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EXPERIMENTS ON A PERMANENT-MAGNET, COMPLETELY RADIATION-COOLED MAGNETOPLASMADYNAMIC ARC THRUSTER

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16. Abstract

Tests of the first completely radiation-cooled multikilowatt magnetoplasmadynamic arc are reported. It was constructed by integrating a permanent magnet with an existing radiation-cooled anode-cathode assembly. The resulting thruster was successfully operated to an arc power of 27 kW while an acceptable maximum magnet temperature of 835 K was maintained. The total thruster specific mass was 2/3 kg/kW. The thruster efficiency was somewhat lower (11 as opposed to 14 percent at 1000-sec specific impulse) than the best previously reported performance for a similar thruster with a water-cooled electromagnet.

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EXPERIMENTS ON A PERMANENT-MAGNET, COMPLETELY RADIATION-COOLED MAGNETOPLASMADYNAMIC ARC THRUSTER

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SUMMARY

Tests of the first completely radiation-cooled multikilowatt magnetoplasmadynamic arc are reported. It was constructed by integrating a permanent magnet with an existing radiation-cooled anode-cathode assembly. The resulting thruster was successfully operated to an arc power of 27 kW while an acceptable maximum magnet temperature of 835 K was maintained. The total thruster specific mass was 2/3 kg/kW. The thruster efficiency was somewhat lower (11 as opposed to 14 percent at 1000-sec specific impulse) than the best previously reported performance for a similar thruster with a water-cooled electromagnet.

INTRODUCTION

Before magnetoplasmadynamic (MPD) thrusters can be effectively used in flight missions a completely radiation-cooled thruster must be developed. A thruster with a radiation-cooled anode and a water-cooled electromagnet has been developed under NASA contract (ref. 1). Tests in the vacuum facilities at the Lewis Research Center at pressures of 10^{-4} torr were reported in reference 2. After these tests the electromagnet of the thruster was replaced by a permanent magnet, which made the thruster completely radiation-cooled. The results of both thermal and performance tests are given in this report.

A radiation-cooled thruster requires fairly high temperatures (2000 K) in some parts of the thruster for efficient radiative cooling. However, the residual magnetic field of a permanent magnet is seriously reduced by elevated temperatures. The amount and permanence of the magnetic field reduction depend on the magnet material, the maximum magnet temperature, and the length of time the magnet is held at that temperature. The Curie temperature, where all residual magnetic field disappears because of crystal change, is the limiting case of such a magnetic-field reduction. If a permanent magnet is held for several days at a temperature below the Curie temperature but above some critical temperature, the crystal structure will slowly change and the residual magnetic field will be reduced. Since it is anticipated that MPD arc thrusters will be operated continuously for long periods, the critical temperature for this effect is an upper limit on the allowable magnet temperature. For the Columax 9 material used in these experiments, the critical temperature is approximately 823 K (ref. 3).

In addition to the permanent losses in residual field, a permanent magnet may have reversible or recoverable losses. If a newly cast and magnetized bar of Columax 9 is cycled several times to approximately 800 K, it will lose about 10 percent of its initial field (ref. 3). Most of this loss can be recovered by remagnetizing at room temperature, but the recovered field will again be lost when the temperature of the magnet is raised. In addition, the magnetic field at 800 K will be approximately 12 percent lower than the stable field at room temperature (ref. 3). This reduction in magnetic field is recovered as the temperature is lowered.

While reductions in the residual magnetic field of the permanent magnet were noted during the experiments reported herein, no attempt was made to separate the various effects mentioned previously. A temperature of approximately 823 K was set as the nominal upper limit on magnet operating temperature.

APPARATUS AND PROCEDURE

The permanent magnet thruster is shown in figure 1. The magnet is assembled from Columax 9 material. The inner pieces are three hollow Columax cylinders with an inside diameter of 2.7 cm and an outside diameter of 5.4 cm. Surrounding these cylinders are four layers of bar magnets, also Columax, each approximately 0.70 cm thick (fig. 1(b)). The total length of the magnet is 15.2 cm. The components of the magnet are held together with three hose clamps (fig. 1(a)). The mass of the permanent magnet including clamps is 8.87 kg. The mass of the cathode-anode assembly is 9.24 kg, so that the total thruster mass is 18.1 kg. This figure does not include the mass of the copper thermal shield discussed in the section RESULTS AND DISCUSSION, nor does it include the mass of the mounting stand shown in the photographs.

No attempt was made to optimize the magnet geometry. Rather, Columax 9 material purchased previously for another experiment was used, and the geometry which was most compatible with the McDonnell-Douglas X-7 thruster was selected. The thruster performance would probably be improved by using a permanent magnet with a more optimum geometry.

All tests were conducted in a 15-ft-diameter, 65-ft-long vacuum tank. The background tank pressure was approximately 2×10^{-4} torr. During performance tests the propellant (ammonia) mass-flow rate was measured with small sonic orifices, and the thrust was measured using a parallelogram-pendulum thrust stand, with a steel bucket or "thrust killer" to momentarily block the directed energy of the beam. The method of making these measurements is described in detail in reference 2.

During the assembly of the engine, two thermocouples were placed on the magnet. They are marked A and B in figure 1(b). Thermocouple A is on the front face of the magnet 1.9 cm from the centerline, and B is on the internal wall of the magnet 7.6 cm from the end. Both thermocouples are between the magnet surface and the thermal insulation adjacent to the magnet (fig. 1(b)).

After the magnet was assembled to the thruster, the initial magnetic field strength was 0.080 T at the cathode tip.

RESULTS AND DISCUSSION

During the first run the electrical power to the thruster arc was increased from 12 to 20 kW. After $2\frac{1}{2}$ hr of operation the temperature at thermocouple A had reached 915 K and was still increasing. The temperature at B was 620 K and increasing. The thruster was shut off because of the excessive temperature at A, considerably above the desirable value of 823 K. The residual magnetic field after this run was 0.072 T at the cathode tip.

During a second run the electrical power to the thruster arc was increased to 15 kW and then reduced to 12 kW. After $3\frac{1}{2}$ hr of operation the temperature at A had reached 955 K and was still increasing slowly. The temperature at B was 630 K and increasing. The thruster was shut off because of the excessive temperature at A.

During these two runs the arc voltage was approximately 41 V, which is typical for an MPD arc thruster operating in the low-voltage mode with ammonia propellant (ref. 4). The ammonia flow rate was 0.06 g/sec.

The long thermal delay time in these first two runs indicated that the thermal insulation of the magnet was adequate. The thermal conduction of the magnet was apparently too small and led to large temperature gradients within the magnet and very little effective radiation over large areas of the magnet. The poor thermal conductivity of the magnet was probably due to its compound structure.

To overcome this difficulty a copper shield or "can" was added to the magnet assembly, as shown in figure 2, to increase thermal conductivity and radiation surface at the high-temperature location. The shield consists of a circular copper plate 0.635 cm thick and 11.4 cm in diameter and a cylindrical strip 0.318 cm thick and

5.08 cm wide welded to the outer circumference of the copper disk. This shield was placed between the thruster and the magnet (fig. 2(b)).

During installation of the copper shield additional thermocouples (C to H) were installed on the magnet, as shown in figure 2(b). Thermocouple A is on the copper shield; B is at the same location as on the other thruster, on the internal surface of the magnet. Thermocouple C is on the steel mounting plate of the engine, so that the difference between A and C is the temperature drop across the thermal insulation; D is inside the magnet, in the third layer of bar magnets; E is on the outside surface of the magnet near the center; F is on the outside surface of the magnet at the corner under the copper shield; G is on the outside surface of the magnet at the corner of the rear face; and H is on the rear steel mounting plate, 6 cm from the centerline.

After the magnet, copper shield, and thruster were reassembled, the magnetic field at the cathode tip was 0.053 T.

The test runs performed after the addition of the copper shield clearly show a reduction in the operating temperature of the magnet. Table I shows the steady-state temperatures of thermocouples A and C as a function of input power to the arc. Thermocouple A is on the copper shield and represents the maximum temperature of any point in the magnet. At 16 kW arc power the maximum magnet temperature was 750 K. At 27 kW arc power the maximum magnet temperature was 835 K. During these tests the arc voltage varied from 41 to 39 V as the arc power was increased from 16 to 27 kW. The ammonia flow rate was 0.06 g/sec. The steady-state temperature distribution within the magnet is shown in table II, for an arc power of 16 kW.

It was noted while taking the data in table II that approximately 2 hours were required for the thruster to reach equilibrium temperature, and an additional 2 hr, for a total of 4 hr, were required before the magnet came to an equilibrium temperature.

After the thermal tests on the thruster and magnet, the magnetic field at the cathode tip had not changed, but remained at 0.053 T. The thruster was disassembled, the magnet remagnetized, and the thruster reassembled. This procedure raised the magnetic field at the cathode tip to 0.0635 T.

A performance test of the thruster, again using ammonia propellant, was made at this increased magnetic field, and the results are shown in figure 3. The arc power is held constant at approximately 24 kW, and the thrust plotted as a function of propellant mass-flow rate. Figure 4 shows the corresponding efficiency as a function of specific impulse and compares it with the performance (ref. 2) of a similar thruster with a water-cooled electromagnetic.

The thrust efficiency is defined as

$$N_T = \frac{T^2}{2m P_a}$$

where T is thrust, m is the mass-flow rate, and P_a is the power supplied to the arc. Figure 4 shows that the permanent-magnet thruster performance is somewhat lower than the best previous performance of a similar thruster with a water-cooled electromagnet. This difference may be due to differences in the temperature in the region of the cathode.

During the performance tests on the permanent-magnet thruster the magnetic field at the cathode tip was approximately 0.06 T, compared to approximately 0.14 T for the data of reference 2. In addition, the divergence of the permanent magnet field was lower than that of the electromagnet. A crude measure of the magnetic-field divergence is given by the ratio

$$\frac{B_1 - B_2}{\frac{1}{2}(B_1 + B_2)}$$

where B_1 is the axial magnetic field at the cathode tip, and B_2 is the axial magnetic field at the center of the exit plane. The value of this parameter was 0.75 for the permanent magnet and 1.0 for the electromagnet.

The water used for cooling the electromagnet also lowers the temperature of other components, particularly those in the region of the cathode. When the permanent magnet is used, the temperature in this area is much higher, perhaps an additional 400 to 500 K. What effect this has on the arc, the plasma, and the performance is unknown.

The thruster components used in the permanent-magnet thruster were previously used in other tests and were noticeably worn before installation with the permanent magnet. While this did not affect the thermal tests of the permanent magnet, the geometry changes may have had some effect on thruster performance.

Any one of these effects, or some combination of them, may be the reason for the change in thrust efficiency.

After the performance test the magnetic field at the cathode tip was 0.062 T, that is, was reduced by 0.0015 T.

CONCLUSIONS

Tests have shown that a magnetoplasmadynamic arc thruster operating on ammonia and with a permanent magnet can be completely radiation-cooled to magnet temperatures less than 835 K at power levels less than 27 kW. Thermally insulating layers and a copper radiator were necessary because of the low thermal conductivity of the compound magnet used. The maximum magnet temperature was 800 K at 23.5 kW and increased only 35 K when the arc power was raised to 27.0 kW. The thrust efficiency at 0.06 g/sec mass flow was 11 percent, compared to 14 percent for the same thruster operating with a water-cooled electromagnet.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 24, 1971,
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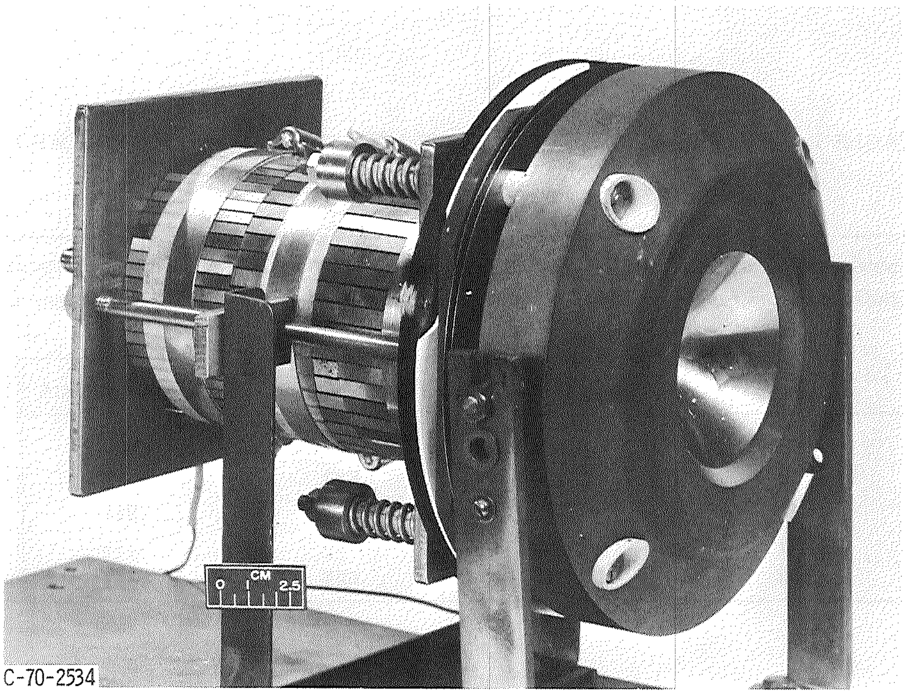
TABLE I. - TEMPERATURES AT VARIOUS LOCATIONS ON OPERATING MPD THRUSTER AS FUNCTION OF ARC POWER

Arc power, kW	Thruster temperature at thermocouple C, K	Magnet temperature with copper shield, K		Magnet temperature without copper shield, K	
		Thermocouple A	Thermocouple B	Thermocouple A	Thermocouple B
12.0	----	---	---	>955	>630
16.0	1100	750	533	---	---
20.0	1145	775	565	>915	>620
23.5	1200	800	590	---	---
27.0	1250	835	620	---	---

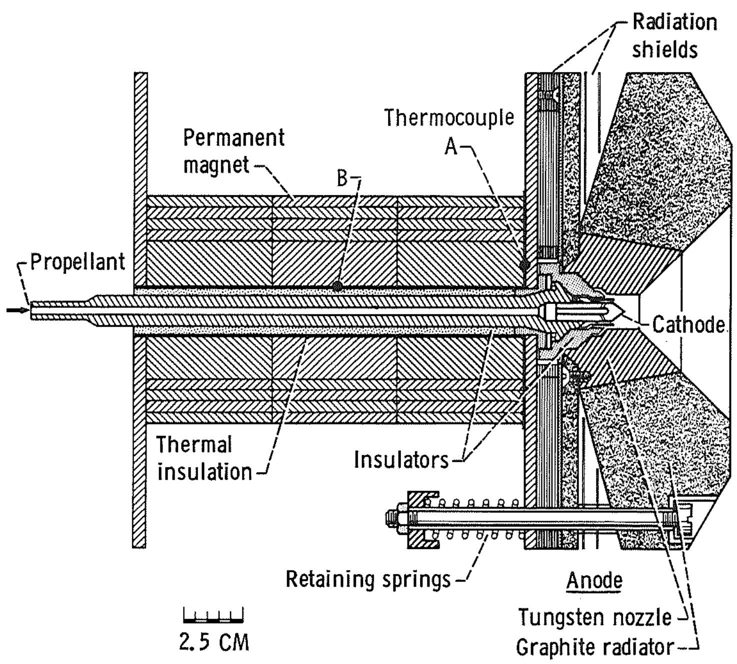
TABLE II. - TEMPERATURE DISTRIBUTION IN MAGNET AT 16-kW ARC POWER

Thermocouple (a)	Temperature, K
A	750
B	530
C	1100
D	590
E	555
F	530
G	625
H	555

[a]See fig. 2(b).

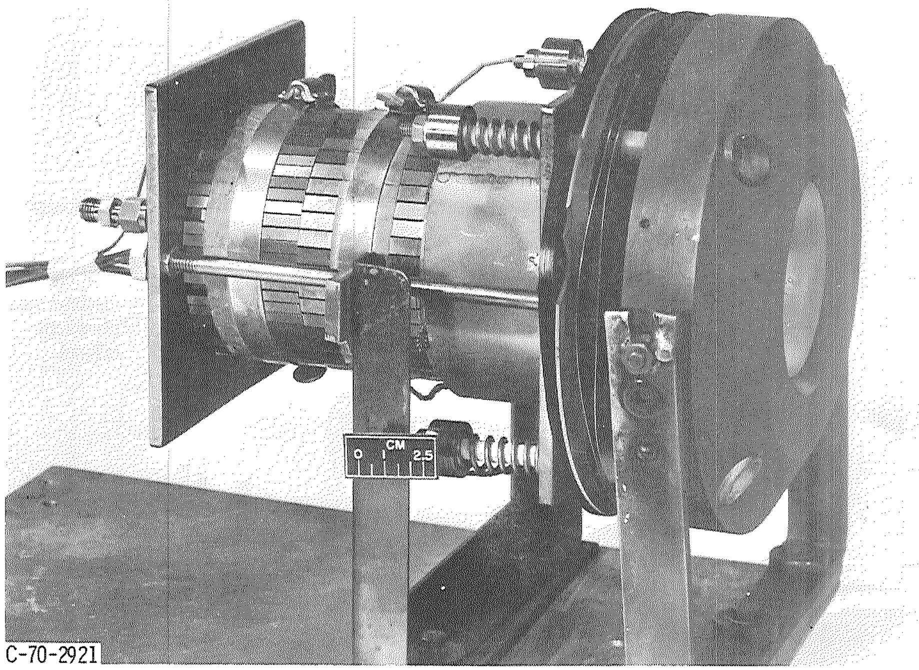


(a) Overall view.

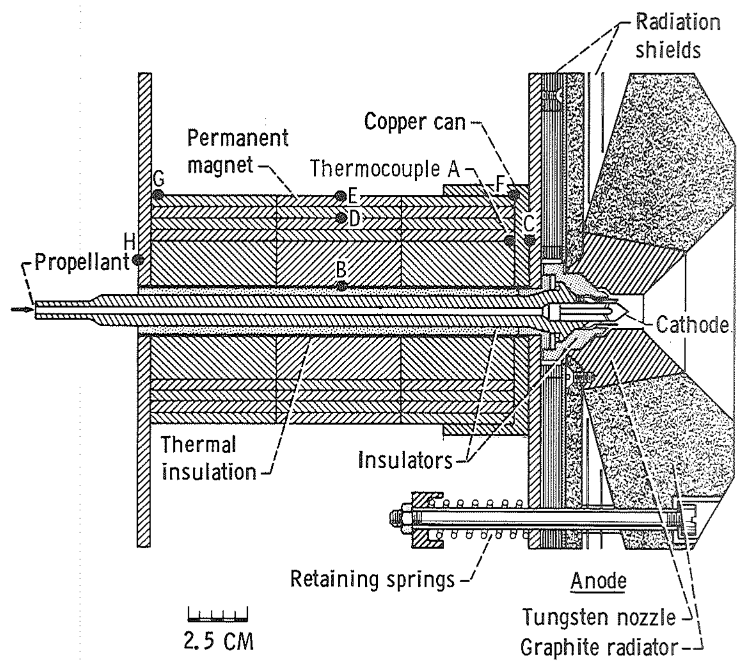


(b) Schematic diagram, showing location of thermocouples.

Figure 1. - Permanent-magnet, radiation-cooled MPD arc thruster.



(a) Overall view.



(b) Schematic diagram, showing location of thermocouples and heat shield.

Figure 2. - Permanent-magnet, radiation-cooled MPD arc thruster with copper heat shield added.

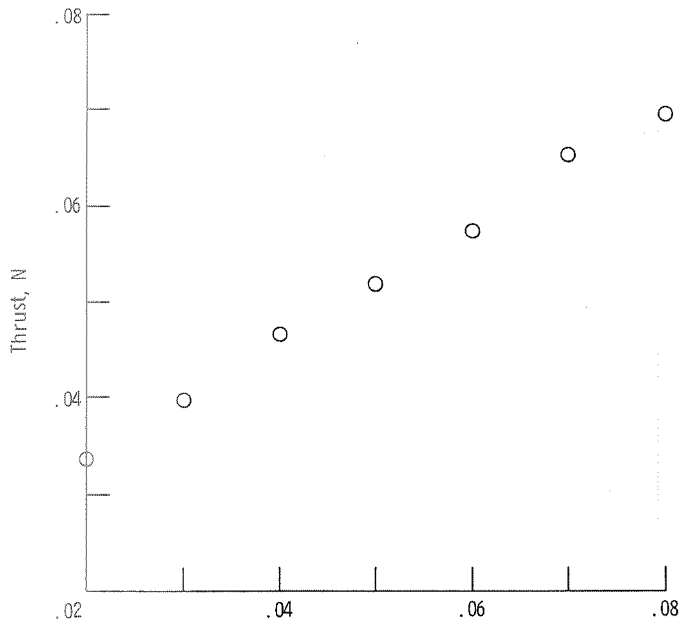


Figure 3. - Thrust as function of mass-flow rate for permanent-magnet radiation-cooled engine. Arc power, 24 kW; propellant, ammonia.

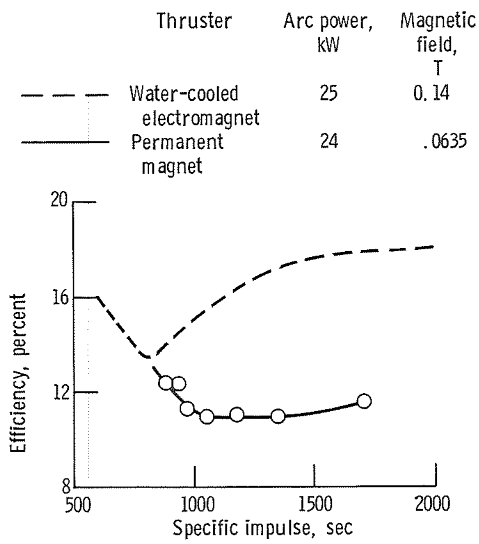


Figure 4. - Comparison of thrust efficiency as a function of specific impulse for a permanent magnet thruster and electromagnet thruster.

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