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The NASA Electric Propulsion Program

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ABSTRACT

The NASA OAST Propulsion, Power, and Energy Division supports an electric propulsion program aimed at providing benefits to a broad class of missions. Concepts which have the potential to enable or significantly benefit space exploration and exploitation are identified and advanced toward applications in the near and far term. This paper summarizes recent program progress in mission/system analyses; in electrothermal, electrostatic, and electromagnetic propulsion technologies; and in propulsion/spacecraft integration.

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INTRODUCTION

Prospects now appear high for broad acceptance and application of electric propulsion systems (ref. 1). Low power, pulsed plasma thrusters are utilized for precise orbit control on Navy NOVA spacecraft (ref. 2), and 500-W class electrothermal (resistojet) hydrazine thrusters are used on geosynchronous communications satellites (ref. 3). Electrostatic (ion) propulsion is planned for its first operational use on the Japanese Engineering Test Satellite VI (ref. 4). The successful operation of these systems has led to increased user confidence, and further operational use of electric propulsion appears imminent.

Electrothermal propulsion is currently performing North-South stationkeeping (NSSK) on a number of geosynchronous satellites and will be used for the space station and man-tended platforms (ref. 5). The electrothermal auxiliary propulsion program includes the development of resistojets for high specific impulse and for long life compatibility with multiple propellants. Arcjets are being developed to provide increased life for high power geosynchronous satellites. Power electronics technology is required for all of these concepts and is, therefore, an integral part of the program, as it is also in the electrostatic and electromagnetic areas.

The National Commission on Space advocated a number of challenging missions, such as a return to the Moon, unmanned and manned exploration of Mars and its moons, and unmanned scientific exploration of the rest of the solar system (ref. 6). Many of these missions would be enhanced, and some would be enabled by high specific impulse electric propulsion. To perform the challenging future missions, high power and high specific impulse systems will be required. Candidate systems include electrostatic (ion) and electromagnetic (magnetoplasmadynamic or MPD) engines, with electrodeless approaches representing a longer term possibility. To perform these challenging future missions, the total impulse capability must be advanced from the currently demonstrated 10^6 N-s for both ion and MPD engines to at least 10^8 N-s. There are also many potential applications for high I_{sp} electric propulsion at the tens of kilowatts available from large solar power systems. For example, a USAF study has shown a high potential payoff for a solar electric orbit transfer vehicle for the delivery of satellite constellations to their operational orbits (ref. 7).

MISSION AND SYSTEM ANALYSES

Mission analyses covering spacecraft from small, solar-powered (refs. 8 and 9) to large, megawatt nuclear-powered spacecraft (refs. 10 to 14) show enhancing to enabling levels of capability for exploration of the planets and beyond. The Lunar Get Away Special (LGAS) study (ref. 8) considered a tiny 180 kg demonstration spacecraft, with one instrument and a 1.5 kW solar array, using ion propulsion for transportation from low Earth orbit (LEO) to lunar orbit. The LGAS mission would carry one instrument, nominally an Apollo gamma ray spectrometer, and would carry 36 kg of xenon propellant in a spacecraft that fits within a Get Away Special (GAS) canister and has a total wet mass of 149 kg. The Thousand Astronomical Unit Explorer (TAU) study considered a multimegawatt nuclear-powered electric propulsion system to reach 1000 au in 50 years (ref. 10). Both of these spacecraft accomplish the mission propulsion with a minimum propellant mass and, thereby, maximize the science payloads at the destinations. The Comet Rendezvous Asteroid Flyby (CRAF) mission was studied with an ion propulsion system added to a spacecraft and mission designed initially for chemical propulsion. Even though the mission and science package were not optimized for use of electric propulsion, the net effect was to reduce trip time by three years and increase the launch mass margin by 600 kg (ref. 13).

An ion thruster system for planetary missions has recently been designed and is undergoing engineering tests (ref. 15). The focus of these activities is on reduction of system complexity, with the goal of reducing the cost of development and flight qualification. Proposed design changes are also evaluated in terms of mission impact (ref. 16).

A range of solar- and nuclear-powered Earth orbital missions have been studied and show cost/mass reduction benefits (refs. 7, 17 and 18). For auxiliary propulsion, both ion engines (ref. 17) and arcjets (ref. 18) show mission benefits by extending the life of communications satellites.

ELECTROTHERMAL

NASA's electrothermal auxiliary propulsion technology program (ref. 19) includes the development of options for high specific impulse (arcjet), and high thrust-to-power ratio (resistojets). This paper will discuss progress (primarily since publication of ref. 19) on hydrazine arcjets for Earth-orbital satellites and platforms with sufficient power, high-performance storable propellant resistojets for power limited applications, water resistojets for man-tended platforms, and multi-propellant resistojets for the space station.

High Performance Resistojets

To advance storable propellant resistojets beyond the current state-of-the-art 300-sec mission average specific impulse (ref. 20), several efforts have been undertaken. Improved heat exchanger performance, longer-life higher-temperature heaters (ref. 21), and improved nozzle performance (refs. 22 and 23) are being sought. The importance of high-quality facilities for evaluating resistojet performance has been demonstrated (ref. 24). It has been shown that increasing facility background pressure increases the convective heat losses from the engine, resulting in decreased performance, as shown in figure 1.

Water Resistojets

Interest in water resistojets developed as a spin-off to the space station multi-propellant resistojet development. For man-tended, shuttle-serviced platforms such as the Industrial Space Facility (ISF), ease and safety of propellant resupply and ground handling operations are critical issues, which leads to the interest in water as a propellant. With a resistojet capable of steam operation already being developed for the space station, water resistojets were baselined for the ISF (ref. 25). This necessitated the development of a zero-gravity steam generator when it was determined that available steam generators, such as that developed for the Manned Orbiting Laboratory, did not perform stably and reliably and that operation of the space station resistojet with liquid water feed could be quite unstable (ref. 26). A cyclone steam generator (fig. 2) was developed after evaluation of a number of boiler concepts studied for space power system applications. Further development of this concept led to an integrated vaporizer/resistojet utilizing a single heater as described more fully in reference 27. This concept is shown in figure 3; the liquid water is swirled to the outer wall and boiled by heat radiated from the central heater which also heats the resistojet by conduction. Losses are reduced since the outer wall operates at temperatures below saturation. This design also overcomes the many stability and phase separation problems typically encountered in zero-gravity boilers.

Multipropellant Resistojets

As previously mentioned, multipropellant resistojets have been baselined on the space station. The requirements for space station propulsion are quite different from most other propulsion applications in that long life and integration features are much more important than performance (refs. 28 to 30).

Utilizing space station wastes as propellant minimizes resupply requirements, and may eliminate the need to return some wastes. Grain-stabilized platinum was selected as the thruster material following a series of propellant/material compatibility tests (refs. 31 and 32) and confirmed by a 2000-hr cyclic life test of a laboratory model thruster (ref. 33). Performance characteristics on a wide range of possible propellants have been obtained on an engineering model thruster (ref. 26), and long term life tests are underway with 6100 hr and 83 thermal cycles demonstrated to date. A power controller was developed to enable the thruster to operate on the high frequency power to be provided on the space station (ref. 34). To facilitate the integration of this technology on the space station, propellant and feed systems options were assessed (ref. 35) and interfaces defined (ref. 36). The exhaust plumes of the thrusters are of concern because of potential effects on sensors and experiments and potential attenuation of signals propagating through the plume, as discussed in a later section.

Arcjets

Arcjets offer a very significant (greater than 50 percent) performance increase over state-of-the-art auxiliary propulsion, and thereby provide significant mass savings for spacecraft with sufficient power. Over the past few years, arcjet technology has advanced from its status in the late 1960's, when work was terminated due to insufficient power availability on spacecraft and lack of firm mission requirements, to its present near flight-ready status. Because of the broad range of applications and the potential benefits for a number of NASA and USAF missions, the Air Force Astronautics Laboratory (AFAL) and the NASA Lewis Research Center (NASA Lewis) have agreed to pursue a joint research and technology program (ref. 37). The main focus of the NASA program is on low power thrusters for stationkeeping applications. The power available for auxiliary propulsion on communications satellites is currently limited to about 0.5 to 3.0 kW. Arcjet thrusters operated with storable propellants in that power range should provide significant benefits to the user community. The simplicity of the arcjet system and its elements of commonality with state-of-the-art hydrazine resistojet systems offer a relatively low risk transition to significantly enhanced performance levels. Successful performance of arcjets in such applications should validate performance and integration approaches and increase the likelihood that the large benefits of arcjets, and other electric thrusters, may be realized for many other missions.

The modern (1980's) arcjet program was initiated with a 1-kW arcjet, originally designed in the late 1960's for a short flight test using hydrogen propellant (ref. 38). Rapid erosion was observed, and stability problems limited operations, but the performance results indicated that beneficial performance levels could be obtained with storable propellants. Stability and power processor integration issues have been successfully addressed (refs. 39 and 40). Start up and transition to steady-state operation are now repeatable and nondamaging (refs. 41 and 42). To demonstrate starting reliability and the potential for pulsed mode operation, over 11 000 pulses (3 sec on and 3 sec off) were demonstrated (ref. 43). Life issues have also been successfully addressed, (refs. 41 and 42) indicating the potential for necessary mission life. A specific impulse as high as 729 sec was obtained with hydrazine in a conventional constricted arc design, (ref. 44) and other tests with mixed gas propellants (ref. 45) confirm the high specific impulse potential of this approach. However, the results from testing an approach incorporating a mixing chamber intended to improve efficiency gave relatively poor performance (ref. 46). Since the performance and life of hydrazine propulsion systems, including arcjets, are dependent on the catalytic gas generator, an experiment was conducted to determine the variation in output composition as a function of time (ref. 47). In 28 hr of testing over a 3 month interval, the catalyst bed efficiency increased rapidly with increasing temperature (which is, in turn, flow dependent) for temperatures below 450° C and remained essentially constant, with about 11 percent NH_3 at higher temperatures.

Based on these successes, a long-term, autonomous cyclic life test was initiated (ref. 48) and recently successfully completed (ref. 49). Over 500 cycles of 2 hr duration were performed at a specific impulse and power level of about 450 sec and 1.2 kW, respectively. The life test thruster is shown in figure 4, and its specific impulse versus thrust-to-power ratio characteristics are shown in figure 5. Typical performance histories of several cycles are shown in figure 6. No significant changes were seen throughout the test. At the design current of 11 A, the specific impulse variation was less than 2 percent over the duration of the test, while the voltage rose gradually to 110 percent of its original 101 V. The test was voluntarily terminated with the total firing time simulating 20 years of service on a communications satellite. The electrodes were still in excellent condition (fig. 7), and a cathode mass loss of only 6 mg was measured.

Advanced Electrodeless Concepts

Electrodeless thruster concepts offer the potential for very high energy coupling efficiency, and are, therefore, of great interest for high power systems (refs. 50 to 56). Electromagnetic energy is applied at radio through microwave frequencies to provide electrothermal, cyclotron resonance, or ion-cyclotron resonance heating of the propellant. Limitations imposed by electrode erosion in other electric thrusters may be avoided. NASA is evaluating the microwave electrothermal thruster, which absorbs the applied power in a plasma discharge and heats the gas propellant by high pressure thermalization. Advantages include high efficiency power absorption and conversion; high power density; and external control of discharge location, shape, and volume.

ELECTROSTATIC

Electrostatic (ion) propulsion is the highest specific impulse option with sufficient technical maturity to be considered for near-term applications. Benefits have been identified for both primary (refs 7, 9, 13 and 14) and auxiliary propulsion (refs. 4, 17 and 57). The technology program is, therefore, focused on power levels appropriate for both solar- (primary and auxiliary) and nuclear-powered (primary) applications (refs. 17 and 58 to 65).

An extended test of 567 hr was conducted on a 30-cm diameter, divergent-field ion thruster (fig. 8) using xenon propellant at a 10 kW power level (ref. 58). Primary wear mechanisms were identified so that long-life, high power engines can be developed. Three mechanisms were identified: nonuniform erosion on the upstream side of the baffle; oxidation, deformation, and cracking of the tantalum cathode tube, probably due to cold startup, but possibly related to the high partial pressure of water in residual facility gases; and charge exchange ion erosion of the accelerator grid. Screen grid erosion, which was the life-limiting mechanism for 3 kW mercury ion thrusters, was reduced greatly (fig. 9). Based on the experimentally obtained erosion data, the screen grid life is projected to be over 7000 hr. Addition of one percent nitrogen to the xenon propellant has been shown to reduce erosion by a factor of four (ref. 65).

Scaling of ion engines to larger size is desirable for nuclear class power levels, and preliminary results have been obtained (ref. 59). Laboratory and engineering model 30-cm diameter thrusters were operated with xenon propellant over a power range from 2 to 20 kW. Preliminary performance results were also obtained for laboratory model 50-cm diameter cusp- and divergent-field thrusters operating with both 30- and 50-cm diameter ion optics over the 10 kW range. These results represent the first output of a program aimed at developing scaling technology and, ultimately, nuclear class ion engine systems.

ELECTROMAGNETIC

The electromagnetic propulsion effort is focused primarily on magnetoplasmadynamic (MPD) thrusters. Both self-field and applied-field (fig. 10) thrusters are being investigated (refs. 66 to 73). Much of the recent research into the fundamentals of self-field thrusters has been conducted using pulsed-mode rather than continuous operation (refs. 66 to 68). A summary has recently been completed on the performance and life characteristics of quasi-steady state and continuous MPD thrusters (ref. 69). High efficiency is required and values up to 0.43 and 0.69 have been reported for hydrogen and lithium propellants, respectively. Other propellants show efficiencies in the 0.10 to 0.38 range at 1000 to 4500 sec specific impulse. High thermal efficiencies at megawatt power levels in pulsed operation and low electrode erosion rates have recently been reported, indicating that MPD thrusters may be developed with sufficient life and performance for extended, very high power missions. High power, continuous operation has recently been demonstrated at NASA Lewis, where an MPD arc thruster has been operated at over 130 kW in both self- and applied-field (0.3 T) modes (fig. 11).

PROPULSION/SPACECRAFT INTEGRATION

Because of the differences between electric and chemical propulsion systems, there are a number of integration issues which must be resolved to the satisfaction of potential users, such as electromagnetic interference (EMI) and plume effects. Plume characteristics differ significantly from those of chemical engines in that the exhaust may be slightly to highly ionized and Reynolds numbers are low.

For the multipropellant resistojets baselined on the space station, the exhaust plumes of thrusters are of concern because of potential effects on sensors and experiments and potential attenuation of signals propagating through the plume. Analytical and experimental techniques have been developed, (ref. 74) and a preliminary assessment made of the effect of nozzle geometry on plume characteristics (ref. 75). The effect of a plume shield has been evaluated and found to be small (ref. 76).

After the successful demonstration of arcjet performance and life, it was appropriate to initiate an investigation of those thruster/spacecraft integration characteristics required to enable the use of arcjets on operational spacecraft. A prefight development effort has been initiated to minimize the risks associated with flight testing of an arcjet to facilitate the achievement of operational status. Areas of concern are thermal loading, exhaust plume interaction, and both conducted and radiated electromagnetic interference. Thermal loading is a function of individual system design and plume characteristics. Electromagnetic interference (EMI) concerns are being addressed in ground testing, but experience based on space tests with more highly ionized plumes indicates that any problems should be manageable (ref. 77). Experiments have been conducted in a large vacuum facility to determine arcjet plume plasma characteristics using Langmuir probes, and the plumes were found to be less than one percent ionized (refs. 78 and 79). Based on these results, an analytical study has been conducted of the communications impact of a low power arcjet thruster by modeling the plume as a plasma slab. Except for propagation paths which pass very near the arcjet thruster, the impacts of transmission appear to be minimal (ref. 80).

CONCLUDING REMARKS

With the ongoing successful operational use of low power systems, applications of electric propulsion are growing. For example, the space station has baselined multipropellant resistojets for drag makeup. The NASA electric propulsion program is advancing the technology base for electrothermal, electromagnetic, and electrostatic propulsion systems to support these developments, and is, furthermore, addressing spacecraft integration issues to facilitate applications of electric propulsion.

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- FIRST OBSERVATION OF CORRECTED-THRUST DEPENDENCE ON FACILITY PRESSURE
- STANDARD PRESSURE-AREA CORRECTION NOT ADEQUATE FOR HEATED FLOW
- PERFORMANCE DEGRADATION DUE TO THERMAL LOSSES
- INDUSTRY INCORPORATING THERMAL CORRECTIONS IN PERFORMANCE EVALUATIONS

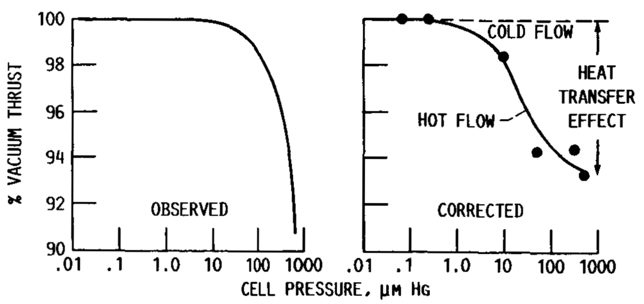

FIGURE 1. - FACILITY EFFECTS ON RESISTOJET PERFORMANCE.

- VORTEX BOILER CONCEPT DEFINED AND TESTED
  - GAS/LIQUID SEPARATION ENHANCED
  - EFFICIENT HEAT TRANSFER
- STABLE HIGH-QUALITY STEAM GENERATION DEMONSTRATED
- MINIMUM SENSITIVITY TO ORIENTATION ("G") EFFECTS

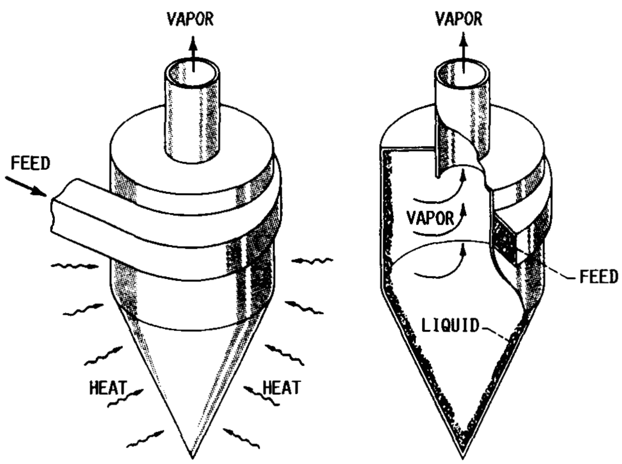

FIGURE 2. - CYCLONE STEAM GENERATOR.

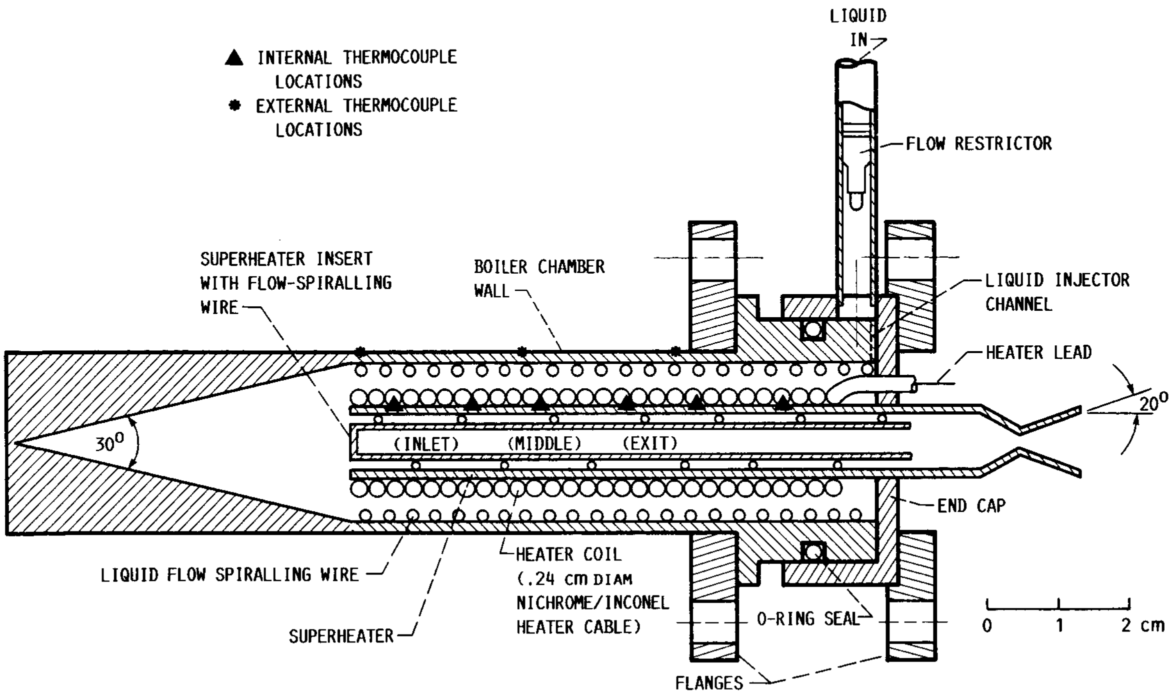

FIGURE 3. - INTEGRATED WATER VAPORIZER/RESISTOJET.

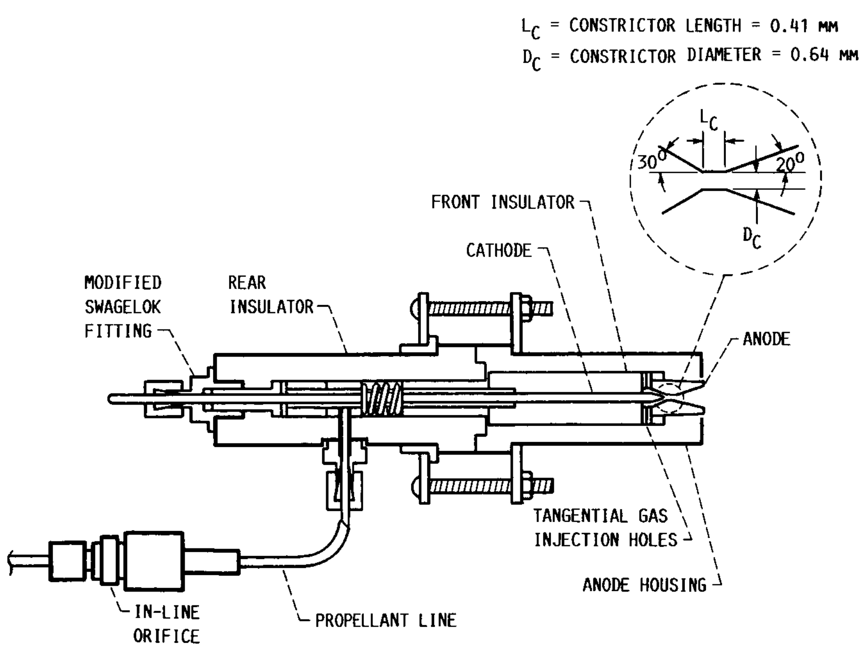

FIGURE 4. - LIFE TEST ARCJET.

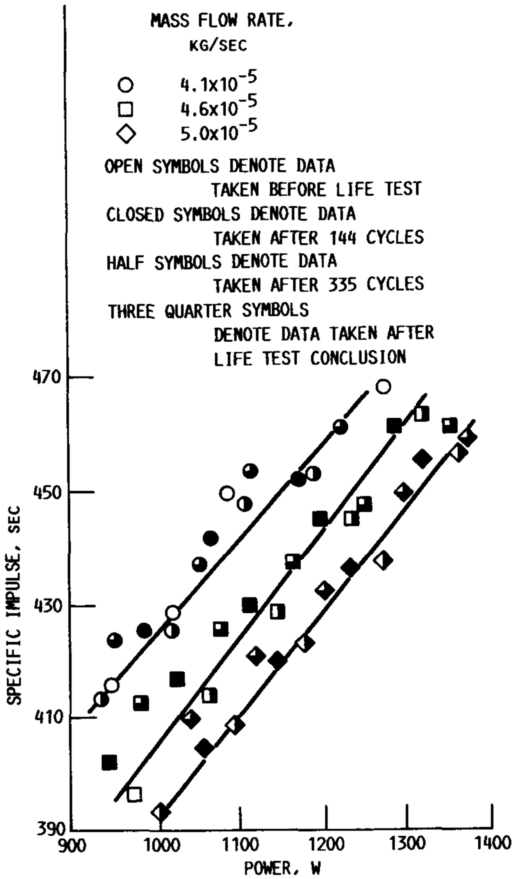

FIGURE 5. - ARCJET PERFORMANCE DATA TAKEN BEFORE AND DURING LIFE TEST.

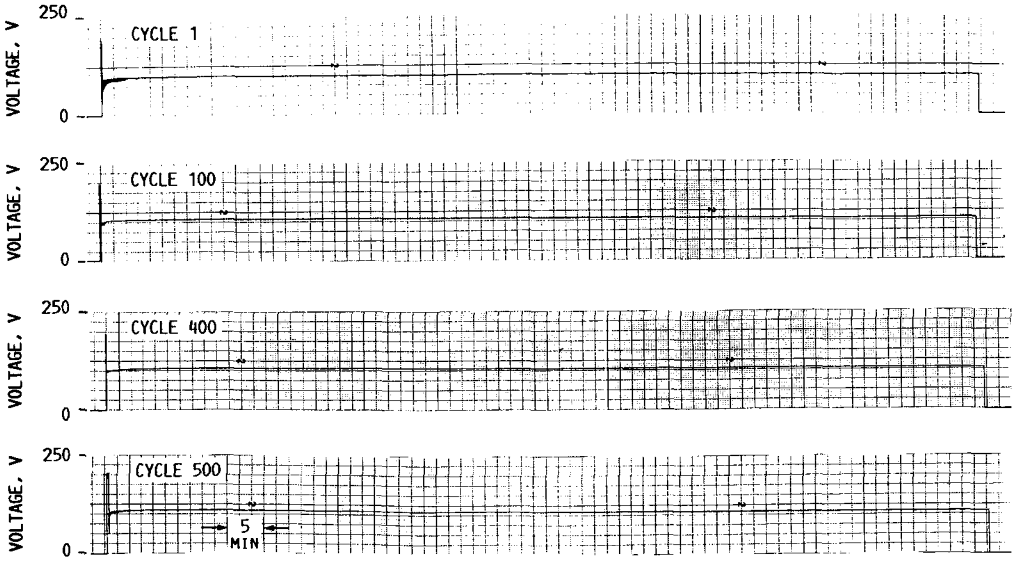

FIGURE 6. - TYPICAL ARCJET PERFORMANCE DURING 1000-HR LIFE TEST.

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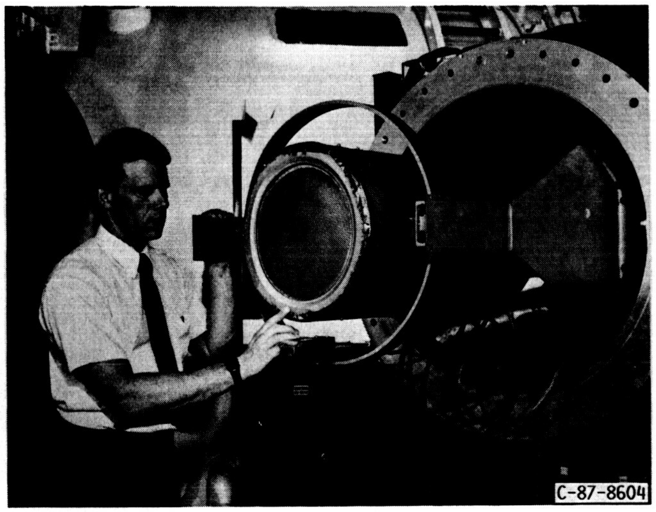
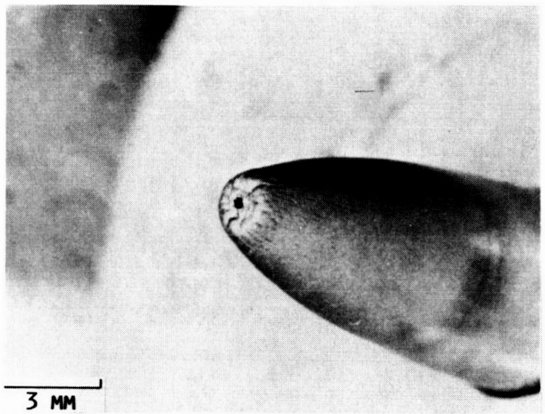


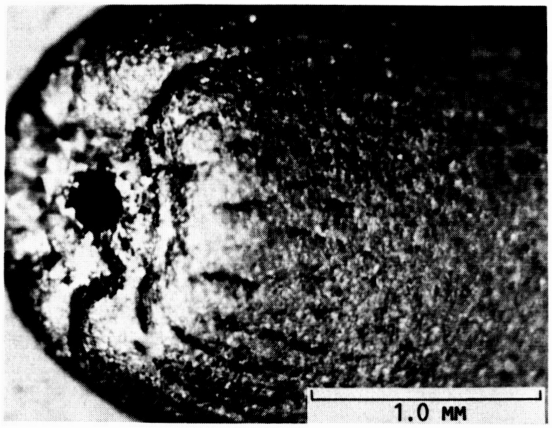
FIGURE 8. - 10 kW XENON THRUSTER.

CATHODE | ANODE

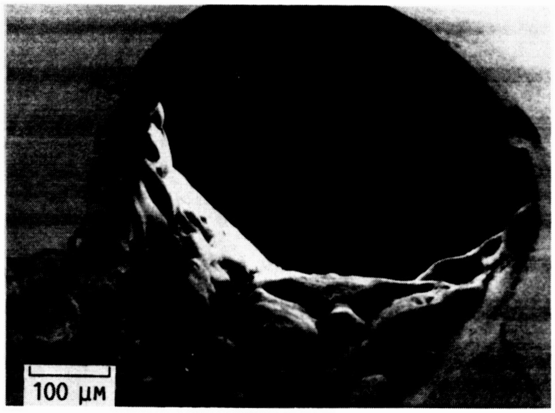


(a) CATHODE TIP.

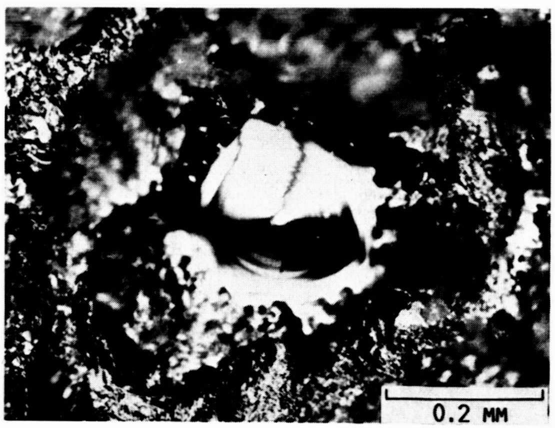
(d) CONVERGING SIDE OF NOZZLE.



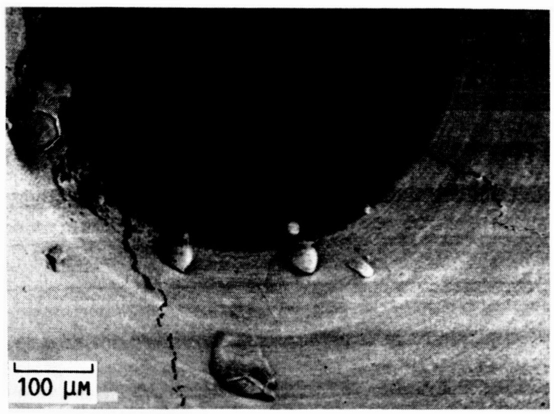
(b) CATHODE CENTER.



(e) DIVERGING SIDE OF NOZZLE.



(c) MOLTEN POOL.



(f) DIVERGING SIDE OF NOZZLE.

FIGURE 7. - ELECTRODES FROM LIFE TEST.

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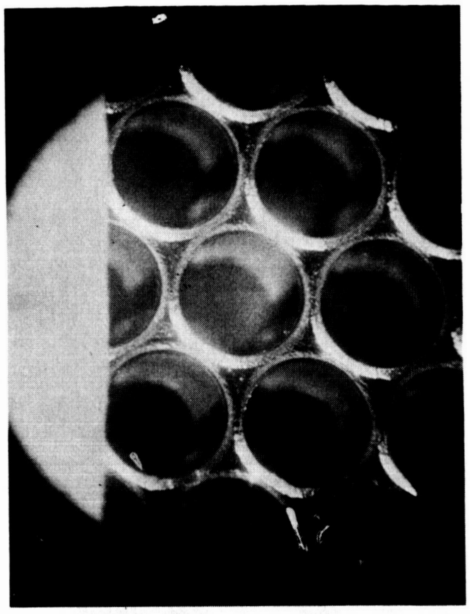
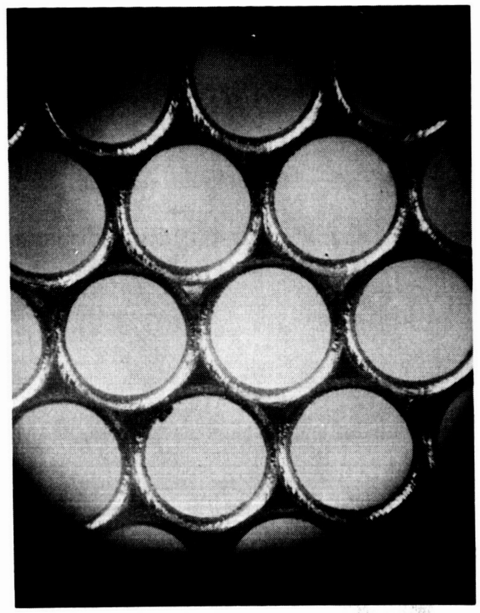
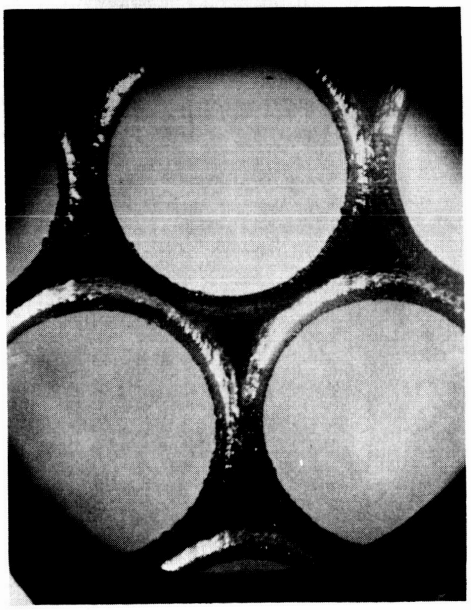


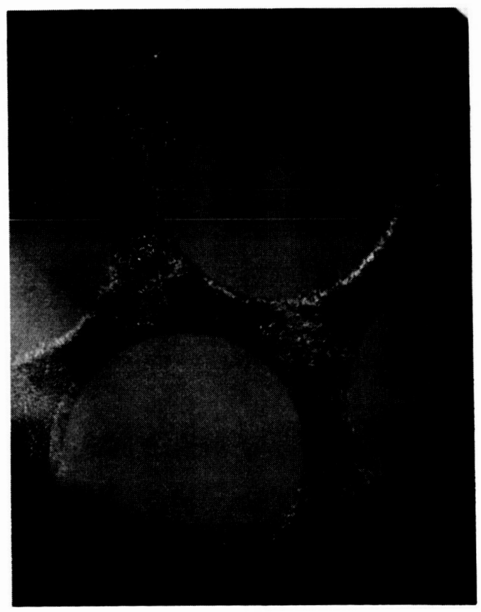
(a) UPSTREAM SIDE, BEFORE TEST.



(b) UPSTREAM SIDE, AFTER TEST.



(c) UPSTREAM SIDE, AFTER TEST.



(d) DOWNSTREAM SIDE, AFTER TEST.

FIGURE 9. - SCREEN GRID.

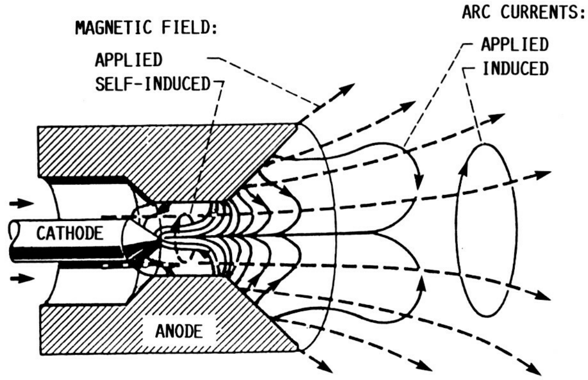


FIGURE 10. - MPD ARC THRUSTER CURRENTS AND FIELDS.

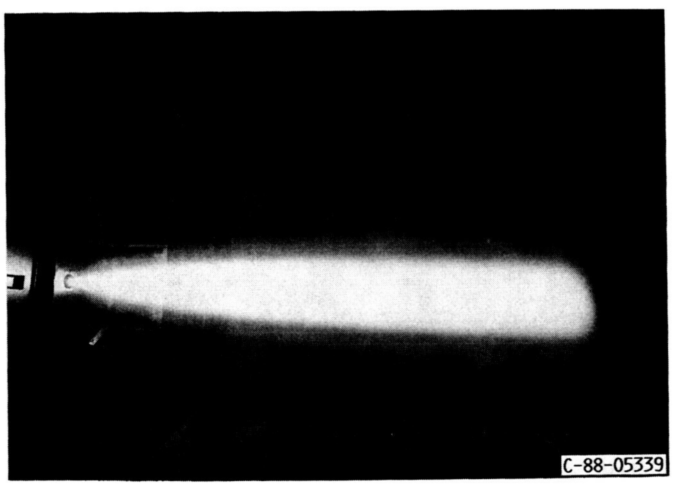


FIGURE 11. - MPD ARC THRUSTER OPERATING AT 102 kW INPUT POWER.

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15. Supplementary Notes

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16. Abstract

The NASA OAST Propulsion, Power, and Energy Division supports an electric propulsion program aimed at providing benefits to a broad class of missions. Concepts which have the potential to enable or significantly benefit space exploration and exploitation are identified and advanced toward applications in the near and far term. This paper summarizes recent program progress in mission/system analyses; in electrothermal, electrostatic, and electromagnetic propulsion technologies; and in propulsion/spacecraft integration.

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