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ELECTROSTATIC THRUSTORS

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Early workers in the chemical rocket field (such as Goddard and Oberth) recognized the possibility of using electrical energy to accelerate a propellant, but no significant progress was made in electric propulsion prior to the advent of practical fission powerplants. Papers by Shepard and Cleaver (1948, 1949), and Stuhlinger (1955, 1956) showed the substantial payload advantages of electric-propulsion systems using fission powerplants. Although enough information was available for preliminary powerplant estimates, it was clear that the thrust-producing devices - or thrustors - would require a new technology. The electric-propulsion research program in the United States was therefore directed primarily at the development of thrustors. Work had been started on nuclear powerplants for a variety of space applications, and it was hoped that some of these powerplants would be suitable for early electric-propulsion missions. The problems that would be met in the realization of these powerplants were expected to be mostly developmental. That is, the problems were expected to consist principally in applying available knowledge to a new area. The powerplant and thrustor programs will be compared further near the end of this article.

Experimental work was initiated on a variety of thrustor concepts in 1958 and 1959, but with more emphasis on an electrostatic thrustor employing contact ionization than any other type of electric thrustor. There were several reasons for this emphasis. The contact-ionization concept gave promise of good overall efficiency. This concept also lent itself to the division of an electric thrustor into components - a great aid to a systematic engineering approach. The final reason, and not necessarily the least, is that the contact-ionization thrustor was the first to be described in literature in anything like a workable design (by Stuhlinger in 1954).

The contact-ionization thrustor (fig. 1) makes use of the fact that a low-ionization potential atom will lose an electron when it strikes a high-work-function surface. The surface must be hot enough to evaporate the ions (which are held by induced image charges) or the surface will quickly become coated and cease operation. The radiated heat from the hot ionizer, 1300° to 1500° K, constitutes the major loss for this type of thrustor. Cesium as the low-ionization-potential propellant and tungsten as the high-work-function ionizer have been used almost to the exclusion of other combinations. The voltage difference between the ionizer and the accelerator electrode (typically several thousand volts) gives the ion its high velocity. The electrons extracted during the ionization process are added to the ion beam by the neutralizer. The ions are usually given some deceleration after the acceleration process. This deceleration may be accomplished by making the neutralizer somewhat positive relative to the accelerator. This provides a potential barrier which prevents the neutralizer electrons from going in the wrong direction and short-circuiting the ion accelerator.

The other major type of electrostatic thrustor uses high-energy electrons to ionize the propellant. Although electron bombardment has been used to ionize particles for many years, the more-efficient conventional electron-bombardment sources (such as the von Ardenne duoplasmatron) produce too dense a stream of ions to be transmitted by practical accelerator systems. The value of the electron-bombardment thrustor introduced by Kaufman and Reader in 1960 was in matching the ion source to the current-density requirements of a long-life electrostatic accelerator operated in the exhaust-velocity range of interest.

The electron-bombardment thrustor (fig. 2) uses a thermionic emitter as the electron source. The emitted electrons are contained in the radial direction by a magnetic field (produced by the field winding) and in the axial direction by an electric field (the ends of the ionization chamber are operated at the same potential as the cathode). Thus the electrons can escape through the magnetic field to the anode only by collision processes. Some of the collisions ionize propellant atoms, and the ions that diffuse to the accelerator system are accelerated by the potential difference between the two grids (again several thousand volts). Electrons are again added to the ion beam by the neutralizer. Both mercury and cesium have been used as the propellant in the electron-bombardment thrustor. The major power losses are the heating power for the cathode, the discharge power in the ionization chamber (on the order of 500 ev per ion), and the power to the magnetic-field winding. (The latter loss is eliminated in a light-weight permanent-magnet design introduced by Reader in 1963.) The neutrals that escape without being ionized (5-20 percent) also constitute a significant loss for this type of thrustor.

A third, but considerably less-developed, type of electrostatic thrustor uses charged colloidal particles instead of ions. A discussion of colloidal thrustors, though, is more appropriate at the end of this article where present trends are discussed.

The need for some form of neutralization was recognized in the earliest electrostatic-thrustor papers. The subsequent development of neutralization concepts is one of the more interesting facets of electric propulsion. The basic requirements for neutralization are: (1) equal rates for the ejection of opposite charges (current neutralization) to avoid building up a large charge on the space vehicle, and (2) equal densities of opposite charges in the beam (charge neutralization) to avoid large space-charge effects within the beam.

The earliest concept of neutralization proposed was that since oppositely charged particles attract each other, all one had to do was to provide for the emission of electrons somewhere near the ion beam. Electrostatic attraction would then assure that the proper number of electrons were pulled into the beam and distributed evenly. The next step was to obtain mathematical solutions that described this process. Collision processes were assumed negligible in these solutions - partly because the mean free paths between two-body collisions are long in ion beams, but mostly because mathematical solutions appeared to be impossible without this assumption. The solutions obtained indicated that electrons had to be introduced at not more than twice the ion velocity if a neutralized beam was to be obtained far from the vehicle. Space-charge considerations, together with the requirement for low electron velocities, would then result in the electron source being hundreds of times larger in area than the ion source. In fact, just the thermal velocity with which electrons are emitted would exceed twice the ion velocity for many combinations of design and operating conditions.

The net result of these analytical studies was that neutralization appeared very difficult. By 1960 a number of ion thrustors were operating at conditions that should have caused neutralization problems - but none were encountered. The earlier thrustors were operated at very low ion beam currents, so that space-charge effects were not expected to be large. But by 1960 ion-beam currents of over 100 milliamperes had been obtained at steady-state operating conditions - with no evidence of "blow-up" or "turn-around". The analytical studies were clearly inadequate. Experimental studies by Sellen and Shelton of transient phenomena in ion beams indicated that secondary electrons from the test facility would cause charge neutralization even if no intentional electron sources were present. Later tests by Sellen and Kemp employed the pulsed-beam technique to obtain measurements during the time that an ion beam was traveling from the thrustor to the other end of the test facility. Thus the measurements were obtained before secondary electrons could be emitted and, at least for the length of the beam, a close simulation of space was obtained. The length of the pulsed beam was extended to about 80 feet in subsequent experiments by Sellen and Kemp in a NASA vacuum test facility. Although space tests will be required for final verification, there now appears to be little doubt that neutralization will be obtained in space. The failure of the analytical studies was due, of course, to the basic assumption of no collisional effects. Even small collisional effects will eventually reduce excess directed electron velocity to acceptable random motion. In the case of large relative velocities between the electron and ion populations, collective collision processes can be far more effective than two-body collisions in producing randomization.

The mainstream of contact-ionizer work has been on the porous-tungsten type in which the cesium reaches the ionizing surface by diffusing through the pores of the ionizer. This type of contact ionizer appears to offer the best combination of high ion currents and low neutral escape rates. The ionizer usually consists of a number of pieces of porous tungsten, either in the shape of strips (fig. 3) or that of buttons (fig. 4). As the contact-ionization thrustor has been improved, and to some extent standardized, greater emphasis has been placed on whether one uses strips or buttons. The resultant discussions are somewhat reminiscent of arguments for various cylinder arrangements in automobile engines.

Because of the importance of porous tungsten to contact-ionization thrustors, the progress of the latter is closely linked to the technology of the former. The machining of porous tungsten to complex shapes was one of the early problems. Spark removal of metal has been used to some extent. The most used method at present, though, is filling the porous tungsten with copper, machining to shape by normal methods, then removing the copper. This sequence permits precise machining without the usual loss of porosity. The porous tungsten must also be joined to a manifold of refractory metal, and this joining presents problems. Various brazing processes have been developed by thrustor manufacturers. The recent development of electron-beam welding, in which the work is placed in a vacuum and an electron beam provides the heat for welding, appears to offer the best general solution to these joining problems.

Analyses of the cesium diffusion and ionization processes with porous tungsten indicate that a very fine pore structure is desired. But the fine powders that give the desired pore structure also promote further sintering (with accompanying dimensional changes) during normal use. A porous tungsten fabricated from spherical tungsten powder (reported by Kuskevics and Thompson in 1963) has the best combination of fine pore structure and low sintering rates available at present.

The major problem area of the electron-bombardment thrustor (fig. 5) has been the cathode. Bombardment by ions with up to 50 ev of energy erodes the low-work-function coatings that are necessary for efficient electron emission. Oxide-matrix cathodes (in which a large quantity of the active oxide emitter mix is held in a metal matrix) have been operated as long as 1600 hours in component tests and over 600 hours in a complete thrustor. Considerable improvement is necessary before the goal of 10,000 hours can be reached, which is roughly the lower limit of lifetime required for interplanetary missions. An electron-bombardment cathode that appears certain of reaching a 10,000 hour lifetime is the autocathode developed by Speiser. Prior to the autocathode, mercury was used almost exclusively as the propellant for electron-bombardment thrustors. In an interesting mating of contact and electron-bombardment technology, Speiser used the usual contact-thrustor propellant (cesium) in an electron-bombardment thrustor of his own design (fig. 6). The cesium propellant is passed through the cathode to continually replenish the low-work-function coating. The bombardment of ions is turned to advantage by using it to supply the necessary heating, so that no external power is required for cathode heating after the initial start-up.

Electrostatic-thrustor efficiencies of 60 to 80 percent are presently possible at exhaust velocities from 40,000 to 100,000 meters per second (which covers much of the range of interest). Although the electron-bombardment thrustor apparently has a slight edge in efficiency, there is no guarantee that this will be the case in the future. Regardless of which type of thrustor ultimately predominates, the presently achievable efficiencies are adequate for most proposed missions. The emphasis in electrostatic thrustor research has therefore shifted towards achieving long lifetimes. The porous ionizer and cathode problems have already been mentioned, but there is another lifetime problem that both thrustors have in common. That problem is charge-exchange erosion of the accelerator system. The state of the art in accelerator design is such that virtually all the ions produced on the contact ionizer or in the ionization chamber can be focused to miss the accelerator electrodes. In traversing the accelerator system, some ions pass near escaping neutrals and pick up electrons from those neutrals. This charge-exchange process thus results in the production of fast neutrals and slow ions within the accelerator structure. The fast neutrals usually escape to perform their desired function of providing thrust. The slow ions, however, are more likely to strike accelerator electrodes and cause erosion, and ultimately, destruction. Analysis of the charge-exchange process shows that charge-exchange impingement should vary inversely as the square of ion-beam current density. The problem could be alleviated, then, by operating at low enough current densities - or with large enough thrustor exit areas. For the electron-bombardment thrustor a large ion beam area means a heavy, but tolerable, thrustor weight. For the contact-ionization thrustor, with a smaller loss of neutrals, the weight problem is not as serious. But the power losses of the contact thrustor are directly related to thrustor size - the more hot ionizer area, the greater the losses. The long lifetime requirement thus tends to limit contact-thrustor efficiency - but again at a tolerable level. The research program on ion thrustors has brought us to where reasonable efficiencies and lifetimes are in sight, even if more advanced thrustor concepts should not prove successful.

As for improved electrostatic thrustors, the most-promising concept is the use of heavier charged particles. The energy required to charge a particle constitutes a loss. This loss can be made smaller relative to the kinetic energy acquired by the particle in being accelerated to a given exhaust velocity, by making the particle heavier. An upper limit is set on the particle mass by the accelerator voltage difference, which increases with particle mass. The range of interest for particle mass thus extends upwards from the heavier atomic species, through heavy molecules, to colloidal particles with several thousand atomic mass units per electronic charge. Heavy molecules have been investigated, but excessive fragmentation has accompanied the ionization process. Colloidal particles appear promising, but much work remains before a good evaluation can be made. As for electric thrustors of types other than electrostatic, it is always possible that new concepts will prove worthwhile. Electrostatic thrustors, however, currently have the best performance for interplanetary missions.

The importance of power sources to electric propulsion makes it appropriate to say a few words about such sources. A widely read article by Evvard (published in 1963) pointed out the comparative lack of progress in power generation. To be useful for interplanetary missions, the power supply should have a lifetime of about 10,000 hours and a specific weight of not more than about 10 kilograms per kilowatt. (A nuclear rocket would be more attractive for missions to Mars or Venus if the specific weight were significantly greater than this value.) No power-generation system is as yet far enough along in development to be reasonably sure of meeting these requirements.

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In retrospect it can be said that a thrustor is an easier device to build than a power source. The only natural limit that was found for electrostatic thrustor performance was charge-exchange impingement. For the nuclear turboelectric systems that appear nearest realization there are the limits of nuclear radiation from the reactor, Carnot cycle efficiency for the conversion of heat to electricity, the Stefan-Boltzmann radiation law for rejecting heat from the radiators, and the impingement of meteorites on these radiators. The many studies of such power sources have shown that these natural limits can best be dealt with (and still meet the requirements for electric propulsion) by making very large power supplies. While the analyses indicate little doubt that satisfactory power sources can be built, the sizes needed make the development process a slow one.

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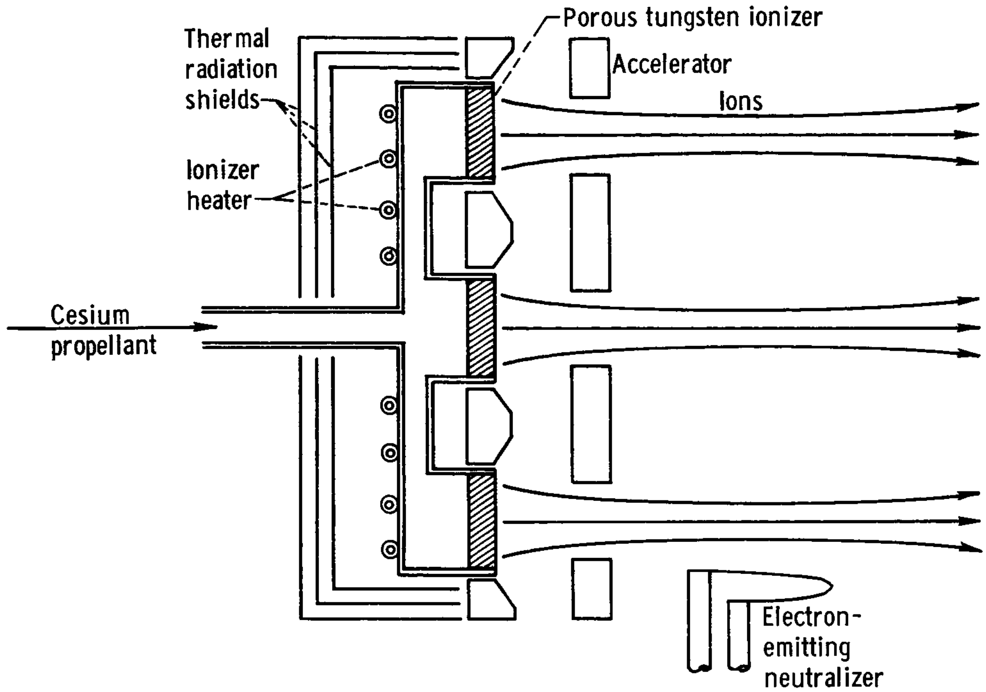

Figure 1. - Sketch of contact-ionization thrustor.

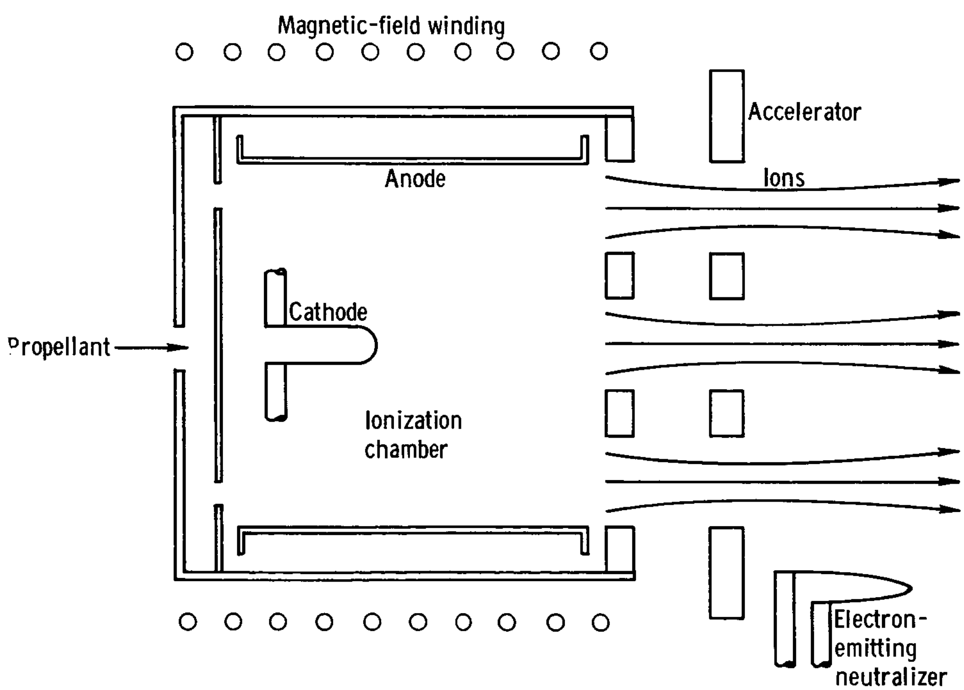

Figure 2. - Sketch of electron-bombardment thrustor.

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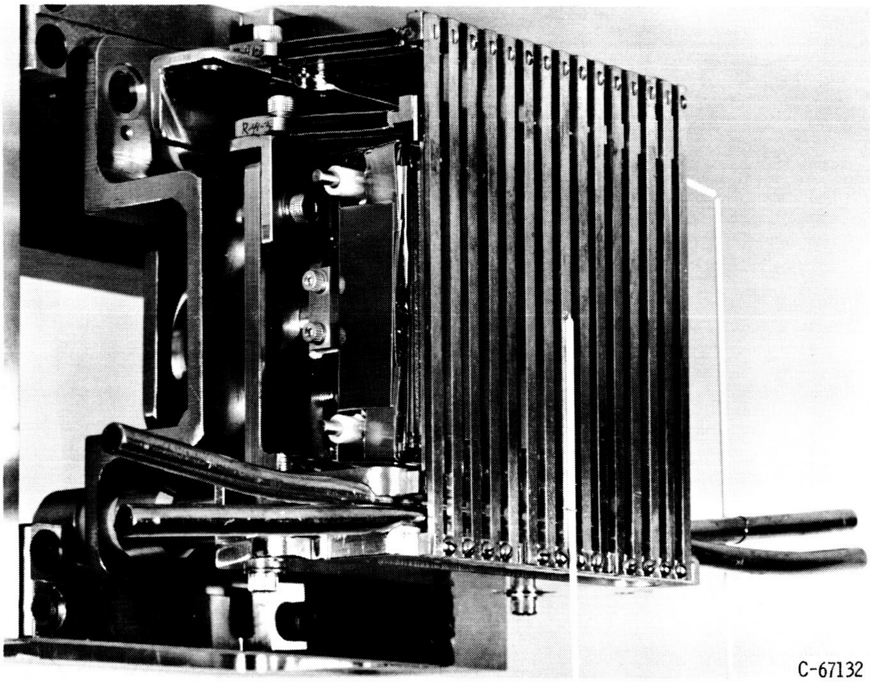

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Figure 3. - Contact-ionization thrustor under development by Hughes Research Laboratories, Inc.

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Figure 4. - Contact-ionization thrustor designed at Electro-Optical Systems, Inc.

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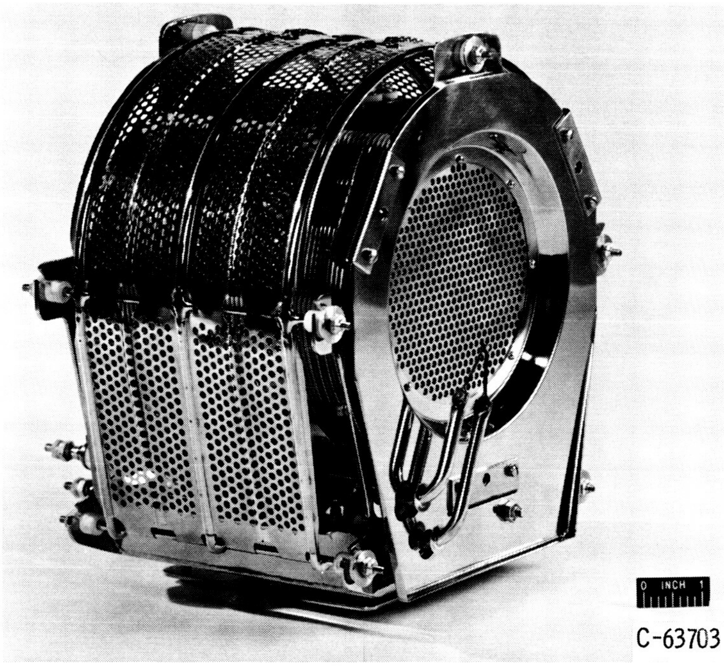

Figure 5. - Electron-bombardment thrustor designed at the NASA Lewis Research Center for mercury propellant.

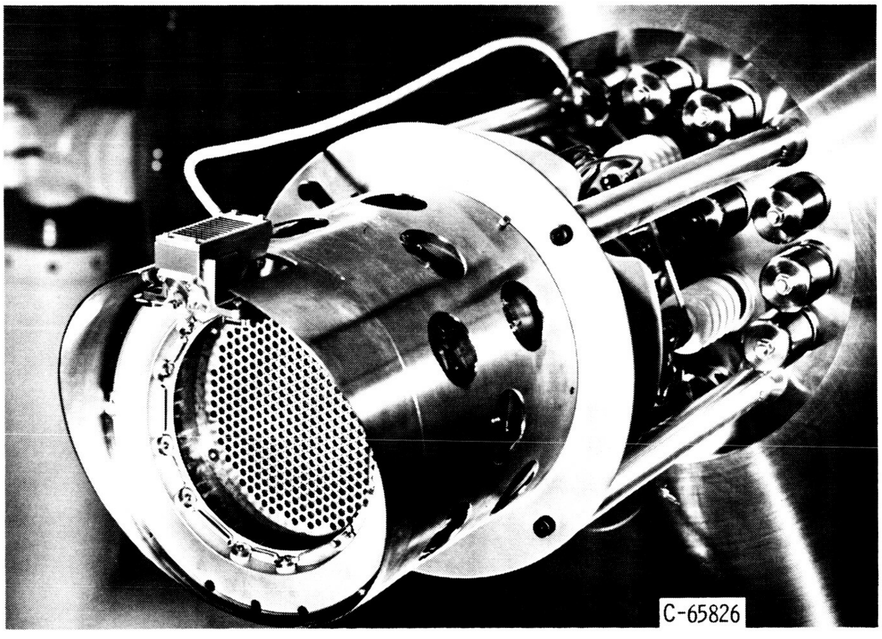

Figure 6. - Electron-bombardment thrustor designed at Electron-Optical Systems, Inc. for cesium propellant.