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A Critical History of Electric Propulsion: The First 50 Years (1906–1956)

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Nomenclature

A = beam cross-sectional area
a = vehicle acceleration
$i \equiv p/V$ = current per unit vehicle mass
j = current density
M_v = vehicle mass
$\dot{m}$ = propellant mass flow rate
P = input electric power
$p \equiv P/M_v$ = input electric power per unit vehicle mass
T = thrust
u_{ex} = rocket exhaust velocity
V = voltage
η = thrust efficiency

WHEN writing history, it is tempting to identify thematic periods in the often continuous stream of events under review and label them as "eras," or to point to certain achievements and call them "milestones." Keeping in mind that such demarcations and designations inevitably entail some arbitrariness, we shall not resist this temptation. Indeed, the history of electric propulsion (EP), which now spans almost a full century, particularly lends itself to a subdivision that epitomizes the progress of the field from its start as the dream realm of a few visionaries, to its transformation into the concern of large corporations. We shall therefore idealize the continuous history of the field as a series of five essentially consecutive eras:

1) The Era of Visionaries: 1906–1945
2) The Era of Pioneers: 1946–1956
3) The Era of Diversification and Development: 1957–1979
4) The Era of Acceptance: 1980–1992
5) The Era of Application: 1993–present

This is not to say that the latter eras were lacking in visionaries or pioneers, nor that EP was not used on spacecraft until 1993 or that important conceptual developments did not occur at all until the 1960s, but rather that there is a discernible character to the nature of EP-related exploration during these consecutive periods of EP's relatively long history. The preceding classification is intended to give a framework to our discussion, which will be useful for comprehending EP's peculiar and often checkered evolution [1]. The present paper, which represents the first installment of our historical review, deals with the first two eras, which correspond to the first 50 years of the history of the field.

What makes the history of EP a bit unlike that of most aerospace technologies is that despite EP's recent, albeit belated, acceptance by the spacecraft community, it still has not been used for the application originally foreseen in the dreams of its earliest forefathers, namely, the systematic human exploration of the planets. The irony of still falling short of that exalted goal while much ingenuity has been expended on inventing, evolving, and diversifying EP concepts can be attributed to two problems that were likely unforeseeable to even the most prescient of the early originators.

The first problem is EP's decades-long role as the technological "prince in waiting" of spacecraft propulsion. Despite the relatively early maturity of some EP concepts, their systematic use on commercial spacecraft was delayed until the last two decades of the 20th century. A measure of this forced detainment can be gleaned from a hypothetical contrast to the history of atmospheric flight, in which the demonstration of powered flight at Kitty Hawk in 1903 would not have led to acceptance of the airplane until 1940. This retardation is doubtless caused, partially, by the technological conservatism that is endemic in the spacecraft industry, where more traditional and well-proven propulsion systems have been, perhaps understandably given the immense financial stakes, difficult to supplant. Breaching this psychological barrier did not fully occur in the West until around 1991. It was not only the result of an overdue realization on the part of aerospace planners of the cost-savings benefits of EP and a demonstration that the associated risks were well worth taking, but also to the the acceptance and success EP has had in the Soviet Union. That the first electrically propelled spacecraft to go into deep space did not do so until almost a century after the first EP conceptions is a fact that would have disheartened their visionary authors.

The second and far more hindering problem that stood, and remains, in the way of EP-enabled human exploration of the planets, is the frustrating lack of high levels of electric power in space. U.S. efforts to develop nuclear power sources for spacecraft have been fraught with repeating cycles of budgetary, political, and programmatic setbacks over the past five decades, despite considerable technical achievements in programs that were either discontinued or did not come to fruition in a space flight [2]. Lyndon B. Johnson was the U.S. president when the last and, to date, only U.S. fission [3] nuclear power source was launched in space (SNAP-10A; 650 We output; launched 3 April 1965). The record of the most powerful nuclear power source in space is still held at about 5 kWe by

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the 1987 flight of the Soviet Topaz 1 fission reactor onboard the Cosmos 1818 and 1867 spacecraft. This 5-kWe record makes the present prospects of a 10-MWe electrically propelled piloted spaceship seem as dim as six 100-W lightbulbs compared to a fully lit Yankee Stadium.

As much as the realization of viable nuclear power generation on spacecraft is critical to the fulfillment of EP's ultimate role, we shall not discuss it further here. Although its current chapter is unfolding now, and not without the usual optimism [4], the history of placing powerful nuclear power sources in space has not been on the whole a success story. Suffice it to say that when that history is documented it would make that of EP, in comparison, one of steady and linear progress.

Despite these major obstacles to its development, the history of EP turned out to be a success story: Almost 200 solar-powered satellites in Earth orbit and a handful of spacecraft beyond Earth's gravitational influence have benefited to date from the mass savings engendered by EP.

Before starting our review of that history, we wish to state some assumptions and define a few self-imposed limitations. These might limit the scope of our coverage, but will hopefully render the review easier to assimilate and bound its expansiveness. Specifically, we shall assume that the reader is acquainted with the major classifications of EP systems (electrothermal, electrostatic, electromagnetic) and somewhat familiar with the basic features of the main EP concepts. The uninitiated reader might benefit from reading our recent article[3] or referring to the predecessor textbook.[4] To keep the flow of the main discussion unimpeded by mathematical derivations, ancillary information, or technical and historical details, we shall relegate these to endnotes, which will be frequent and often extensive.

Furthermore, we shall admittedly favor for inclusion work performed predominantly in the United States. We will however mention, without any pretension to be all inclusive or exhaustive, a number of seminal works and important advancements that occurred outside the United States and provide references, whenever possible, to publications where these developments have been described. We hope this U.S.-centric history will not lessen the essential appreciation that without the contributions of workers in the former Soviet Union (both in its present and former incarnations), Europe, and Japan, EP would, at best, still be in its adolescence. We will also undoubtedly be forced, for practical reasons, to omit the names of some individuals whose contributions might well outweigh those of some of the people we do mention. Such omissions will be more frequent when discussing the latter eras in which the sheer number of outstanding contributions makes any obsessive attempts to fairness or inclusiveness futile. Except in a few instances, we shall not be concerned with the achievements made on EP subsystems (e.g., power conditioning, mass feeding, propellant storage, etc.) nor can we attempt any fair accounting of the milestones in ancillary, albeit critical, fields (e.g., low-thrust trajectories, mission planning, etc.). Instead, we will concentrate on the evolution of the EP concepts themselves. Also, we shall focus more on technical milestones and less on programmatic developments (e.g., histories of various NASA and U.S. Air Force EP programs) even though the attainment of the former often depends on the success of the latter.

Finally we should mention that our intent is not to merely compile a factual and dry chronicle of events and accomplishments, but rather to present a critical history that does not shy away from being analytical and reflective when appropriate [5].

I. Era of Visionaries: 1906–1945

It is difficult to think who in aerospace history, perhaps even in the history of modern science and technology, embodies the quintessential qualities of the archetypical visionary more than Konstantin Eduardovitch **Tsiolkovsky** [6] (1857–1935). It is also difficult to find a more vivid encapsulation of the essence of visionary work than his own words:

> This work of mine is far from considering all of the aspects of the problem and does not solve any of the practical problems associated with its realization; however, in the distant future, looking through the fog, I can see prospects which are so intriguing and important it is doubtful that anyone dreams of them today (Ref. 8, p. 28).

The "official" [7] history of modern rocketry and astronautics starts in **1903** with Tsiolkovsky's (eventually) celebrated article "Investigation of Universal Space by Means of Reactive Devices, [8] from which the preceding quote is taken. That article contains the derivation of the Tsiolkovsky rocket equation, which is the most fundamental mathematical expression in the field of space propulsion and the encapsulation of the *raison d'être* of EP (see our EP review article[3] for an introduction). Eight years later, in **1911**, we come across Tsiolkovsky's first published [9] mention, albeit germinal, of the idea of electric propulsion: "It is possible that in time we may *use electricity to produce a large velocity for the particles ejected from a rocket device*" (Ref. 8, p. 95). The italics are ours and are meant to underscore the suitability of that quote as any modern dictionary's definition of electric propulsion. The subsequent sentence in the same text,

> It is known at the present time that the cathode rays in Crookes' tube, just like the rays of radium, are accompanied by a flux of electrons whose individual mass is 4,000 times less than the mass of the helium atom, while the velocities obtained are 30,000-100,000 km/s i.e. 6,000 to 20,000 times greater than that of the ordinary products of combustion flying from our reactive tube.

is quite revealing. It points to cathode rays—one of the most intriguing problems in physics in the few years preceding that writing [10]—as the source of inspiration for the idea of electric propulsion. It is not difficult, in retrospect, to appreciate how someone concerned with increasing rocket exhaust velocity would be inspired by the findings, well known at that time, of physicists working on cathode rays, such as J.J. Thomson's pronouncement in 1906:

> . . . in all cases when the cathode rays are produced in tubes their velocity is much greater than the velocity of any other moving body with which we are acquainted. It is, for example, many thousand times the average velocity with which the molecules of hydrogen are moving at ordinary temperatures, or indeed at any temperature yet realized.[13]

This clearly stated disparity between the velocity of electrostatically accelerated particles and that of thermally energized atoms was bound to capture the imagination of someone considering the problem of rocket propulsion.

A casual and modern reader might wonder why Tsiolkovsky was considering a flux of electrons (as opposed to ions) to be useful for propulsion when he knew of their exceedingly small mass (and thus small momentum flux). The answer is simply that only electrons were known to attain such high velocities (as per Thomson's preceding quote) and that the concept of the ion, as an atomic-sized particle possessing a net positive charge, had not yet been fully established, although much work and debate was ongoing at that time on the nature of the positively charged "rays" observed in cathode ray tubes [11]. In that sense, Tsiolkovsky came as close as he could have, given the state of physical knowledge in 1911, to envisioning the ionic rocket. In sum, it was his discovery of the central importance of rocket exhaust velocity to space propulsion combined with his awareness of the existence of extremely fast particles (albeit electrons) in cathode ray tubes, that led to his almost prophetic anticipation of EP.

Tsiolkovsky was a self-taught schoolteacher who lacked the clout of the graduate scientists who dominated the scientific world of his day. His works, almost exclusively theoretical, were originally published at his own expense, and many of his earlier writings remained in the form of unpublished manuscripts decades after they were penned. His intellectual output was prodigious until his death, and he was vindicated by the fact that numerous accomplishments in modern astronautics can be traced to his ideas [12]. However, despite his detailed calculations and quantitative analysis in the field of chemical rockets and astronautics, he did not attempt any analytical study of the application of electricity to rocket propulsion.

Fig. 1 Robert H. Goddard.

He acknowledged that EP was at present a dream, and his attention was to be dedicated to more prosaic problems. This is illustrated vividly in the following quote from 1924 (by which time the nature of positively charged atoms had been known, the proton had been discovered, and he had recognized the better suitability of ions to propulsion) (Ref. 8, p. 222):

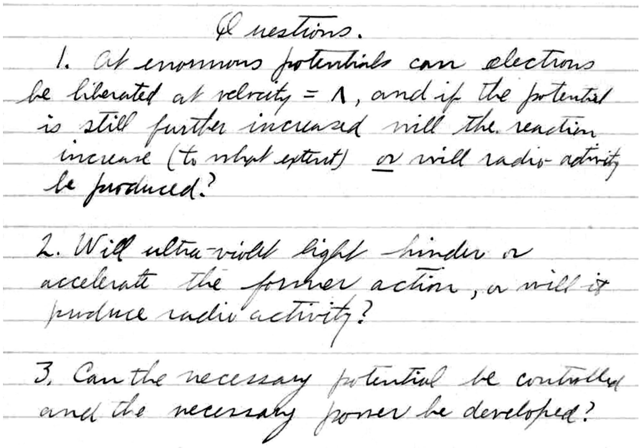
> It is quite probable that electrons and ions can be used, i.e. cathode and especially anode rays. The force of electricity is unlimited and can, therefore, produce a powerful flux of ionized helium to serve a spaceship. However, we shall leave these dreams for a while and return to our prosaic explosives [13].

There is no evidence that Tsiolkovsky was sufficiently versed in electricity and magnetism, let alone the newly burgeoning field of gaseous electronics, to tackle the problem of EP. That problem was first addressed, and at an even earlier date than Tsiolkovsky's first qualitative speculations, by a young American visionary who was trained precisely in these nascent branches of physics and who shared a passion for space travel with the "dreamer from Kaluga," despite never having heard of him or his ideas [14].

Robert Hutchings **Goddard**'s (1882–1945) [15] early career as a young academic physicist was divided between his official research work on electricity and his personal passion for propulsion [16]. That this would lead him to think of electric propulsion was natural if not inevitable.

Aside from an amusing anecdote [17] about his "earliest recollection of a scientific experiment" at the age of five[17]—and which, incidentally, involved the use of "electricity" for "propulsion"—the first documented instance in which Goddard considered the possibility of electric propulsion dates to 6 September **1906**. On that day the 24-year old Goddard set out to address the problem of producing "reaction with electrons moving with the velocity of light" and wrote down his thoughts on this problem in his notebook. In particular he posed the question: "At enormous potentials can electrons be liberated at the speed of light, and if the potential is still further increased will the reaction increase (to what extent) or will radio-activity be produced (Ref. 18, p. 84)?

Goddard quickly demonstrated in these handwritten pages (Ref. 18, pp. 82–88) (dated 6 and 9 September 1906) that he was quite aware of the most recent developments in physics concerning the nature of cathode rays [18]. However the incomplete state of that knowledge hindered him from answering his questions. Despite highly educated attempts, he was not able to calculate the levels of required energy or power nor resolve the issue of what happens when the electrons reach the speed of light and the accelerating potential is raised further. His notes and calculations on 9 September demonstrate that he was well aware of Walter Kaufmann's careful measurements, published in 1901, which indicated that the inferred mass of the electron increased as its speed neared that of light. Although he was, apparently, not yet aware of Einstein's special relativity theory, which was only published a few months before and had not yet gained much acceptance [19], Goddard found himself contending with the conjecture that the electron's inertia at the speed of light might be infinite. He did remain hopeful, however, that experiments might determine "the voltage necessary to give a speed equal to the velocity of light."



Questions.

1. At enormous potentials can electrons be liberated at velocity = Λ, and if the potential is still further increased will the reaction increase (to what extent) or will radio-activity be produced?

2. Will ultra-violet light hinder or accelerate the former action, or will it produce radio activity?

3. Can the necessary potential be controlled and the necessary power be developed?

Fig. 2 An excerpt of the the entry dated 6 September 1906 in Goddard's handwritten notebook showing some of the questions he attempted to answer quantitatively in order to assess the feasibility of electric propulsion using electrostatic potentials to accelerate electrons to the speed of light (represented by the symbol Λ).

It is interesting to consider why, at that early stage, Goddard was more concerned with the electrostatic acceleration of electrons rather than ions despite his knowledge of canal rays, and why these early ideas, not surprisingly, still fell short of a workable thruster concept. We can suggest five reasons:

1) As we already mentioned in endnote 11, the nature of these rays was still debated at that time and the ionization physics underlying the production of electron-ion pairs was not clear.

2) There was the implicit belief in these early writings that high accelerating voltages (and not high beam currents) were the main technical difficulty. This, consequently, favored electrons as the propellant needed to reach extremely high velocities.

3) There was still a lack of appreciation of the immense difficulty, stipulated by the laws of special relativity, in accelerating a particle having a finite rest mass to a speed very near that of light [20].

4) It is doubtful that Goddard, at this early time, had fully appreciated the practical (i.e., system-related) penalty incurred by an electric rocket with an exceedingly high exhaust velocity [21].

5) There is another system-related penalty that must have been far from Goddard's mind. Electrostatic acceleration of lighter atoms, let alone electrons, although less demanding on the voltage, results in beam currents which, because of space charge limitation, incur adverse demands on the required area (and therefore size and mass) of the accelerator [22].

These five problems, which confounded Goddard's first thoughts on EP, were eventually dealt with one by one by him and other pioneers, but only over a time period extending over the next four decades.

Goddard's notebooks show that EP was a constant, if not a consuming, idea in his mind. Between 1906 and 1912 the evolution of his thoughts on that subject led him to appreciate the advantages of relying on the reaction of ions in an electrostatic accelerator, and the need for neutralizing the charged exhaust with a stream of oppositely charged particles. He explicitly stated the latter realization in the following quote from the March 9, 1907 notebook entry: If negative particles are shot off, the car will have an increasing positive charge until the potential is so great that negative particles cannot be shot off. Hence positive particles must be emitted in a quantity equal to that of the negative particles. As in many instances [23] in the career of this ingenious and practical scientist, his ideas culminated, by 1917, in two inventions whose importance to the history of EP has been largely unrecognized.

The first invention, whose patent application was filed in **1913** (granted in 1915), is a method for producing "electrically charged

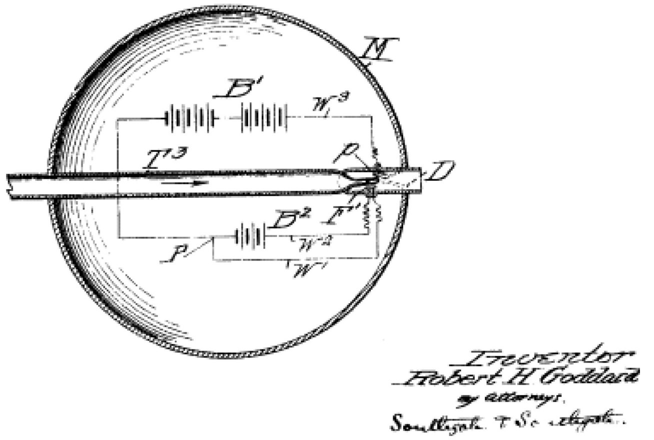


Fig. 3 World’s first documented electrostatic thruster. Schematic of Goddard’s third variant of his 1917 invention as it appears in U.S. patent #1,363,037 (granted in December 1920).[20] The propellant is injected through the tube labeled T^3; charge is added to the flow from the cathode filament F^1, which is placed in the wake of the stream and whose anode is a metallic plate at location P. The filament is powered by the power supply B^2. The whole is enclosed in a metallic sphere M, which is “kept at a very high potential” using the power supply B^1. “The sign of the charge on M is the same as that of the ions in the jet thus causing their repulsion away from the device at high velocities proportional to the applied potential.”[20]

particles,”[19] which relies on an applied magnetic field to confine electrons in a gas and thus greatly enhances the probability of their ionizing collisions with neutral molecules—much like it is done in the ionization chamber of modern electron bombardment ion thrusters and magnetron plasma sources. In **1917** Goddard, who by then had become an assistant professor of physics at Clark University, filed another U.S. patent application titled “Method of and Means for Producing Electrified Jets of Gas.”[20] In that patent [24], granted in 1920, Goddard presented three variants of apparatus, the first two of which are means of charging a stream of gas without having the stream affect the charging process. The third variant, however, is of direct relevance to our history as it is the world’s first documented **electrostatic ion accelerator** intended for propulsion. Goddard, in his patent description of this particular variant of the invention, in fact mentioned propulsion as the main application [25] and stated, referring first to the exhaust velocities of a chemical rocket from an earlier patent [26].

> These velocities are the greatest that have yet been produced in any way with masses of gas of appreciably large magnitude, but are much less than are possible by the method herein described, for the reason that the potential of the container *M*, which produces the high velocity, may be as high as desired.

The schematic of that accelerator is shown in Fig. 3, whose caption describes the concept [27].

With the entry of the United States into World War I on 6 April 1917, Goddard offered his services to the Smithsonian for developing rockets for military applications. By this time his intermittent but visionary explorations of EP seem to have ceded to his almost exclusive intellectual dedication to chemical rocket launch vehicles.

It is at this point in our story of EP that we must deal with the historically problematic role of Yuri V. **Kondratyuk** [28] (1897–1941). There is no doubt that this relatively little known thinker deserves a place in the pantheon of astronautical visionaries for his bold, far-reaching and original ideas [29], and that his name also deserves to be featured in EP’s early history. In a section under the heading “Concerning other Possible Reactive Devices” in a manuscript quaintly titled “To whomsoever will read in order to build” [30], dated **1918–1919**, [31] Kondratyuk, like Tsiolkovsky and Goddard before him, wrote about EP in the context of cathode rays. Speaking of the high-velocity charged particles, however, he noted, “Their drawback is the tremendous energy required, and their velocity is greater than need be; the larger the velocity, the greater the amount of energy that we must expend to obtain the same reaction . . . ” (Ref. 9, p. 23). The last sentence demonstrates that Kondratyuk was fully aware of Eq. (3) in endnote 22 and its practical implications. That he fully appreciated the advantage of accelerating more massive particles is evidenced by a schematic that he added, apparently at a later date (see endnote 31), to the same section of the manuscript and which might well be the first conceptualization of a **colloid thruster**. Accompanying the simple schematic, Kondratyuk had written (most likely at a later date than 1919 but definitely before 1938):

> Reaction [force can be produced] from the repulsion by electrical discharges of material particles of nonmolecular dimensions, for example, graphite powder or a finely pulverized conducting fluid. It is readily calculated that the velocity of such particles with a large (but fully practicable) potential could be made exceedingly high-greater than the molecular velocity of an intensely heated gas.

Elsewhere in the same manuscript (Ref. 9, p. 43) he also recognized the affinity between electric propulsion and solar-electric power generation.

Because the dissemination of Kondratyuk’s writings was quite limited until the mid-1960s, his speculations on EP, as visionary as they might now seem considering their early date, had little if any influence on the evolution of the field. They do serve to illustrate, however, to what extent the imagination of these early spaceflight pioneers was fueled by their recognition of the importance of high exhaust velocities and their awareness of the concomitant results from the field of cathode-ray physics.

Much like Goddard and Tsiolkovsky, Kondratyuk felt that chemical rockets deserved a higher development priority than their electric counterparts and when, in 1927, he edited his manuscript “Conquest of Interplanetary Space”[24] for publication he decided to omit references to “speculative” concepts such as EP in favor of those he felt were realizable in the near future.

Just as no overview of astronautics and modern rocketry could be complete without a discussion of the work of Hermann Julius **Oberth** (1894–1989), any descriptions of the dawn of EP would be glaringly wanting without an account of his role in bringing the concept of EP into the limelight. To exaggerate only a little the procreational similes often used to describe the “fathers” of rocketry [32], we could say that if Oberth is now recognized as a father for rocketry and astronautics he should be lauded as a midwife for electric propulsion. We say so because Oberth’s major contribution, as far as EP is concerned, was not in having developed specific inventions, or having undertaken technically rich conceptualizations, but rather in having defined, for the first time publicly and unambiguously, EP as a serious and worthy pursuit in astronautics. If the field of electric propulsion is not indebted to Oberth for a lasting technical contribution, it can trace its conceptual origin as a discipline to the last chapter of his all-time astronautics classic *Wege zur Raumschiffahrt*[25] (*Ways to Spaceflight*) published in **1929**. Oberth devoted that whole chapter, titled “Das elektrische Raumschiff” (“The Electric Spaceship”), to spacecraft power and EP. In that chapter he extolled the mass-savings capabilities of EP, predicts its future role in propulsion and attitude control outside the atmosphere, and advocated electrostatic acceleration of electrically charged gases, which can be created from refuse on the orbiting space station that is a major theme of the book.

His electric thruster concepts are essentially qualitative sketches, based on the experimentally observed effect of “electric wind,” which have more kinship with Goddard’s earlier electrostatic accelerator than with the modern ion thruster championed by later pioneers such as Stuhlinger. In the former concept, charged particles are injected into a stream of gas, and the action of the electrostatic field on the whole stream is effected through momentum coupling between the charged and neutral particles. In the latter concept a low-density gas is fully ionized first, then ions are extracted electrostatically. As late as 1957, Oberth still believed that the former method had promise as he argued in his book [33] *Man into Space*[26] by contrasting his method to what he called Stuhlinger’s method.

Tsiolkovky's proclamations on EP might have been read by a handful of contemporaries, Kondatyuk's by even less, and Goddard's by practically no one except those who, decades later, read his personal notebooks and reexamined his patents. In contrast, Oberth's 1929 book was a bible for an entire generation of serious and amateur space enthusiasts [34]. It brought EP simultaneously into the minds of science fiction writers and scientists. Although it immediately took roots in the writings of the former, it took decades for the minds of the latter to digest and evolve it. Indeed, the next milestone on the road of EP's scientific development does not occur until more than 15 years after the publication of Oberth's book. (This statement is strictly correct only if we limit ourselves, to EP's predominant variant throughout all its early years: electrostatic acceleration.) However, there was a notable parenthesis in this early history and one that was to be a harbinger of the succession of ingenious concepts in which electric power is harnessed for spacecraft propulsion, which mark the later chapters of EP's history.

This parenthesis was opened by another pioneer of space propulsion, Valentin Petrovich **Glushko** (1908–1989), who aside from his early work on EP, went on to play a major role in the development of the Soviet space program [35]. Shortly after joining Leningrad's Gas-Dynamics Laboratory in 1929, Glushko embarked on an activity with his coworkers that led, in the period 1929–1933, to the development of an electric thruster prototype in which thrust was produced by the nozzled thermal expansion (just as in a standard chemical rocket) of the products of electrically exploded wires of metal or electrically vaporized liquid metals.[28] Not only was this the first **electrothermal** thruster of any kind, but quite likely the first electric thruster to be built, albeit for laboratory use, with spacecraft propulsion in mind as the sole application. It is also likely the first electric thruster ever to be tested on a thrust stand.[29] That this exploding wire thruster left no direct progenies in the modern arsenal of EP devices and that no other electrothermal thruster was developed for decades after should not diminish the historical significance of this early development.

With the closing of this parenthesis in the early 1930s, EP entered a hiatus of more than 15 years during which it appeared only in the science fiction literature as a scientifically thin but enthralling simulacrum of advanced propulsion for interplanetary travel. It is not difficult to speculate on the reasons for this hiatus. First and foremost, the vigorous development of EP concepts would have been premature before the chemical rockets needed to launch spacecraft from Earth had become a reality. Second, the prospect, then the reality, of WWII made EP with its minute thrust levels of no relevance to military applications. Third, unlike chemical rockets, which can be tested in the atmosphere, the realm of electric thrusters is the vacuum of space, and simulation of that vacuum, to say nothing of the complexities of the required auxiliary subsystems, was not within the reach of most laboratories. Thus, chemical rocketry almost exclusively dominated the interest of propulsion scientists and engineers in the 1930s and 1940s.

The next time we encounter a mention of EP in the international scientific literature is at the close of the war in a short and qualitative article in the December **1945** issue of the *Journal of the American Rocket Society*.[30] There, a young engineering student, Herbert Radd, looked aspiringly to a future of space conquest with solar power, ion propulsion, space suits, and other dreams that only shortly before would have seemed frivolous to a planet stepping out of a nightmare. If the article is thin on technical substance [36], it is full of the exuberance and hope of a new generation determined to make spacefaring a reality [37]. In it, the name "**ion rocket**" was first coined. A new era for electric propulsion was dawning—that of the pioneers.

II. Era of Pioneers: 1946–1956

The first 40 years of the history of EP defined an era of bold and broad brushstrokes by visionary men who might seem to us now too quixotic with their stream of ideas to worry about the fine points of their implementation. It was time, during the following decade, to flesh out these originative ideas with careful analysis and quantitative conceptualization. This had become possible with the relative maturity of the relevant scientific fields (physics of gas discharges, atomic physics, quantum mechanics, special relativity, materials science, electrical engineering, etc.). It was, however, still not the era of EP experimentation and dedicated groups of investigators, but rather a period when a few individual scientists took it upon themselves to champion a field whose time on center stage was yet to come. One must not forget that at the outset of that era the orbiting spacecraft was still a speculation and by its close still not a reality. Therefore, to some extent, the foresight of these pioneers can be hypothetically likened to the precognition of those working on the problems of jet-powered supersonic flight before the first powered airplane had flown.

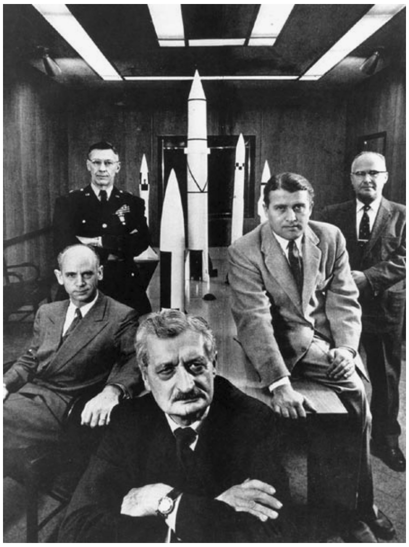


Fig. 4 Hermann Oberth (foreground) flanked by Ernst Stuhlinger (left) and Wernher von Braun (right). In the back standing are General Holger Toftoy (left) who commanded the operation of bringing German propulsion scientist to the United States, and Eberhard Rees (right) Deputy Director of the Development Operations Division at the Army Ballistic Missile Agency in Huntsville, Alabama. Picture taken in Huntsville in 1956.

If there was a single individual that personified the characteristics needed to link the earlier era of visionaries to the later age of developers, it was undoubtedly Ernst **Stuhlinger** [38] (1913–). He possessed the prerequisite connection to the forbearers of EP to take their ideas seriously, the education, intellect, and ingenuity to develop and expound these ideas with the highest scientific standards, and the acumen, discipline, and scholarship needed to document these findings in classic publications that would be studied by practically all contemporary and future EP workers.

The mantle was passed on from visionary (Oberth) to pioneer (Stuhlinger) in 1947 at the Army Camp Fort Bliss in Texas with none-other than Wernher von Braun as the catalytic instigator. After feeling reluctance on the part of his colleague to look into Oberth's ideas on "electric spacechip propulsion," von Braun goaded Stuhlinger by saying (Ref. 31, p. vii): "Professor Oberth has been right with so many of his early proposals; I wouldn't be a bit surprised if one day we flew to to Mars electrically!"

But before Stuhlinger published his first article on EP in 1954, there were a few developments that were to inspire him and set the path for his work. The first among these was a paper, "Zur Theorie der Raketen" ("On the Theory of Rockets"),[32] authored by Jakob **Ackeret** [39] (1898–1981) and published in **1946**, which, although it never mentioned electric propulsion nor dealt with it explicitly, had a great influence on the mind of the 33-year old pioneer. Ackert's paper presented a long-overdue generalization of Tsiolkovky's rocket equation by including relativistic effects to explore the ultimate limits of rocket propulsion. The relevance of this derivation to EP was that it considered the case of a vehicle propelled by a rocket whose power supply is carried on the vehicle. The result is therefore doubly general as Tsiolkovsky's rocket equation is recovered when the exhaust velocity u_{ex} is small compared to the speed of light c and when the power supply mass is made to vanish. (This case would then correspond to that of a standard chemical rocket.) Although the paper focused on the reduction (from the classically predicted value) of the terminal velocity of the vehicle when u_{ex} is a significant fraction of c, what caught Stuhlinger's attention was a brief calculation of the exhaust velocity that leads to the maximum vehicle terminal velocity and, in particular the demonstration that the corresponding ratio of the propellant mass to the total initial mass approaches a constant (which Ackeret calculates to be approximately 4). This result indicated to Stuhlinger that EP-propelled vehicles lend themselves to well-defined optimizations—a topic to which he would later devote a whole chapter in his 1964 classic *Ion Propulsion*[31] (and in which he showed that the aforementioned ratio is 3.92 and, more importantly, that it is independent of the energy conversion factor and any other parameter of the propulsion system).

While chemical rocket research was flourishing through the vigorous postwar research and design programs that sprung up in the United States and the Soviet Union, EP was still in the same cocoon where Oberth had placed it in 1929, waiting quietly for the pioneers to hatch it. A measure of this disparity can be gleaned from a review[33] of the state of the art of rocket propulsion, published in **1947**, in which, after more than a dozen and a half pages extolling the progress in chemical propulsion, EP is dismissed in a mere paragraph on the grounds that

> . . . the energy required to separate the raw "fuel" into ions suitable for acceleration away from the rocket would be rather large, and this energy would be wasted. At the present time the intensity of the beams of charged particles from existing accelerators is far too small to furnish any appreciable thrust.

Although both of these statements were true, and in fact remain so even today, they ironically mark the eve of the great dawning of electric propulsion, which we can confidently date as March **1949** when the *Journal of the British Interplanetary Society* published the fourth installment[34] of a series of articles titled "The Atomic Rocket" by the British physicists L.R. **Shepherd** and A.V. **Cleaver** [40].

In the previous three installments of that work[35–37] (published in September and November 1948 and January 1949), which constitute a ground-breaking treatise in the field of nuclear thermal propulsion, Shepherd and Cleaver expounded authoritatively on the requirements and prospects of rockets that use nuclear fission energy to heat their propellants. They concluded that until the advent of nuclear fuels with more favorable properties, materials with exceptionally high mechanical strength and melting point, and reactor designs with advanced heat-transfer methods, the prospects of nuclear thermal rockets would remain dim. This impasse proved felicitous for the evolution of EP, as the authors then turned their attention, in the fourth and last installment, from what they called the "thermodynamic" scheme (which they reckoned could a best produce an exhaust velocity of 10 km/s) to the electric one. If using the nuclear core to directly heat the propellant was fraught with many difficulties, what about using it to generate electric power to accelerate the propellant electrostatically?

Shepherd and Cleaver's study did not deal with aspects of ion rocket [41] design, although it did envision an electrostatic accelerator that would produce an exhaust ion beam (as in the modern version), as opposed to an exhaust with a stream in which charge has been injected (as imagined by the early visionaries). Instead it presented the first quantitative analysis of the feasibility of electrostatic propulsion for interplanetary missions [42] and marked a number of notable accomplishments:

1) It articulated the antagonism, inherent to EP, between the power supply (and power rejection) mass penalty that must be paid to produce thrust at high exhaust velocities and the propellant mass penalty that would be incurred by a (high-thrust) vehicle with low exhaust velocity (as we discussed in endnote 21). It then pointed out that for missions in field-free space or stable orbits the required acceleration would be low enough to render, in principle, the high exhaust velocity (10–100 km/s) of the ion rocket admissible, even desirable. After establishing that ion propulsion was admissible, the authors proceeded to evaluate if it was possible.

2) It unambiguously established the desirability of a propellant with high atomic weight by recognizing that high current is far more burdensome than high voltage (see endnote 22).

3) It recognized the essential role of beam neutralization and anticipated correctly that it could be effectively accomplished with electrons ejected from an auxiliary heated cathode or a similar source. With the preceding accomplishments the obstacles (enumerated in Sec. I) that had obstructed the conceptualizations of the early visionaries were removed, once and for all.

Where the study fell short, however, was in its final verdict on the feasibility of ion propulsion. Although obviously enchanted by its possibilities, Shepherd and Cleaver concluded, albeit reluctantly [43], that the ion rocket was too impractical in view of the massive power requirements it demanded. It is worthwhile, in the spirit of our critical historical review, to examine how such a dismissal was arrived at.

The key to understanding this conclusion lies in the authors' calculation of the power per unit vehicle mass p required to effect an acceleration a of 0.01 gravity to a space vehicle using an ion rocket with an exhaust velocity u_{ex} of 100 km/s. This is simply given by the formula [44] $p = au_{\text{ex}}/2\eta$, which, even for a thrust efficiency of unity, yields the exorbitant estimate of 5 kW/kg. Not surprisingly, a multiton interplanetary vehicle with such a propulsion system could not be deemed feasible. However, had Shepherd and Cleaver set their ambitions much lower, say, on a 500-kg robotic spacecraft requiring only an acceleration of 10^{-5} gravity, they would have found (using the same relations in their paper or equivalently those in endnote 44) that even a 70%-efficient ion engine, using xenon with $u_{\text{ex}} = 30$ km/s, could accomplish a quite useful interplanetary, albeit robotic, mission (increment its velocity by 3 km/s over a year) while consuming a mere 50 kg of propellant and about 1 kW of power (at a beam current of 1.75 A). In other words they could have anticipated a mission very much like Deep Space 1 that was launched half a century later, flew by two asteroids and a comet, and was a resounding success. Therefore, their negative verdict was as a result of their assumption of an unfavorably high required vehicle acceleration of 0.01 g.

Luckily for the evolution of EP, a verdict opposite to that of Shepherd and Cleaver was arrived at by another pioneer, the American astrophysicist Lyman **Spitzer** [45] (1914–1997) who, two years later in a paper read before the Second International Congress on Astronautics in September of **1951**, found that ion propulsion was perfectly feasible. As he explained in a footnote to the journal version of that paper,[38] published in 1952, his opposite verdict stemmed from his assumption of a required vehicle acceleration ($a \approx 3 \times 10^{-4}\ g$) that was "some 30 times" less than that assumed by Shepherd and Cleaver [46].

Spitzer, at the time of his 1951 presentation, was an outsider to astronautics and was not aware of Oberth's influential book, the fourth paper of Shepherd and Cleaver, nor of any previous thoughts on ion propulsion. It was, in fact, L.R. Shepherd himself who later attracted his attention to these works [47]. Despite Spitzer's lack of concern for the priority of his ideas [48], he should be credited for at least two contributions to EP's history. First his contrasting evaluation of the feasibility of ion propulsion opened a door to ion propulsion that could have been closed for a long time by Shepherd and Cleaver's less propitious evaluation. Second, although the space-charge limited current law had been known from the work of C. D. Child[40] and I. Langmuir[41] for about 40 years, it was Spitzer who first applied it to calculate the general design parameters of an ion rocket [49]. He also proposed the thruster's ion accelerating potential to be set up by "two fine-mesh wire screens" placed a small distance apart, and he emphasized the necessity of beam neutralization, which he suggested could be effected through thermionic electron emission from the outer screen.

Although Spitzer's might well be the earliest quantitative description of a "gridded" ion thruster in the literature, it is worthwhile to mention that EP's pioneers were, by that date, benefitting from significant advances during the 1940s in the development of ion sources for atomic and molecular beam work. These included the development of efficient sources such as the so-called Finkelstein ion source[42] in 1940, other high-current steady-state sources[43–45] and even electrodeless high-frequency sources[46] in the late 1940s. When introducing his ideas on ion propulsion, Spitzer acknowledged[38] that "the production of intense ion currents ha[d] been extensively studied in the past decade."

Citations to laboratory ion source work from that era abound in a **1952** paper[47] by the British scientist H. **Preston-Thomas** in which an EP system consisting of a large array of ion "guns" was chosen as the enabling technology for a fission-powered planetary "tugboat" that would bring to Earth orbit rare metals from extraterrestrial sources. Although this work, like its antecedents, did not yet describe in any detail the design of ion engines, it is of historical relevance because of a number of enlightened, even if qualitative, projections: It foresaw the importance of grid erosion by impinging ions, the role of charge-to-mass ratio distribution in performance, and the benefits of using radio-frequency (RF) electrodeless discharges as ionization sources [50]. The latter idea anticipated the presently well-established EP variant: RF ion thrusters.

Before we follow these germinal ideas to their burgeoning in the work of Stuhlinger, we should mention two contemporary advancements that were made in the new field of low-thrust trajectory analysis. Although a review of this ancillary field will remain outside our main focus, these early milestones deserve a place in our story as they were instrumental in establishing the veracity of EP's claims of feasibility and superiority. In 1950, G.F. Forbes published an abridged version[49] of his Massachusetts Institute of Technology Masters' thesis in the *Journal of the British Interplanetary Society* and started in earnest the field of low-thrust trajectory analysis. Forbes' paper showed, for the first time, how low-thrust space vehicles can accomplish certain space maneuvers more efficiently than their high-thrust counterparts. This was followed, in 1953, by H.S. Tsien[39] whose low-thrust orbital mechanics work (see endnote 46) vindicated Spitzer's adoption of the low (10^{-4} g) vehicle acceleration that had led him to reclaim the feasibility of ion propulsion.

By **1954** the stage was set for Stuhlinger to launch the field of EP on a trajectory of continuous development and sophistication. His first paper,[50] published that year, differed starkly from all previous publications on the subject in its depth, detail, and the extent of the lasting contributions it made. The paper presented a holistic design of an electrically propelled spaceship including details of the ion thruster and the power supply (turboelectric generators driven by a solar concentrator) and rules for performance optimization. In it we see for the first time a number of new ideas, rules of thumb, and design guidelines that would become central in the field. In particular, he introduced and showed the importance of the specific power as an essential parameter for EP analysis; he demonstrated that for given specific power and mission requirements there is an optimum exhaust velocity; he showed that the charge-to-mass ratio of the particles should be as low as possible to minimize the beam size (see endnote 22); he advocated the suitability of the contact ionization process to produce ions and pointed out the advantages of alkali atoms, in particular cesium; and he calculated that ion propulsion, even with the contemporary state of technologies, could lead to vehicle acceleration levels (10^{-4} g) that recent low-thrust trajectory studies had deemed useful.

That paper, and two following[51,52] published in **1955** and **1956** in which Stuhlinger described a similar vehicle but with a more advantageous nuclear reactor, mark the culmination of an era in which the main goal was to evaluate the feasibility of EP [51]. This conceptually demonstrated feasibility would now take ion propulsion from an intellectual pastime of a few prescient scientists, almost all of whom, incidentally, never ventured again into the field of EP [52], to a serious and vibrant technological and scientific discipline with its own dedicated practitioners. It must be said, in that context, that Stuhlinger was the first and, for more than a decade, the leading figure among these professional EP specialists. He thus played both the role of a pioneer at the conclusion of an era of conceptual exploration and that of a leading investigator in the following era of development.

III. Some Concluding Comments on the First 50 Years

There are a few aspects of the history of EP up to 1956 that are worth emphasizing:

First, even the more analytical contributions were mainly concerned with the feasibility of EP rather than with detailed aspects of the devices. This is of course to be expected given the infancy of astronautics and related technologies at that time.

Second, with the exception of Glushko and his exploding wire electrothermal thruster, the focus of the early EP practitioners was almost exclusively on the electrostatic branch of electric propulsion. This can be traced to EP's roots in cathode-ray physics whose steady-state gaseous discharges, with their enigmatic monochromatic glow, captivated many of the best minds of the late 19th century, and cast their spell, with reports of electrostatically produced high particle velocities, on the imagination of EP's progenitors. Experimental magnetohydrodynamics (and its corollary, electromagnetic acceleration of plasmas), on the other hand, did not fully emerge until the second half of the last century.

Third, the primary concern of the early EP visionaries and pioneers was with the prospect of human-piloted interplanetary travel, which remained the *raison d'être* of EP. Perhaps the restless imagination of these men could not foresee the value of the relatively more sedentary near-Earth commercial satellites and robotic missions or, more likely, were not so much inspired by them [53]. Perhaps some of this bias can be traced to the science fiction and fantasy literature (especially of Jules Verne) that sparked much of the early thought on modern rocketry. It seems unlikely that the minds of these men in their youth could have been equally captured by stories of space exploration with no human explorers. This predilection for human-centered exploration, along with the postwar promise of nuclear fission, colored the conceptualization of EP as the domain of massive nuclear-powered, human-piloted spaceships with initial masses of hundreds of tons and power levels of many megawatts. It was only with the advent of solar cells and the relatively mundane interests in commercial telecommunications and military surveillance brought about by the prosperity and paranoia of the cold-war era that the sights were lowered and EP ushered into its later eras of acceptance and application.

Fourth, over the first half-century of the history of EP, there was a virtual absence of dominant institutions [54] vis-a-vis individuals. This can be attributed to the same reasons as those behind the bias for human-piloted spaceships. Although the development and maturity of EP would later result from the collective efforts of workers in various institutions, the first more leisurely five decades will always be recalled as the dominion of far-sighted individuals such as Goddard, Oberth, Shepherd, Cleaver, Spitzer, and Stuhlinger.

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Endnotes

[1] The reader will soon note a measure of the vagaries of that evolution: although the earliest thoughts and experiments related to EP are almost all about electrostatic propulsion, the first laboratory electric thruster was electrothermal, and the first electric thruster to ever fly in space was of the pulsed (mostly electromagnetic) plasma type.

[2] The SP-100 program aimed for 100-kWe output, consumed half a billion dollars and was terminated in 1993. The Nuclear Electric Propulsion Spaceflight Test Program centered around the Russian Topaz II reactor (40 kWe) met the same fate around the same year.

[3] Although radioisotope thermoelectric generators have been used reliably on 24 U.S. spacecraft, their electric power output and specific power make them wholly inadequate for EP on piloted or heavy cargo missions. Even the most advanced radioisotope power systems today have specific powers below 10 We/kg (Ref. 1).

[4] NASA's Prometheus program promises to be synergistic with electric propulsion.[2]

[5] Throughout the text of this article, we use a bold font to highlight consecutive year numbers in order to provide a visual trail of the chronology. Also, the names of some of the visionaries, pioneers and key individuals in the history of EP, as well as the first occurrence of the names of various EP concepts, are highlighted in bold font for easy reference.

[6] The alternate transliterations "Tsiolkovskii" and "Tsiolkovskiy" also appear in the latin-scripted literature. For biographies of Tsiolkovsky and discussions of his numerous original ideas on spaceflight and propulsion, see Refs. 5–7.

[7] Tsiolkovsky in fact had written about the use of rockets for space flight and interplanetary travel in a manuscript titled *Svobodnoye Prostranstvo* (*Free Space*) dated 1883, which was found posthumously (Ref. 8, p. 3) and which remains unpublished, and in a story titled "Outside the Earth" started in 1896 and published in 1920 (Ref. 8, p. 4, footnote). Going much further back, the idea of rocket space propulsion appears in the fantasy literature as early as the 17th century with Cyrano De Beregerac's 1656 *L'histoire Comique des Etats et Empires de la Lune* (*A Comic History of the States and Empires of the Moon*). While Jules Verne's classic *De La Terre á la Lune* (*From Earth to the Moon*) mentions the use of rockets only in the context of steering a cannon-launched spaceship, it had incalculable impact on the young minds of all three of the early fathers of rocketry, Tsiolkovski, Goddard and Oberth, by their own admission. It is perhaps worth mentioning that a number of 19th century authors, engineers, and tinkerers, especially in Russia, had seriously considered and evaluated the use of rockets (or more generally reaction propulsion) for atmospheric flight. Sokol'skiy (Ref. 9, pp. 125–155) discusses these early ideas in his fascinating history of Russian work on rocketry. A history of liquid chemical rockets written most recently by G.P. Sutton has been published in this journal in two papers covering separately activities in the USSR and the United States.[10,11]

[8] This title ("Issledovaniye Mirovykh Prostranstv Reaktivnymi)" was that of the article as it first appeared in the Journal *Nauchnoye Obzorniye* (*Scientific Review*), No. 5, 1903. Later, in 1924, Tsiolkovsky republished the same article at Kaluga as an independent brochure but with the title "A Rocket in Cosmic Space." That this latter title almost literally echoes that of Oberth's famous 1923 book *Die Rakete zu Den Palentenenräumen*[12] is no doubt an expression of Tsiolkovsky's frustration with the impression, at that time, that the original ideas on the use of rockets in space are Oberth's. Tsiolkovsky also used his 1903 article title "Investigation of Universal Space by Means of Reactive Devices" for two subsequent articles in 1911 (Ref. 8, pp. 60–95) and 1926 (Ref. 8, pp. 111–215), which contained vastly different material, as well as for a supplement to the 1911 article published in 1914 (Ref. 8, pp. 99–110). We point this out because Tsiolkovsky's use of the same title for four different articles has caused some of confusion in the literature.

[9] While Goddard's thoughts on EP, which we shall discuss shortly, appear in his personal notebooks as early as 1906, and thus predate this quote by Tsiolkovsky, the latter seems to be the first *published* mention of the use of electricity for spacecraft propulsion.

[10] In 1895 Jean-Baptiste Perrin had demonstrated conclusively that cathode rays consist of particles, and in 1897 J.J. Thomson concluded that these are electrons (which he called "corpuscles") and inferred the electron's charge-to-mass ratio. His findings and especially his hypothesis that electrons are "the substance from which the chemical elements are built up" was not generally accepted until 1899.

[11] Eugen Goldstein observed in 1886 that in addition to cathode rays there exists in cathode ray tubes radiation that travels away from the anode. These were called canal rays because they emanated from holes (canals) bored in the cathode. The realization that these are atoms that have had electrons stripped away did not occur until after the discovery of the photoelectric effect and the demonstration by the German physicist Philipp Eduard Anton Lenard (1862–1947) in 1902 that the effect is caused by the emission of electrons from metal, thus pointing to the conclusion that atoms contained electrons. Subsequently, Ernest Rutherford (1871–1937) suggested in 1914 that the positive rays are positively charged atom-sized particles. His later experiments, which led to the discovery of the proton in 1920, confirmed this and led to a final acceptance of Thomson's earlier speculation that the atom consists of positively charged material surrounded by negatively charged electrons.

[12] One example is the little recognized fact that he had clearly anticipated laser propulsion (another EP concept of sorts) in this quote from 1926 (Ref. 8, p. 134): "We may have a case when, in addition to the energy of ejected material, we also have an influx of energy from the outside. This influx may be supplied from Earth during motion of the craft in the form of radiant energy of some wavelength; . . . ."

[13] The word "explosives" in Tsiolkovsky's parlance refers to liquid chemical propellants.

[14] There seems to be no evidence to doubt the claims made by each of Tsiolkovsky, Oberth, and Goddard of having arrived at many of their early findings regarding chemical rockets independently. Oberth stated in a letter addressed to Goddard and dated 3 May 1922 (Ref. 14) that he had just learned of Goddard's work as he was preparing the manuscript of his book *Die Rakete zu den Planetenräumen* for publication. In response Goddard sent him a copy of his famous 1919 monograph "A Method of Reaching Extreme Altitudes," which Oberth subsequently cited in an appendix of his book. This letter therefore fixes 1922–1923 as the date when both men became aware of each other's work. It is most likely that Tsiolkovsky learned of his Western counterparts' works not long after the publication of Oberth's well-disseminated book in 1923, well after the (limited) publication of the first two versions (1903 and 1911) of his own "Investigation of Universal Space by Means of Reactive Devices," but before his extensive work of 1926 carrying the same title. Goddard and Oberth seem to have remained unaware of the work of the Russian visionary until around 1927, the year of the Moscow exhibition on "Interplanetary Apparatus and Devices," where Tsiolkovsky was hailed as the Russian father of rocketry. (Goddard's wife Esther wrote on a souvenir scrapbook of that exhibition notes that decried the insufficient recognition given to her husband's work.[15]) We had already mentionned in endnote 8 Tsiolkovsky's reaction, as early as 1924, to Oberth's popularity. Later, Oberth wrote to Tsiolkovsky "I would certainly be much further in my own work today . . . had I taken into account your superior work."[14]

[15] Refs. 14–16 are three of the biographical books on Goddard.

[16] This duality of interest is epitomized by his work habits during his memorable stay at Princeton University as a research fellow in electricity and magnetism during the academic year of 1912–1913. During the day, he worked on displacement current experiments, his official research project (a byproduct of which led to a patent that was instrumental in the development of the radio tube), and he spent his evenings working on the theory of rocket propulsion.[14,16]

[17] The story involves a five-year old Goddard trying to propel himself upwards after rubbing zinc from a battery on his shoes and scuffing them vigorously on a gravel walk to cause electric sparks.[14,17]

[18] This was not the first time the young Goddard considered the application of cathode rays to propulsion. A few months earlier, in another entry in the same notebook (Ref. 18, pp. 38–41), dated 18 February 1906, he conceived a device (which he also illustrated schematically) in which two parallel tubes, one producing (negative) cathode rays and the other (positive) canal rays, were thought to yield a net reactive force. This would seem to be the earliest documentation of an electric rocket concept. However, a close examination of his notes reveals that he did not discuss the device in terms of the rocket effect, that is, reaction caused by mass expulsion, but rather in terms of creating a momentum imbalance. Specifically, Goddard stated that the cathode and anode rays would "simply serve as ways to increase an effect which is unbalanced." These ideas of propulsion trough unbalanced internal forces were constant on his mind since his first thoughts on the subject while in a cherry tree[15] in 1899. He did not totally give up such a concept, it seems, until 4 March 1907 when, after conceiving another device where charged particle acceleration in opposing direction was to produce a momentum imbalance, he wrote in his notebook (Ref. 18, p. 150): "The device . . . cannot be used, as the two opposite accelerations on each end of the condenser battery would neutralize each other," and concluded with the insight; "A simpler plan would be to expel the electrons after they had acquired a significantly great velocity."

[19] It was not until Planck and Minkowski published their ideas on special relativity in 1908 that Einstein's famous 1905 publications on the subject were taken seriously. In 1905 Einstein was only a "technical expert third class" at the Bern patent office.

[20] Although even late-19th century cathode-ray tubes accelerated electrons to speeds that are a fraction of that of light, the technology of powerful radio-frequency sources capable of accelerating electrons through linear resonance accelerators to speeds very close to that of light was not developed until after 1940.

[21] This penalty can be seen by expressing the thrust-to-power ratio T/P of an EP system as a function of its exhaust velocity. Using the definition of thrust efficiency

$$\eta \equiv \left[\left(\tfrac{1}{2}\right)\dot{m}u_{\text{ex}}^2\right]\Big/P \tag{1}$$

and

$$T = \dot{m}u_{\text{ex}} \tag{2}$$

we can write

$$T/P = 2\eta/u_{\text{ex}} \tag{3}$$

which shows how raising the exhaust velocity, even at a maximum thrust efficiency of 1, will incur a power supply mass penalty through the decrease of the amount of thrust per unit power. This mass penalty could easily overwhelm the mass savings, as a result of high exhaust velocity, indicated by Tsiolkovksy's rocket equation. Thrust with relativistic electron velocities is therefore most expensive from a power supply point of view.

[22] This might not be directly evident but can easily be seen by using the definitions of thrust, mass flow rate, and current density to write

$$T = \dot{m}u_{\text{ex}} = (j/q)m_i A u_{\text{ex}} \tag{4}$$

and invoking the Child's law for space-charged limited current density (for an idealized one-dimensional electrostatic accelerator)

$$j \propto (2q/m_i)^{\frac{1}{2}}\left(V^{\frac{3}{2}}\Big/d^2\right) \tag{5}$$

then solving for the exit area A of the accelerator in terms of thrust and exhaust velocity (and not in terms of applied potential as more commonly done):

$$A \propto \left(Td^2\Big/u_{\text{ex}}^4\right)(q/m_i)^2 \tag{6}$$

In practice d is limited by design constraints, and the thrust and exhaust velocity are mission requirements. This leaves the area to scale with the square of the ion's charge-to-mass ratio and emphasizes the benefits of heavier propellants.

[23] There are 214 patents in Goddard's name.

[24] In an autobiographical article written in 1927 and published in 1959 (Ref. 17), Goddard stated that the experimental work which checked the conclusions set forth in that patent was carried out at Clark University by two students during 1916–1917.

[25] Although the word "space" was not mentioned in the patent (instead Goddard stated that the intended application was "jet propulsion"), there is little doubt that Goddard, who was well aware of the smallness of the reactive forces inherent in electrostatic acceleration, was thinking of spacecraft propulsion as the ultimate application. (This assumption would best be ascertained by experimental measurements or more detailed description Goddard and his students might have made with an actual device; however, we did not find any such documentation in the Goddard's Archives at Clark University.) It is relevant to mention in this context that while Goddard often wrote in his notebooks about the technical problems of space travel he rarely mentioned this ultimate application in official communications and confined his stated goals to the "reaching of high altitudes" for scientific studies. Later in his career he stated[21]: "I regard it as most unfortunate that the interplanetary aspect of rocket theory was seized upon and sensationalized. This has discouraged public confidence and in some cases has turned away serious support from the researches that need to be carried on into the fundamental problems of rocket and jet propulsion." It is often said that Goddard never fully recovered from the humiliation of a 1920 *New York Times* editorial[22] in which his ideas on the use of rockets in the vacuum of space were severely ridiculed.

[26] U.S. Patent No. 1,102,653, "Rocket Apparatus"; application filed 9 October 1912; patent granted 7 July 1914.

[27] A possible reason why this early electrostatic accelerator was overlooked as such is that the patent description deals with a number of aspects of "electrified jets of gas" only one of which is electrostatic acceleration.

[28] There is presently no extensive biography, in English, of this most obscure of early thinkers on astronautics. The following events of his life have become known through a recent biographical sketch.[23] His original name, Alexander Shargei, was changed to evade the authorities in the course of a woeful life. He landed in prison in Kiev while still in his mother's womb. After demonstrating his intellectual brilliance at the gymnasium of his birthplace town of Poltava in the Ukraine, he was forced to abort his engineering education in Kiev to command a machinegun platoon on the Transcaucasian Front during WWI. He then had a stint with the White Guard army, was almost killed by the Cheka while trying to escape to Poland, escaped to Siberia where he worked as a mechanic in Novosibirsk, then was caught and served three years in a labor camp before being released to work on wind turbines in Kharkov. He disappeared in late 1941 while on assignment in the region of Kaluga, where, coincidentally, Tsiolkovksy had lived and died. Between 1916 and 1927 Kondratyuk managed to write down his numerous space-related ideas in four extant manuscripts (Ref. 9, p. 145), only one of which (Ref. 24) was published during his lifetime.

[29] He seemed to have arrived at Tsiolkovsky's rocket equation independently, predicted the central role of rockets in space exploration, and speculated often qualitatively, but sometimes analytically and quantitatively, on such topics as multistaging, launch aerodynamics, spacecraft guidance and stability, aerobraking, the use of solar energy for propulsion, and the creation of interplanetary bases. The extent to which these ideas were completely original remains debatable although Kondratyuk maintained that he did not become familiar with the works of Tsiolkovsky and others until 1925.

[30] *Tem kto budet chitat,' chtoby stroit.'* An English translation of that manuscript is available on pp. 15–56 of Ref. 9.

[31] It was not until 1938 that Kondratyuk wrote the date 1918–1919 on his "To whomsoever will read . . . " manuscript before he sent it to his editor (Ref. 9, p. 49). It was obvious from the manuscript that there were a number of additions and corrections that Kondratyuk had made at different times. Consequently, even Soviet

historians of astronautics, who were often too eager to attribute exclusive originality to their comrades, have questioned the definitiveness of Kondratyuk's dates.

[32] These are often taken to include Tsiolkovsky, Goddard, and Oberth and, sometimes, Esnault-Pelterie.

[33] This book also contained a chapter called "Electric Spaceships," which is very similar to that appearing in the 1929 book but with some additional remarks.

[34] A measure of the book's success is its winning the REP-Hirsch prize coestablished by another pioneer of astronautics, the French aeronautical engineer and inventor Robert Esnault-Pelterie (1881–1957).

[35] On 15 May 1929 Glushko joined Leningrad's Gas-Dynamics Laboratory (GDL) and organized a subdivision to develop electric and liquid rockets and engines.[27] This subdivision grew into a powerful organization (GDL-OKB), which he led from 1946 to 1974 and which was a primary developer of rocket engines in the Soviet Union. From 1974 to 1989, Glushko led NPO Energia whose role in establishing the supremacy of Soviet launchers is paramount.

[36] The relevant passage is only a brief paragraph, but, in fairness, we should give Radd the credit of thinking of an ion rocket in which a highly ionized gas is first formed, then ions are extracted and accelerated as a beam, an accelerator that resembles more the modern ion thruster than the "electric wind" devices conceived by Goddard and Oberth.

[37] The article ends with the almost oracular pronouncement: "Other walls of difficulties shall place themselves in the path of progress, but with the inevitability comparable to life and death, science will hurdle these impedances until we finally reach the greatest of all man's goals: The Conquest of Space."

[38] Born in Niederrimbach Germany in 1913, Stuhlinger received a doctorate in physics at age 23 from the University of Tuebingen. He became an assistant professor at the Berlin Institute of Technology and continued research on cosmic rays and nuclear physics until 1941 when he served with the German army on the Russian front. He was then transferred to the Peenemünde rocket research center where he became a leading member of the German rocket development team. After the war he came to the United States in 1946 with Wernher von Braun and other German rocket specialists, as part of Project Paperclip, to work, first at the U.S. Army at Fort Bliss, Texas, where he test fired captured German V-2 missiles for the Army, then starting in 1950, at the Army's Redstone Arsenal in Huntsville, Alabama. He received the Exceptional Civilian Service Award for his part in the launch of Explorer 1 and after the Marshall Space Center was formed in 1960, he became its Associate Director of Science. He retired in 1976 and continues being a champion for space exploration and a strong advocate for a human mission to Mars.

[39] Jakob Ackeret, a Swiss pioneer of aerodynamics, was one of the leaders of the theoretical and experimental study of supersonic flows about airfoils and channels. He made major and fundamental contributions to the fluid mechanics of gas turbines and supersonic flight.

[40] Shepherd was a nuclear physicist at the Cavendish Laboratory, and Cleaver became the head of Rolls Royce Rocket Division.

[41] In the same paper the authors also coined the term "ion rocket" and seemed unaware of the recent appearance of that term in Radd's paper.[30]

[42] It presented the first, albeit general, published scenarios for EP-based interplanetary travel whereby chemical propulsion is used for high-gravity portions of the trajectory and EP for the rest.

[43] Faced with the exorbitant calculated mass of the mechanical machinery needed to convert the heat of the nuclear core into the electricity required to power the ion engine, the authors, in a last effort to salvage the promise of ion propulsion, looked into a far-fetched alternative of using the particle kinetic energy of the nuclear reaction to directly generate the accelerating electrostatic field.

[44] Because the required power is $P = \dot{m}u_{\rm ex}^2/2\eta = Tu_{\rm ex}/2\eta = M_v a u_{\rm ex}/2\eta$ (where we have used $T = \dot{m}u_{\rm ex} = M_v a$) we have, for the power per unit accelerated vehicle mass, $p \equiv P/M_v = a u_{\rm ex}/2\eta$. Furthermore, the voltage for electrostatic acceleration can be calculated, once the propellant (atomic mas m_i) is chosen, by solving $u_{\rm ex} = \sqrt{(2eV/m_i)}$ for V and the corresponding current per unit vehicle mass i from $i = p/V = a u_{\rm ex}/2\eta V$. Finally, the propellant mass flow rate per unit vehicle mass $\dot{m}'$ is simply $\dot{m}' \equiv \dot{m}/M_v = T/M_v u_{\rm ex} = a/u_{\rm ex}$. For the example in Shepherd and Cleaver's paper ($a = 0.01$ g, $u_{\rm ex} = 100$ km/s, and mercury propellant), the preceding relations yield $p \approx 5$ kw/kg, $V = 10.4$ kV, $i = 0.47$ A/kg, and $\dot{m}' \approx 1$ mg/s/kg.

[45] A pioneer on many fronts and a leading astrophysicist, Spitzer championed fusion research in the united states, authored the plasma physics classic "Physics of Fully Ionized Gases," made substantial contributions to the understanding of stellar dynamics, and, a decade before the launch of the first satellite, proposed the development of a space-based telescope that would not be hindered by Earth's atmosphere. He is recognized as the father of the Hubble Space Telescope to whose advocacy, design, and development, he contributed immensely. He is also recognized as the father of the Hubble Space Telescope to whose advocacy, design and development, he contributed immensely. In December of 2003 NASA's Space Infrared Telescope Facility was renamed the Spitzer Space Telescope in his honor.

[46] Although Spitzer assumed this value, like Shepherd and Cleaver did theirs, without *a priori* rationalization he was justified a posteriori a year later by Tsien[39] whose work on low-thrust trajectories showed that even lower accelerations (10^{-5} g) could be used in effecting useful orbital maneuvers in acceptable time.

[47] See footnote 3 of Ref. 38.

[48] He stated[38]: "The chief purpose of this paper is not to claim priority for any ideas but to focus attention on what promises to be the most practical means for interplanetary flight in the near future."

[49] Spitzer chose nitrogen for propellant for its then supposed abundance in planetary atmospheres. For an interplanetary spaceship with an acceleration of 3×10^{-4} g, he calculated, using the same relations presented in endnotes 22 and 44, the following design parameters for an ion rocket with $u_{\rm ex} = 100$ km/s: a power level of 1.5 MW, a voltage of 730 V across a gap of 1 mm, and a current of 2 kA from a beam area of 7.2 m^2.

[50] Another equally ambitious conceptual designer of super-spaceships, D.C. Romick, published a design for a 1000-ton ion-beam propelled spaceship in a 1954 paper[48] whose main relevance to our historical review is that it contained the first reference to the problem of beam divergence.

[51] Belonging to the same era is the work of D. B. Langmuir and J. H. Irving of the Ramo-Wooldridge Corporation (which is the RW of the TRW corporation formed later in 1958 when Ramo-Wooldridge merged with Thompson Products Company of Cleveland, Ohio) published only in limited-release technical reports.[53,54] In that work we encounter for the first time the idea of using a variable exhaust velocity to optimize the performance of en electrically propelled vehicle.[31]

[52] This statement applies to Goddard, Oberth, Shepherd, Cleaver, Spitzer, and Preston-Thomas.

[53] An evidence that tends to support the second half of this argument is the case of Stuhlinger who got to be a witness to, and a leading participant in, the age of robotic space exploration but remains a vociferous champion for human interplanetary travel.

[54] With the possible exception of the USSR's Gas Dynamics Laboratory.

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