50	60	70
	Final velocity of rocket, m/sec								
0.3	370	406	439	556	609	658	741	812	872
0.5	573	628	678	859	942	1,017	1,145	1,255	1,356
0.7	748	820	885	1,122	1,230	1,328	1,496	1,640	1,771
1	980	1,074	1,160	1,450	1,611	1,740	1,946	2,151	2,320
2	1,545	1,694	1,830	2,329	2,553	2,744	3,105	3,404	3,676
3	1,951	2,139	2,310	2,927	3,208	3,465	3,903	4,278	4,620
4	2,275	2,494	2,693	3,414	3,741	4,040	4,550	4,988	5,387
5	2,534	2,778	3,000	3,801	4,166	4,500	5,068	5,555	6,000
6	2,752	3,016	3,258	4,127	4,524	4,886	5,503	6,033	6,524
7	2,940	3,222	3,480	4,410	4,834	5,220	5,879	6,445	6,960
8	3,107	3,405	3,678	4,660	5,108	5,517	6,213	6,811	7,355
9	3,256	3,570	3,855	4,885	5,354	5,783	6,513	7,139	7,710
10	3,391	3,717	4,014	5,086	5,575	6,021	6,781	7,434	8,028

B. Velocity of the Rocket Achieved after Partial Burning of the Fuel Supply

10. Let us assume that the mass of the burned explosives with respect to its total supply is y.

11.

$$\frac{M_2 - M}{M_2} = y.$$

12. From this we have

$$M = M_2 (1 - y).$$

13. If we assume that $M_2/M_1 = x$, we obtain /352

$$v = v_1 \ln \frac{1+x}{1+x(1-y)}.$$

14. Let us assume that the burned part is y = 0.5.

Then we find

$$v = v_1 \ln \left(\frac{1+x}{1+0{,}5x}\right).$$

From this equation we see that the velocity of the rocket does not increase indefinitely when we have an infinitely large supply of fuel (x) but has a limit. Indeed, let us assume that x equals infinity, then $v = v_1 \ln 2 = v_1\ 0.693$. If, for example, $v_1 = 3{,}000$, the velocity of the rocket will be 2,079 m/sec in spite of the fact that we have an infinite supply of ejected matter (x). From this we can see that if we are to consume only half of the fuel, there is no advantage in making this fuel supply very large.

15. By means of the above equation we prepare Table 15 which confirms this statement. The table gives the velocity of the rocket in m/sec when only half of the entire supply of explosives is used up. x is the total supply. We have in mind an ideal transformation of heat into the motion of ejected matter and the motion of the rocket.

The first line gives the total relative supply of explosives, the first column gives the relative velocity of ejected matter. Even if we assume that it is 2,000 m/sec, we can see that the velocity of the rocket, when the total fuel supply is 4 and when half of it is expended, reaches only a value of 1,023 m/sec. When the total supply is 2, and half of it is used up, the velocity of the rocket is 1,215 m/sec, if the relative velocity of the ejected material is 3,000 m/sec.

C. The Velocity Which Can be Reached by One Rocket When Assisted by Auxiliary Rockets /353

16. We shall see now the significance of a limited expenditure of explosives when we try to achieve cosmic velocities.

17. Let us assume that we have many identical rockets, each having a fuel supply x = 1. Let us assume that each rocket expends half of its

Table 15

x (supply) / v_1 in m/sec	0.1	0.3	0.5	1	2	3	4	5	6	7	8	9	10
1,000	46	122	182	287	405	470	511	539	567	573	588	598	606
2,000	93	245	365	575	810	940	1,023	1,078	1,134	1,146	1,176	1,196	1,212
3,000	139	368	547	863	1,215	1,410	1,534	1,617	1,701	1,719	1,764	1,794	1,818
4,000	186	490	729	1,150	1,620	1,880	2,046	2,156	2,268	2,292	2,352	2,392	2,424
5,000	232	613	911	1,438	2,024	2,350	2,557	2,695	2,835	2,865	2,940	2,990	3,030
6,000	279	736	1,094	1,726	2,429	2,820	3,068	3,234	3,402	3,438	3,528	3,588	3,636

supply. Let us assume that the velocity of ejected matter is the same for all rockets and is 4,000 m/sec.

If we use a squadron of these rockets and refuel some of them in space, we may obtain higher velocities which cannot be obtained by a single rocket. The refueling of an airplane in air is not only possible, but has actually been accomplished.

18. Let us assume that one rocket is flying. Then, according to Table 4, its maximum velocity will be 2,772 m/sec.

19. Now let us assume that two rockets are flying side by side. Let us assume that each uses up half of its fuel supply. Then they will have a velocity of 1,150 m/sec (see Table 15). Then one of the rockets transmits its unburned fuel to the other and glides back to Earth. Now the second rocket has the full fuel supply of one and will achieve an additional velocity of 2,772 m/sec and will reach 1,150 + 2,772 = 3,922 m/sec.

20. Now let us assume that four rockets are flying. When they all use up half of their fuel supply, they will attain the same velocity of 1,150 m/sec. However, two of these rockets will replenish the supply of the other two and will glide back to Earth. Then the two rockets which remain in the air travel further and again use up half of their fuel supply. As a result of this they will have a velocity of 2,300 m/sec. After this, one will replenish the supply of the other and glide back to Earth. The last rocket with a full supply of explosives /354 will achieve an additional velocity of 2,772 m/sec and will thus have a total velocity of 5,072 m/sec. After this, it will have to glide back to Earth.

Table 21

Number of rockets. . . .	1	2	4	8
Velocity in m/sec. . . .	2,772	3,922	5,072	6,222
Number of rockets. . . .	16	32	64	128
Velocity in m/sec. . . .	7,372	8,522	9,672	10,822
Number of rockets. . . .	256	512	1,024	2,048
Velocity in m/sec. . . .	11,972	13,122	14,272	15,422
Number of rockets. . . .	4,096	8,192	16,384	-
Velocity in m/sec. . . .	16,572	17,722	18,872	-

21. We prepare a table showing the velocities of the last rocket as a function of the total number of rockets, assuming that $v_1 = 4{,}000$ m/sec and the supply is 1.

22. The first line of Table 21 shows the number of rockets which participate in providing one rocket with the maximum velocity. The second line shows the velocity of the latter in m/sec.

23. The first cosmic velocity is achieved when we have 32 rockets. To escape from Earth it is necessary to have 256 rockets, and to escape from the planets and the sun we require 4,096 rockets.

24. The most important point is to fly beyond the atmosphere of Earth and become fixed as Earth's satellite. A further increase in the velocity may be obtained by other means which are much simpler than on Earth. Nevertheless, the number of rockets required is tremendously large.

25. However, it is possible to take a large supply of explosives, for example, a supply equal to 4. Then, with a modest ejection velocity of 3,000 m/sec, the velocity of the rocket will be 1,534 m/sec when half of the fuel is used up (see Table 15). The total velocity, on the other hand, is 4,827 m/sec (see Table 4). This is sufficient for us to propose a new table.

Table 25

Number of rockets.	1	2	4	8	16
Velocity in m/sec.	4,827	6,361	7,895	9,429	10,962
Number of rockets.	32	64	128	256	512
Velocity in m/sec.	12,497	14,031	15,565	17,099	18,633

In this case, if we wish to wander among the suns of the Milky Way, it is sufficient to have 256 rockets. It requires 4 rockets to become a satellite of Earth and 16 rockets to become the sun's satellite.

26. The velocity of the ejected matter may be greater than 3 km/sec; then we require fewer rockets to achieve cosmic velocities.

27. We may derive a general equation for the velocity of the last rocket as a function of the number of rockets, the velocity of their ejected matter v_1, and the relative supply of explosives. Then the velocity of a single rocket will be (see equation (3))

$$v_0 = v_1 \ln(1+x),$$

where x is the total relative supply of explosives. When the number of rockets is 2^n, where n is the number of transfusions, the velocity of the last rocket will be /355

$$v = nv_1 \ln \frac{1+x}{1+0,5x} + v_1 \ln(1+x) =$$
$$= v_1 \left[(n+1)\ln(1+x) - n\ln(1+0,5x)\right].$$

28. The first term of the right side has a limit, regardless of how large x is or how large the relative supply of explosives is (see Section 14). It is equal to 0.693 nv_1. Nevertheless, it is capable of increasing without limit when we increase n or the number of rockets (2^n). However, the second term increases without limit as x is increased, or as the relative amount of explosives is increased. Thus, the values of x and n should be increased as much as possible.

29. Even if it is not possible to increase the supply of explosives x and the relative velocity of the products of combustion v_1, the number of rockets (2^n) is at our command, and we can therefore also control the velocity of the last rocket in a group.

30. Practice has shown that materials may be exchanged between airplanes moving at the same velocity. Fuel has been transmitted from one airplane to another. It is only necessary to develop the best technique for doing this. In our case, the matter is more complicated because we must transfer two different elements: hydrocarbons (fuels) and oxygen compounds. This may be done in various ways; for example:

(a) refueling by a tube connecting the two flying machines;

(b) transferring tanks containing the elements of explosion;

(c) directing a jet of fuel in the rear part ahead of the flying device (injection, fire engine). Experience will show which of these approaches is best.

D. The Practical Course

31. It will be necessary to begin using the most imperfect and low-power, reactive airplanes. First we learn how to fly one. The smallest ejection velocity must be used, for example, 2,000 m/sec, with a supply of explosives equal to unity. Table 4 shows us that the maximum velocity is 1,386 m/sec. Such a rocketplane may fly horizontally or along an inclined path. If we do not take into account the resistance of air, it may reach an altitude of 96 km with this velocity. However, because of the resistance of the medium it will not reach this altitude, but because of some residual velocity it will ascend to at least 50 km. At this point it uses up its fuel supply and descends by gliding to a solid or liquid surface of the planet.

Since the maximum velocity achieved by this modest rocketplane does not exceed 1 km/sec, the elongation of the ship need not be too great. /356

32. We present here the necessary elongation of rocketplanes as a function of the maximum given velocity (see my article "Pressure," 1930).

v, in km/sec		1	2	3	4	5	6	7	8
λ		4	8	12	16	20	24	28	32
v, in 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 us the velocity of the device in km/sec, while the second line gives us the necessary minimum elongation when the shape is optimum. We see from the table that the first modest rocket may have a limited elongation of 4. If the elongation is below the value indicated in the table, then no matter how much the surrounding air is rarefied, it condenses in front of the device to a point where it serves the same purpose as a steel wall.

33. Since a large velocity of approximately 5 km/sec is achieved outside the atmosphere, the elongation in general will not exceed 20 (see table).

34. After we have learned how properly to operate one rocketplane with an elongation of 4, we begin to construct two identical rockets with a greater elongation. At the same time we shall start practicing the refueling of one rocketplane by another. Then we shall go to a group of four rockets and increase their elongation even more, then to a group of eight rockets, etc. At the same time the devices will be perfected; for example, the relative supply of explosives will be increased, and the velocity of the ejected material will also be increased.

35. For the time being we propose a modest table of velocities for the rocketplanes as a function of their number, assuming that the ejection velocity is 2,000 m/sec and that the supply of explosives is equal to unity. The table also includes the required minimum elongation of the group. In preparing this table we make use of Tables 4 and 15:

Number of rockets	1	2	4	8	16	32	64	128	256	512
v, in km/sec	1,386	1,961	2,536	3,111	3,586	4,271	4,846	5,421	5,996	6,571
λ.	5	8	10	12	14	16	20	22	24	26
Height of ascent with constant gravity . .	95	192	320	484	680	910	1,170	1,470	1,800	2,160

The first line shows the number of rockets in a group, the second line shows the maximum velocity, and the third line shows the elongation of each member of the group, while the fourth line gives the maximum altitude in km achieved when all of the velocity is used up. /357

In practice, of course, only half of this will be achieved. For a group of eight or sixteen rocketplanes it is possible to go beyond the limits of the atmosphere where elongation no longer has any significance. Therefore, it will not exceed twelve to fourteen. This means that the projectile with a maximum cross section of 2 m will have a length not greater than 24-28 m.

36. However, we hope that during the period of these exercises or sooner we can obtain an ejection velocity greater than 2 km/sec, because its limit is 6 km/sec. The fuel supply may also go from unity to 5 or more. Then even with small squadrons of identical rocketplanes, which are not too elongated, we can achieve cosmic velocities.

37. As a limit for our successes we may take an ejection velocity equal to 6 km/sec and a fuel supply equal to 10. On the same basis (Tables 4 and 15) we obtain the following table:

Number of rockets.	1	2	4	8	16
v, in km/sec	14,388	18,024	21,660	25,296	28,932

Here we cannot even speak of altitude or of elongation. Both the single rocket and the group rapidly fly beyond the atmosphere without even having a velocity of 2 km/sec in it. Thus, an elongation of 8 is quite sufficient for all rockets if we succeed to the limit.

38. However, at the present time we cannot hope for such success. It is limited by the multiplicity of secondary conditions which follow from theoretical conclusions.

E. The Purpose of the New Approach

The purpose of what we have presented is to indicate the approaches which can be used when we have a single imperfect rocketplane, to combine several of these for the achievement of cosmic velocity sufficient not only to conquer the solar system, but to travel among the stars within the limits of our Milky Way. This approach consists of utilizing a group of rocketplanes and refueling them in space, so that we obtain one final rocketplane capable of achieving the highest cosmic velocity.

39. Previously we have proposed the use of rocket trains and artificial earth runways for this purpose. This is of course possible and proper; however, at the present time it is not feasible due to high cost and other reasons.

40. Earth cannons similar to the proposed runways are even less feasible because of their high cost. All these trains and "cannons" will find application in the distant future when the significance of /358 interplanetary travel becomes great, when it attracts the attention of mankind more, and when it develops more confidence and produces real hopes, thereby justifying greater expenses and sacrifices than those incurred for all the other needs of mankind.

41. The approach of using a group of the first low-power devices and refueling is more within the reach of the brains of mankind in their present state of development. Even one rocketplane will produce a desire for experimentation with two identical and unperfected devices.

Each of these devices is valuable in itself; it may serve the needs of mankind. Experiments with several rocketplanes will be conducted, for example, as interesting tricks. However, these tricks will inevitably lead to the achievement of cosmic velocities.

Thus, the basis of this success is the achievement of the first rocketplane, even though it is very poor in performance. The construction of two such similar projectiles will start us on the path to increased velocities, for which there is apparently no limit.

In the preceding chapters we have presented the principles for constructing individual rocketplanes. Of course, the more perfected these rocketplanes become, the better will be the results of operating them in groups.

F. Ejection Velocity of the Products of Explosion

43. Let us return once again to the individual lone rocketplane. The ejection velocity of the products of explosion is of great significance. What does it depend on? In an earlier chapter "The Energy of the Chemical Combination of Substances" we gave tables for the ideal, maximum velocities for the ejection of the products of explosion. They are accomplished almost entirely under the following mutual conditions:

(a) when the products of combustion are gaseous or are very volatile;

(b) when there is no external pressure which inhibits the expansion of gaseous products;

(c) when the tube through which the ejected matter flows is rather long;

(d) when it does not diverge too much towards the exit, i.e., does not deviate too much from a cylindrical form (a conic form, on the other hand, decreases the length of the tube);

(e) when we have no heat loss by thermal conductivity and radiation;

(f) when the diameter of the tube is so large that we can neglect the friction of gases along the internal walls of the tube.

44. All of these conditions cannot be met in full in practice. We shall indicate some of the deviations.

The projectile is usually of small size. The tube therefore is short. In order to utilize the expansion of gases more advantageously and to convert heat into their motion, it is necessary to have a conic tube.

External pressure is removed only in a vacuum when the rocket has ascended beyond the atmosphere, or when the velocity is greater than 300-500 m/sec, when the blunt forward part of the rocket is subjected to vacuum due to high speed motion. The bow of the rocket, generally speaking, is narrowed down. However, its part where the explosion tube exits is necessarily blunt. The rarefied region would form here (but it is, of course, filled with the ejected products of explosion). /359

Due to the limited dimensions of the explosion tube and due to a finite external pressure, the ejected gases do not have time to cool to absolute zero and retain some portion of the energy, depending on the

Table 38. Velocity of Rocket When Half of Fuel Supply Has Been Used Up and When Thermal Efficiency is 50, 60, and 70 Percent

Total relative supply of explosives	Supply of expended explosives	Velocity of products of explosion (ideal) km/sec								
		2			3			4		
Thermal efficiency		50	60	70	50	60	70	50	60	70
Velocity of products of combustion in m/sec		1,414	1,550	1,674	2,121	2,325	2,511	2,828	3,100	3,348
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	1,017	1,145	1,255	1,355
3	1.5	665	729	787	996	1,093	1,180	1,329	1,457	1,574
4	2.0	723	733	856	1,084	1,189	1,284	1,446	1,585	1,712
5	2.5	762	835	902	1,143	1,253	1,353	1,525	1,671	1,805
6	3.0	800	877	947	1,199	1,315	1,420	1,600	1,753	1,894
7	3.5	815	892	963	1,225	1,338	1,446	1,627	1,783	1,926
8	4.0	831	911	984	1,246	1,367	1,476	1,663	1,822	1,968
9	4.5	846	927	1,001	1,268	1,390	1,497	1,691	1,853	2,002
10	5.0	858	940	1,015	1,285	1,409	1,522	1,714	1,879	2,029

degree of their expansion. Thus, not all of the thermal energy of combustion is transformed into the movement of the gaseous jet. Due to this incomplete utilization of heat, the velocity of the products shown in the tables will actually be smaller in practice.

This has been taken into account in the preceding tabulation.

The first horizontal line of the table indicates the ideal velocity of the products of explosion, which depends only on the chemical energy of their combination. Here we specify a velocity of 2-4 km/sec, although it may reach a value of 6 km/sec. The second line indicates the utilization of the heat of combustion in percent, depending, of course, on the temperature of the gases ejected from the mouth of the tube. /360

The first column contains the total relative supply of the fuel elements: from 0.3-10.

The second column contains half the relative fuel supply used to obtain the velocities.

Finally, where the lines are intersected we see the magnitude of the velocities in m/sec, when half of the explosives is used up.

These are all very moderate and feasible conditions.

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APPENDIX

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Preface and Remarks by F. A. Tsander to the Work of
K. E. Tsiolkovskiy Entitled "Selected Works,"
Published in 1934

In his books K. E. Tsiolkovskiy was the first in the world to present calculations which determine the flight of a rocket, its fuel consumption necessary to achieve a given velocity under various conditions, and also its efficiency, both thermal and mechanical.

Tsiolkovskiy belongs to a group of people who, due to their love of work and a penetrating brain, have discovered something new in the field where the men of science have done very little to clarify the existing practical possibilities. In the scientific works life on other planets was depicted in an environment so unusual that it was even difficult to imagine how mankind could exist in it. Fiction writers have described only methods of flight which were not suitable for real flights into space. However, a series of them had pointed to the rocket as a means of flight to the moon.

The rocket was used to change the course of a projectile in interplanetary space by the well-known French author Jules Verne in his book called "Voyage to the Moon."

However, Tsiolkovskiy was the first to give a scientific basis to this problem, as contained in his works published here.

The organic deficiency (deafness) which developed in his youth had a profound effect on his entire life and activity, forcing him to retire and to develop many scientific problems by himself, without the aid of contemporary scientific disciplines. This independence and isolation from the technical ideas of his time left their mark on the works of Tsiolkovskiy and on the manner of their presentation. Thus, in his works to designate length and weight (km, kg) Tsiolkovskiy uses the same expression "kilo." In the article "Pressure on a Plane" we omit Section 46, which appears on page 8 of the original because an erroneous conclusion is made here that the quantity which according to conventional definition is designated by 1:(k-1), where k is the adiabatic exponent, is proportional to the absolute temperature and inversely proportional to the absolute pressure.[1] Then, on page 8 of the work "The Reactive Airplane," Tsiolkovskiy did not multiply the work required to obtain 1 m^3 of compressed air by the consumption of air necessary for 1 kg of fuel, which leads to an erroneous conclusion regarding the possibility of compressing air by means of a compressor to very large pressures. Here we have made the corresponding corrections and have also corrected some of the numerical values in the tables. Finally, Tsiolkovskiy, having assumed a definite solution to a series of problems, does not complete the design of the proposed construction, although he states that the design calculations must be completed, before we know how this construction can be reduced to practice. As a result of this, the constructions which he proposes are of limited application. In all of the books he assumes that the temperature of the gases near the end of the nozzle is so low that the cold may be used to cool the air compressed in the supercharger. However, this cold can be obtained only under special conditions, first, when we have very large initial pressures or very low terminal pressures; secondly, in the proposed method the heat is imparted to the products of combustion which expand in the nozzle at a rather low pressure, so that with the final expansion at the end of the nozzle very little heat is transformed into the kinetic energy of the moving products of combustion, as shown by me in detail in the corresponding remarks. /362

The design of the supercharger given by Tsiolkovskiy is incomplete. In the work "The Compressor of Gases," 1931, more complete and more interesting results are presented. However, great difficulties will be encountered in reducing to practice the powerful devices for cooling required by multistage compression. Here, the calculations are insufficient.

At the end of the article "Pressure on a Plane" Tsiolkovskiy presents a table of permissible flight velocities without showing the calculations used to obtain these velocities.

In the work "Semi-reactive Airplane" Tsiolkovskiy does not prove that the reaction obtained with an increased velocity of flight will be of sufficient magnitude for the flight. Flight will be possible only when the engine is sufficiently powerful. Although in the article "Reactive Airplane" an airplane with a large engine is described, the calculations are subject to the error mentioned above. In this case the work expended on compression must be approximately eleven times greater than the value computed by Tsiolkovskiy. Nevertheless, within certain limits the construction of the airplane may find an application.

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[1]Tsiolkovskiy designates this quantity by the letter A.

Tsiolkovskiy's scheme for a reactive airplane requires proof that, from the aerodynamic point of view, the shape proposed by him is sufficiently advantageous to give desired results, together with the advantages of light weight and simplicity of construction. In general this proposition is quite interesting.

In the book "Investigation of Universal Space" Tsiolkovskiy omitted a factor x in the expression for the differential work performed by the resistance of the atmosphere. As a result, the integral for the work is incorrect and has two variables, whereas it should be a much simpler integral with only one variable. The corresponding places on the subsequent pages were corrected by me, and Table 10 pertaining to the remaining work of atmospheric resistance was changed in a corresponding manner. /363

In his books "A Rocket into Cosmic Space" and "Investigation of Universal Space" Tsiolkovskiy comes to the conclusion that there is a definite optimum flight angle. In the book by Oberth "The Roads to Cosmic Flight" ("Wege Zur Raumschiffahrt," 1928) there is a different conclusion, according to which for the unmanned flight of a rocket the optimum flight path is vertical, while for a rocket with passengers the optimum flight is along a special curve which he has called synergetic. However, the two results do not contradict each other since Tsiolkovskiy assumed that the acceleration of the rocket would be constant, while Oberth assumes a variable acceleration for the unmanned rocket, such that there is a maximum increase in the velocity at each moment of time at a given altitude and with a given expenditure of fuel; in other words, he determines the optimum velocity of flight. For passenger rockets Oberth also assumes a maximum accleration which can be withstood by human beings. Tsiolkovskiy computes all of the work required for the ascent and for overcoming the atmospheric resistance, and in this way obtains an average optimum slope for flying through the entire atmosphere. Oberth computes the optimum slope for each instant of time and therefore obtains a curved line for the trajectory.

The special feature of Tsiolkovskiy's books, which makes it difficult to read them rapidly, is that the designation of mathematical quantities are made by the abbreviation of corresponding words, using two or three Russian letters. This is due to the fact that the Kaluga printing house had a shortage of Latin letters and mathematical symbols. All of these symbols have been replaced by those in common usage. In the book called "A Rocket into Cosmic Space" and at the beginning of the book "Investigation of Universal Space," where Latin letters were used in the equations, they have been left without changes.

In the book "A Rocket into Cosmic Space" the drawing of the rocket was replaced by a drawing made by Tsiolkovskiy himself. This was done because, as he developed his work, Tsiolkovskiy dropped the convolutions which existed on the replaced drawing and which were to be used in ... to attain the stability. /364

In the book "Cosmic Rocket. Experimental Preparation" we have omitted a section in which Tsiolkovskiy develops an idea which is not absolutely correct. This idea concerns a definite constant temperature of dissociation and the fact that the temperature of combustion of hydrogen is less than the temperature of combustion of carbon.

The question of life in a space ship and of the program for constructing an interplanetary ship have been only partially retained in the present collection of works.

The works of Tsiolkovskiy are extremely varied and because he generally published short articles (except for the book "Investigation of Universal Space," which comprises five printer's pages), there are many ideas and calculations in various places. Tsiolkovskiy himself does not give an entirely clear, easily comprehensible line of demarcation between the various calculations, which makes it very difficult to look for specific design data in his works.

The New Airplane

In his work "The New Airplane" Tsiolkovskiy tries to use simplified equations to take into account all the quantities important for the flight of the airplane. In doing this he makes simplifications of the following nature:

(a) the weight of the shell is determined as the weight of the cylinder (19);

(b) the area of the horizontal projection of the airplane's wing is determined as a projection of a cylinder (20);

(c) the loads due to the weights of (1) shell, (2) engines and control devices, (3) fuel with tanks, (4) people and cargo, and (5) supplies are assumed to be equal to each other, so that each load represents 1/5 of the total weight (23);

(d) the stresses in the shell are computed on the assumption that it is a cylinder (24);

(e) the pressure on the plane normal to the load is obtained from the Langley equation (28), which is not correct for many profiles.

The equations lead Tsiolkovskiy to a series of definite conclusions concerning the velocity of flight, the required specific power of the engine, the load lifting capacity, etc.

It should be pointed out that calculations of this general nature are applicable for a specific type of airplane. The work in question may be useful to obtain approximations; however, to obtain results useful in practice it is necessary to carry out the calculation by means of graphs rather than equations. Then the simplications which Tsiolkovskiy made may be invalid; for example, instead of the equal loads we may have to assume that the loads are exactly what they have to be to realize the actual construction of the airplanes. Similarly, we shall get different results by using different types of engines: it is necessary to take the actual weight of an engine for various horsepowers.

The end of the work describes a series of airplanes of various types.

In regard to the special type of airplanes proposed by Tsiolkovskiy, we should point out that in view of the feasibility of experiments with models of airships it will also be possible to determine the flight characteristics of the proposed airplanes. However, the experiments must be carried out with curved shapes and with a train of such shapes. Apparently it will be necessary to cover the entire airplane with a streamlined shell.

The work is of considerable interest, and its inclusion in the "Selected Works" should stimulate investigative work in the direction proposed by Tsiolkovskiy.

Projects of this type are appearing abroad.

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