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COMPARATIVE ANALYSIS OF THE DESIGNS AND IMPLEMENTATION
OF VEHICLES BASED ON REACTIVE PROPULSION PROPOSED DURING THE
NINETEENTH AND BEGINNING OF THE TWENTIETH CENTURIES⁺

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In studying the history of rocket technology, the question arises: to what extent were the ideas and proposals expressed during the nineteenth and beginning of the twentieth centuries actually realized? This report is devoted to a preliminary investigation of this question.

Examination of the presently known historical scientific literature related to the problem of reactive flight indicates that considerable attention had already been given to this problem in the nineteenth century—suffice it to say that about 30 designs for reaction flying vehicles were proposed during this period. Inventors were attracted by the apparent simplicity of the solution to the problem of flight with engines based on the reaction principle. However, the authors of a majority of the designs limited themselves only to a presentation of a diagram of the engine or an account of the principle of its operation, giving neither plans for its structural development nor precise calculations of the amount of energy required for accomplishing reaction flight. Such an approach was typical of the nineteenth century and is indicative of the extremely low level of theoretical development attending this problem. None of these authors considered the reaction flying vehicle as an object of variable mass, their choice of energy sources was extremely random, and the theory of the flight of reaction flying vehicles remained completely undeveloped.

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An analysis of the designs of reaction flying vehicles developed and proposed in the nineteenth century (Table 1) shows that they can be divided into three groups, depending on the method for producing lift (the horizontal motion for the vehicles of all three groups was accomplished due to the reaction of ejected particles of matter):

Group one--aerostatic principle--lighter-than-air reaction flying vehicles; the lift is produced with a gas lighter than air.

Group two--aerodynamic principle--heavier-than-air reaction flying vehicles; the lift is produced by the flow of air around the support surfaces (wings).

Group three--rocket-dynamics principle--heavier-than-air rocket flying vehicles; the lift is produced by the reaction of ejected particles of matter.

The principle difference between vehicles in the second and third groups is that the atmosphere is necessary as a supporting medium for the flight of vehicles in the second group, whereas the atmosphere is not only unnecessary, but even detrimental, for vehicles in the third group, i.e., it produces additional drag.

Flying vehicles of the first group--reaction aerostats--appeared unpromising and did not undergo further development. Refinement of vehicles of the second group led eventually to the creation of jet aviation, while the vehicles of the third group led to the creation of long-range rockets.

It is also of interest to divide the proposed designs into groups depending on the energy source. As proposed, such sources included: compressed air or other gas, water or alcohol vapor, and also combustible products which divided themselves into three subgroups corresponding to solid-propellant rocket engines (SPRE), liquid-propellant rocket engines (LPRE), and jet engines (JE). From the point of view of examining energy sources, the greatest interest attaches to the designs of S. S. Nezhdanovsky who, during the first half of the 1880s, proposed a design of a liquid-propellant rocket engine operation with double-component propellant.¹ Liquid hydrocarbons served as the fuel, and nitric acid or nitric oxides as the oxidizer.

The development of designs for reaction flying vehicles in individual countries did not always coincide with the general direction of development of the ideas of reactive flight in the nineteenth century. Thus, for example, designs of vehicles belonging to the first group (reaction aerostats) predominated mainly in France, Italy, and the USA, while designs of vehicles belonging to the second group (reaction aircraft) predominated in England and Germany. Together with vehicles belonging to the first two groups, much consideration (six designs) was given vehicles belonging to the third group in Russia. Work on such vehicles was also conducted in Spain.

Vehicles in group three are of the greatest interest for the history of astronautics, i.e., they did not require the atmosphere as a supporting medium and could

TABLE 1
PROPOSALS FOR THE CREATION OF JET PROPULSION FLYING VEHICLES SUGGESTED
DURING THE NINETEENTH CENTURY

Propellant Vehicle Group	Compressed Air or Other Gases	Water or Alcohol Vapor	Combustion Products		
			Single-Component Propellant	Liquid Fuel + Air Oxidizer	Liquid Fuel + Liquid Oxidizer
Lighter- than-air vehicles (reaction aerostats)	Tretesy /1849/ Sokovnin (1866) Nezhdanovsky <1882> Teyer (1884)	Tretesy /1849/	Italia (1831) Tretesy /1849/ MacLaret (1852) Petersen (1892) Beatty (1893)	Lebedev <1892>	
Heavier- than-air vehicles (jet air- craft)	Nezhdanovsky <1882>	Golightly (1841) Battler & Edwards (1867) Nezhdanovsky <1884> Ganswindt (1887)	Mafioti (1858) Evald /1886/	Teleshev (1867) Nezhdanovsky <1889>	
Heavier- than-air vehicles (rockets)	Nezhdanovsky <1889> Fedorov (1896)	Ganswindt (1887)	Arias /1872/ (1876) Nezhdanovsky <1880> Kibal'chin /1881/	Arias /1872/ (1876)	Nezhdanovsky <1882 - 1884>

Notes: 1) Dates of proposals contained in published works (books, articles, patents) are indicated in the table in parentheses (); dates of proposals contained in reports or demonstrated at exhibitions by / /; dates of proposals contained in unpublished manuscripts or authors' notebooks by < >.

2) The table does not include proposals of E. Zhir, V. Angius, Sh. Luvriet, S. M. Nemirovsky, V. D. Spitsin, and several other authors, i.e., in the materials at our disposal there are insufficient data about the operating principle and design of the vehicles they proposed.

be applied in principle for flight in the vacuum of space. However, in all of the designs presented above, the authors considered the application of the principle of reactive motion only for flight within the terrestrial atmosphere. Not one of them, including Arias, Kibal'chich, Nezhdanovsky, Ganswindt, and Fedorov, whose vehicles did not require the atmosphere as a supporting medium, raised the question about the possibility of applying these vehicles for interplanetary flight. This application was first proposed and scientifically justified by one of the greatest scientists of modern times, K. E. Tsiolkovsky, whose name is inseparably connected with the beginnings of rocket and space science and technology.

The end of the nineteenth and beginning of the twentieth centuries are characterized by increasing interest in the theory of interplanetary flight. Isolated works devoted to this problem appeared in a number of countries—mainly in Russia and Germany. The appearance of these works, whose authors first attempted to justify theoretically the possibility of flight in interplanetary space and proposed scientifically sound designs of spacecraft intended to solve this problem, indicates that the foundations of the theory of space flight began to be formed in just this period.

The urge of mankind to explore other worlds had previously arisen in earliest antiquity; however, for a very long time that urge was abstract and speculative in nature, and was embodied in the most fantastic flight proposals. This was caused in part by the repeatedly changing ideas about the structure of the universe, which went through a long and complex evolution—from the idea of geocentricity and the Earth as the only inhabitable celestial object, to the present physical picture of the universe. Only in the last century and a half, in connection with the development of science and technology, did technically more valid space flight designs begin to appear—in the forms of super long-range artillery, circular railways, a gigantic sling, etc. However, none of them could be realized in practice. Only at the end of the nineteenth century was the only realistic way for solving the problem found—using flying vehicles based on the reaction principle.

Tsiolkovsky became interested in the problem of interplanetary flight in the 1870's and 1880's, and in 1897² he derived the now widely known formula of rocket dynamics that bears his name and established the dependence between rocket flight velocity V_{\max} , discharge velocity of the products of combustion V_1 , the mass of the propellant M_2 , and the mass of the rocket structure M_1 :

$$V_{\max} = V_1 \ln \left(1 + \frac{M_2}{M_1} \right)$$

Of course rockets were well known long before Tsiolkovsky. They were used for fireworks and for delivering signals, for illumination, and as military ordnance. Many scientists and inventors worked on improving rockets, but not one of them proposed using them as a means for accomplishing interplanetary flight. On the other hand, many inventors, even before Tsiolkovsky, thought about the problem of flight in space, but none of them proposed using rockets for this purpose.⁺ Tsiolkovsky served to unite these two technical directions, justified scientifically the possibility of the application of the reaction principle for space flight, and developed the fundamentals of the theory of rocket dynamics.

At the beginning of the twentieth century a number of scientists and inventors, independently of each other as a rule and often not even aware of analogous proposals made by other authors, became occupied with the problem of space flight. Besides Tsiolkovsky and Ganswindt who began work in this area at the end of the nineteenth century, this problem occupied R. Goddard (USA), R. Esnault-Pelterie (France), H. Oberth (Germany), G. von Pirquet, F. von Hoefft (Austria), and other investigators (Table 2).

Considering the proposals in the theory of space flight suggested during the end of the nineteenth and the first third of the twentieth century, the very wide range of proposed energy sources is noteworthy—from solid propellants (dynamite cartridges and smokeless powder) to electrical and nuclear energy and radiation pressure. Also very typical, when considering the possibility of space flight, the authors of this group of designs gave much more attention to problems of determining the required amount of energy and the theoretical calculations of rocket flight.

An analysis of the Tsiolkovsky formula indicates that the most effective method for increasing the velocity of rocket flight is an increase in the discharge velocity of the products of combustion. Thus, efforts of scientists during this period were directed to the selection of the highest caloric propellants having the greatest caloric value. Starting from just these considerations, in 1903 Tsiolkovsky proposed liquid hydrogen and oxygen as propellant components. He calculated theoretically the value of the ideal discharge velocity equaling 5700 m/sec. "I do not know of a single group of substances," he said in justifying his choice, "which would liberate such a

⁺It should be noted that references to rockets used for flight to other celestial objects are encountered in several science-fiction works such as, for example, "L'histoire comique des états de la lune," Cyrano de Bergerac (1647 - 1650), "A Journey to Venus," Ashil Heriot (1865), and "From the Earth to the Moon," Jules Verne (1874). However, the topic of all these literary works was not scientific technical designs, but rather focused on the fantasies of the novelists.

TABLE 2
DESIGNS FOR ACCOMPLISHING SPACE FLIGHT PROPOSED AT THE END OF THE 19TH AND
BEGINNING OF THE 20TH CENTURIES

Energy Source	Achievement of Space Velocities			Launch From Orbital Station and Flight into Space
	Using Single-Stage Rockets	Using Multi-Stage Rockets	Launch From Flying Vehicles	
Solid propellant	Ganswindt / 1893 / (1899) Oberth <1909>	Goddard (1919)	Ganswindt <1901>	
Liquid propellants	Hydrocarbons + oxygen	Tsiolkovsky (1914)	Oberth <1918> Tsiolkovsky (1929)	
	Hydrogen + oxygen	Tsiolkovsky (1903) Goddard <1907 - 1909> Oberth <1912> (1923) Kondratyuk 1917 - 1919 Tsander /1923/ (1924)	Oberth (1923) Tsiolkovsky (1926 - 1929) Hoefft (1928)	Tsiolkovsky (1918) Oberth (1923) Tsander /1924/ Hoefft (1928)
Metals (structural material)	Tsander <1909>	Kondratyuk <1920> (1929)	Tsander (1924)	
Nuclear energy	Tsiolkovsky <1903 - 1911> (1912) Goddard <1907> Esnault-Pelterie /1912/ (1913) Tsander <1925>	Bing (1911)		
Electrical energy				Goddard <1906> Tsiolkovsky <1911> (1912) Ulinsky <1915 - 1916> (1920) Kondratyuk <1917> Tsander /1926/ Glushko /1928 - 29/ Oberth (1929)
Radiation pressures				Kondratyuk <1917> Tsiolkovsky <1921> Tsander /1923/ (1924)
Energy source not indicated		Goddard <1907>	Goddard <1907>	Pirquet (1928)

Note: Dates of proposals contained in published works are indicated in the table in parentheses (), dates of proposals contained in oral reports and materials presented before various organizations are indicated in / /; dates of proposals contained in unpublished manuscripts and notebooks are indicated in < >.

tremendous amount of energy per unit mass of products with their chemical combination."³

This same propellant was later considered by R. Goddard (1907-1909),⁴ H. Oberth (1912-1923),⁵ Yu. V. Kondratyuk (1917-1919),⁶ F. A. Tsander (1923),⁷ and other investigators. However, the energy requirements of the propellant often conflicted with operational requirements. The application of such components as liquid hydrogen and oxygen involved great operational difficulties. Moreover, during the first quarter of the twentieth century the production of liquid hydrogen in quantities sufficient for practical requirements did not exist. Thus, the authors of a number of designs discussed less caloric, but safer and more available propellants, replacing the liquid hydrogen with various hydrocarbons (such as, for example, alcohol, gasoline, kerosene, etc.).

Others soon learned that there are fuels having a greater caloric value than the combination of hydrogen and oxygen. In 1909 Tsander first arrived at the thought of the possibility of using the structural materials of the interplanetary craft as fuel.⁸ Beginning in 1917, he began experiments in the ignition of molten metals, and soon obtained numerical values of the caloric value of magnesium oxide and other materials.⁹ During 1920-1924, Kondratyuk also wrote about the possibility of using high-caloric metals as fuel.¹⁰ However, even this path—the application of high-caloric metallic fuel—did not make it possible to solve the problem of space flight during this time. Calculations indicated that single-stage rockets operating with chemical propellant could not (with a feasible mass ratio of propellant-to-structure) even achieve orbital velocity. Thus, scientists and inventors continued to search for other forms of energy significantly exceeding the energy of chemical propellants.

Nuclear energy was one such form. In one of the unpublished manuscript versions of the work "Exploration of Space with Rocket Devices," Tsiolkovsky had already indicated the possibility of using the energy of the atom, which upon disintegration releases "particles moving with the velocity of light (or close to it), i.e., 6000 times more rapid than particles of water vapor."¹¹ The proposal for the use of energy of atomic decay for space flight is also found in the manuscripts of Goddard in 1907.¹³ R. Esnault-Pelterie struck upon the possibility of using nuclear energy for space flight during this same year. He expressed this idea in a report given in November 1912, and published in 1913.¹⁴

Electrical energy is another promising form of energy for space flight, wherein the propellant is accelerated to very high discharge velocities in the rocket engine. Tsiolkovsky¹⁵ and Goddard,¹⁶ independently of each other, had already arrived at the idea of producing electro-rocket engines during the first decade of this century. Tsiolkovsky first published this idea in the journal Vestnik vozdukhoplavaniya (1912).¹⁷ Goddard conducted experiments directed toward producing an ion rocket engine in 1916-1917.¹⁸ In 1920, he obtained a patent for "A method of and means for producing

electrified jets of gas."¹⁹ During this same year, P. Ulinsky (Austria) publicly discussed his idea of producing an electron spacecraft,²⁰ an idea he had conceived during 1915-1916, as several authors have verified.²¹ The problems of using electro-rocket engines for space flight later occupied R. Goddard (1916-1929), Yu. V. Kondratyuk (1917-1919), K. E. Tsiolkovsky (1921-1925), F. A. Tsander (1926), P. Ulinsky (1927), V. P. Glushko (1928-1929), and H. Oberth (1929).

During the first third of this century, however, proposals to use these forms of energy for solving the problem of space flight could be considered only as potential developments; i.e., the state of technology did not yet permit creating the proposed engines in a form suitable for use in flying vehicles. Moreover, these low-thrust engines could find practical application only after overcoming the gravitational pull of the Earth and the escape of the flying vehicle into a space orbit. Thus, the problem of finding a practical near-term method for achieving space velocities continued to haunt the investigators.

A second way to increase the velocity of rockets, also following directly from the Tsiolkovsky formula, involves altering the passive mass of the rocket during flight. Analysis of the fundamental equation of rocket dynamics led to the conclusion that, to increase the velocity of a rocket in flight, it is necessary to eliminate unnecessary structural elements as soon as possible with the depletion of propellants, while retaining only those parts which are necessary for the subsequent normal functioning of the rocket. Starting with this, in 1909 Goddard arrived at the idea of multi-stage rockets.²² In 1911, A. Bing obtained a patent²³ for "A vehicle for investigating the upper layers of the atmosphere," that also contained this idea.²⁴ In 1912, Tsander also perceived the suitability of ejecting individual exhausted structural elements.²⁵ This same proposal is contained in the works of Kondratyuk of 1917-1919.²⁶

But the multi-stage rocket idea was expressed most completely in 1914 by Goddard, who obtained a United States patent for a two-stage rocket during this year.²⁷ In 1919, he proposed using a two-stage rocket for sending a projectile to the Moon.²⁸ The multi-stage rocket idea for space flight was later developed by Oberth, who considered it in detail in his work of 1923,²⁹ and by Tsiolkovsky, who developed in 1926-1935 the fundamentals of the mathematical theory of multi-stage rockets.³⁰

The use of the principle of multi-stage rockets permitted solving the problem of achieving space velocities in the shortest possible time. In fact, experimental work had already begun in the 1930s in a number of countries; an altitude on the order of 400 km was achieved in the 1940s with a two-stage rocket, and in 1957, the first

[†]In this connection, there is no patent of A. Bing in the Soviet Union. Information about his design is given on the basis of reference 24.

artificial satellite of the Earth was sent into orbit with the help of a two-stage rocket with five engines. Multi-stage rockets are now very widely used. However, the application of this principle did not completely solve the problem of eliminating the negative effect of the passive masses of the rocket. The unnecessary parts of the rocket were simply ejected, without bringing any benefit. Thus, other investigators began to consider the possibility of using these parts for increasing the active mass of a rocket (i.e., the mass of the propellant).

Tsander (1909),³¹ and somewhat later Kondratyuk (1920),³² gave an affirmative answer to this question, proposing the use of the structural parts of the rocket as additional fuel.⁺ This proposal was published in the 1920s,³⁵ although it has not yet received practical realization. Scientists and engineers at present cannot give a firm answer to the question about the probability of its implementation in the future. But this proposal was examined rather thoroughly in the 1920s, and excited significant interest.

The third method for solving the problem of achieving space flight velocities attracted great attention among investigators, particularly at the initial stage of the creation of the theory of space flight. It involved firing the rocket not directly from the Earth, but from a high altitude launch base which could be, in the opinion of the inventors working on this problem, either a high mountain or a flying vehicle that would raise the rocket to a significant altitude. Such a proposal was first suggested at the beginning of the twentieth century by G. Ganswindt, who proposed raising his spacecraft as high as possible with helicopters, and only then starting the rocket engine.³⁶ Analogous proposals (but with the use of aircraft-aerostats) were also suggested during the first quarter of the twentieth century by Goddard (1907),³⁷ Tsiolkovsky (1911),³⁸ Oberth (1923),³⁹ and von Hoefft (1928).⁴⁰

This approach attracted the attention of inventors because it would eliminate the necessity of overcoming the drag of the lower, denser layers of the atmosphere, and would therefore economize on the amount of energy required. However, its practical accomplishment presented significant difficulties, completely insurmountable at that time; indeed, it has not yet been practically employed.

⁺It should be noted that the notebooks of Goddard for 1908³³ and also his manuscript of 1913³⁴ contain mention of "rockets consisting almost entirely of propellant" or even "consisting completely of fuel." However, on the basis of material of Goddard at our disposal, it is not possible to respond unambiguously to the question whether the proposal in this case was the use of elements of the rocket structure as propellant or simply consideration of the theoretical case with negligibly small mass of the structure as compared to the mass of the propellant (or a hypothetical design case with a combustible shell), especially as there is no direct indication of the use of metallic fuel anywhere in the materials of Goddard known in the Soviet Union.

Using an artificial satellite of the Earth as an "intermediate station," (i.e., to launch a spacecraft from an artificial satellite) appeared more promising. This proposal is encountered in the works of a number of investigators. In 1928 von Pirquet considered the problem of using artificial satellites of the Earth as intermediate interplanetary stations in detail.⁴¹ Kondratyuk expressed a very interesting idea using an artificial satellite of the Moon as an intermediate base for interplanetary flights.⁴² The idea of using artificial satellites of the Earth as intermediate bases is very promising, and is an element in a number of present designs for reaching distant celestial objects. However, even today this proposal, though considered in numerous designs, has still not obtained practical realization (because of its complexity).

Some investigators also considered the Moon, the natural satellite of our planet, and other celestial objects as intermediate interplanetary stations.⁴³ As a rule, they started from the premise that elements would be found on them which could be used as propellant components. They also accounted for their significantly smaller mass (as compared to Earth), which made escape velocity possible with significantly smaller propellant consumption. However, none of the mentioned investigators considered the problems of obtaining and processing the required materials, preparation of the launch complex, and other operations related to the technical organization for preparing and launching spacecraft once on the Moon or another celestial object.

Scientists working on the solution of the problem of space flight during the first quarter of the twentieth century also suggested using radiation pressure for flight in interplanetary space.⁴⁴ They gave the completely correct relation between the periods of operation of engines of the various types. For flight to and from Earth, at times when it is necessary to overcome the gravitational attraction of the Earth and to impart significant accelerations to the spacecraft, they indicated that one should use the energy of chemical propellants; after escape into orbit and at a significant distance from the Earth, with flight in interplanetary space, one should use the energy of radiation pressure.

Consideration of the proposals made during the first quarter of the twentieth century on possible methods for achieving space velocities for space flight indicates a very wide range in the proposed form of energy, as well as the structural-component designs for spacecraft. During this time, the following questions were examined:

- . production of liquid-propellant rocket engines;
- . application of high-caloric metallic fuel;
- . other forms of energy (nuclear and electro-reaction engines, solar radiation pressure);
- . the structural material of the rocket itself as additional fuel;
- . application of multicomponent and multi-stage rockets;

- . intermediate interplanetary bases in the form of artificial satellites of the Earth and other celestial objects;
- . application of wings for a gliding descent to Earth and other planets having atmospheres;
- . the relative motion of celestial objects for acceleration or deceleration of spacecraft.

At the same time, other problems were also considered: the launch of spacecraft, determination of the optimum angle of launch, search for optimum trajectories and flight modes, spacecraft heating with passage through dense layers of the atmosphere, life support systems for the crew, return of the craft to Earth, analysis of flight trajectories of spacecraft, and a number of other scientific and technical questions related to the problem of space flight.

Thus, the works of the theoreticians of astronautics in the initial period of the development of rockets and space science and technology that ended in the 1920s provided the fundamental solution of the basic problems and established the principles of the theory of space flight before reliable rocket engines and rocket vehicles had been produced in any single country. At the same time, many investigators were separated from immediate practical problems and very often looked for solutions in such remote areas as using electro-rockets, nuclear engines, solar radiation pressure, and the like. During the development of the theoretical principles of space flight, many other problems were raised and solved separately from the main stream of the development of rocket technology, without which the practical solution of the problem of space flight would have been impossible.

At the end of the nineteenth and beginning of the twentieth centuries, to be sure, rockets were no longer used as military ordnance. Nevertheless, attempts were repeatedly made to reactivate this weapon, particularly in the years immediately preceding the First World War. The contemporary successes in the area of aeronautics and aviation augured a large military role for an air force in a future war. In this connection, attempts were soon made to produce a new type of military rocket for arming flying vehicles. Work was also conducted on producing rockets intended for field battles.

Analysis of the experimental work in the area of rocket technology carried out at the beginning of the twentieth century indicates that designers and inventors working on rockets had to solve, in essence, the same basic problems that confronted them in the middle of the preceding century: to increase the range and improve the accuracy of rockets. However, the progress achieved in other areas of technology now permitted solving many of these problems. At the beginning of the twentieth century, seamless steel cases began to find application in rocket construction and improved

measuring instrumentation began to be used. Methods for stabilizing rockets became more refined. The majority of projects at the beginning of the twentieth century eliminated guiding rods and replaced them with other forms of stabilization—by applying stabilizing surfaces or employing the gyroscope effect.

But the level of scientific knowledge in the area of rocket construction during this period remained as low as before. Most of those working on the creation of new forms of rockets were not acquainted with the theoretical works in the area of reactive motion, and in a number of cases held to naive, often erroneous ideas about the cause and nature of the reaction force. They did not even attempt to solve the theoretical problems related to the velocity and range of rocket flight and, as a rule, were completely uninterested in such concepts as the efficiency of the rocket engine itself, or the entire rocket as a whole.

A basic deficiency in almost all rocket designs at the beginning of the twentieth century involved the adherence, as before, to comparatively low caloric propellants, such as black powder, as the energy source. This hindered the progress of rocket technology and led to tactical, technical, and operating data that differed little in essence from the rockets produced in the middle of the nineteenth century (comparatively short range, significant scatter, premature rupture of the rocket case). Thus, the problem of producing military rockets comparable with rifled artillery had not been solved up to the First World War. Satisfactorily operating flare rockets also had not been produced. Further improvements in rockets called for replacing black powder with an improved, higher caloric rocket propellant. Replacing gun powder with a higher caloric rocket propellant—smokeless powder—had been discussed often at the end of the nineteenth and beginning of the twentieth centuries by B. T. Unge, R. H. Goddard, I. P. Grave, V. A. Artem'yev, and other investigators. The greatest successes in this direction were achieved by Goddard, who successfully carried out experiments with smokeless powder rockets with completely satisfactory results.⁴⁵

Rockets remained practically unused as war material during the First World War (except for individual cases of applying incendiary rockets against enemy aircraft). Other forms of rockets (signal, flare) were also little used during the war years. Attempts by various inventors to improve rocket projectiles were unsuccessful. Only at the very end of the war did Goddard develop and produce samples of successful, albeit experimental, military rockets.⁴⁶

At war's end, interest in rocket projectiles declined sharply and work on them in a majority of countries was discontinued. At the same time, interest in the possibility of using rockets for interplanetary flight increased significantly. Beginning in the 1920s, influenced by the works of Tsiolkovsky, Oberth, Goddard, and other investigators occupied with problems of space flight, an ever increasing number of

people began to think about the possibility of penetrating space; groups, unions, and scientific societies, joining people interested in these problems, arose in various countries as more investigators became involved in the scientific problems related to the implementation of space flight. Nonetheless, a majority of those working in this area erred significantly in estimating the possible time for accomplishing space flight (these estimates varied from a few years to several centuries)—either guessing much too soon, or much too far in the future.

One of the most complex problems confronting investigators in the area of astronomical theory involved the possible sources for financing space flight projects. This problem inevitably confronted anyone who attempted to move from theoretical speculation to the practical implementation of his idea. It is striking that virtually no one devoted himself to a clear accounting of what expenditures of effort and means were actually required for a program to accomplish space flight. However, it soon became clear that such expenses could not be managed by individuals, or by entire organizations, unless these organizations were interested in solving practical problems and obtaining concrete results. The renewed interest of military circles in rocket armament intervened.

At the end of the 1920s and the beginning of the 1930s, military interest made a definite impression on the subsequent development of rocket research and, to a certain degree, determined a break in the development of rocket technology. It also became clear during this time that space flight could not be accomplished in the immediate future, i.e., neither the contemporary scientific and technical potentialities nor the required material means were sufficient for this endeavor. The discrepancy between the high level of theoretical development and the contemporary technology limited by practical potentialities was very typical (at the end of the 1920s and beginning of the 1930s). Thus, the beginning of the 1930s marked a rather sharp transition, away from research directed toward space flight, and toward investigations of a strictly applied nature, directed toward the solution of specific problems confronting rocket technology.

Now, the development of rocket technology included a large group of investigators who could be referred to as the second generation of pioneers, who carried the burden of work in creating the first rockets of a new type (liquid propellant). To overcome the skepticism and guarded attitude of the broad masses, they had first of all to show that rockets actually could achieve specified altitudes and flight ranges. The specialists working during these years in the area of rocket technology directed their efforts mainly toward creating liquid-propellant rocket engines and ballistic rockets.

In the development of ballistic rockets (Table 3), one can clearly distinguish two main directions: solid-propellant and liquid-propellant rockets (SPRE and LPRE, respectively). The first of these—solid propellant rockets—continued the many

TABLE 3
BALLISTIC AND WINGED ROCKETS TESTED IN FLIGHT UP TO THE BEGINNING OF THE 1940s

Type of Propellant	Ballistic Rockets			Winged Rockets		
	< 50 kg	50 - 500 kg	> 500 kg	< 50 kg	50 - 100 kg	> 100 kg
Solid Propellant	RS-82 (1932) RS-132 (1933) Damblanc (1935) ARS (1935-1939) M-8 (1939) M-13 (1939)	Damblanc (1938-39) R-604 (1940-41) R-521 (1940-41)		Tilling (1932) 48/I (1934-35) 48/II (1934-35)	217/I (1936) 217/II (1936)	803 (1940)
Liquid Propellants	Gasoline (kerosene) + oxygen	Goddard (1926, 1928-1932) Repulsor (1931) ARS No. 2-4 (1933-1934)	Goddard "A" (1935) Goddard "LA" (1936) Goddard "LB" (1936-37) Goddard "LC" (1937-38) Goddard "P" (1939-41)			
	Ethyl alcohol + oxygen	GIRD-10 (1933) GIRD-07 (1935) RBD-01/2 (1936) R-03, R-06/B (1936-1938) ANJR-5 (1939)	A-2 (1934) "Aviavitro" (1936)	A-3 (1938) A-5 (1939)	06/III (216) (1936-37)	
Hybrid propellants	Kerosene + nitric acid (oxides of N)	R-604 (1940) R-521 (1940)				212/603 (1939) 803 (1940)
Ramjet engine (chemical propellant)	GIRD-09 (1933) GIRD-13 (1933)			06/I (1934) 06/II (1935-36)		
	Rocket of Merkulov (1939)					

centuries of development of military and pyrotechnic black powder rockets. However, in place of this unpromising form of propellant, the rockets of the twentieth century began to feature smokeless powder on a completely different basis—the so-called double-base powder consisting of nitroglycerin and nitrocellulose.

Double-base powders have a number of advantages: they possess higher caloric energy, are significantly less dangerous to handle, and withstand much longer storage times and significant variations in temperature. It is true that many disadvantages characteristic of the old powder rockets remained—the practical impossibility of regulating the thrust, the necessity of placing all the propellant in the combustion chamber, the impossibility of reigniting the engine, and the lower energy content of the powder as compared with liquid propellant. However, solid-propellant rockets also had a number of advantages, in particular their constant readiness, that permitted them to compete successfully in a number of cases with liquid-propellant rockets.

The second major direction—liquid-propellant rockets—was more promising for accomplishing space flight from the energy point of view, i.e., they could use much more energetic propellants. Moreover, the use of liquid propellants permitted their gradual introduction into the combustion chamber, which simplified the solution of whole series of structural and technological problems.

In an overwhelming majority of the rockets flight-tested during the 1930s, liquid oxygen, considered by investigators as most effective from the energy point of view and most promising for future space flight, was used as the oxidizer. However, its application involved significant difficulties of an operational nature. Moreover, under the specific conditions (with the scales of rockets of that time), the application of oxygen did not give the expected energy gain compared to the less caloric, but denser, higher-boiling oxidizers. This also resulted in the tendency to use high-boiling oxidizers in a number of designs which were more convenient in operational respects. The most successful work on higher-boiling nitric acid LPREs was carried out during this period in the USSR, where several dozen such engines were produced during the first half of the 1930s.⁴⁷ The best of these—ORM-50, ORM-52 and ORM-65—gave thrusts from 150 to 300 kg, with a specific impulse up to 210-215 sec. The experience in work on these engines was also later used for producing aviation LPREs.

In addition, a great variety of structural solutions, component designs, and methods for stabilization and control were typical for the liquid-propellant rockets of this time, because the theory of rocket design was still very poorly developed, and this work was almost exclusively empirical.

The initial period of liquid-propellant rocket development, which encompassed about 20 years (1926-1945), can be divided into three stages. The basic problem confronting investigators during the first stage (the end of the 1920s and beginning of

of the 1930s) was verification of the possibility in principle of producing liquid-propellant rockets. The main attention of investigators during these years was concentrated on producing an operational LPRE. After this problem was solved in principle by the efforts of scientists and designers of a number of countries (USA, Germany, USSR, etc.), and it was practically proven that a liquid-propellant engine could operate and produce a thrust sufficient for launching a rocket vehicle, a new problem confronted investigators: to provide for extended, safe, and reliable operation. This stage encompassed the mid-1930s. The engine remained the principal focus of attention of scientists and engineers working in the area of rocket technology during both the first and second stages.

During this second period the investigators occupied themselves with such problems as the selection of the most convenient propellants, the methods for their delivery to the combustion chamber, the organization of a stable burning process, provision for a sufficiently reliable cooling of the combustion chamber and nozzle, and other problems related to providing stable and reliable operation of the engine.⁴⁸ However, in the mid-1930s, when it became clear that the problem of producing a liquid-propellant rocket engine was basically solved (although a whole series of theoretical, structural, and technological problems remained), a new problem confronted investigators: the necessity of producing control systems capable of providing stable flight of rocket vehicles on a specified trajectory.

This problem was not new theoretically, i.e., the pioneers of theoretical astronautics had not ignored the problem of rocket vehicle flight control. However, there was no practical experience in working in this area, as there had been essentially no sufficiently thorough scientific investigation of this problem. During the third stage of development, compassing the second half of the 1930s and the beginning of the 1940s, even this problem was successfully solved in principle and, with consideration of the experience accumulated in producing automatic aircraft flight control systems, controllable rockets—already rather sophisticated for their time—were produced.⁴⁹

The significant increase in the scale characteristics of liquid-propellant rockets was also a distinguishing feature of this stage. While by the mid-1930s the thrust of LPRE tested in rockets did not exceed 30 kg, the maximum launch weight of rockets was no more than 165kg, and their flight range did not exceed 4-6 km; but rocket engines with a thrust of 25-27 T and ballistic rockets with a launch weight exceeding 12 T and flight range of about 300 km were produced in the 1940s during the latter stage.

Along with ballistic rockets, winged rockets were also developed and used comparatively widely during the 1930s for carrying out various experiments and flight investigations. They acted as an intermediate link between ballistic rockets and rocket gliders. Winged rockets were studied during this period in Germany (Tilling, 1932), in

the USSR (RNII, 1934-1939), and in other countries. Winged rockets were later used during World War II.

The problem of producing jet aircraft was also solved in principle during the 1930s. The first practical attempts to accomplish manned flight in heavier-than-air reaction powered vehicles occurred at the end of the 1920s, when the first reaction gliders and aircraft with SPRE were tested in Germany.⁵⁰ Inventors dwelt initially on solid-propellant engines (ordinary powder rockets) as the propulsion plants for reaction aircraft, largely because these were the only reaction engines checked in practice. Moreover, their simplicity, accessibility, and comparative adjustability of production played a great role.

However, engineers soon learned that solid-propellant aviation engines have a number of serious disadvantages which make it practically impossible to use them as the main propulsion plants of flying vehicles (they were used somewhat later as supplementary engines--launch boosters). These disadvantages include:

- . impossibility of regulating thrust or repeated starting of the engine;
- . comparatively low energy content of the solid propellants then known;
- . the high relative weight of the propulsion plant.

Thus, attempts to apply solid-propellant engines were soon abandoned, and a new proposal was suggested at the very beginning of the 1930s--to use liquid-propellant rocket engines having a number of advantages compared to SPRE as the main propulsion plant of flying vehicles. At the end of the 1930s and beginning of the 1940s, this proposal was realized with successful flights of such experimental aircraft and gliders as the He-176 (Germany, 1939), RP-318-1 (USSR, 1940) Me-163B-1 (Germany, 1941), BI-? (USSR, 1942), Northrop MX-324 (USA, 1944), etc. (Table 4).

The successful flight tests of aircraft with LPRE demonstrated the possibility of using this type of engine as a main propulsion plant. However, excessive fuel consumption made its application economically inefficient. Therefore, neither in this period nor later (even to the mid-1970s) did liquid propellant rocket engines become very widely applied in aviation as the main propulsion plants of aircraft flying within the Earth's atmosphere.

This particular subject has obvious interest, because even at the beginning of the 1930s, in selecting the best possible type of reaction engine for aircraft, a majority of inventors and designers dwelt on liquid-propellant rocket engines and not on jet engines that had a number of obvious advantages and, in the final analysis, later became the main type of aviation propulsion plants used for reaction aircraft. This question--why jet engines (JE) lagged in development--requires more detailed investigation. However, several preliminary conclusions can be expressed. An essential role

TABLE 4
JET PROPULSION AIRCRAFT AND GLIDERS TESTED IN FLIGHT FROM THE END
OF THE 1920s TO THE FIRST HALF OF THE 1940s

Engine Type	Jet Aircraft			Jet Gliders (Flying Laboratories)
	With 1 Engine	With 2 Engines	With 3-4 Engines	
SPRE				Valier-Opel (1928) Opel-Hetry (1929) Valier-Espenlaub (1929) Cataneo (1931)
LPRE	Henkel He-176 (6-1939) Messerschmitt Me-163B (4-1941) Bolkhovitinov BI-1 (5-1942) Northrop MX-324 (7-1944) Junkers Ju-248 (9-1944)		Oka-II (1944)	He-112 (1937) RP-318 (1940)
TJE	Henkel He-178 (8-1939) Glouster 40/E28/29/ (6-1941) DeHaviland DH 100 (9-1943) Lockheed F-80 (T-33) (1-1944) Henkel He-162A-1 (12-1944)	Henkel He-280 (4-1941) Messerschmitt Me-262 (7-1942) Bell P-59A (10-1952) Glouster G-41 (3-1943) Arado A-23B-2 (6-1943)	Junkers Ju-286VI (8-1944)	Me-110 (1941) Gota Co-145 (1941) Wellington (4-1942) E28/29 (3-1943) Lancaster (6-1943) F-9/40 (11-1943) Junkers Ju-88 (10-1943)
MOTOR COMPRES-SOR ENGINE	Caproni-Campini No. 1 (8-1940)	Messerschmitt Me-328B (6-1944)		
PULSED RJE	Fieseler Fi-103 (4-1944)			
JE				Il5 Bis (1-1940)

Note: Numerical dates in parentheses refer to the month and year.

evidently was played by the relative simplicity of LPRE as compared to turbojet engines (TJE), and because at the beginning of the 1930s there was practically no detailed JE design. Also important at this time, the problem of applying reaction engines in aviation was being studied principally by investigators whose main interests lay in the area of the development of rocket technology and the theory of space flight, which also determined their interest in LPRE. Moreover, this type of propulsion plant promised an interceptor aircraft with a rapid ascent rate, capable of flying at great altitudes, i.e., under conditions where the atmospheric oxygen would be insufficient to use as an oxidizer.

All of these factors evidently caused attention to focus on LPREs at beginning of the 1930s. However, engineers soon realized that rocket engines (LPRE and SPRE) could not satisfactorily solve the problem of producing serviceable reaction aircraft, and that engines using the oxygen of the surrounding air as the oxidizer were more efficient. Various countries successfully applied this type of engine at the beginning of the 1940s in reaction aircraft, and it later received very wide application. Thus, our analysis of the designs of reaction flying vehicles proposed and developed in the nineteenth and first half of the twentieth centuries indicates that two principal groups of flying vehicles were developed during this period: ballistic rockets based on the rocket-dynamic principle for producing lift, and reaction aircraft based on the aerodynamic principle. Sustained work in these two areas of interest predetermined further advances in aerospace technology in the mid-twentieth century.

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