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N64-16575

CODE NONE

AIAA ELECTRIC PROPULSION CONFERENCE

Broadmoor Hotel, Colorado Springs, Colo. March 11-13, 1963

AN ELECTRON-BOMBARDMENT ION ROCKET WITH A PERMANENT MAGNET

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(AIAA Paper No. 63-031) N.Y., Am. Inst. of Aeron. and Astronautics [1963] 8 p refs 2# Presented at the AIAA Elec. Propulsion Conf., Colorado Springs, 11-13 Mar. 1963

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AN ELECTRON-BOMBARDMENT ION ROCKET WITH A PERMANENT MAGNET

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SUMMARY

The electron-bombardment ion sources investigated to date normally employ a magnetic field to contain the energetic primary electrons and thus enhance the ion production process. A solenoidal winding is usually used to produce this containment field.

A program was undertaken at the Lewis Research Center to determine the feasibility of utilizing a permanent magnet circuit to provide the magnetic field of the shape and strength required for the efficient operation of a low-current-density electron-bombardment ion rocket. The experimental results of the investigation are the subject of this paper.

The method used to design the magnetic circuitry is described. An experimental comparison of ion chamber efficiency (i.e., ev/beam ion) is made between the permanent-magnet and solenoid types. Experimental flight-type designs for both magnetic field systems are compared for total weight and system requirements.

The permanent magnet circuit is a reliable, mechanically strong and efficient replacement for the solenoid on the electron-bombardment thrustor. The circuit can be designed to yield total thrustor weights comparable to units with flight-weight solenoid coils, in addition to eliminating the weight of the power supply and controls required by the field windings. The permanent magnets serve as a return path for the magnetic flux lines, which substantially reduces the field external to the thrustor. The use of this concept for flight hardware will enhance the simplicity and reliability of the thrustor system.

INTRODUCTION

AUTHOR

The electron-bombardment ion sources investigated to date normally employ a magnetic field to contain the energetic primary electrons and thus enhance the ion production process. A solenoidal winding is usually used to produce this containment field.

A program was undertaken at the Lewis Research Center to determine the feasibility of utilizing a permanent-magnet circuit to provide the magnetic field of the shape and strength required for the efficient operation of a low-current-density electron-bombardment ion rocket. The experimental results of the investigation are the subject of this paper.

A cutaway sketch of an electron-bombardment ion rocket is shown in figure 1. The propellant flow rate is controlled by a calibrated orifice between the boiler and the flow distributor. After leaving the distributor, the flow enters the ion chamber where the propellant is bombarded with electrons from the cathode. The solenoidal windings surrounding the ion chamber provide an axial magnetic field, which increases the probability of electron-propellant collisions by preventing the rapid escape of electrons to the anode. Escape of electrons to the ends of the chamber is prevented by operating these ends at the same potential as the cathode. Some of the propellant is ionized by the bombarding electrons, and some of these ions arrive at the screen and are accelerated to produce an ion beam. A neutralizer (not shown in fig. 1) then current and charge neutralizes the ion beam.

Experience to date with this type of source has shown that an electrically efficient field coil design comprises a significant fraction (one-fourth to one-half) of the total thrustor weight. Reduction of the magnet coil weight is traded for increasingly higher magnet power consumption, which produces weight increases in the power conditioning and control devices and higher power demands on the power supply.

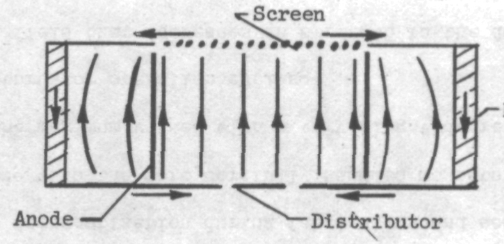
An apparent solution to this problem would be to replace the field winding with a permanent-magnet circuit. The desired characteristics of this circuit would be low weight, field-strength stability, and thrustor performance similar to the field coil design. The problems to be discussed may be grouped under the following headings: permanent-magnet circuit design, comparative thrustor performance with solenoid and permanent magnet, and a weight comparison of flight-type thrustors with each system. These areas will be discussed in this order in the following sections.

PERMANENT-MAGNET CIRCUIT DESIGN

Considerable information on the theory and application of permanent magnets may be found in handbooks such as reference 1. For the intended application the magnets and permeable paths of the circuit must be arranged to provide the magnetic field of the shape and strength required for the efficient operation of the ion chamber. The areas of application in which the equations in the reference apply most rigorously are considerably exceeded by the required circuit characteristics.

The gap between the poles is large, and the fringing effects are difficult to determine. The thermal and electrical effects on the magnets during operation cannot be accurately determined analytically.

The strength of a permanent magnet begins to deteriorate the moment it is removed from the magnetizer unit. While it is "open circuited", that is, operating in no magnetic circuit other than that formed by itself and a unit permeability return path of indeterminate length and cross section, the pole faces of the magnet exert a self-imposed and very severe demagnetizing influence. Once installed in its intended place in the circuit, the magnet is subjected to the demagnetizing effects of the working gap, heat, vibration, and stray fields associated with the operating environment. These effects must all be considered to allow the required field to be maintained when the magnet reaches a stabilized value of performance. For these reasons the most simple circuit geometry was chosen as a first attempt at comparing thrustor performance with the permanent-magnet circuit and the electromagnet. The circuit chosen is shown in sketch (a).

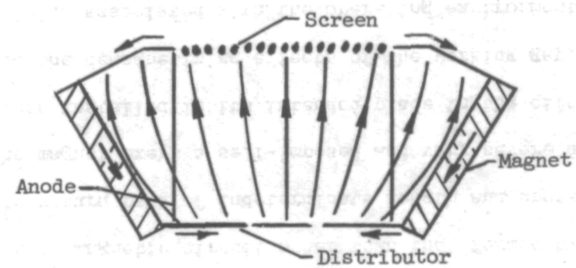


(a)

The screen and distributor of the thrustor were fabricated of mild steel and used as permeable paths or pole pieces to distribute the flux across the ion chamber. The magnets act as a return path for the flux. The pole pieces were made twice the diameter of the ion chamber to reduce fringing inside the chamber. Flux leakage was neglected, and the product of flux density times area in the magnet was set equal to flux density times area in the gap, with the area in the gap simply the projected area of either pole piece. The value of flux in the magnet was assumed to be 50 percent of the maximum possible magnetic strength of the material used. This figure is often quoted in reference 1 as a typical stabilization level under severe conditions. The field required in the chamber was specified, and the amount of magnet volume was determined from the previous considerations. The thickness of the pole pieces was chosen so as not to exceed a flux density of 12,000 gauss anywhere within the material. The critical areas, that is, most nearly saturated, were at the ends of the magnets and at the webs of the perforated downstream pole piece, which became the screen grid. Short permeable collars were added to the pole pieces both to receive and mechanically aline the ends of the magnets and reduce magnetic flux concentrations. A cutaway sketch of the first permanent-magnet thrustor is shown in figure 2. The screen and distributor, as previously mentioned, were mild steel. The high-temperature magnets were sintered Alnico V. The accelerator plate was 0.060 molybdenum, match drilled with the screen grid. The remainder of the thrustor with the exception of the insulators and filament was fabricated of nonmagnetic stainless steel. A flight-type propellant vaporizer is shown in the cutaway.

The measurements of flux density in the ion chamber before the thrustor was operated showed typical values very near the stabilized design value, which as mentioned previously was about half the maximum strength expected from simplified design calculations. After several complete cycles of thrustor operation (operated until thermal equilibrium was attained during each cycle), an additional set of measurements was made that showed no further decrease in the magnetic field strength in the ion chamber. It was concluded that the demagnetizing forces that occurred during the fabrication and assembly of the magnet circuit were at least as severe as those encountered during thrustor operation. For this reason, special care was taken in handling the magnets to keep demagnetization during fabrication and assembly to a minimum. Measurements made with the more carefully handled magnets show values 60 to 70 percent of the maximum values with a very slight decrease in field strength during several thrustor operation cycles.

A magnetic field that decreases in strength in the downstream direction gives a significant improvement in ion chamber performance. This trend is extensively documented in reference 2. The best performance was obtained with a configuration with a downstream-to-upstream field-strength ratio of approximately 0.6. To obtain the tapered field with the permanent magnets, the relative shape of the pole pieces was changed as shown in sketch (b).



(b)

The pole area ratio would be inversely proportional to the field-strength ratio if fringing were ignored. In order to compensate for the anticipated effects of fringing, which would decrease the effect of area changes, the upstream pole piece (distributor) was made half the area of the downstream face. The actual measured field-strength ratio along the axis of the chamber was found to be 0.8. A cutaway sketch of a tapered-field permanent-magnet thrustor is shown in figure 3. All internal geometry is identical with the other engines, only the magnetic circuit configuration has been altered.

THRUSTOR PERFORMANCE COMPARISON

The basic thrustor configurations tested can be seen in figures 1, 2, and 3. A field coil that produces a tapered field is shown in figure 1. A solenoid that produced an approximately uniform field was also used on the same thrustor during the tests. All of the sources had ion chambers that were 10 centimeters in diameter. The accelerator geometry was also similar. The 0.469-centimeter holes were spaced to give an accelerator blockage of 50 percent. The grid spacing was 0.4 centimeter. The distributors of all thrustors were similar. All internal geometry was made as physically identical as possible.

The thrustors were tested in one of the 5-foot-diameter, 16-foot-long vacuum tanks at the Lewis Research Center. The same power supplies and metering system were used throughout the investigation.

A measure of the ion chamber efficiency is the energy dissipated in the ion chamber discharge per beam ion. To account for the low-energy secondary electrons, the losses are properly written as the ion chamber potential difference times the difference between the current collected by the anode and the beam current. The energy dissipated in the ion chamber discharge, in electron volts per beam ion, is then obtained by dividing this dissipated power term by the beam current.

Figure 4 shows an ion chamber performance comparison between a uniform 50-gauss field produced by a solenoid and a similar field produced by a permanent-magnet circuit. The discharge energy losses in electron volts per beam ion are plotted against the ion chamber potential difference (discharge potential). The propellant utilization efficiency was 0.8. The beam current was 0.125 ampere at a mean specific impulse of 5600 seconds. The performance of the two configurations is very similar. The maximum performance differences, which occur at about 55 volts, are less than 10 percent.

Although both configurations had excellent axial field uniformity, the permanent-magnet circuit had a more constant radial profile. As is common with wire loops, the solenoid produced a greater flux density away from the axis of the coil. The more constant flux profile of the permanent-magnet configurations is felt to be the cause of the slight performance gain exhibited by the configuration in figure 4.

Figure 5 shows the performance comparison using tapered magnetic fields. The permanent-magnet circuit shown in sketch (b) and figure 3 had, as indicated previously, a field-strength ratio of 0.8. A solenoid was wound to provide the same field strengths at the distributor and the screen. The discharge losses in electron volts per beam ion are again plotted against the discharge potential. The propellant utilization efficiency, beam current, and specific impulse were 0.8, 0.125 ampere, and 4800 seconds, respectively. The magnetic field strength was 40 gauss at the screen and 50 gauss at the distributor.

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The performance of both magnet types again compared very favorably. The permanent magnet continued to show slightly lower losses. The slight performance difference for the two types was felt to be due to variations in magnetic field strength and shape at other than the specified locations. The general performance of both tapered-field magnet configurations indicates gains over the uniform-field configurations of figure 4 (ref. 2).

As seen in figures 4 and 5, there are no ion chamber performance losses associated with replacing the field windings with a permanent-magnet circuit. The accelerator impingement current of both types was 1 to 2 percent and presumably could have reduced further with more careful alinement and optimization of thruster operating parameters.

The only significant change in thrustor performance was the elimination of the solenoid power loss by the use of the permanent magnet and an associated 2- to 4-percent increase in thrustor power efficiency.

THRUSTOR WEIGHT COMPARISON

The problem that has been associated with the field windings has been a compromise between weight and power. Research thrustors, where weight is unimportant, can have heavy field windings with low power losses (fig. 1). Such research windings at Lewis may weigh as much as 10 pounds for a 10-centimeter-diameter beam and have power losses as low as 50 watts. On the other hand, a flight-type thrustor for the same field strength had a field winding that weighed only 1 pound. The power required, however soared to almost 200 watts.

The permanent magnets and permeable paths of the thrustor shown in figure 3 weigh 1.5 pounds. The total weight of the thrustor is 3.0 pounds. This compares almost exactly with a flight-type thrustor of similar thrust with a solenoid that has a total weight of 2.9 pounds. Both of the thrustors were weighed without propellant feed systems.

Part of the weight saving results from the incorporation of the permanent-magnet circuit into the thrustor structure, which trades magnet weight for distributor and screen material.

The permanent-magnet weights quoted herein are not optimum designs. Two possible reductions in the magnetic circuit weight are possible. First, the screen and distributor thickness might be reduced in areas of low magnetic saturation, which would result in lighter pole pieces. Secondly, a mode of operation might be chosen that requires lower magnetic field strengths. This could be accomplished by using a propellant with a lower ionization potential than mercury (cesium or a heavy molecule), which reduces the field strength required to maintain an efficient discharge. Lighter magnetic circuit elements would then be required.

CONCLUDING REMARKS

No problems were encountered during electron-bombardment thrustor operation with the substitution of a permanent-magnet circuit for the solenoid. The total thrustor weight remains the same when the magnetic circuit elements are incorporated into the thrustor structure. System characteristics are improved through the elimination of the solenoid power supply and controls. Overall system and thrustor electrical efficiency would be improved.

Along with these obvious system and thrustor performance gains, there is another effect that should be considered. The system loses a degree of flexibility. Once assembled, the magnetic field is constant. For general

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thrustor research this presents a problem, but for practical flight-type systems the benefits to be derived by the use of permanent-magnet circuits far outweigh this loss of flexibility.

REFERENCES

1. Underhill, E. M., et al.: Permanent Magnet Handbook. Crucible Steel Co. Am., 1957.

2. Reader, Paul D.: Investigation of a 10-Centimeter-Diameter Electron-Bombardment Ion Rocket. NASA TN D-1163, 1962.

FIGURE LEGENDS

Figure 1. - Electron-bombardment ion rocket.

Figure 2. - Uniform-field permanent-magnet thrustor.

Figure 3. - Tapered-field permanent-magnet ~~engine.~~ thrustor

Figure 4. - Ion chamber performance comparison for permanent and solenoid windings with 50-gauss uniform field. Beam current, 0.125 ampere; mean specific impulse, 5600 seconds.

Figure 5. - Ion chamber performance comparison for permanent and solenoid windings with tapered field. Both fields were 40-gauss at screen and 50-gauss at distributor. Beam current, 0.125 ampere; mean specific impulse, 4800 seconds.

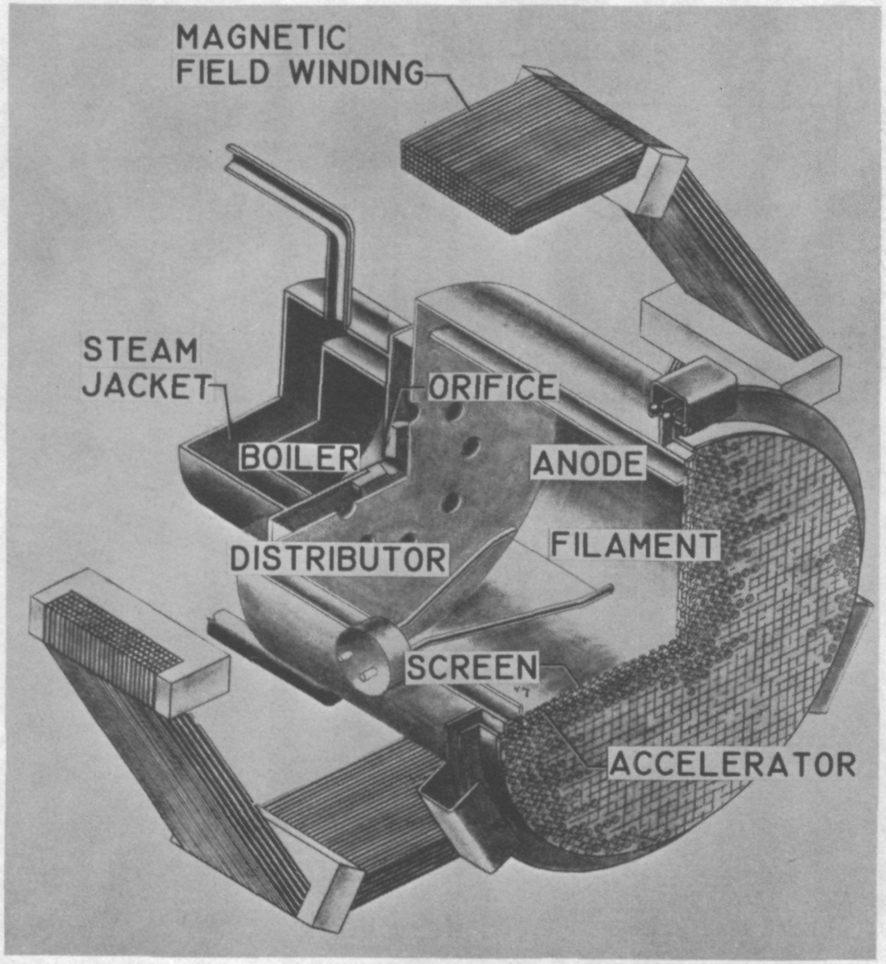

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Figure 1. - Electron-bombardment ion rocket.

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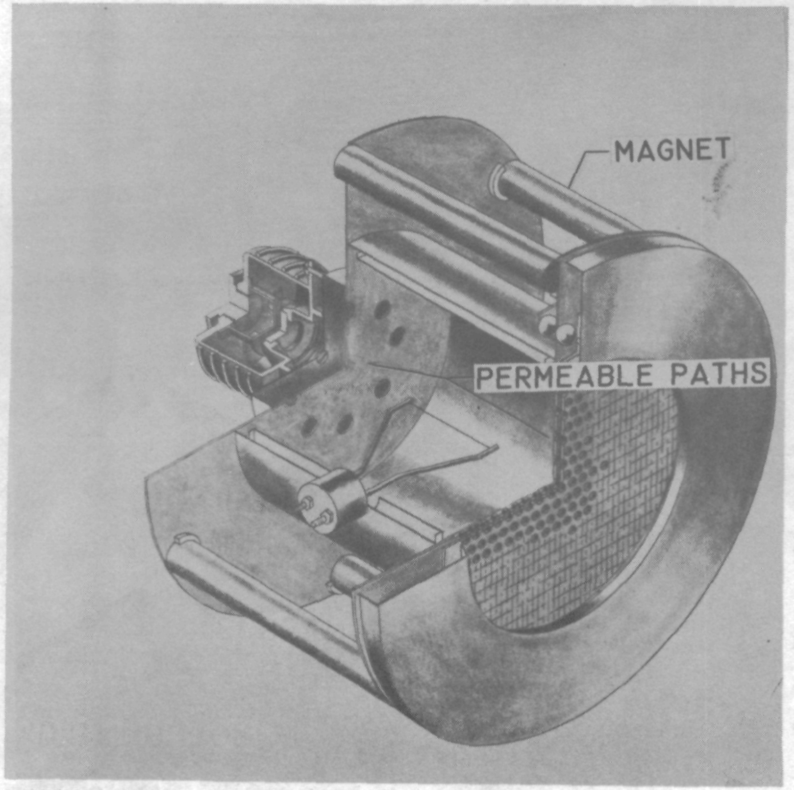

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Figure 2. - Uniform-field permanent magnet thrustor.

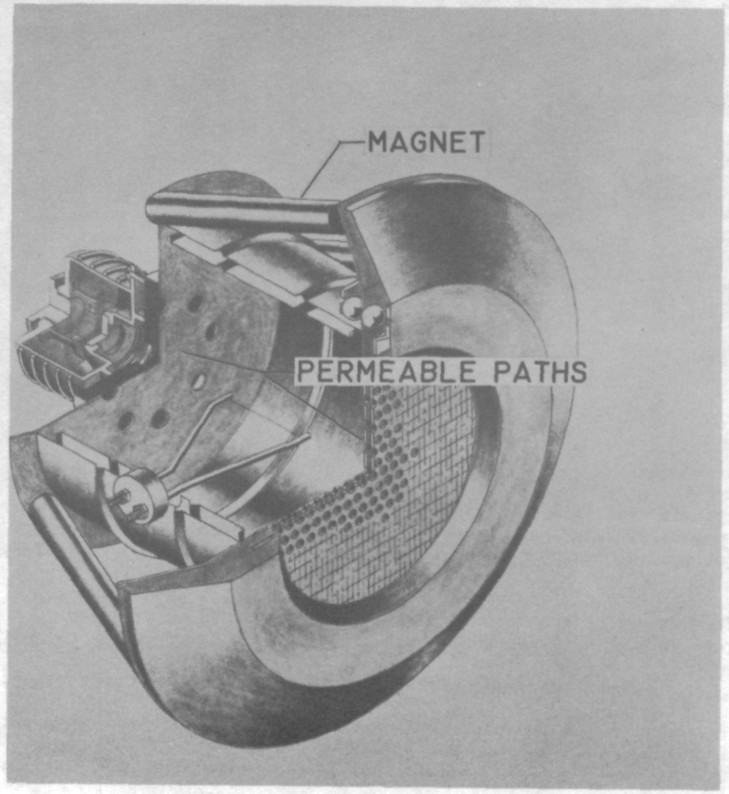

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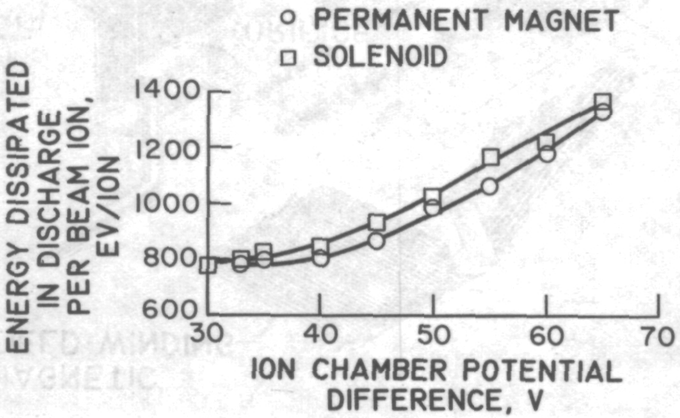
Figure 3. - Tapered-field permanent-magnet thrustor



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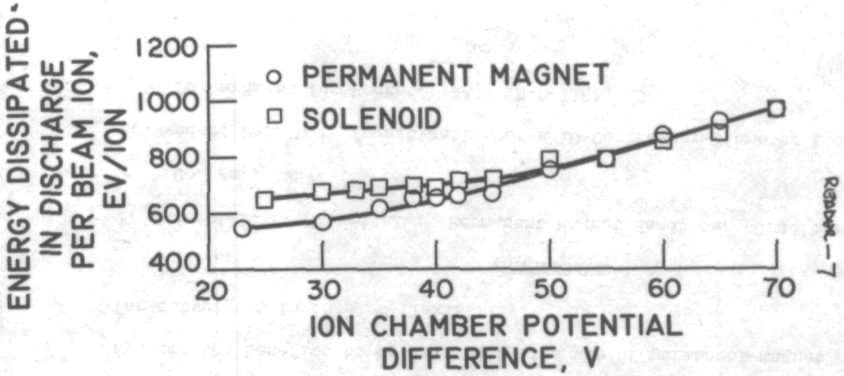

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