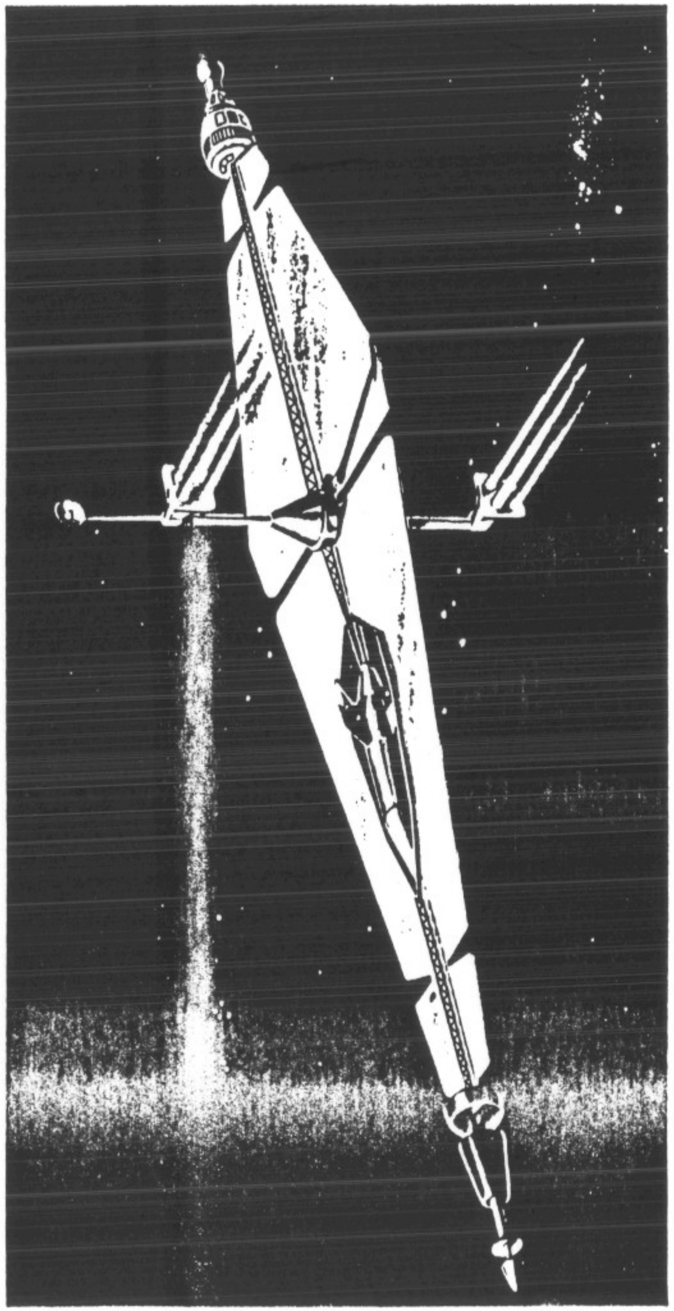

Ion-propelled spaceship on round trip to Mars.

ION PROPULSION FOR SPACE FLIGHT

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performance parameter of chemical rocket engines. Electric propulsion systems, however, are better described by more basic physical quantities.

The following relations hold:

$$\text{Specific impulse} = I_{sp} = \frac{\text{rocket thrust force}}{\text{rate of propellant consumption}}$$

Correct definition:

$$\text{CGS system:} \quad I_{sp} = \left[\frac{\text{dynes}}{\text{g/sec}}\right] = \left[\frac{\text{g-cm-sec}}{\text{g-sec}^2}\right] = \left[\frac{\text{cm}}{\text{sec}}\right]$$

$$\text{MKS system:} \quad I_{sp} = \left[\frac{\text{newtons}}{\text{kg/sec}}\right] = \left[\frac{\text{kg-m-sec}}{\text{kg-sec}^2}\right] = \left[\frac{\text{m}}{\text{sec}}\right]$$

$$\frac{I_{sp} \text{ (in CGS units)}}{I_{sp} \text{ (in MKS units)}} = 100$$

Customary definition:

$$I_{sp} = \left[\frac{\text{lb thrust}}{\text{lb propellant/sec}}\right] = \left[\frac{\text{lb}}{\text{lb/sec}}\right] = [\text{sec}]$$

In this definition, *lb force* is equated to *lb mass*.

The "correct definition" of the specific impulse implies that I_{sp} is equal to the exhaust velocity of the propellant particles. It should be noted, however, that this is true only in those cases where all propellant particles leave the rocket motor with the same velocity. This ideal situation is approached by chemical rocket motors; it does not exist in ion propulsion systems where a certain fraction of the propellant particles do not acquire electric charges and therefore are not accelerated. For that reason, propellant utilization and exhaust velocity, instead of specific impulse, are used in the present book to describe the performance of ion motors. Where specific impulse figures are quoted, they were obtained through the relation

$$I_{sp} = \frac{v}{g_0}$$

where I_{sp} = specific impulse, sec
v = exhaust velocity, m sec^{-1}
g_0 = 9.81 m sec^{-2}

CHAPTER 1

HISTORY OF ELECTRIC PROPULSION

The earliest known record in which the idea of an electric propulsion system for rocket vehicles appears at least implicitly is a page in the notebook of R. H. Goddard [1]. The great rocket pioneer, who was better known in his days as a physicist and schoolteacher, experimented with an electric gas discharge tube in 1906. As he observed the very high velocities which were imparted to the charged particles while the temperature of the tube remained fairly low, the thought occurred to him that electrostatically repelled particles might be the answer to the problem of obtaining high exhaust velocities at bearable chamber temperatures. He wrote down a brief remark in his notebook on February 18, and the frequent recurrence of remarks concerning electrostatic propulsion in his notebooks for the years 1906 to 1912† reveals that the ion rocket had taken a firm foothold in the thinking of this exceedingly brilliant mind more than fifty years ago. Goddard speaks of "high-velocity streams of negative and positive particles," energized by solar-electric power supplies, which would be applied after the burnout of a chemical booster rocket to accelerate a planetary vehicle during the first half, and decelerate it during the second half, of its trajectory between the earth and a planet. Electrostatic forces could be used either to accelerate the ionized exhaust particles of a hydrogen-oxygen rocket, or to accelerate ions generated from alkaline atoms on hot tungsten surfaces. As early as 1916, Goddard and his students conducted experiments with ion sources and with "electrified jets," consisting of chemical rocket jets into which ions had been injected. In his Report concerning Further Developments, of March, 1920, Goddard devoted a number of paragraphs to the production of an ionized jet of gas, and he supplemented his remarks in this report by several subsequent memorandums. Speaking of these reports, Mrs. Goddard wrote in 1960: "I do know

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† "The Papers of Robert H. Goddard" are presently being edited by Mrs. R. H. Goddard. Permission to read the unpublished papers, and to include part of their content in this chapter, is gratefully appreciated.

that my late husband felt [the ionized rocket] was a definite probability for the future."†

Not much is known of the ideas about electric rocket propulsion which may have roamed through the mind of the distinguished Russian rocket pioneer, Konstantin Eduardovitch Tsiolkovskii of Borovsk in the district of Kaluga. In 1895 he wrote his first article about space travel and rocket vehicles [2], and he derived the famous *Tsiolkovskii equation* which has been ever since the basis of all theoretical work on rocket propulsion. This equation, relating the burnout velocity of a rocket with its exhaust velocity and its mass ratio, shows how important it is that the exhaust velocity of a rocket motor be as high as possible. Recognizing the severe limitations of gunpowder as a rocket propellant, Tsiolkovskii searched for more energetic propellants, and even went so far as to propose liquid hydrogen and liquid oxygen as fuel and oxidizer for rocket engines. As a mathematics and physics teacher, Tsiolkovskii undoubtedly had knowledge of the experiments which were made with electrons and electric discharges in many laboratories toward the end of the century. It would be only natural to assume that the high particle velocities in electric discharges struck his mind as being potentially useful for rocket propulsion, and it may well be that only his personal modesty kept him from publishing his early ideas.

Hermann Oberth, the third of the brilliant triple-star constellation of early rocket pioneers, contributed probably more to the theoretical foundation of the broad field of rockets and space flight than any other individual. Characteristically perhaps, he, too, was a schoolteacher, and even today many of his sharp-witted arguments begin with a modest "As we have learned in school . . . ." Oberth wrote his first essay on a manned rocket spaceship in 1909, and as early as 1912 worked on the design of a rocket engine which burned liquid hydrogen with liquid oxygen. In 1918—forty years before the Atlas-Centaur project took shape—Oberth proposed a two-stage rocket vehicle with alcohol-oxygen in the first and hydrogen-oxygen in the second stage. Many of his early thoughts found precipitation in the book "Wege zur Raumschiffahrt" (1929) [3], probably the outstanding classic of rocketry and space travel. One chapter in this book deals with electric propulsion. In a later book, "Man into Space" (1957), the same ideas were taken up again and presented in a similar form [4]. Oberth first described the old classroom experiment where a needlepoint, connected with a source of high voltage, produces an "electric wind," and he then elaborated on methods of generating a flow of electrically charged particles from the thrust engine of a space vehicle. Porous plates, he wrote, will provide a finely dispersed flow of propellant; high voltage applied to the plates will form a spray of charged particles which leaves the vehicle with high velocity. Almost any kind of material, even refuse from the vehicle crew, could be used as propellant. The rate of propellant flow will always be small, but since the exhaust velocity is high, a noticeable thrust will be developed. It is characteristic of electric propulsion engines that they will produce a low thrust over a long period of time; hence, electric systems will find application in space vehicles which are designed to travel to distant targets.

While the science and technology of chemical rockets developed at a rapid pace between 1930 and 1950, the idea of using electric power to eject charged particles from a thrust chamber progressed slowly, and with long intervals between times of creative thought. Herbert Radd [5], as a young student of engineering, wrote on Some Tentative Solutions in Space Travel in 1945, and recommended the use of fast, electrically accelerated particles to save fuel mass. He was probably the first who suggested the name *ion rocket*. In 1946, a very interesting and valuable contribution to electric propulsion was made by Jakob Ackeret [6], the famous Swiss aerodynamicist and thermodynamicist. Although he did not derive any formulas specifically for the case where ions or electrons are ejected from a rocket engine, his method of analyzing the performance capability of a rocket vehicle is directly applicable to electrically propelled space vehicles. Ackeret started out from the fact that a nonchemical propulsion system requires a special on-board power supply which first generates the necessary power, and then converts it into a form suitable for operating the propulsion engine. The total kinetic energy which is carried away by the exhaust beam during the time of operation corresponds to a reduction of the mass of the vehicle as expressed by the equation $E = mc^2$. Under the assumption that a certain fraction of the vehicle mass can be converted into kinetic beam energy, the total propellant mass can be calculated which will lead to a maximum terminal velocity of the vehicle. The result is independent of particle size, time of propulsion, conversion method, and magnitude of the vehicle. The optimum exhaust velocity is determined automatically by the process of maximization of the terminal velocity. As an example, Ackeret assumed a conversion factor of 0.2 per cent, which resulted in a terminal velocity of 15,000 km sec^{-1}, and in a ratio of 4:1 for propellant mass to terminal mass. Technologies which are known at present do not permit the conversion of more than about 10^{-7}, or 0.00001 per cent, of the terminal mass of a space vehicle into kinetic energy of an exhaust beam. The mass ratio 4:1,

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† Mrs. Esther C. Goddard in a letter to the author, Dec. 13, 1960.

however, is independent of the conversion factor, as will be shown in Sec. 4-1.

A comprehensive survey article on The Physics of Rockets, in which electric propulsion was briefly mentioned, was written in 1947 by H. S. Seifert, M. M. Mills, and M. Summerfield [7]. "Jets of charged particles" were described as potential rocket propellants, even though the intensities of ion beams as they could be produced at that time were thought to be still too low to warrant consideration of a development project. The authors pointed out that an electrically propelled vehicle must expel positive and negative particles at equal rates in order to keep the vehicle electrically neutral.

Two very active and well-known rocket scientists, L. R. Shepherd and A. V. Cleaver, subjected the idea of electric rocket propulsion to a close technical scrutiny in 1949 [8]. Deviating from Oberth's method of an electric spray, but in line with Radd's ion rocket, they proposed to accelerate ions of elements or compounds by well-defined electrostatic fields. They compared the potentialities of such a system with a nuclear-heated rocket engine, and they found that much higher exhaust velocities, up to about 100 km $\sec^{-1}$, could be produced without severe heat-transfer problems in the thrust chamber. Heavy ions, they stated, would be preferable because they would result in a lower electric current at the same thrust; also, electrons must be expelled besides ions in order that the vehicle stay electrically neutral.

The rate at which studies on electric propulsion systems were published increased somewhat from about 1950 on. In that year, G. F. Forbes [9] began publishing a number of excellent papers on low-thrust vehicles. Ion rockets were given particular attention. He showed that ion propulsion systems would be capable of achieving flights to the planets, and he discussed, besides principal aspects of these systems, factors like efficiency, optimization, and thrust vector programs. Similar studies were published, also from 1950 on, by D. Lawden, with particular emphasis on the mathematics of low-thrust vehicle trajectories in interplanetary space [10].

A very substantial and valuable contribution to the understanding of the physics of ion engines was made by L. Spitzer, Jr., in several papers beginning in 1952 [11]. Discussing some details of the ion source, he mentioned that the ion flow from the source is subject to space charge limitation. Nitrogen and other gases were suggested as possible propellants. Like Shepherd and Cleaver, Spitzer recommended a fission reactor and a turbogenerator as power source. The low temperature of the heat cycle should be chosen so that the mass of the radiation cooler would become a minimum. Considering the relationship among power, exhaust velocity, and thrust, he concluded that exhaust velocities of the order of 100 km $\sec^{-1}$ would be desirable.

H. Preston-Thomas, in 1952 [12], made a very interesting proposal involving electric propulsion. Space flight, he argued, will be developed only when some commercial value can be derived from it. He suggested that some of the asteroids may contain an abundance of minerals and metals which are highly priced on earth because of their scarcity. If such asteroids were forced into trajectories which eventually brought them to the surface of the earth, the revenues from the precious materials could easily finance this entire "operation space haul." The most suitable tugboats for moving the asteroids would be electric propulsion systems. Since at least the greater part of a hauling maneuver would be accomplished without the presence of men, time would not be of the essence, and the low-thrust long-duration mode of electric engines would represent the most economical method of transportation.

E. Saenger, in his brilliant paper, Zur Theorie der Photonenrakete (1953), derived a number of formulas which are applicable to any kind of rocket system [13]. Ion rockets were not treated at length in this study, but it is easy to estimate their principal performance parameters, and their limitations, from the basic equations presented in the paper, and to see how electric propulsion systems find a natural place between chemical and photonic systems.

The question of how useful electric engines with their low thrust would be for space flight was investigated by H. S. Tsien in 1953 [14]. Applying the low-acceleration system to the problem of orbital transfer, he found that accelerations of 10^{-5} to $10^{-4}g_0$ are sufficient to change the radius of an orbit substantially within a period of days or weeks, provided that the thrust vector is aligned exactly, or very nearly, in a direction tangent to the spiral trajectory. If the thrust vector acts in a radial direction, the situation is different. An outward spiral will result only when the force acting on the vehicle in a radial direction, as caused by the thrust vector, is equal to or greater than one-eighth of the local gravitational force. If it is smaller, the vehicle will assume an osculating trajectory around the central body (earth), but its average distance from the center will not change.

A proposal for an ion-propelled spaceship, including many details of its interior installations, was written by D. C. Romick in 1954 [15]. The ship was intended to use an atomic reactor with turbogenerator as a power source, and a linear accelerator to produce a beam of fast ions.

In the same year, E. Stuhlinger presented a paper which contained a comprehensive study of the major components of an ion propulsion system [16]. In the process of optimizing the more important design parameters, several characteristic relations were found whose decisive influences on the performance of an electric propulsion system have since been commonly accepted: The parameter of greatest importance is the *specific power* of the power-producing plant, expressed in kilowatts of electric power per kilogram of power-plant mass. The exhaust velocity of the ions should not be as high as possible, but should have a carefully chosen value depending on the possible, but should have a carefully chosen value depending on the specific power, the duration of the propulsion period, the desired terminal velocity, and the desired payload-to-total-mass ratio. The space charge law of Child and Langmuir, which limits the flow of ions through ion source and thrust chamber, also governs the flow of ions from the exit orifice of the thrust chamber into space, requiring neutralization of the beam by admixture of electrons within a very short distance from the exit. The mass-to-charge ratio of the particles should be large to facilitate beam neutralization, and to keep the cross-sectional area of the thrust chambers small. The most suitable propellant material is cesium because it can be ionized with almost 100 per cent efficiency simply by having cesium atoms impinge on hot tungsten or molybdenum surfaces. The radiation cooler of the power-producing plant should be designed so that it represents an optimum compromise between two opposing requirements: a large size for a low exit temperature of the heat cycle, and a small size to save mass, and to offer a small area to meteoroid damage. The accelerations of electrically propelled vehicles, based on contemporary technologies, were shown to be of the order of $10^{-4}g_0$.

While this first study envisioned a solar power supply, consisting of a number of mirrors with boilers and turbogenerators, a second study in 1955 described an electrically propelled space vehicle powered by a nuclear fission reactor [17]. A vehicle designed for a Mars mission would be lighter and somewhat faster if powered by a nuclear reactor than if it were powered by solar energy. A further study in 1957 dealt with details of a flight trajectory to Mars, with subsequent return to earth [18]. The flight would consist of a series of accelerating and decelerating sections, timed and oriented in such a way that the vehicle would approach its target at the required velocity, and in the required direction. The total flight time for the one-way trip, based on technologies which appeared realistic in 1957, was about 400 days.

Beginning in 1956, a number of very valuable studies were made by D. Langmuir and his coworkers [19]. Emphasis was placed on the properties of space vehicles which, as a characteristic feature, require a separate power source to supply the kinetic energy of the exhaust beam. The dominating influence of the specific power of the power-producing plant, and the existence of an optimum exhaust velocity for a given flight mission and specific power, were pointed out. J. H. Irving, in the same year [20], considered the problem of improving the overall performance of an electrically propelled vehicle by varying the exhaust velocity according to a time-dependent program. R. W. Bussard, also in 1956 [21], presented a study of the dynamical problems and possibilities of electric propulsion systems powered by a nuclear reactor.

A detailed description of some aspects of the ion engine was given by R. H. Boden in 1957 [22]. Choosing the ratio of accelerating voltage to particle mass, V/A, as fundamental parameter, he presented other parameters of an electrically propelled vehicle as functions of V/A, such as the power to total mass, the thrust to total mass, the power to thrust, the exhaust velocity, the current to thrust, the propellant flow rate to thrust, and the operating time for unit thrust to mass ratio. The ratio V/A, as can easily be verified, is proportional to the square of the exhaust velocity.

The question of how to orient the thrust vector of a low-acceleration vehicle with respect to the direction of flight was investigated by H. Michielsen in 1957 [23]. He showed that the direction of the tangent to the desired flight path is not necessarily the optimum thrust vector direction, but that a slightly different orientation, programmed with respect to other flight parameters like velocity and direction of gravitational forces, would lead to a noticeable gain in overall performance.

The study of an early flight vehicle project, based on electric propulsion, was initiated in 1957 by M. I. Willinsky and E. Orr [24] (Project Snooper). Powered by a small nuclear reactor, the vehicle was designed to carry scientific instruments into deep interplanetary space, after being boosted to escape velocity by a chemical rocket.

The year 1957 marks the beginning of a significant transition period in the history of electric propulsion. During previous years the studies were concerned with the feasibility and the usefulness of electric systems; now the attention began to concentrate on specific problem areas: ion sources, beam neutralization, and lightweight electric power supplies. Whereas previously the studies were carried out by individuals, mostly even during their spare time, ion propulsion work now began to enter into its legitimate phase: teams formed around the individuals, forward-looking companies sponsored in-house studies, and the Air Force's Office of Scientific Research let the first two study contracts to commercial firms "to determine the feasibility of the idea." Around the same time, missile engineers began to realize that electric propulsion systems are not limited to ion systems, but that electric energy can be applied to heat a gas to temperatures not obtainable with chemical reactions (electrothermal or arc-heated systems), and that magnetic fields can be utilized to accelerate a highly ionized gas or plasma to very considerable exhaust velocities (electrodynamic or magnetofluidmechanic systems).

During 1958, when most space-minded physicists focused their interest on the brilliant accomplishments of the young satellite projects, very competent and active working teams developed at a number of companies. The Air Force's Office of Scientific Research (AFOSR), the Office of Naval Research (ONR), the Army Ballistic Missile Agency (ABMA), and the Advanced Research Projects Agency (ARPA) supported company research and development by negotiating a number of contracts. Rocketdyne, a division of North American Aviation, engaged in the development and operation of a small laboratory model of an ion engine under R. H. Boden, A. T. Forrester, and R. C. Speiser [25]. Electro-Optical Systems, Inc., under A. M. Zarem and S. Naiditch, developed cesium-tungsten ion sources and designed an ion engine model [26]. Thompson-Ramo-Wooldridge attacked the problem of ion production and beam neutralization under D. B. Langmuir, H. Shelton, and others [27]. The General Electric Company, with G. C. Baldwin, M. Ghai, and R. Edwards, also concentrated on ion production, beam formation, and beam neutralization, and at the same time initiated work on arc-heated and plasma systems [28]. The Goodrich–High Voltage Engineering Company investigated ion sources under A. J. Gale [29]. Aerojet-General, under Y. C. Lee and R. Schultz, directed their attention to charged colloidal particles as propellant materials [30], and so did R. E. Wiech at Thiokol Chemical Corporation [31].

At Plasmadyne, G. M. Giannini and R. Buehler [32] developed arc-heated hydrogen engines for propulsion purposes. A. Kantrowitz at AVCO [26], and W. Bostick of the Stevens Institute experimented with plasma propulsion systems [33]. M. U. Clauser at Space Technology Laboratories [34] directed studies of plasma acceleration by varying magnetic fields. The Hughes Aircraft Company, under G. Brewer and M. Currie, brought the very powerful tool of the particle trajectory analogue simulator to bear on the problems of beam formation and beam neutralization [35]. The Convair Divisions at Fort Worth and San Diego, United Aircraft, Republic Aviation, Lockheed Aircraft Company, Curtiss-Wright, and others initiated theoretical and experimental work in the area of electric propulsion. What had been a rare extravagance in 1956 became

a natural part of the research and development program of almost every rocket, aircraft, and instrumentation firm.

In August, 1958, the first ion engine model was in operation at Rocketdyne, and another model followed at Electro-Optical Systems in January, 1959. General Electric and Thompson-Ramo-Wooldridge operated their first small ion motors in 1959. It is true that their lifetimes were short, that their thrusts had to be measured in milligrams, that their efficiencies were only a few per cent, and that the problem of beam neutralization had not yet been solved, but the experiments demonstrated at least partially the feasibility of the principle, and thus set an important milestone in the development of electric propulsion.

The Lewis Flight Laboratory of the NACA,† under J. Evvard, J. H. Childs, W. Moeckel, H. Kaufman, H. Mirels, W. Mickelsen, and others, initiated an experimental and theoretical research program for electric propulsion in 1957 [36, 37]. This program grew rapidly, and numerous investigations of ion sources, beam-forming systems, neutralization schemes, trajectory optimization, and missions were carried out during recent years. An impressive array of test facilities was established, and the laboratory announced the successful operation of a small ion engine model in 1959.

The Jet Propulsion Laboratory formed a study group for electric propulsion systems and their applications to space exploration in 1959. In 1960, a program for research and development of electric propulsion systems was established by the National Aeronautics and Space Administration as part of the official NASA space program. It was assigned at that time to the George C. Marshall Space Flight Center. Early in 1962, all the electric propulsion activities of NASA were transferred to the Lewis Research Center in Cleveland, Ohio.

Very little is known about Russian efforts to develop electric propulsion systems. Yu. Ya. Stavisskii and coworkers wrote a short paper in 1958 [38], in which they described a cesium ion engine model whose thrust was measured in a laboratory experiment. A remarkable number of studies were carried out by Russian scientists during recent years which deal with surface ionization of alkali atoms on hot metal surfaces, and with ion and plasma problems in general.

The most difficult but also most challenging single problem with which the developer of an ion propulsion system found himself confronted during the years 1958 to 1961 was the neutralization of the electric space charge within the ion beam immediately behind the exit orifice, and investigators of ion systems gave it their foremost attention. Advanced laboratory models of ion engines with

† National Advisory Committee for Aeronautics.

provisions for beam neutralization have been in operation since 1961. However, successful operation of an ion engine under laboratory conditions does not necessarily mean that the problem of beam neutralization has been solved, because the residual gases within the vacuum chamber, and the influence of walls and target electrodes, act through secondary emission effects to fulfil the conditions of beam neutralization. True beam neutralization must be accomplished, though, if an ion engine is to operate successfully under space conditions. During 1961 and 1962, further theoretical and experimental studies gave rise to a more optimistic attitude toward this problem. It is expected that the first real space tests will be made in 1964, and that they will mark a decisive step forward in the solution of the neutralization problem.

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