History of Rocketry and Astronautics

Proceedings of the Fifteenth and Sixteenth
History Symposia of the International Academy of Astronautics

Rome, Italy, 1981
Paris, France, 1982

Roger D. Launius, Volume Editor

R. Cargill Hall, Series Editor

AAS History Series, Volume 11

A Supplement to Advances in the Astronautical Sciences

IAA History Symposia, Volume 6

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 1994

ISSN 0730-3564

ISBN 0-87703-382-X (Hard Cover)
ISBN 0-87703-383-8 (Soft Cover)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198

Printed and Bound in the U.S.A.

Chapter 14

Konstantin Eduardovich Tsiolkovsky and the Present Times[1]

A. A. Kosmodemjansky[2]

The present brief paper is concerned with the analysis of the forecasts drawn from the fundamental discoveries and designs made by Konstantin Eduardovich Tsiolkovsky—a leading scientist and pioneer of spaceflight from Russia (Figure 1).

K. E. Tsiolkovsky was born on 17 September 1857 to the family of a forester in a village called Izhevskoye, in the district of Spassk, Rjazan province. Recalling his childhood, Tsiolkovsky wrote in his autobiography: "I loved reading passionately, and I read whatever books were available . . . I indeed liked to immerse myself in dreams . . . In my dreams I was taking high leaps, climbing up poles or ropes like a cat. Absolute lack of gravity was my dream."[3]

When ten years of age he was taken ill with scarlet fever. The illness became serious, and he nearly lost all of his hearing. "Because of deafness," he recalled, "my biography is but of low interest, since I was deprived of personal contacts, and hence of observations and adoptions. My biography is poor in personalities or personal intercourse."[4] From age 10 to 14 Tsiolkovsky reported that his experience was "of the most melancholy mood, being the darkest period of my life. . . . Nothing to speak of well during that time."[5] When about 14 years of age, while borrowing books from his fa-

[1] Presented at the Sixteenth History Symposium of the International Academy of Astronautics, Paris, France, 1982.

[2] U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

[3] K. E. Tsiolkovsky, "Features from my life," *Collections of K. E. Tsiolkovsky*, (Moscow: Aeroflot, 1939), p. 19.

[4] *Ibid.*, p. 20.

ther's library, he came across a work on arithmetic, and started studying it. It came easily to him, and he immersed himself in the reading of other books concerned with natural and physico-mathematical sciences. He recalled:

> I was enthralled with an astrolabe, taking a great interest in measuring distances to inaccessible objects, in taking plans, finding heights. And I had set up an astrolabe-goniometer. With the aid of this instrument, without leaving home, I had identified the distance to a fire-tower. I found it to be 400 arshins. Then I go out and check. Proved correct. From that time on I put trust in theoretical approach.[6]

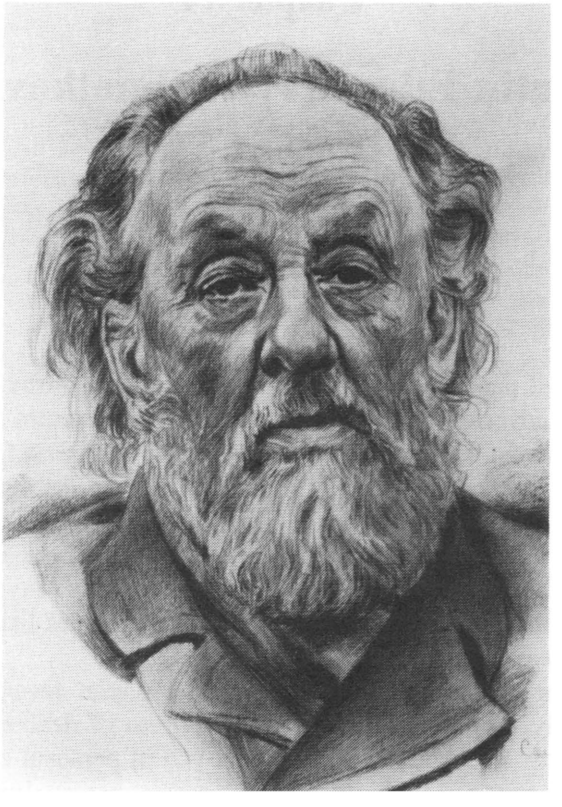

Figure 1 Konstantin Eduardovich Tsiolkovsky (1857-1935), father of Russian cosmonautics and space philosopher. Courtesy of NASA History Office.

[5] *Ibid.*, p. 23.

[6] *Ibid.*, p. 24.

The inquiring mind and gift for original reflection manifested by young Tsiolkovsky were noted in the family, and his father urged him to move to Moscow, where the young man had made up his mind to study by himself. For three years, while working in libraries (from 16 to 19 years of age) he thoroughly studied courses in mathematics and physics. When 17 years old, he already "had perused courses in higher algebra, differential and integral calculus, analytical geometry, spherical trigonometry and the like."[7] At the same time he was preoccupied with varied scientific and engineering problems, and he did his best to resolve these with the aid of the knowledge acquired.

It was during these years that an idea arose in his mind as to how a person might fly within the atmosphere of the terrestrial globe as well as in outer space, by utilizing the properties of centrifugal forces. A machine, as conceived by Tsiolkovsky, would be comprised of a box (a cabin) wherein two pendulums with massive balls at the end of the rods were to execute an oscillating motion, while being mounted vertically upward, with the balls at the top. According to the concept developed, centrifugal forces produced by the oscillating rods would lift the cabin, carrying it over boundless distances into outer space. "Having conceived such a machine, I went into raptures over my invention," he remarked:

> and being unable to keep my seat I went outdoors to vent off the joy which could nearly choke me. An hour or two I was rambling about the streets of Moscow at night, meditating and verifying my discovery. Alas . . . The delusion vanished yet in the streets. However, the burst of ecstasy was so stunning, that throughout my whole life I saw this machine in my dreams: it was indeed an extraordinary fascination to levitate with the help of this craft.[8]

It is worth noting here that this faulty idea set forth by young Tsiolkovsky as to how to give motion to a flying vehicle through the action of inner (with respect to a given mechanical system) forces, cannot escape the minds of some contemporary inventors up to the present day. "Further fuel to the already blazing fire" had been added by some Russian popular scientific periodicals, which published inaccurate information on the invention made by an American. Suggestions had been made to exert motion to the center of mass of a mechanical system with the aid of a "rectifier of centrifugal forces" (a copy of Tsiolkovsky's idea), and to develop a range of apparatuses ("Inertiacidos") which were supposed to refute by way of experiment the law of conservation of momentum of a mechanical system without any external forces. In fairness, it took Tsiolkovsky but a single night to realize the falsity of his suggestion, while years are sometimes not enough for our contemporary inventors to give a fair analysis to their errors.

---

[7] *Ibid.*, p. 25.

[8] *Ibid.*, p. 26.

To follow a poorly grounded tradition in dwelling upon the incentives from which Tsiolkovsky's interest arose, in developing a theory of jet propulsion, one should mention the writings of Jules Verne and A. Fodorov, however, there are evidences that rocket dynamics and astronautics were dreamed about by Tsiolkovsky as early as his teen years.

He wrote in the "Introduction" to his *Exploration of Outer Space by Means of Jet Apparatuses* (1911-1912):

> It seems to me—wrongly, I believe—that the basic ideas and an unceasing flame rushing there—towards the Sun, releasing from the bonds of gravity, were within me from the very birthday. At any rate, I remember quite clearly that in early childhood, prior to books, my favorite dream was to dimly realize a medium free-of-gravity, where one can freely move towards any direction, feeling himself better than a bird in the sky.
>
> Up till now I cannot comprehend where these desires came to me from; there are no such fairy-tales either, but I had a dim faith, a sensation of and a desire for this very free-of-gravity medium. An old sheet of paper in my manuscripts comprising final formulae relating to a jet apparatus is dated as of August 25, 1898. Clearly, I had been previously concerned with such an apparatus.[9]

We are in a position to prove from archives and published papers that it was as early as 26 years of age when Tsiolkovsky realized that a rocket is an apparatus with the aid of which mankind "would timidly penetrate beyond the atmosphere, subsequently conquering for his own sake the entire circumsolar space." In 1954, the Soviet Union published a scientific diary compiled by Konstantin Eduardovich Tsiolkovsky, titled *Free Space*, all the entries thereto were made in the year of 1883. This diary includes considerations given to regularities inherent to the simplest phenomena of mechanical motion which is not affected by gravity or forces of resistance produced by a medium (aerodynamic forces). The basic conclusion arrived at by Tsiolkovsky is as follows: within a free space, the most rational way of imparting motion to some stationary object ("body"), or of changing motion being executed by a body is to throw off particles of a matter, i.e., with the aid of a reactive force. Should one be able to direct, at will, a jet along any of the three mutually normal directions, one would be capable of ensuring any curvilinear motion of the body.[10] Incidentally, as early as in 1883, Tsiolkovsky clearly realized that the simplest way of setting or changing motion within a free space was to utilize the reaction of an out-flowing gas jet.

In his first publication concerned with the theory of jet propulsion, titled *Exploration of the Outer Space by Means of Jet Apparatuses* (1903),[11] Tsiolkovsky derived a number of fundamental formulas, which enable one easily to mathematically establish the flight performance of rockets. Tsiolkovsky's formula, which gives the maximum

---

[9] K. E. Tsiolkovsky *Selected Works* (Moscow: U.S.S.R. Academy of Science, 1962), p. 167.

[10] *Ibid.*, pp. 11-12.

[11] *Ibid.*, pp. 136-66.

capabilities of the jet-propulsion technique of imparting motion within a free space, has enjoyed world-wide fame.[12] Using the up-to-date designations, this formula can be written as follows:

$$\vartheta_{max} = V_r \ln (1 + Z) \cong 2.3\ V_r \lg (1 + Z) \quad (1)$$

where ϑ_{max} is the maximum velocity of the rocket; V_r is a constant relative velocity of exhausted particles; $z = m/M_k$ is Tsiolkovsky number (m = mass of fuel within the rocket; M_k = mass of the rocket without fuel). If for example, $z = 9$, and $V_r = 3440$ mps, then $\vartheta_{max} = 7912$ mps, i.e., equal to the orbital velocity as applied to the planet Earth.

A critical part of Tsiolkovsky's work was a 1903 essay, titled "Among gravity: Vertical return to the Earth," where he first calculated formulas for establishing a storage of propellant required for a "soft" landing onto a planet without atmosphere.[13] He developed a relatively simple solution to the problem of establishing a propellant tankage capacity for a rocket which must acquire velocity ϑ_1, within a free space, and then suppress it. The formula is as follows:

$$\frac{M_{init}}{M_{fin}} = (1 + Z_1)^2 - 1 \quad (2)$$

where Z_1 is Tsiolkovsky number, which ensure the attainment of velocity ϑ_1.

If, as is the case for the previous example, $\vartheta_1 = 7912$ ($Z_1 = 9$), then $M_{init}/M_{fin} = 100 - 1 = 99$. This means that to reduce soft landing into practice calls for a rather large storage of propellant, being as yet impractical as applied to a single-stage rocket. Note, that unfortunately it is rather seldom that a rudimentarily simple formula (2) given by Tsiolkovsky is mentioned in our home literature on rocket dynamics.

If we assume that the field of gravity of a planet (for example, Earth) is uniform with a certain range of altitudes, and that free fall acceleration is constant, being equal to $g = 9.81\ m/s^2$, then, provided that acceleration accounted for by a reactive force is also constant,[14] being equal to p, we set:

$$\frac{M_{init}}{M_{fin}} = \left(1 + \frac{pZ_1}{p - g}\right)^2 - 1 \quad (3)$$

---

[12] It will be noted here that in his science-fiction story "Beyond the Earth" (the first part of which was written in 1896) K. E. Tsiolkovsky considered motion of a rocket within a uniform gravity field, presuming that at the ascending powered rectilinear section of the flight, acceleration of the center of mass of a rocket will be at a constant level. In this case, equation for the motion of the rocket will be $Ma = \phi - Mg$, where a = const, $\phi = -dM/dt\ V_r$ – reactive force, g = const, is the force of gravity. Thus $dM/M = -[(a + g)/V_r]dt = -adt$ and $M = M_o e^{-\alpha t}$, where α = const., i.e., in this case, mass of the rocket will be changed according to the potential law. This case had been analyzed by K. E. Tsiolkovsky in great detail in his work published in 1903.

[13] Tsiolkovsky, *Selected Works*, pp. 158-161.

[14] In this case, the reactive force must be proportional to the mass of a rocket, and hence, the mass of the rocket would be changed according to the exponential law.

If $p = 4g$, and $z_1 = 9$, then $M_{init}/M_{fin} = 168$, which conclusively shows how difficult it is to fulfill a soft landing onto a free-of-atmosphere planet which has a gravity field similar to that of the Earth.

In 1929, Tsiolkovsky, taking into account the practically attainable velocities of particles exhausted from a nozzle of a jet engine (i.e., real values for v_r), developed a theory for multistage rockets (or "rocket trains" as he called them), having proved through a strict mathematical way that even with practically attainable figures for z one can achieve fairly high ratios between the initial mass of a rocket and its final mass.[15] We will point out here that the U.S. Apollo used this case in performing a soft landing onto the surface of the Moon, followed by successful return to the Earth:

$$\frac{M_{init}}{M_{fin}} = 3140/5 = 628$$

We would also like to point out here that the upper stages of the modern large ballistic types of rockets can be converted to winged flying vehicles that can then be employed in making intercontinental passenger flights in minimal time. From the theory of elliptical trajectories, the flight time could be established (approximately, taking no account of the atmosphere) as given in Table 1 below.[16]

Table 1

Distance of Flight (Kilometers)	Maximum Time of Flight
5,566	22 min 06 sec
10,019	32 min 14 sec
15,585	40 min 13 sec
20,038	42 min 13 sec

As can be seen from the formula given by Tsiolkovsky, the increase in the maximum velocity of a rocket can be achieved by means of increasing either the relative velocity v_r of particles being exhausted, or Tsiolkovsky number z. One can immediately appreciate that to improve v_r calls for advanced design of jet engines and for higher calorific power of the propellant components (combustible fuel and oxidizer).

Today, in modern U.S. laboratories, scientists have tested many promising fuel pairs for liquid-propellant rocket engines as:

1. Liquid fluorine + liquid hydrogen ($v_r = 4500 - 4700$ m/s is achieved);

[15] Tsiolkovsky, *Selected Works*, pp. 367-393.

[16] A brief description of the optimum elliptical trajectories can be found in A. A. Kosmodemjansky, *Course of Theoretical Mechanics* (Moscow: U.S.S.R. Academy of Sciences, 1975), Part 1, pp. 246-265.

2. Combination propellant: liquid fluorine + liquid hydrogen + lithium (v_r up to 6000 m/s is achieved).

Rocket engineers all over the world are dreaming of mastering monatomic hydrogen (estimated exhaust velocity v_r is up to 10,000 m/s), as well as of developing and mastering gaseous-phase reactors with the process medium (hydrogen), whereby an estimated v_r = 20,000 to 25,000 m/s can be achieved.

Simple calculations show that for v_r = 20 000 and $z = 9$, maximum velocity of a rocket in a free space will be ϑ_{max} = 2.3 (20,000) lg (10) ≅ 46 km/s.

To develop gaseous-phase reactors for the practical purposes of employing them in jet engines *shall mark an advent of a new era as far as interplanetary communication and mastering of the circumterrestrial outer space is concerned.*

Even with the already tested combination propellants ($F_2 + H_2 + Li$) maximum velocity of a single-stage rocket will be ($z - 9$) ϑ_{max} = 13,800 m/s, i.e. higher than the escape velocity (ϑ_r = 11,189 m/s).

This demonstrates that in years to come, single-stage rockets shall play a decisive role in mastering the circumterrestrial space (with due regard for losses due to gravity and resistance exerted by terrestrial atmosphere). We think that the major achievements or "milestones" in cosmonautics are as follows:

1. Launching of the first man-made satellite *Sputnik I* (1957, U.S.S.R.);
2. Flight made by Yuri Gagarin—the world's first flight ever made by a man at space velocity (1961 U.S.S.R.);
3. The first space-walk completed by a man (A. A. Leonov)—flight made by P. I. Beljaev and A. A. Leonov (1965, U.S.S.R.);
4. Launching of the first geostationary satellite of the Earth (1963, U.S.A.);
5. First men on the Moon (N. A. Armstrong and B. Aldrin) (1969, U.S.A.);
6. Launching of the first long-term orbiting stations (1971, *Salyut 1*, U.S.S.R.; 1973 *Skylab*, U.S.A.);
7. Successful flights of automatic interplanetary stations to the nearest planets of the solar system—Venus and Mars (1961-1977, U.S.S.R. and U.S.A.);
8. Creation of the world's first scientific and research space complex "*Salyut 6*", *Soyuz 26* and *Soyuz 27* (1977-1978, U.S.S.R.);
9. The longest flight (185 days) of the orbiting scientific and research complex *Salyut 6/Soyuz* (pilot-cosmonauts L. I. Popov, V. V. Ryumin).

Tsiolkovsky understood that his works were the source of revolutionary transformations in both science and engineering. In 1924 he wrote: "We witness that European science literally supports my conclusions both on a full possibility of space travel, and a possibility of setting up there [in outer space] dwellings, inhabiting the solar system. The latter yields two billion times the solar energy received by the Earth. Things are flaring up, and I have sparked off that fire."[17]

[17] Konstantin Eduardovich Tsiolkovsky, *The Rocket to Space* (Kaluga: 1924), p. v.

We should like to specifically emphasize the breadth and versatility of the talent possessed by Tsiolkovsky, as well as a great variety of scientific and engineering problems analyzed by him. An idea of the many-sided creative work done by this scientist and thinker can be gathered from the four volumes of the Collection of his works (published by the U.S.S.R. Academy of Sciences, 1951-1964).

Tsiolkovsky clearly understood the importance of his major works for the further advance of science and engineering. He saw "seductive and important prospects" for the advance of rocket engineering and cosmonautics. He knew that experimental aerodynamics is quite an indispensable component of the successful development of aviation and aerostation. He had discovered a reliable and strictly scientific way of mastering the cosmos and the circumterrestrial space. His research in the theory of multi-stage rockets has shown how to achieve space velocity of flight while employing commonly used propellant combustibles and oxidizers. During the last years of his life he published a variety of works relating to high-velocity aviation, and it was he who uttered the prophetic words that the era of propeller-driven aircraft shall be followed by the advent of the era of jet aircraft or "stratospheric" aircraft; he also anticipated the idea of developing vehicles riding on air cushions.

His astute mind was also interested in many problems of biology. In his remarkable paper "Plants of the Future," he pointed out that the major factor identifying the value of a plant used by a man for nourishment is the process of assimilating solar energy. Assuming that the corn yield provided by one hectare is one ton, then, as estimated by Tsiolkovsky, it turns out that the harvest would comprise but 1/6000 of energy received by the hectare from the Sun per year. In his writing "Plants of the future" he presented the following observation: "Wheat utilizes 0.016 percent energy received from the Sun. Banana utilizes 1.6 percent, i.e, 100 times that of wheat. The Burbank cactus utilizes up to 29 percent."[18]

In addition, Tsiolkovsky outlined a far-reaching program of mastering solar energy by means of *new* plants specifically developed for the purpose. He emphasized the poor efficiency or imperfectness of plants known at present, and placed a specific significance on the fact that they waste a lot of solar energy to overheat leaves, fruits, trunk, and branches.

He argued that the atmosphere of the Earth is poor in carbon dioxide (CO_2), which is necessary for growing plants and ensuring their good crop capacity; from the above follows the importance of designing green houses with a high CO_2 percentage.

[18] Konstantin Eduardovich Tsiolkovsky, "Plants of the Future," in his *Collection of Writings* (Moscow: U.S.S.R. Academy of Sciences, 1964), 4: 286-294.

We must point out unfortunately, that biologists do not pay enough heed to these writings of Tsiolkovsky. Academician A. E. Fersman, remarked, for instance:

> The article is of interest in its analysis given to the nature and life of plants, and in the emphasis made on those negative aspects which must be improved with respect to the energy equilibrium and chemical behavior of vegetable organisms . . . A brilliant idea which, as I presume, had not been ever set forth in this way prior to Tsiolkovsky.[19]

Tsiolkovsky was a meticulous and single-minded researcher. Indeed, his associates were amazed at his passionate animation and flights of creativity, his obsession with whichever problem was under study. He used to joke that deafness saved him from mean-spirited irritations generated by his surroundings, but allowing for overstatement, that may have helped him to immerse himself into his own reflections so thoroughly. He possessed a good memory, an encyclopedia-like mind, and a marvelous capacity for work. In studying his writings one is startled with both his strength of thinking and of feeling. His 1913 statement seems a fitting testament of his activities: "Life presented me much grief, and it was only my soul, which was boiling with a joyful world of ideas, that helped me overcome these misfortunes."[20] He worked daily, notwithstanding some severe life situations: poverty, loss of his near ones, mockery on the part of his colleagues/teachers and others in the streets of Borovsk and Kaluga towns, hunger and cold suffered during the Civil War, inability to publish writings ready for publication, through which writings he strived to bring his dearest ideas to his people.

Four months before his death, Tsiolkovsky broadcast to the Soviet Union a statement about his hopes for the future. He said: "Heroes and bold spirits will pioneer the first space route: Earth-orbit of Moon, Earth-orbit of Mars, and still further: Moscow-Moon, Kaluga-Mars." Since that time, many of the ideas presented by Tsiolkovsky have been taken up by scientists and engineers and have helped to chart the present course of the Soviet Space program.

---

[19] A. E. Fersman, "Analysis of General Writings by K. E. Tsiolkovsky," in *K.E. Tsiolkovsky, Collected Writings*, 4: 423-451, quote from pp. 335-346.

[20] Konstantin Eduardovich Tsiolkovsky to J. I. Perelman, 8 September 1913, in Archives of the U.S.S.R. Academy of Sciences, f. 796, reg. 3, file 23, pp. 1-2.