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ABSTRACT

A cyclic lifetest of a low power dc arcjet thruster using a hydrogen/nitrogen propellant mixture simulating hydrazine is currently in progress. Over 300 hr of operation have been accumulated to date in 2 hr duty cycles at a power level of about 1.15 kW, approximating that available on commercial communications satellites. A burn-in period was carried out before consistent operation was attained. After this period, the arcjet operated in a very stable fashion from cycle to cycle. At the beginning of each cycle, there was a brief starting transient followed by a rapid rise to a steady-state voltage. The steady state voltage increased by about 5 V over the first 95 cycles. After this, it increased by only 1 V through the remainder of the test. Thrust measurements taken before the life test and again after the completion of the 144th cycle showed that both thrust, specific impulse and arc voltage had increased over this period of operation. No life limiting mechanisms were observed during the course of the testing.

INTRODUCTION

Early research and development efforts on arcjet thrusters for space propulsion began in the 1950's and continued for about a decade.[1] The goal of most of these government sponsored programs was to bring a 30 kW class hydrogen arcjet to technological readiness for use in missions requiring primary propulsion.[2-5] Ammonia was also studied as a propellant in some cases and recently interest in high power ammonia arcjets has been rekindled.[6,7] In the earlier development programs, 1 and 2 kW hydrogen arcjets were studied at the Plasmadyne Corporation.[8,9] Efforts to run at low power on alternate propellants met with little success.[10]

Presently, a new research program has focused on the development of a low power arcjet thruster to replace the monopropellant hydrazine and resistojet thrusters presently used for North-South stationkeeping of geosynchronous communications satellites. This program has been largely successful in demonstrating that arcjets can be operated on propellants other than hydrogen at power levels available on satellites currently in use.[11-15] Performance characterizations of the arcjet have shown that specific impulse values ranging from 400 to 600 sec can reasonably be expected. Other important aspects of arcjet operation such as starting phenomena[16-18] and plume impacts[19] have also been examined. To date, however, only a limited amount of lifetesting has been performed. In one recent test, 104 hr of operation was accumulated on an arcjet running at approximately 0.9 kW on a hydrogen/nitrogen mixture simulating the decomposition products of hydrazine.[20] Problems with the thruster rendered much of the data inconclusive, but the test did show that electrode wear should not be a serious problem on this time scale. A series of 20-hr tests on arcjets operated at between 1.2 and 2.0 kW on hydrazine decomposition products have also been reported.[15] The only other life test performed on a low power dc arcjet thruster was that of a 2 kW hydrogen arcjet in 1962.[9] This test involved a single start and 200 hr of continuous operation. To perform actual stationkeeping duties, a hydrazine arcjet will be required to operate over many hundreds of hours accumulated in short duration cycles.[21]

This paper presents results from the first 300 hr of a cyclic life test of a low power arcjet which is currently in progress. The laboratory thruster was operated on a mixture of hydrogen and nitrogen to simulate the decomposition products of hydrazine. Cycle duration and thruster operating parameters were selected to approximate conditions expected in near-term mission applications. Descriptions of the vacuum facilities, arcjet thruster, and thruster diagnostics are provided. Arcjet operating characteristics, performance trends, and observed phenomena throughout the life test are fully documented. Projections for realistic mission expectations are made.

APPARATUS

The lifetest was performed in a small bell jar facility, shown in Fig. 1. This facility has been previously described in detail.[13] Briefly, the dimensions of the chamber are 0.64 m in length and 0.64 m in diameter, and it was serviced by a single mechanical roughing pump with a pumping speed of 17 000 l/min. at 1 torr (133 Pa). In operation, an ambient pressure of approximately 0.75 torr (100 Pa) was maintained at the mass flow rate of the hydrogen/nitrogen mixture used in the test (4.07×10^{-5} kg/sec). The hydrogen/nitrogen mixture ratio was 2:1. A previous study has shown that the arcjet has the same voltage current characteristics at this level of background pressure as it does in high vacuum facilities.[13] Commercially available mass flow controllers were used to supply the hydrogen and nitrogen to the arcjet. These controllers had a 0 to 10 L/min. capacity and were operated by a central, multiple channel power supply console. The gases were stored and metered separately, and then mixed in the propellant feed line to the arcjet thruster.

A pulse-width modulated power supply[22] was used to provide power to the arcjet. This power supply provided up to 130 V at up to 12 A for steady-state operation. A pulsed, high voltage starting circuit was included in the power supply for arc ignition. At the beginning of each cycle, this circuit provided a series of high-voltage pulses until current was sensed. The pulse repetition rate was 1 Hz. Arcjet starting phenomena will be discussed in more detail in a following section.

Both the power supply and the mass flow controllers were configured so that they could be operated automatically. To provide the automatic cycling capability, a small programmable controller was installed in the facility. This controller had a capacity of 16 input and 12 output relays and was configured to cycle the flow controllers and power supply in a programmed timing sequence. The arc voltage was monitored by an analog panel meter with dual set points and these were monitored continuously by the controller. The high-voltage set point was chosen to be approximately 30 V above the normal operating voltage of the arcjet and, as such, would indicate that the arc had gone out. The low voltage set point was chosen to indicate arc anode attachment upstream of the throat, a condition commonly referred to as low mode operation. At the beginning of the "on cycle" the controller was programmed to ignore set point violations for the first 60 sec to allow the arcjet to start and stabilize. After this period, set point violation initiated shutdown of the power supply system. A system reset was provided to return the system to initial conditions so that experiments would always start at the beginning of a cycle.

Due to availability of the thrust measurement facilities, arcjet performance measurements before and during the test were taken in different high vaccum tanks. These facilities have been described elsewhere.[11,23] Both were equipped with diffusion pumps and the background pressure in each was below 3.5×10^{-4} torr (0.0466 Pa) at the flow rates run in the tests. A common flow control system was used for all performance tests. These were calibrated in-situ. The same thrust stand was also used in both facilities. This has also been described in detail elsewhere.[17] Experiments performed in both facilities with a previously well characterized thruster and under identical values of current and mass flow rate showed that the thrust measurements varied by less than one percent.

In all facilities, eight-channel strip chart recorders were used to record arc voltage, arc current, propellant flow rates and propellant line pressure. In performance testing, thrust was recorded on one of the channels while in the bell jar facility, one channel was used to record the temperature on the rear insulator of the arcjet. The arc current was measured using a Hall-effect current probe. Once calibrated, the current measurement was accurate to within ± 0.1 A. The arc voltage was taken across a 10:1 voltage divider. An isolation amplifier was used between the divider and the chart recorder. A digital multimeter was used to provide periodic, redundant voltage measurements. These were taken directly across the power feedthroughs to the arcjet.

The arcjet used throughout the test was of the conventional, constricted-arc design. A cross-sectional schematic is shown in Fig. 2. The anode housing was made of titaniated-zirconiated molybdenum (TZM) and the rear insulator of boron nitride. Graphite foil seals were used on critical surfaces. To improve the sealing capability, a shallow spiral groove was machined into the rear sealing surface on the anode housing. Two molybdenum flanges, a stainless steel collar, and four bolts were used to hold the rear insulator and the anode housing together. The anode/nozzle insert, illustrated in the figure, was made from two percent thoriated tungsten. The converging and diverging sides of the nozzle were both conical with half angles of 30 and 20°, respectively. The constrictor was 0.41 mm in length and 0.64 mm in diameter. A photomicrograph of the converging side of the anode with a view down the constrictor is shown in Fig. 3. The diverging side was similar in appearance.

To provide the vortex flow pattern used to stabilize arcjet operation, a molybdenum gas injection disk with graphite foil gaskets on either side was inserted into the housing to seat against the insert on one side. The two tangential injection holes in the disk were nominally 0.34 mm in diameter. Raised ridges were machined on both of the disk faces. These ridges compressed the graphite foil to provide a gas-tight seal when the entire unit was assembled. Immediately upstream of this disk was the front insulator. This was also made of boron nitride and had both a centered hole for the cathode and grooves milled on its exterior surface to allow gas passage. A larger bore was used in the rear (upstream) of this insulator to accommodate an aluminum oxide tube, used to isolate the cathode from surfaces at anode potential.

The cathode was made from 2 percent thoriated tungsten rod, 3.2 mm in diameter and approximately 190 mm in length. The tip was initially ground to a 30° half angle and then polished to remove any rough edges and give the cathode tip a bullet shape as shown in Fig. 4. A stainless steel cathode holder was used to feed the cathode through the rear insulator and locked the cathode in place once the arc gap was set. The aluminum oxide tube extended nearly to the cathode holder and, from back to front in the design, were a boron nitride cylinder to cover the remainder of the face of the holder, a stainless steel anchor for the propellant tube, an inconel spring, and a boron nitride insulator. When completely assembled, the spring was compressed, forcing the front insulator forward to form the gas-tight seals around the injection disk.

The propellant entered the arcjet through the side of the rear insulator. The propellant inlet tube was threaded on the end to match a tapped hole in the propellant tube anchor.

A photograph of the arcjet engine prior to assembly is shown in Fig. 5. The arc gap was set by moving the cathode forward until it contacted the anode, measuring the entire unit, withdrawing the cathode the desired distance, and then tightening the modified compression fitting. The gap was set to 0.58 mm.

PROCEDURE

Thrust measurements were obtained in a similar manner in each of the two high vacuum facilities. Before any measurements were taken all electronics along with cooling water to the thrust stand were turned on and allowed to equilibrate. The mass flow controllers were calibrated to provide ± 1 percent accuracy. The current probe was then calibrated with a current shunt prior to arcjet operation. Thrust stand calibration was performed before and after each run using weights suspended on a monofilament line attached to a windlass. Once the thrust stand calibration was accomplished, cold flow thrust measurements were taken for each mass flow rate to be tested. The cold flow specific impulse obtained was compared to other tests to insure no propellant leaks were present in the arcjet or flow system. The arcjet was then started and thrust measurements were obtained. Thrust data were taken only after the arcjet had reached steady state for a given set of conditions.

The arcjet lifetest was designed to approximate an accelerated stationkeeping application. A 50 percent duty cycle was chosen with the arcjet on for 2 hr and off for 2 hr. Five minutes before each cycle, the propellant flow began and it remained on for five minutes at the conclusion of the cycle. This was done to bring the arcjet body temperature down between cycles and to assure an equilibrium flow rate had been obtained prior to each cycle. In a mission application, only a very brief equilibration period will be necessary and this should not seriously affect average specific impulse. The controller was configured to shut down the test if the arcjet did not start within one minute of the beginning of the cycle. Propellant gases were stored in separate banks of K bottles and necessary changeovers were made during the off cycles. A careful purging procedure was followed to ensure that the flow system did not become contaminated.

RESULTS AND DISCUSSION

OPERATING PARAMETERS

For this initial arcjet lifetest, a fixed operating point was chosen for both the mass flow rate and the current. The operating parameters in an actual flight application will depend on the type of spacecraft and the mission requirements. A mission analysis has recently been published[21] and, from this, propellant mass flow rate (due to the blowdown pressure) is expected to drop approximately 20 percent to an end-of-life value of about 4×10^{-5} kg/sec for a 300-hr mission. Since the lower mass flow rate represents a worst case from the standpoint of both arc stability and thruster temperature, this was chosen as the mass flow rate of the simulated hydrazine mixture to be used throughout the test. A current of 11 amps produced a power level slightly greater than 1.1 kW at the end of the burn-in period. As the power was expected to increase slightly over the course of the test due to cathode recession and, as the power level available per thruster for the auxiliary propulsion function will likely be fairly close to 1.2 kW, the 11 A current level was used in testing.

BURN-IN PERIOD

Laboratory experience has shown that the operational stability of the arcjet is manifested in the steadiness of the plume and the smoothness of the voltage trace. After a performance check of the assembled thruster, a 14 cycle burn-in period was carried out before consistent arcjet operation was obtained. While some of the cycles during this period showed stable voltage readings, a number were characterized by fluctuations in the voltage trace. Some of these were very rapid excursions such as those shown in Fig. 6(a), while others involved step changes in voltage, shown in Fig. 6(b). The excursions were accompanied by motion of the plume. While no positive explanation for these observations exists, it is the authors' opinion that they are due to motion of the arc initiated by changes in the location at which the arc seats on the cathode. In the case of the rapid voltage excursions, the changes in voltage were too fast for the strip chart to record. The step changes involved voltage excursions of up to 15 V. In one case, the arc seated on the converging side of the anode insert at the beginning of a cycle. In this mode, the low-voltage limit was violated and the arcjet system shut down before any damage was done to the arcjet. A system reset resulted in a normal starting sequence. During the course of the 14 cycle burn-in period, the steady state operating voltage increased from an initial value of 96 V to approximately 101 V.

CYCLIC LIFETEST OPERATION

The first 300 hr of the lifetest following the burn-in period were characterized by very stable, consistent steady state operation of the arcjet, as demonstrated in Fig. 7. Figure 7(a) displays the strip chart record of the first cycle of the lifetest. The current, as expected,[21] reached its steady state value almost instantaneously, while the arc voltage exhibited a brief period of instability (less than 5 min). This behavior is common to arcjet operation and is due to the fact that the arc does not immediately come to an equilibrium position on the tip of the cathode. The time required for arc stabilization varied from cycle to cycle but was never longer than that observed at the start of cycle 1. In all cases, the voltage was within 98 percent of its steady state value five minutes after ignition. As noted at the bottom of Fig. 7(a), temperature measured on the rear insulator was seen to rise slowly to a steady state value somewhat above 300 °C during the cycle from a precycle value of about 40 °C.

As discussed previously, variations in the arcjet operating characteristics are clearly manifested in the arc voltage readings. Fig. 7(b) shows the voltage traces from the 50th, 100th, and 300th cycles. These all display typical (short) starting transients followed by stable operation. Visually, no flickering or unsteadiness was observed in the plume during steady state operation. Taken together, these observations indicate that the arc seated in a stable repeatable fashion on both the anode and cathode throughout each test period. However, one problem developed at the start of the fourth cycle. Here, the power supply came on as anticipated, but the arcjet would not start. The high voltage pulse was examined with an oscilloscope and found to be distorted as shown in Fig. 8. The distortion took the form of an interruption in the voltage rise early in the pulse. This indicates the occurrence of a brief, pre-ignition, corona discharge which, upon closer examination, was visible near the flanges and bolts at the center of the thruster. Fortunately, the current drawn by the corona discharge (about 0.1 A) did not completely discharge the inductor in the starting circuit and the voltage continued to rise at the conclusion of the discharge. To continue testing, the energy available in the starting pulse was increased so that the maximum voltage attained following the corona discharge was sufficient to start the arc. This effect was definitely related to the high background pressure in the bell jar and has not been observed in high vacuum facilities. A similar occurrence was observed on cycle 60. Here, the arcjet ran full cycle but several pulses occurred before arcjet ignition was accomplished. Once again, the energy level was slightly increased, but the same phenomenon occurred upon the initiation of cycle 61. Following this, cycle breakdowns began occurring on the first pulse and rarely was more than one pulse required through the remainder of the test. In one instance, a non-distorted pulse of 4 kV was observed which did not start the arcjet.

The steady-state voltage did increase during the life test from its initial value (cycle 1) of approximately 101 V, as shown in Fig. 9. The gradual rise in voltage totalled approximately 6 V over the 300 hr of operation. This rise was likely due to a gradual recession of the cathode tip. Though a constant voltage was not attained by the 150th cycle, the rate of increase in voltage was much greater through the burn-in period and in the first 75 cycles than it was in the last 75. The slightly elevated values observed around cycle 125 were due to a drift in the mass flow controllers. While this trend indicates that a final, steady value may eventually be achieved, cathode recession cannot be ruled out as a long term life limiting mechanism. Further testing of this thruster should provide a better understanding of this phenomenon. In any event, the cathode recession does not appear to cause problems through the first 300 hr of testing, although the increase in power at constant current will have to be addressed from a mission-impacts standpoint.

Two mid-cycle shutdowns did occur during the course of the lifetest. In each case, the chart recorder traces indicated no arcjet-related operational problems that would cause the controller to shut down the power supply. One of the occurrences was traced to an inadvertent activation of a safety relay. The other shutdown remains unexplained, but it is likely that the cause was similar. In both cases, the arcjet cycling program was restarted and the next cycles displayed no anomolous behavior.

ARCJET PERFORMANCE

Prior to the burn-in and lifetest, thrust measurements were taken at the mass flow rate to be used in the test. Nonavailability of vacuum facilities precluded testing after the burn-in period. Thrust measurements were was taken again after 144 test cycles had been completed. As the arc voltage had essentially stabilized well before the 144th cycle, a more extensive set of data, over a range of mass flow rates and current levels, was taken at this point to fully characterize the thruster. Performance data from both runs are presented in Figs. 10 and 11. Data taken in the second test are collected in Table I. Figure 10 shows the voltage-current characteristics of the thruster under various conditions. The plot verifies that after 144 cycles, the thruster characteristics were very similar to those observed in prior tests of similar thrusters on hydrogen-nitrogen mixtures (for example, see Ref. 13). The gradual decrease in voltage with increasing current is due to the fact that, as the current increases, the arc core constricts and increases in temperature, thus increasing in conductivity.[24] The most important feature of the plot is the distinct contrast between the data taken at 144 hr and that taken before the lifetesting was begun. Once again, this demonstrates the need for a burn-in period to insure that no drastic changes in arc voltage and, therefore, power for a given current level occur at a given mass flow rate. This point is illustrated further by the data in Fig. 11 which plots specific impulse versus power for both sets of performance data. The pre-test data falls very close to that obtained at the later time indicating that the relationship of specific impulse to power at a fixed mass flow rate is reasonably constant even as the cathode tip recesses. The current necessary to attain a given power level, however, was higher in the initial test due to the lower voltages observed (approximately 10 V). In the case of a mission application in which maximum available spacecraft power must be used at all times to maximize specific impulse and thrust level, a power supply with a wide range of current capability would be necessary if a burn-in were not performed prior to flight.

The data in fig. 11 also show that specific impulse values in the range of 450 sec (mission average) should be attainable at current levels between 10 and 12 A. In an application with actual hydrazine, the voltage, and hence power the level, would be slightly increased (5 to 10 V) due to the elevated pressure caused by the increased enthalpy of the propellant. The specific impulse values would also increase by about 20 sec for a given power level and mass flow rate.

CONCLUDING REMARKS

The first 300 hr of an autonomous, low power dc arcjet lifetest have been successfully completed. The operating time was accumulated in two hr cycles at a power level of between 1.1 and 1.2 kW in order to approximate a stationkeeping mission for a geosynchronous communications satellite. The mass flow rate of the simulated hydrazine mixture was fixed near the lower limit expected for a five year mission. A fourteen cycle burn-in period was needed to attain stable consistent arcjet operation. At the beginning of each cycle, a brief period of voltage fluctuation was observed before the arc seated in its equilibrium position on the cathode tip. Following this, the arcjet operated in a very stable fashion. No abrupt voltage changes were observed at any time once the arc had stabilized.

A rapid increase in the steady state operating voltage of the thruster during the burn-in period signalled a rapid recession of the cathode tip from its original bullet shape. This recession slowed markedly, however, and throughout the lifetest only a gradual rise in the operating voltage was observed. Testing of this thruster will continue to determine whether a limiting value of cathode recession is reached. While the change in power at a fixed current and mass flow rate caused by the increased voltage will have to be accommodated on a systems level, it does not appear to represent a threat to arcjet life over expected mission durations.

A facility-related corona discharge phenomena necessitated an increase in the rate of rise on the starting pulse. This made the determination of starting breakdown difficult. While no real difficulty in arcjet ignition was observed, future tests in low vacuum facilities should probably include periodic checks of breakdown voltage in higher vacuum facilities in order to accurately access changes in starting characteristics with operating time.

Thrust measurements taken at a point well into the test indicate that both thrust and specific impulse values had increased from the levels observed prior to the burn-in period. The fact that the relation of specific impulse to power at a given mass flow rate did not change significantly between the measurements taken before the burn-in period and after more than 288 hr of operation indicates that there is no change in the thruster's operating mode as the cathode recesses. From the data, it is clear that specific impulse values in the range of 450 sec can reasonably be expected at moderate current levels (10 to 12 A) with real hydrazine decomposition products.

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TABLE I. - PERFORMANCE CHARACTERISTICS TAKEN AFTER CYCLE 144

Current, A	Voltage, V	Power, W	M_{N2}, mg/secx10^3	M_{H2}, mg/secx10^3	M_{total}, mg/secx10^3	Thrust, g	Thrust, m/b	Thrust, N	I_{sp}, sec	η, percent	P/mg, W/secx10^3
--	-----	----	0.0435	0.00619	0.0497	5.96	13.1	0.0583	120	----	------
--	-----	----	.0398	.00568	.0455	5.44	12.0	0.0234	119	----	------
--	-----	----	.0356	.00509	.0407	4.91	10.8	0.0480	121	----	------
9	110.5	994	0.0356	.00509	0.0407	17.3	38.2	0.170	425	34.5	24 423
10	107.8	1078				17.9	39.6	.176	441	34.3	26 486
11	107.6	1184				18.4	40.6	.180	452	32.9	29 091
12	106.9	1283				19.0	42.0	.187	468	32.6	31 523
8	118.4	947	0.0398	0.0568	0.0455	18.3	40.4	0.180	402	36.1	20 813
9	114.6	1031				18.9	41.8	.182	416	35.6	22 659
10	111.9	1119				19.5	43.0	.191	429	35.0	24 593
11	109.6	1206				20.2	44.6	.198	444	34.8	26 505
12	108.0	1296				21.0	46.2	.205	460	34.8	28 484
4.9	143.6	703	0.0435	0.0497	0.0497	17.2	37.8	0.168	345	38.5	14 145
9	118.0	1062				20.1	44.3	.197	404	35.5	21 368
10	115.1	1151				20.8	45.9	.204	419	35.3	23 159
11	112.6	1240				21.6	47.7	.212	435	35.4	24 950
12	111.1	1333				22.6	49.8	.22	454	36.0	26 821

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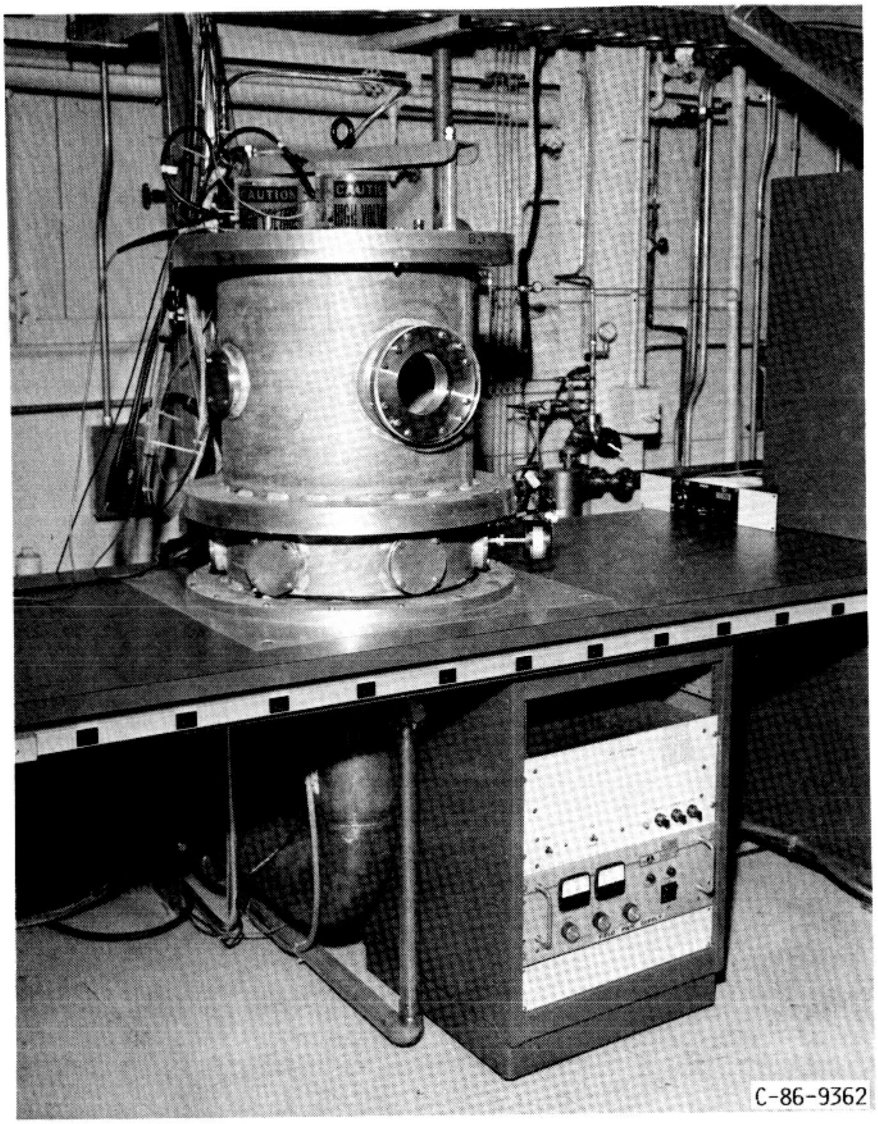

FIGURE 1. - VERTICAL BELL JAR BEST CHAMBER AND PULSE WIDTH MODULATED POWER SUPPLY (BELOW).

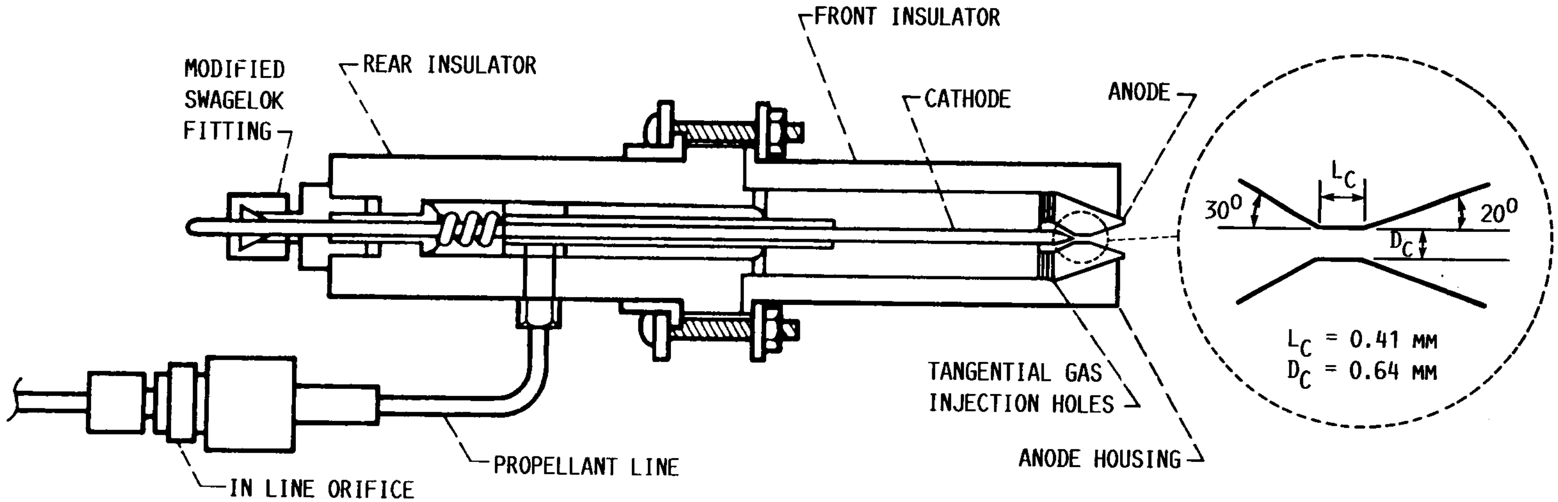

FIGURE 2. - CUTAWAY VIEW OF ARCJET THRUSTER WITH ANODE DIMENSIONS DESCRIBED.

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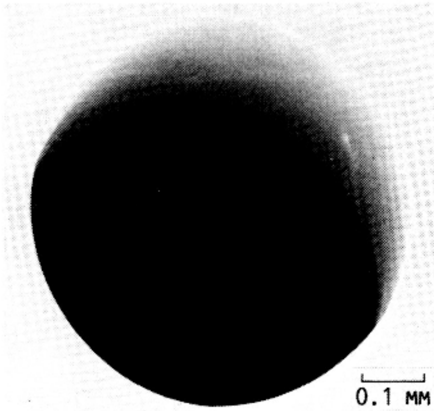


FIGURE 3. - PHOTOMICROGRAPH OF CONVERGING SIDE OF ANODE WITH VIEW DOWN CONSTRICTOR.

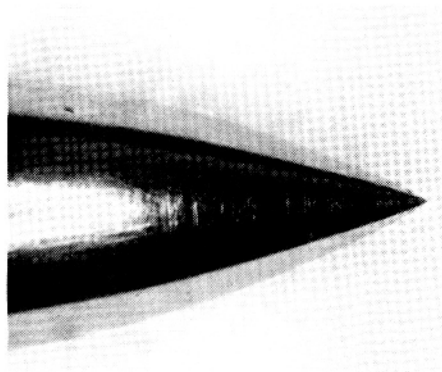


FIGURE 4. - PHOTOMICROGRAPH OF CATHODE TIP BEFORE TESTING .

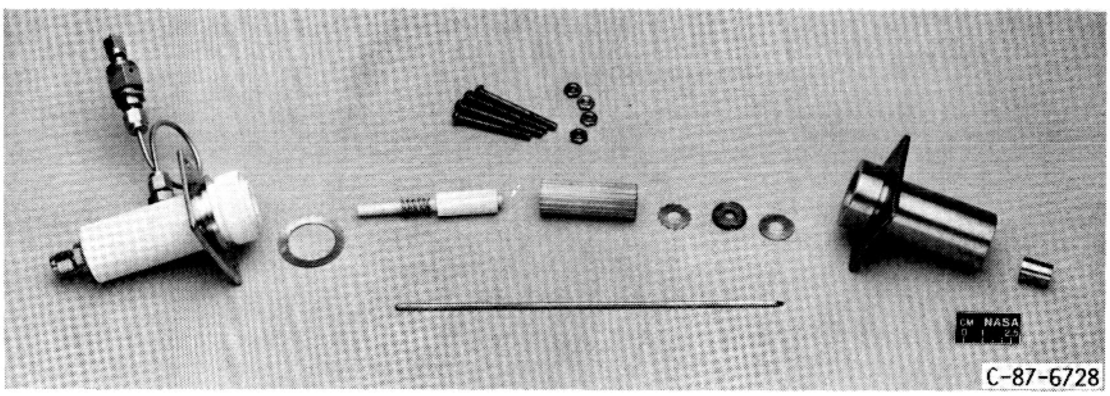
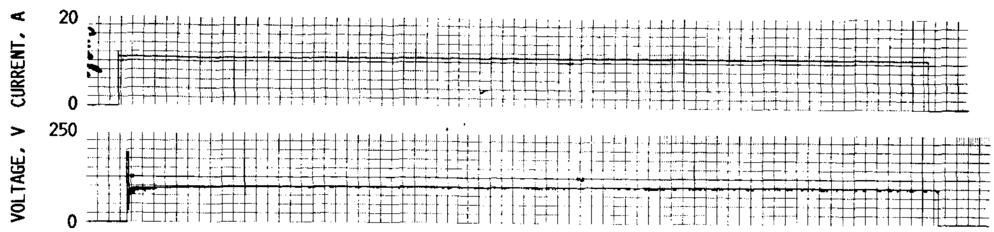
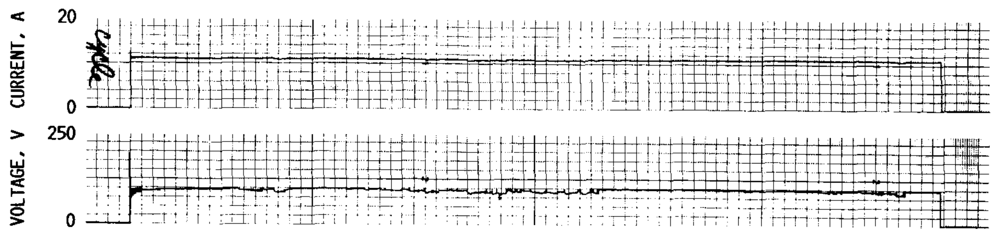


FIGURE 5. - DISSASSEMBLED THRUSTER BEFORE START OF LIFE TEST.

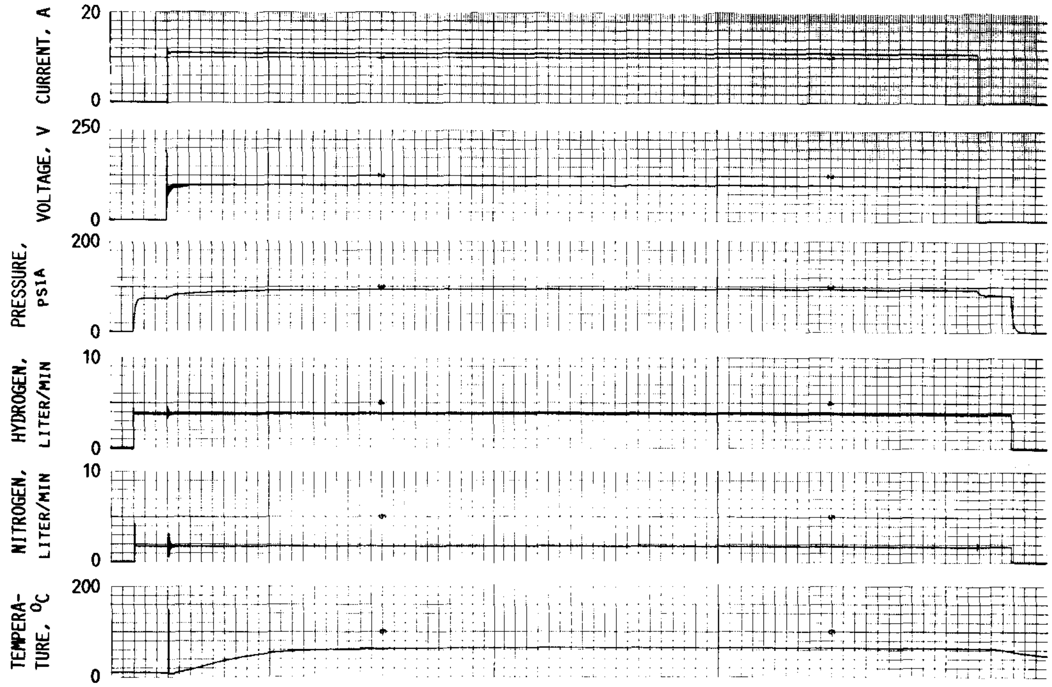


(A) CYCLE 9 - RAPID ARC VOLTAGE EXCURSIONS.

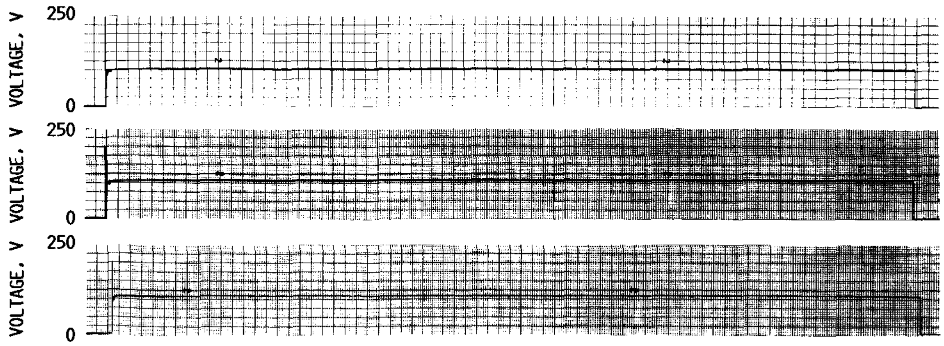


(B) CYCLE 13 - STEP CHANGES IN ARC VOLTAGE.

FIGURE 6. - VOLTAGE AND CURRENT TRACES SHOWING VOLTAGE EXCURSIONS DURING BURN-IN-PERIODS.



(A) STRIP CHART RECORD FROM LIFE TEST CYCLE 1 (POST BURN-IN).



(B) VOLTAGE TRACES FROM CYCLES 50, 100, AND 150.

FIGURE 7. - STRIP CHART RECORDS OF REPRESENTATIVE CYCLES THROUGHOUT LIFE TEST.

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OF POOR QUALITY

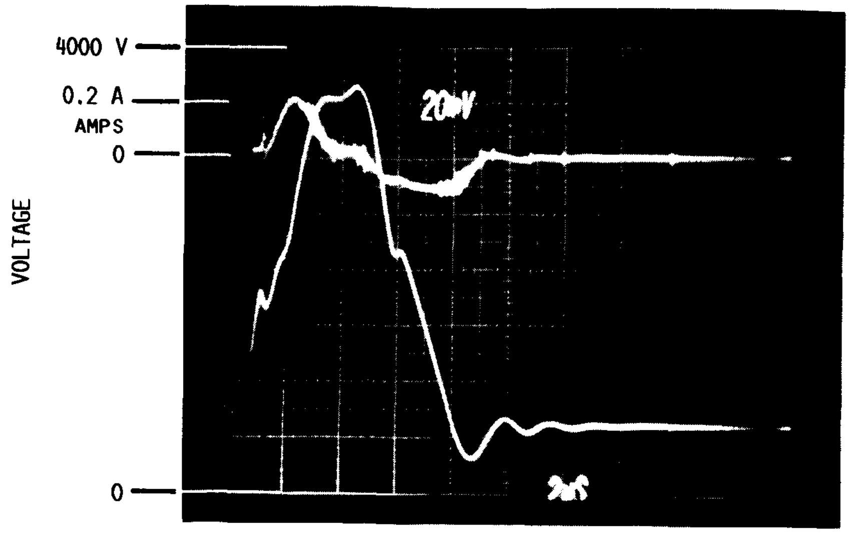

FIGURE 8. - OSCILLOSCOPE TRACE OF STARTING PULSE AND CURRENT - CASE OF CORONA DISCHARGE.

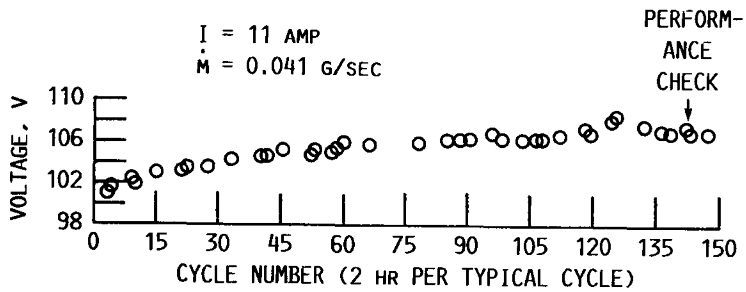

FIGURE 9. - ARC VOLTAGE VERSUS TIME AT CONSTANT CURRENT AND MASS FLOW RATE.

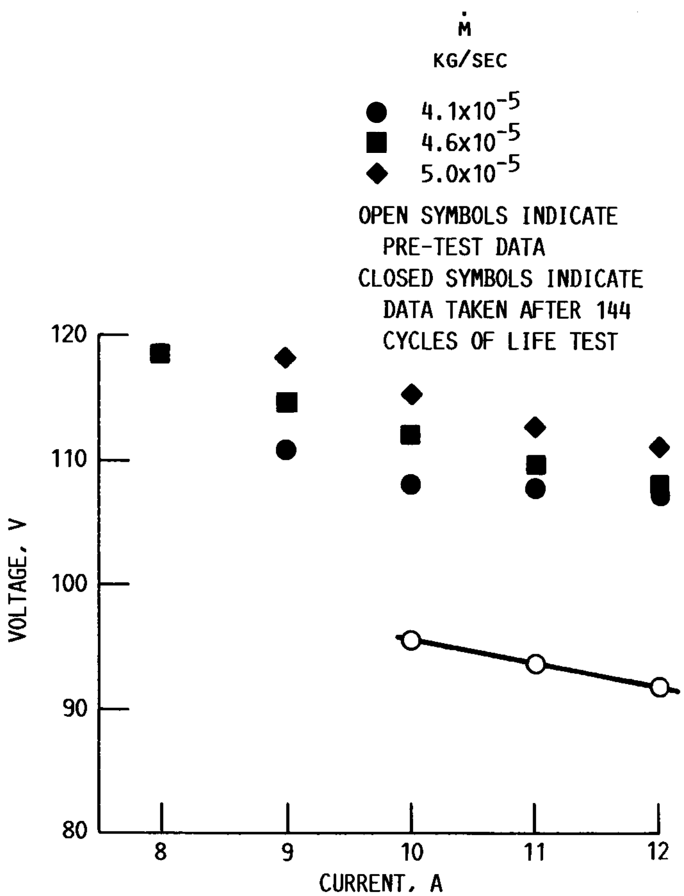

FIGURE 10. - VOLTAGE-CURRENT CHARACTERISTICS PRIOR TO TESTING AND AFTER 144 CYCLES OF THE LIFE TEST.

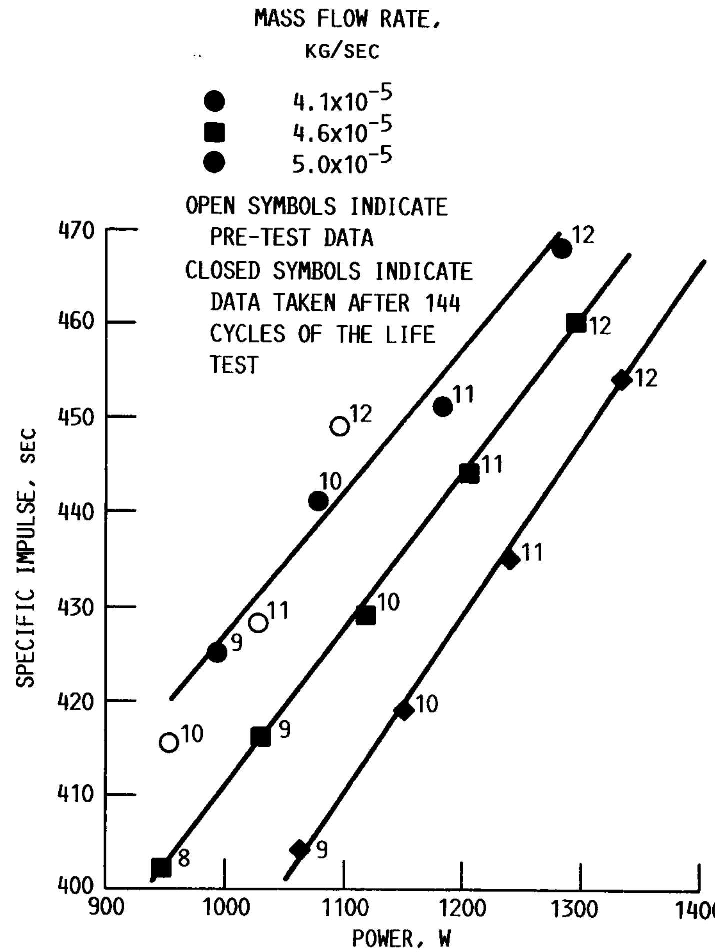

FIGURE 11. - SPECIFIC IMPULSE VERSUS POWER AT FIXED MASS FLOW RATE. NUMBERS NEAR DATA POINTS INDICATE THE CURRENT LEVEL AT WHICH THE DATA WAS TAKEN.

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15. Supplementary Notes

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16. Abstract

A cyclic lifetest of a low power dc arcjet thruster using a hydrogen/nitrogen propellant mixture simulating hydrazine is currently in progress. Over 300 hr of operation have been accumulated to date in 2 hr duty cycles at a power level of about 1.15 kW, approximating that available on commercial communications satellites. A burn-in period was carried out before consistent operation was attained. After this period, the arcjet operated in a very stable fashion from cycle to cycle. At the beginning of each cycle, there was a brief starting transient followed by a rapid rise to a steady-state voltage. The steady state voltage increased by about 5 V over the first 95 cycles. After this, it increased by only 1 V through the remainder of the test. Thrust measurements taken before the life test and again after the completion of the 144th cycle showed that both thrust, specific impulse, and arc voltage had increased over this period of operation. No life limiting mechanisms were observed during the course of the testing.

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