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STATUS OF LARGE VACUUM FACILITY TESTS OF MPD ARC THRUSTOR

by Robert E. Jones and Eddie L. Walker
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
Third Aerospace Sciences Meeting of the
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1965

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ABSTRACT

Performance tests of a magnetoplasmadynamic (MPD) arc thrustor are being conducted in NASA Lewis Research Center's 15-foot-diameter, 65-foot-long vacuum tank. A minimum tank pressure of 5×10^{-5} millimeter of mercury was maintained with an ammonia flow rate of 0.01 gram per second. Arc current was varied from 200 to 500 amperes and the external magnetic field was varied from 600 to 1400 gauss. The thrust efficiency of the MPD arc thrustor with hydrogen or ammonia propellants was in excellent agreement with previously published data when the tank pressure was above 50 microns. A thrust efficiency with hydrogen of 6.5 percent was obtained at 1000 seconds specific impulse and increased to 16 percent at 2200 seconds. As the tank pressure was reduced to the attainable minimum, the thrust efficiency increased to 16.5 percent at 1000 second specific impulse and 25 percent at 2600 seconds. Ammonia propellant showed a tendency to operate in two voltage modes. The thrust efficiency data with ammonia showed the same trends with reduced tank pressure as did hydrogen. At low tank pressure the thrust efficiency varied from 29 percent at 1250 seconds specific impulse to 70 percent at 5800 seconds. However, at the lowest tank pressure and propellant flow rate, the thrust efficiency exceeded the limit determined by energy efficiency at specific impulses greater than 3000 seconds. This obvious anomaly indicates that the proper testing environment for MPD arc thrustors is still undetermined.

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INTRODUCTION

During the past two years considerable interest has been shown in the MPD arc thrustor as a possible space-vehicle propulsion system. The novel feature of this arc device is the manner in which the electric discharge path extends into the jet of exhausting gas. The performance of the MPD arc thrustor exceeds the previously limited performance range of conventional arc thrustors, and it is actually capable of operation over a very wide range of jet specific impulses (ref. 1). Naturally, many new problems have arisen, and they are receiving intensive investigation. One of the most critical problems is the possible entrainment of the ambient or background gas into the arc jet, a portion of this gas then being accelerated as if it were part of the primary propellant. This gas entrainment can in some cases become so large that the arc can sustain itself on the ambient gas with no primary propellant flow. One obvious solution to the gas entrainment problem is to reduce the background gas pressure as much as possible (ref. 2).

The purpose of this paper is to describe preliminary results obtained with an MPD arc thrustor mounted in the 15-foot-diameter, 65-foot-long vacuum tank at the Lewis Research Center of the NASA. The arc thrustor was tested with hydrogen and ammonia as the propellants, over a range of mass flow rates, arc currents, and magnetic field strengths. The tank pressure was varied from 600 microns to the minimum attainable of 5×10^{-5} millimeter of mercury at an ammonia propellant flow rate of 0.01 gram per second. Measurements to date have been confined to those that determined MPD arc thrustor performance. Future diagnostic studies of the arc jet are planned, particularly those that can determine how the path of the arc current in the exhaust plume is influenced by the background gas pressure and how the jet interacts with its surroundings.

APPARATUS

The MPD arc thrustor was mounted in the 15-foot-diameter, 65-foot-long vacuum tank, which was capable of maintaining a pressure of 5×10^{-5} millimeter of mercury with an input flow of 0.01 gram per second of hydrogen gas. A complete description of this vacuum facility is given in reference 3. Figure 1 shows the vacuum tank with the MPD arc thrustor mounted on a thrust stand.

The MPD arc thrustor was identical to those described in reference 4. This is an axially symmetric thrustor consisting of a central cathode surrounded by a coazial anode. Both electrodes are surrounded by an external magnetic field coil. Figure 2 is a cross-sectional view of the thrustor showing the details of construction. The external magnetic field was provided by two coils electrically connected in series. With this coil arrangement, the magnetic field could be varied from 600 to 1400 gauss. Both the magnetic field coil and the MPD arc anode and cathode were cooled with distilled water at a supply pressure of 180 psig.

The MPD arc thrustor was mounted on a commercially available flexure-plate thrust stand. Considerable time and effort were spent to minimize the effects of stray fields and tare loads and to increase the overall thrust-stand sensitivity. The electrical power to the thrustor and to the magnetic field coil was brought onto the thrust stand through large coaxial lines with the final connections made in coaxial mercury pots on the thrust stand. The electric power was supplied by commercially available welding machines.

Conventional meters were used to measure arc current, arc voltage, coil current and voltage, and anode floating potential. The cooling water flow rate was measured with rotating-vane flowmeters, and the temperatures were read with conventional thermocouples. The propellant flowrate was metered with small jeweled sonic orifices.

OPERATING CONDITIONS

The mass flow rates for hydrogen and for ammonia were varied from 0.0125 to 0.05 and from 0.01 to 0.03 gram per second, respectively. Arc currents were varied over a range of 200 to 500 amperes. Higher arc currents could not be obtained because of the current limitation of the existing power supplies. The axial magnetic field strength, measured at the cathode tip, was varied from 600 to 1400 gauss. The vacuum-tank pressure could be changed from 600 microns to the attainable minimum of 5×10^{-5} millimeter of mercury by controlling the number of operating vacuum pumps and by bleeding additional propellant into the tank.

PROCEDURE

The effect of the magnetic field - arc current interaction was calibrated by shorting the arc thrustor cathode to the anode and by running various combinations of arc and magnet current. Tare loads were also measured for magnetic field strength changes and for variations in the propellant flow rate. The thrust stand was calibrated by applying known forces with both the magnetic field and the cooling water flow turned on.

The MPD thrustor was started by setting the magnetic field strength at 600 gauss and increasing the propellant flow until the chamber pressure was 20 millimeters of mercury absolute. The arc power supplies were then turned on. When hydrogen was the propellant, the arc normally started with the application of 320 volts from the power supplies, but ammonia generally required the use of an auxiliary arc starter. Once the arc was started, the arc current and propellant mass flow rate were adjusted to the desired initial test conditions.

DATA REDUCTION AND CALCULATIONS

The thrust was determined by noting the incremental thrust between the "zero level" and the thrust reading. The zero level was recorded on thrustor startup and shutdown. A check on thrust-stand drift was determined by returning to the initial thrustor operating conditions at regular intervals. The thrust stand was calibrated at the start and conclusion of each set of test runs.

The thrust efficiency of the MPD arc thrustor was calculated on the basis of measured thrust, propellant mass flow rate, and power transmitted. The thrust efficiency* is given by

$$\eta_T = \frac{T^2}{2\dot{m}\, P_G}$$

where

T	thrust, N
$\dot{m}$	propellant mass flow rate kG/sec
P_G	power input, W

An energy efficiency was computed from the measured cooling water flow rates and the temperature rise. This energy efficiency can be expressed as

$$\eta_E = \frac{P_G - P_{cw}}{P_G}$$

where P_{cw} is the power absorbed in cooling the thrustor. The specific impulse I_{sp} was calculated from the measured thrust and the propellant mass flow rate as equal to $T/\dot{m}g$

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* The thrust value used in this calculation is the thrust obtained by the addition of electric power and is not the total thrust of the thrustor. The total thrust would include the thrust due to expelling the unheated propellant.

RESULTS AND DISCUSSION

Hydrogen Propellant

A summary of the data obtained with hydrogen propellant is shown in figure 3. The MPD arc thrust efficiency is plotted as a function of the jet specific impulse and is compared with a previously reported performance. These data cover a range of propellant flow rates from 0.0125 to 0.05 grams per second and magnetic field strengths from 600 to 1400 gauss. The thrust efficiencies obtained at high (over 40 microns) tank pressures agree well with the data of reference 4. When the tank pressure was reduced to the range of 1.1 to 2.2×10^{-4} millimeter of mercury, the thrust efficiency increased. This result was unexpected, since the purpose of the tank pressure reduction was to determine to what degree gas entrainment affected results obtained at high tank pressures. As specific impulses increased, the results obtained at low tank pressure approached those obtained at higher pressure. Further experimentation in this regime is planned, but additional current capability must be made available for such tests.

Figures 4, 5, and 6 show the effect of the tank pressure reduction on the size of the thrustor exhaust plume. Figure 4 shows the arc thrustor running in a background pressure of 100 microns. The operating conditions were an arc current of 288 amperes, a magnetic field strength of 620 gauss, and a mass flow rate of hydrogen of 0.0375 gram per second. The operating conditions of figure 5 were the same, but the tank pressure was approximately 40 microns. Figure 6 shows the arc running at a pressure of 6×10^{-4} millimeter of mercury. The large increase in the size of the exhaust plume is obvious.

Figure 7 shows the variation of thrust as the tank pressure is lowered from 200 microns to 1.7×10^{-4} millimeter of mercury. The thrust at 200 microns was 24.5 grams and increased gradually as the pressure was reduced to 36.5 grams at 1.7×10^{-4} millimeter of mercury. The desired tank pressures were obtained by bleeding additional hydrogen into the tank.

Figure 8 shows the arc current - voltage relations at a propellant flow rate of 0.02 gram per second, magnetic field strengths of 600, 1000, and 1400 gauss, and tank pressures of 60 microns and 1.2×10^{-4} millimeter of mercury. Such trends are typical of MPD arc operation.

Figure 9 shows the dependence of the energy efficiency on the arc specific impulse for various magnetic field strengths and tank pressures. The energy efficiency was virtually constant with increasing specific impulse at a value of 60 percent except when the MPD arc was operated at tank pressure above 60 microns and a magnetic field strength of only 600 gauss.

Ammonia Propellant

The results obtained with ammonia propellant are shown in figures 10 through 14. Ammonia was a fairly difficult propellant to use because of the tendency of the arc to operate in two distinct voltage modes, as has also been reported by Patrick (ref. 5) who found that the choice of the voltage mode could be related to the distance between the anode and the cathode. However, the present tests were all conducted with a fixed anode-to-cathode spacing of 3/8 inch. The arc current - voltage relations with ammonia propellant are shown in figure 10. The tank background pressure appears to have had no correlation with the voltage mode in which the arc operated. Although stable operation in either mode could usually be maintained by increasing the arc current or the magnetic field strength, the tendency was for the arc to stabilize in the low-voltage mode. The transition from one mode to another at a given condition of arc current was usually not predictable and could not be stopped. Transition from the low- to high-voltage mode sometimes took as long as 3 to 5 minutes, while the transition from the high to low voltage mode usually occurred within several seconds. There is the same tendency of the arc voltage to increase with increasing magnetic field strength in both voltage modes.

Figure 11 shows the thrust efficiency obtained with ammonia propellant flow rates of 0.03 and 0.01 gram per second at high and low tank pressures. The data obtained at high tank pressure are in excellent agreement with data of reference 4. When the tank pressure was reduced to 2×10^{-4} millimeter of mercury and lower, there was an increase in performance similar to that obtained with hydrogen. The low-voltage mode generally yielded thrust efficiencies higher than those obtained in the high-voltage mode of operation. (Although the thrust was less, the electrical power input was also smaller in the low-voltage mode.) At tank pressures of 17 to 400 microns, the thrust efficiency was not greatly affected by changes of the voltage mode.

Data taken at a propellant flow rate of 0.01 gram per second, a magnetic field strength of 1400 gauss, and a tank pressure of 5×10^{-5} millimeter of mercury fall within the range of the data taken at higher pressures and indicate that the thrust was degraded by increasing the magnetic field from 1000 to 1400 gauss. This effect was noted in both the high- and low-voltage modes of operation.

The energy efficiency with ammonia is shown in figure 12 for a propellant flow rate of 0.03 gram per second. The efficiency obtained in the high-voltage mode of operation was independent of the applied magnetic field strength. The energy efficiency in the low-voltage mode was markedly dependent on the magnetic field strength and increased as the magnetic field strength increased. It should be possible to obtain energy efficiencies in the low-voltage mode that are greater than those obtained in the high-voltage mode by further increases in the magnetic field strength. Such a possibility has been explored in some detail by Patrick and Schneiderman (ref. 5). The data shown were obtained at both high and low tank pressures, as the energy efficiency was not usually affected by the tank pressure.

Figure 13 shows the energy efficiency obtained at a propellant flow rate of 0.01 gram per second. Comparison with the curves of figure 12 shows that the energy efficiency was reduced below that obtained at the higher propellant flow rate, but the trends noted previously were repeated; that is, the energy efficiency in the high-voltage mode was independent of the magnetic field strength, while energy efficiencies in the low-voltage mode were increased with increasing magnetic field strength. The reduced magnitude of the energy efficiency obtained at this propellant flow rate was not encountered at the higher flow rate, where the energy efficiency was usually not affected by changes in the propellant flow rate.

Figure 14 is a comparison of the thrust and energy efficiences obtained when the ammonia flow rate was reduced to 0.01 gram per second. The thrust efficiency became higher than the energy efficiency for both low and high tank pressures. This obvious anomaly is not yet explained. It is possible that at this operating condition, additional propellant mass is being utilized by the thrustor, either in the form of electrode erosion or entrainment of the background gas or in other interactions that are taking place.

TWELVE-HOUR EROSION TEST

One possible reason for anomalously high MPD arc thrustor efficiency is that electrode erosion is contributing additional propellant (ref. 6). Erosion of the tungsten cathode was observed during operation with ammonia, particularly when the propellant flow rate was 0.01 gram per second. A 12-hour endurance test was performed to measure the amount of mass eroded from the electrodes. The MPD arc thrustor was operated at a constant arc current of 400 amperes, a magnetic field strength of 1000 gauss, and a mass flow rate of ammonia of 0.01 gram per second for $12\frac{1}{4}$ hours. The arc voltage varied between 48 and 43.1 volts and was in the low-voltage mode of operation for the entire test period. At the end of the test, the cathode, the anode, and the insulator were reweighed to determine the amount material lost; the cathode lost approximately 0.7 gram, the anode 0.25 gram and the micarta insulator 0.8 gram, for a total loss due to erosion of 1.75 grams. If this loss were to be averaged over the entire period of the test, the eroded mass would be only 0.4 percent of the instantaneous propellant flow. The effect of electrode and insulator erosion on the MPD arc thrustor performance is, thus, not significant in this range of the arc operation.

Cold Flow Tests

To investigate the cause for the increase in thrust as the tank pressure was reduced, cold-flow tests with hydrogen at different tank pressures were run. The thrust record of a typical test is shown in figure 15, which was copied directly from the thrust strip-chart recorder. The procedure followed in these tests was to establish a flow through the thrustor at one condition of tank pressure and then, holding that flow rate constant, change the tank pressure. Tank pressure changes were quickly effected by an auxiliary gas-flow system to bleed additional hydrogen into the tank. As can be seen from figure 15, the thrust level is dependent on the ambient or tank pressure. Such results indicate that the thrustor performance may be seriously affected (perhaps with power addition, as well as with cold flow) by the flow patterns established in the nozzle.

Spectrographic Measurements

To date, only a preliminary spectroscopic analysis has been made of the plasma flow at the exit of the thrustor. A 1.5-meter Bausch and Lomb spectrograph was used for these tests and was focused to observe the jet 2 inches downstream of the thrustor. The spectra obtained with hydrogen propellant was that of the Balmer series with a very faint radiation from molecular hydrogen, which indicated that the hydrogen is very highly dissociated.

The spectras obtained with ammonia as the propellant show that the ammonia is almost completely dissociated in the arc. Molecular-nitrogen and molecular-nitrogen-ion lines were observed, as well as a large concentration of atomic hydrogen and the species NH. The spectrum of molecular hydrogen was also noted, though not as intensely as atomic hydrogen. No indication was found of atomic nitrogen or atomic-nitrogen ions. A trace amount of CN was observed, but disappeared when the micarta cathode to anode insulator was replaced with one made of boron nitride. No indication of other impurities, either copper or tungsten, was found.

CONCLUDING REMARKS

The MPD arc thrustor performance at high tank pressures is in excellent agreement with previously published results for both hydrogen and ammonia propellants. The anomalous result at low propellant flow is as yet unexplained. It has been shown that electrode erosion is not sufficient to account for these results. The data are repeatable, and the thrust measurements are believed to be correct. It is possible that at the low propellant flow rates, mass entrainment could be a dominant factor, since the size of the arc-plume is significantly increased as the tank pressure is lowered. Further tests are being conducted to determine the mechanisms that produce these anomolies and to define the proper testing environment for MPD arc thrustors.

REFERENCES

1. Ducati, A. C., Giannini, G. M., and Muehlberger, E., "Experimental Results In High-Specific-Impulse Thermo-Ionic Acceleration," AIAA J. 2, 1452-1454 (1964).
2. Cann, G. L., Lenn, P. D., and Harder, R. L., "Hall Current Accelerator." NASA CR-64386 (1964).
3. Finke, R. C., Holmes, D., and Keller, T. A., "Space Environment Facility for Electric Propulsion Systems Research," NASA TN D-2774 (1965).
4. John, R. R., and Bennett, S., "Arcjet Technology and Research Development," NASA CR-57452, 1964.
5. Schneiderman, A., and Patrick, R., "Optimization of Thermal Efficiency of a Magnetic Annular Arc," Paper to be presented at AIAA Third Aerospace Sciences Meeting, New York, N.Y., (January 24-26, 1966).
6. Brockman, P., Hess, R., Bowen, F., and Jarrett, O., "Diagnostic Studies in A Hall Accelerator at Low Exhaust Pressure," AIAA Paper 65-297 (July 1965).

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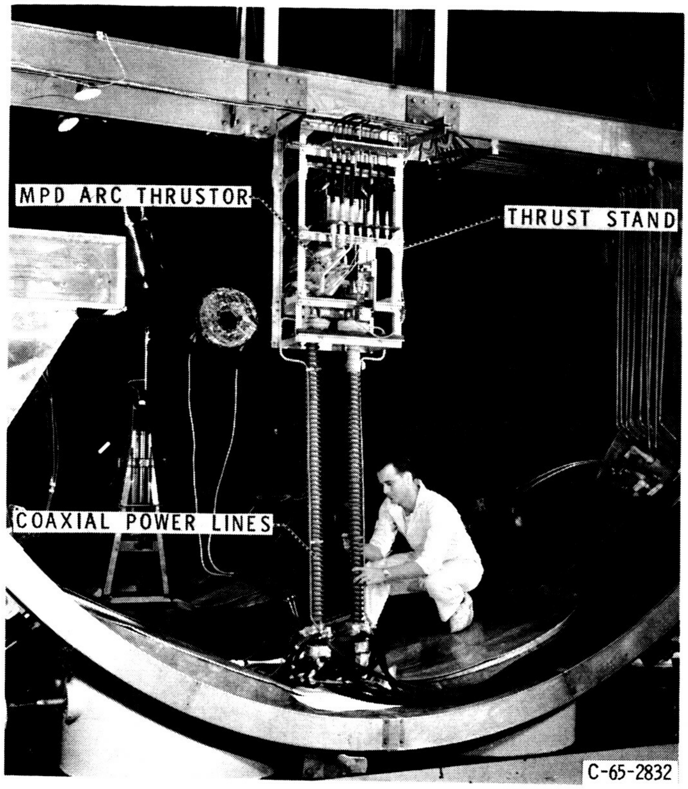

FIGURE 1. - VACUUM FACILITY WITH MPD ARC THRUSTOR INSTALLED ON THRUST STAND.

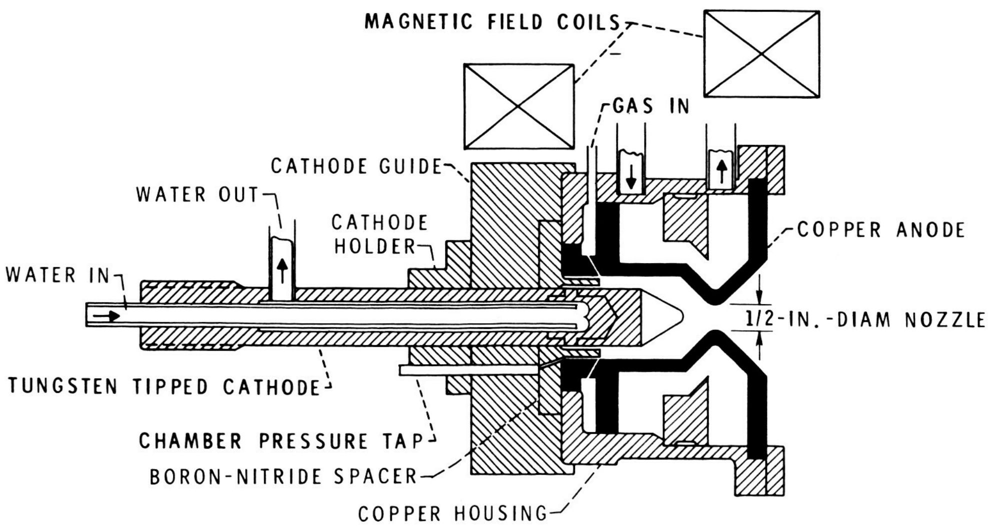

FIGURE 2. - SCHEMATIC OF MPD ARC THRUSTOR.

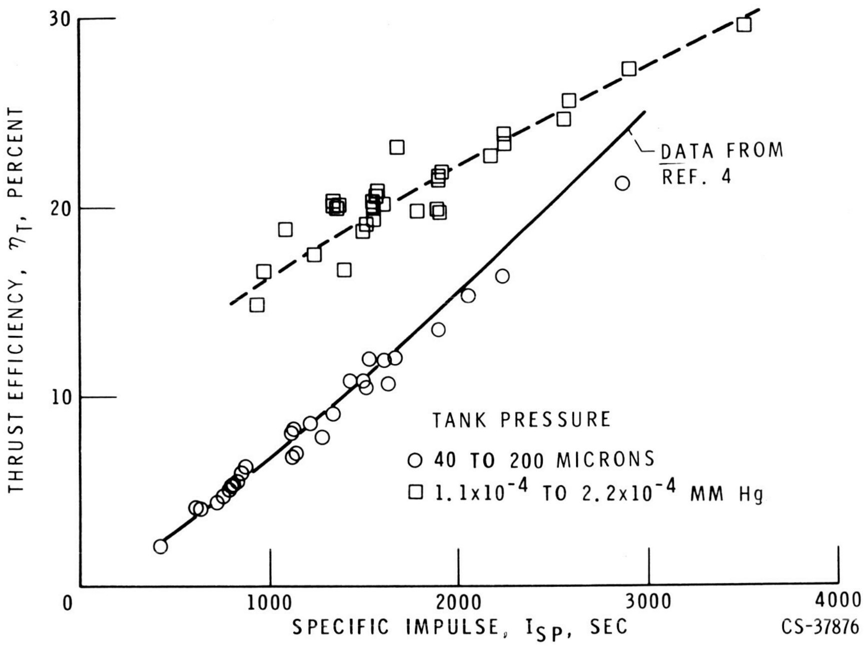

FIGURE 3. - MPD ARC THRUSTOR PERFORMANCE (HYDROGEN PROPELLANT).

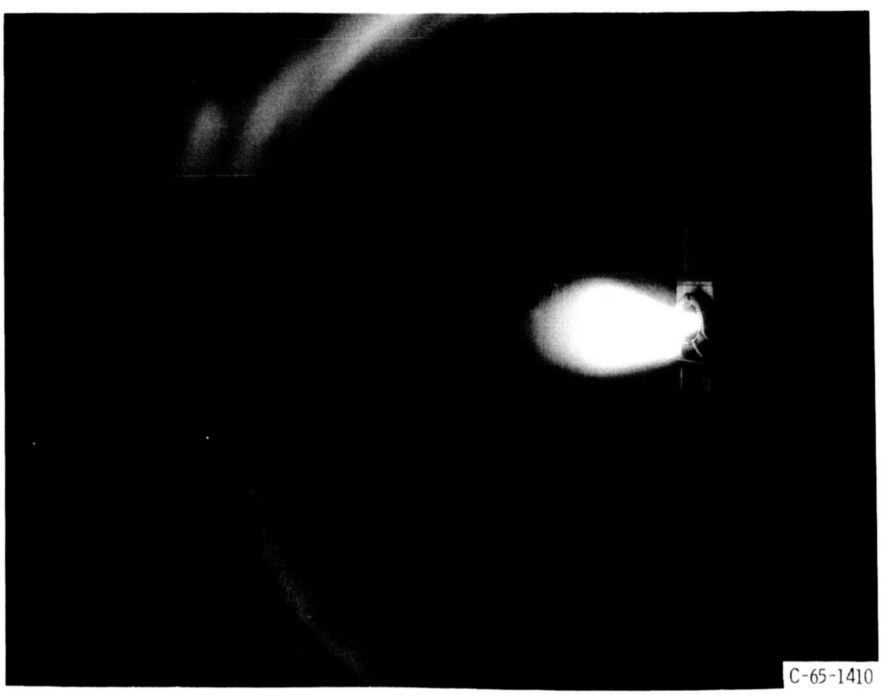

FIGURE 4. - MPD ARC THRUSTOR OPERATING AT 100 MICRONS TANK PRESSURE.

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FIGURE 5. - MPD ARC THRUSTOR OPERATING AT 40 MICRONS TANK PRESSURE.

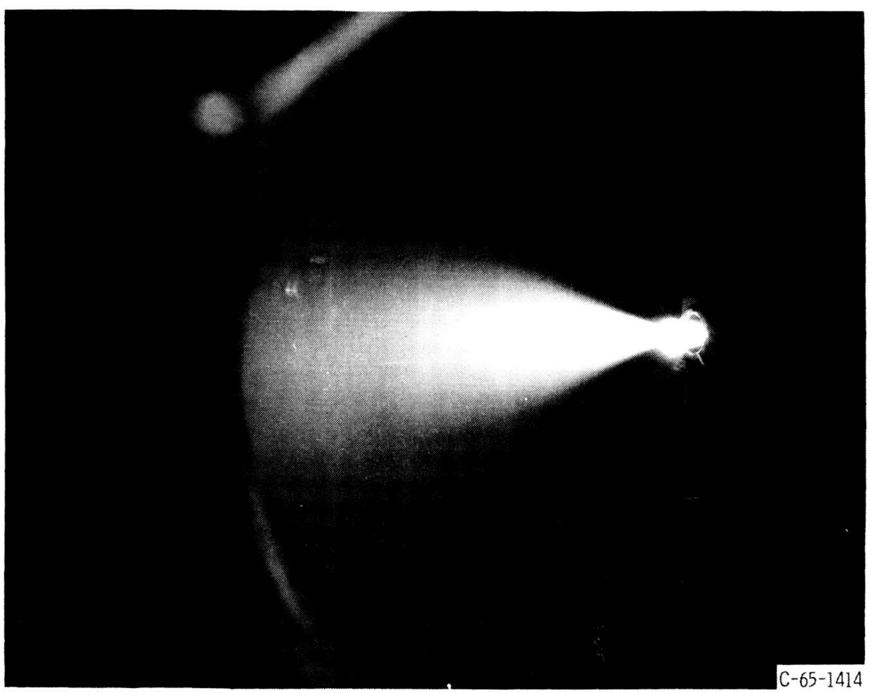

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FIGURE 6. - MPD THRUSTOR OPERATING AT 6×10^{-4} MILLIMETER OF MERCURY TANK PRESSURE.

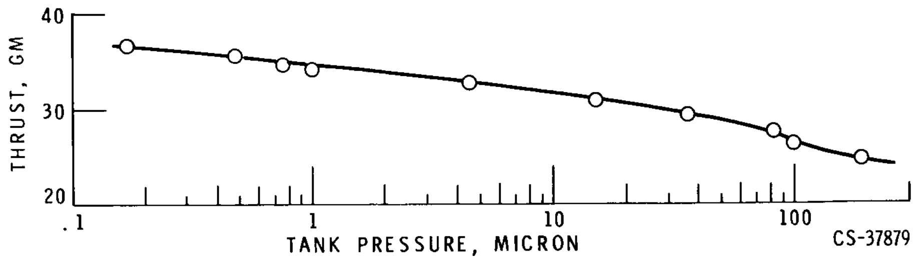

FIGURE 7. - THRUST DEPENDENCE ON TANK PRESSURE; HYDROGEN RATE, 0.02 GM/SEC; ARC CURRENT, 300 AMP; ARC POWER, 17150 W; MAGNETIC FIELD STRENGTH, 600 G.

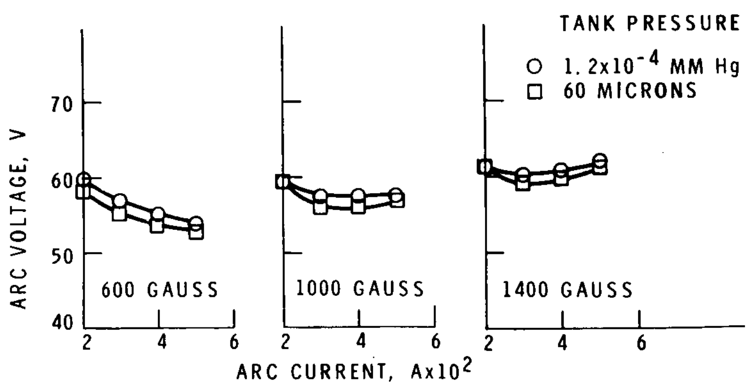

FIGURE 8. - MPD ARC THRUSTOR CURRENT - VOLTAGE RELATION HYDROGEN FLOW RATE 0.02 GRAM PER SECOND.

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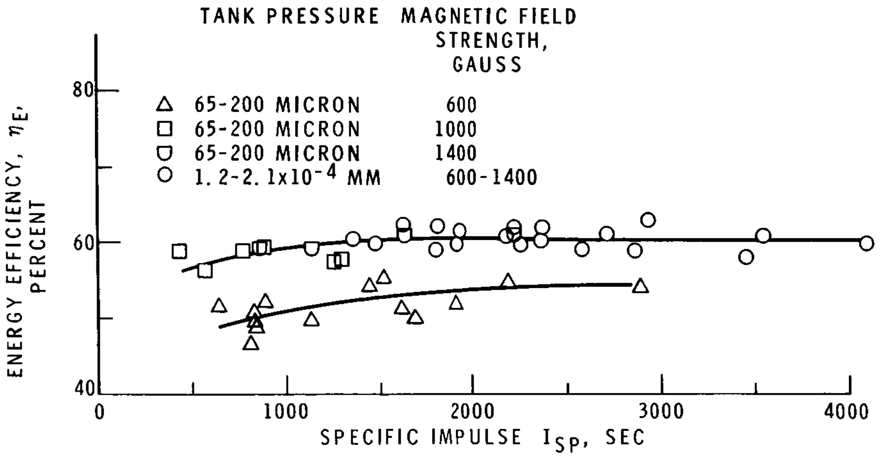

FIGURE 9. - MPD ARC THRUSTOR PERFORMANCE WITH HYDROGEN PROPELLANT.

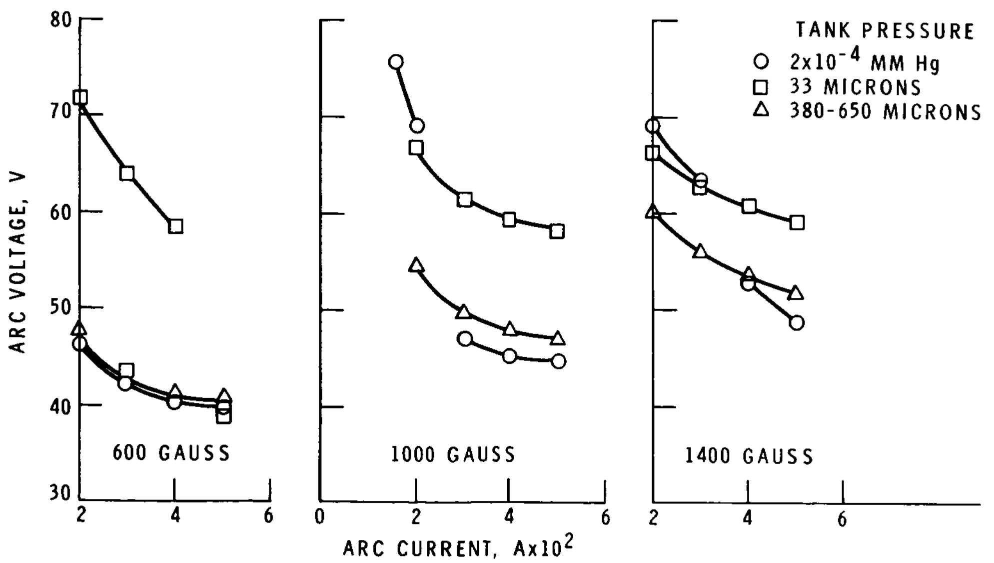

FIGURE 10. - MPD ARC THRUSTOR CURRENT - VOLTAGE RELATION; AMMONIA FLOW RATE, 0.03 GRAM PER SECOND.

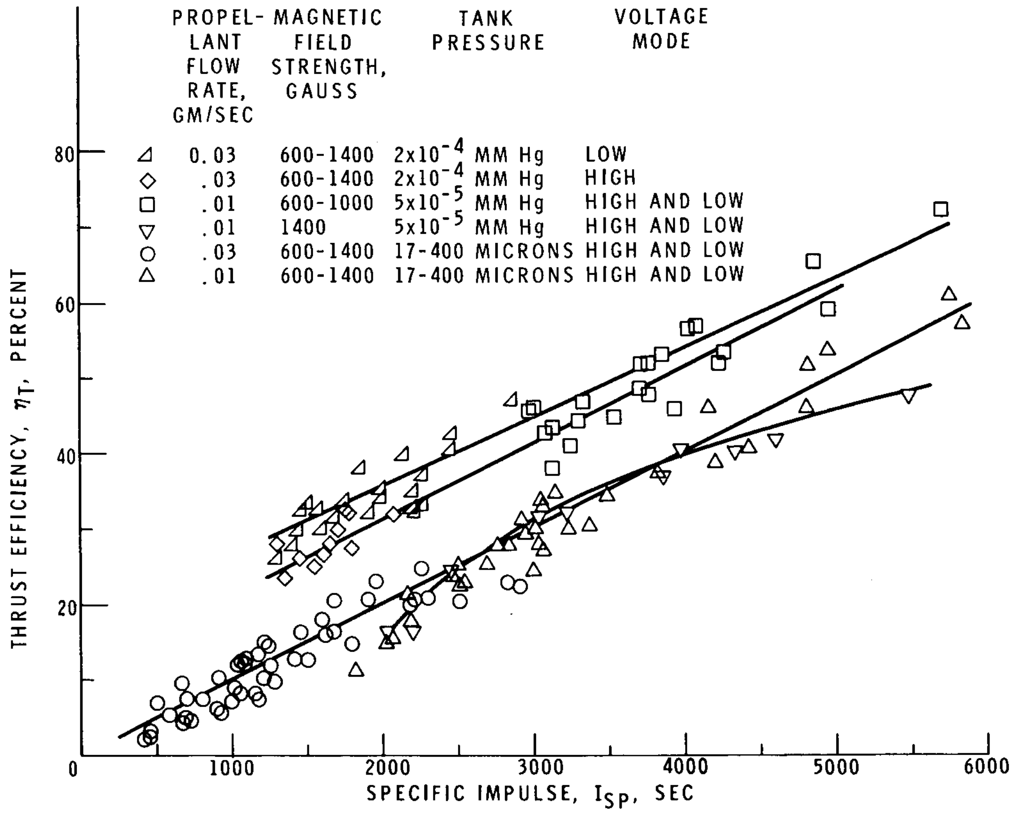

FIGURE 11. - MPD ARC THRUSTOR PERFORMANCE (AMMONIA PROPELLANT).

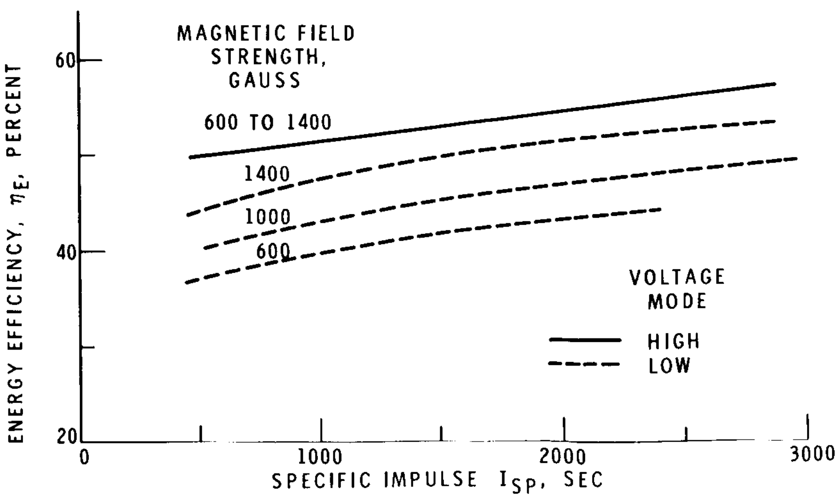

FIGURE 12. - MPD ARC THRUSTOR PERFORMANCE WITH AMMONIA; AMMONIA FLOW RATE, 0.03 GRAM PER SECOND.

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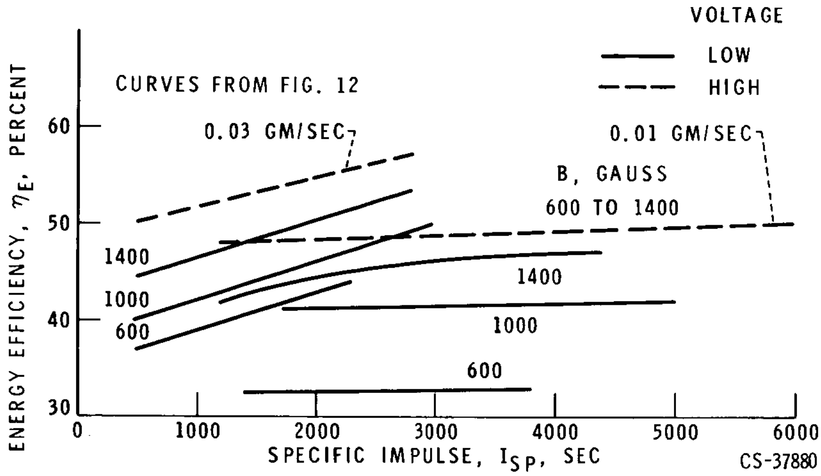

FIGURE 13. - HPD ARC THRUSTOR ENERGY EFFICIENCY; AMMONIA FLOW RATE, 0.01 GM/SEC.

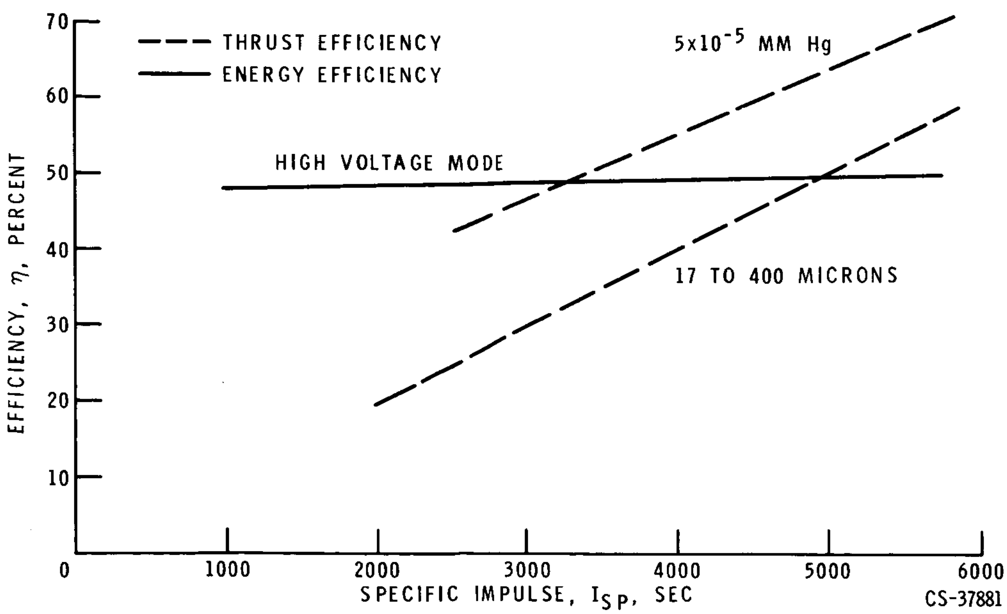

FIGURE 14. - COMPARISON OF THRUST AND ENERGY EFFICIENCIES; AMMONIA FLOW RATE, 0.01 GM/SEC.

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REGION	$\dot{m}$	T	P_T	COMMENTS
1	0	0	7.3×10^{-6}	NO FLOW
2	.0202	5.4	1.5×10^{-4}	THRUSTOR FLOW ON
3	.0202	3.5	28 μ	AUXILIARY FLOW ON
4	0	0	2 μ	THRUSTOR FLOW OFF
5	.0202	3.3	28 μ	THRUSTOR FLOW ON
6	.0202	5.4	1.5×10^{-4}	AUXILIARY FLOW OFF
7	0	0	7.0×10^{-6}	NO FLOW

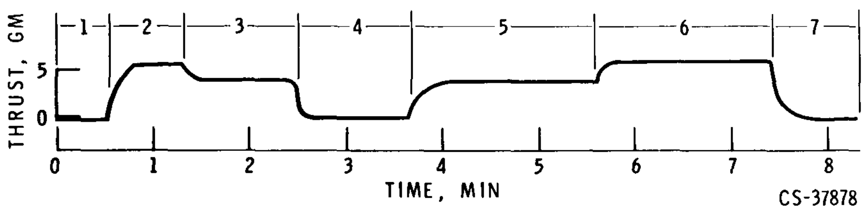

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FIGURE 15. - COLD-FLOW TESTS (HYDROGEN PROPELLANT) - THRUST STAND DEFLECTION.

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