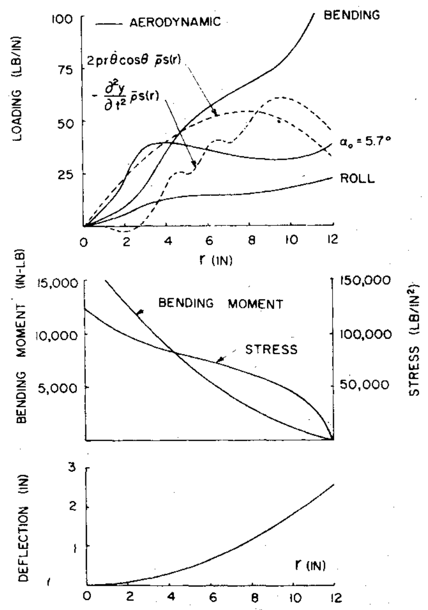

Fig. 4 Spanwise variation of blade loading, bending moment, stress and deflection.

natural frequency. Vibrations at a frequency higher than the fundamental are also indicated in Fig. 3.

Figure 4 shows the spanwise variation of blade loading, bending moment, stress and deflection at maximum loading. Thus, while the Coriolis force initiates the elastic deformation, the excessive flexural divergence is due mainly to the large aerodynamic force associated with tip flexure. With forward opening tail fins, on the other hand, the aerodynamic loads due to bending act to minimize blade flexure and under these conditions substantially reduced stress levels occur.

Finally, it should be pointed out that the results shown in Fig. 4 adequately account for the structural failures mentioned previously (yield-stress of the test blades $\approx$ 70,000 lb/in.^{2}).

Conclusions

High aspect ratio rearward opening tail fins deployed under the influence of projectile spin may experience excessive bending stresses at the root. The problem is one of large transverse blade flexure initiated by Coriolis inertia forces. The high stress levels encountered, however, are due mainly to the associated buildup of large aerodynamic forces which develop as the blade tip sections bend in the supersonic airstream.

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Durability Tests of a 5-cm-diam Ion Thruster System

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Introduction

An ion thruster technology program for small mercury bombardment ion thrusters has been in progress at the Lewis Research Center for several years.[1,2] Within this program, a 5-cm-diam thrust-vectorable structurally integrated ion thruster system was designed and developed by the Hughes Research Labs.[3,4] To determine the ultimate life of the system and to pinpoint potential problem areas not discernible in short-term tests, durability tests have been run at the Lewis Research Center. This Note presents some long-term performance results of the Hughes SIT-5 thruster system modified for specific tests at Lewis. Thruster operation exceeding 8000 hr is described with an abridged history of the durability test. The results of the initial 2023 hr of testing performed with a translating screen vector grid are also included. An independent test conducted concurrently on the propellant feed system is described.

Apparatus and Procedure

The SIT-5 (structurally integrated thruster, 5 cm diam) system has a single gas pressurized propellant reservoir which feeds mercury to the porous tungsten vaporizers of the main cathode and the neutralizer. A propellant isolator allows the feed system to operate at neutralizer potential. For the test at Lewis, the propellant reservoir was removed, and the vaporizers were connected to capillary flow tubes. The neutralizer was mounted on an isolated support and oriented to point downstream parallel to the thruster axis. The vertical vacuum test facility was 1.37 m in diameter, 1.83 m tall, and contained a frozen mercury target and a cryowall cooled with liquid nitrogen. The accelerator grid of the thruster was approximately 75 cm above the frozen mercury target when installed. A set of nonmetallic (Fiberfax, 50% Al_2O_3, 50% SiO_2) baffles were installed so that no metallic surface other than the mercury target intercepted the line of sight of the thruster ion beam. Details of the electrical system, automatic digital data acquisition system, protective control system, and test procedures are described in Ref. 5. The thruster was operated open-looped at nominally fixed conditions with minor day-to-day adjustments.

The propellant reservoir, separated from the SIT-5 system, and an identical CIV (cathode-isolator-vaporizer) assembly were durability tested in a vacuum bell jar.[6] A simulated thruster shell without magnets was mounted on the CIV assembly and the discharge current was drawn to a simulated anode connected to the cathode via a discharge power supply. All parameters were maintained at values typical of thruster operation, and the positive high voltage was applied to the simulated anode to provide a realistic test of the isolator.

Results and Discussion

Performance profile

A performance profile of the thruster with electrostatic vector grid after 8022 and 4250 hr of operation is shown in Table 1. The third column shows values obtained with the translating screen vector grid at 2023 hr, the end of its test segment. The performance profile remained relatively constant while each grid type was being tested. Performance differences between grid types were due to differences in grid design. All tests were run at 25 ma beam current, but beam power was higher with the electrostatic vector grid because of the higher net accelerating potential required for proper ion optics. Discharge power was also higher because of lower screen electrode transparency, 28.8% compared with 45.6% in the translating screen grid. Component power requirements were essentially constant throughout the test except for a slight increase in the neutralizer keeper power. Propellant utilization efficiency varied slightly because of variations in propellant flow rate.

Table 1 Performance profile

Test hours Vector grid type	8022 Electro-static	4250 Electro-static	2023 Trans-lating
Optics transparency, %	28.8	28.8	45.6
Net accelerating potential, v	1300	1300	1000
Beam power, w	32.5	32.5	25
Discharge power, w	15.1	13.8	9.4
Component power			
Accelerator drain, w	0.2	0.2	0.14
Cathode, w	9.0	9.9	9.7
Neutralizer, w	12.8	12.5	11.6
Total input power, w	69.6	68.9	55.84
Power efficiency, %	46.6	47.2	44.9
Utilization efficiency, %	70.5	69.0	69.6
Over-all efficiency, %	32.8	32.6	31.3
Thrust, mlb	0.41	0.41	0.36
Specific impulse, sec	2540	2480	2200
P/T ratio, w/mlb	170	168	155

History of test

The thruster durability test was run at essentially fixed operating conditions. Adjustment to the nominal value of 32–34 ma equivalent flow rate maintained the discharge voltage between 37 and 40 v. The cathode keeper current was current-controlled at 0.30 amp for most of the test. Isolator leakage current, monitored only during the first 2023 hr of the test was always less than 0.1 μa. Sufficient isolator data was not available to risk operation with the electrostatic vector grid at 1300 v, so the vaporizer end of the CIV was floated during this portion of testing. The neutralizer flow rate was held between 2 to 2.3 ma equivalent throughout. Neutralizer keeper current ranging from 0.3 amp to 0.45 amp was tried during the early portion of the test. From the 1000-hr point on, the neutralizer keeper discharge was current-controlled at 0.45 amp.

An abridged history of the test is shown in Fig. 1. Details of the first 2023 hr of test with the translating screen grid are reported in Ref. 5 and the balance of the test in Ref. 6. In addition to the four parameters charted, various beam outage events are marked. Three neutralizer outages in the early hours of the test were attributed to high current surges from the output filter capacitors of the high-voltage power supplies during grid arcs. Addition of series inductive ballasts alleviated this condition. Later neutralizer outages were due to a vector grid arc at 2650 hr and a low-temperature excursion of the neutralizer vaporizer at 4125 hr. Four complete shutdowns of the thruster occurred because of vacuum facility malfunction and high tank pressure above 5×10^{-5} torr. Three beam outages were caused by one or more transistors failing in the current control section of the discharge power supply.

Temporary grid shorts between the screen and accelerator electrodes caused thruster shutdowns because of the protective circuit which guards against high accelerator drain current. Shorts between vector grid elements precluded beam deflection but did not impair thruster operation. In all cases, the shorts were cleared to permit continuation of the test. During normal thruster operation, the accelerator drain current was less than $\frac{1}{2}$% of the beam current as shown in Fig. 1a.

The cathode keeper voltage shown in Fig. 1b exhibited a rise in the early part of the test, but remained at essentially a constant value thereafter until the end of the translating grid test. Exposure to atmosphere while installing the electrostatic vector grid apparently did not degrade cathode operation. Restart after exposure presented no problem. One thousand hours after the exposure, the keeper voltage actually decreased and remained at 12 v. Except for the starting periods, the cathode was operated with no heater power. Cathode and ion chamber discharge characteristics remained essentially unchanged throughout the test.

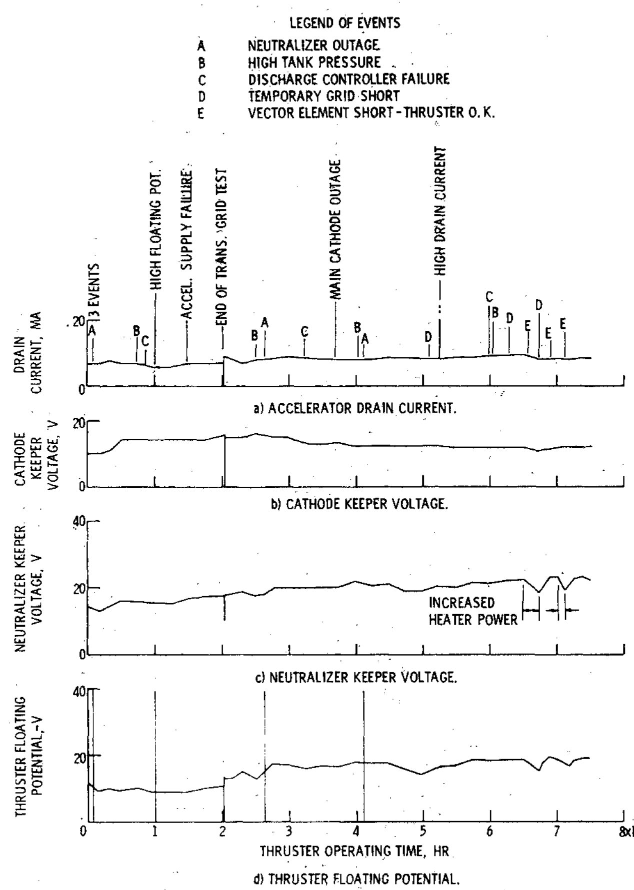

Fig. 1 Time history of durability test.

Neutralizer keeper current. The effects of varying neutralizer keeper current is shown in Fig. 2. In all cases the

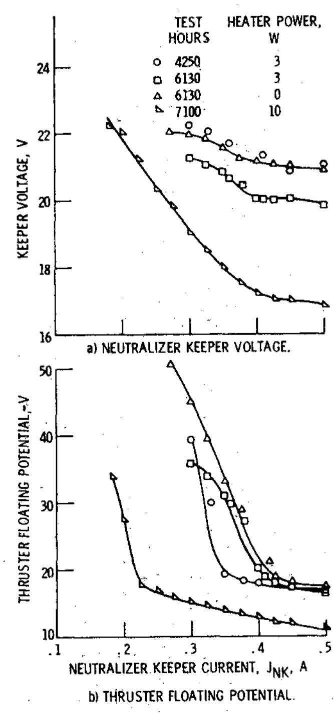

Fig. 2 Effects of varying neutralizer keeper current. Beam current, 25 ma.

thruster floating potential rose steeply as keeper current was reduced. A keeper current of 0.45 amp was sufficient for most conditions in the test. With minor differences, the keeper voltage and thruster floating potential exhibited similar trends at 4250 and 6130 test hours. Reducing tip heater power tended to raise the keeper voltage and floating potential. It is believed that some minimum cathode temperature is necessary to preserve the low work function surface which enhances electron emission. A set of data points was taken at 7100 hr with the tip heater power increased to 10 w. As shown in the history (Fig. 1c and d), both the keeper voltage and the thruster floating potential decreased together. The long-term rise in neutralizer keeper voltage was accompanied by a similar rise in floating potential. Addition of up to 10 w of heater power lowered the keeper voltage and floating potential as shown at 6500 and again at 7000 hr of operation.

Thrust vectoring subsystem. Two types of thrust vectoring grids were used in the durability test. The translating grid has been reported extensively.[4,7] In the present test, after 2023 hr, grid erosion was minimal, giving an extrapolated life of over 20,000 hr.[8]

After starting the electrostatic vector test at 2023 thruster hours, the thruster was not exposed to atmosphere. The grid was operated in the beam deflection mode for a total of 1900 hr in four directions. About 120 hr were at a maximum deflection of 5° based on a deflection voltage of 250 v. The remaining hours were at deflection angles of 2°–4°. These hours approximate the total vectoring requirements of a proposed 5-yr satellite stationkeeping thruster.

Grid shorting noted in the time history occurred between grid elements as well as between the screen and accelerator electrodes. Most shorts were cleared by sustained application of 200–400 v at currents ranging from 6 ma to 70 ma. An alternate clearing method in which a capacitor was discharged across the grid short was highly successful. These shorts are believed to be caused by accumulation of sputtered metal which build up in the intersections, then peel off. Interelectrode shorts between the screen and accelerator may also be caused by buildup of sputtered metal or sputtered metal flakes shed from ion chamber surfaces.

Propellant feed system test

The purpose of the propellant reservoir and CIV assembly test was to evaluate the following factors: 1) long term retention capability of the propellant reservoir pressurizing gas; 2) vaporizer flow control over a long operating period; 3) propellant feed isolator durability under simulated thruster operation; and 4) cathode durability. By the nature of the test, all four factors were evaluated concurrently over the test duration of 5400 hr. The vaporizer was operated at a constant temperature of $340 \pm 2°C$, and 1300 v was impressed across the isolator.

The volume change of the gas, and hence the displacement of mercury propellant was linear with time. Thus the flow rate was constant over the test period and the gas reservoir did not leak. The flow rate of 30.4 ma calculated from the pressure data agreed favorably with those obtained by other means including mass measurements. In the thruster durability test, the same operating temperature on a vaporizer of identical design yielded a propellant flow of 33–34 ma.

The isolator was tested at 1300 v with the cathode operating at conditions representative of thruster operation. The leakage current throughout the test remained at less than 0.1 μa. Electrical breakdowns occurred across the isolator when the voltage was raised to 1350 v.

The evaluation of cathode durability in this test was not a rigorous in-thruster evaluation because of the differences in the configuration and the discharge plasma. Visual inspection after 5400 hr showed no discernible erosion of either the cathode tip or the keeper aperture. All components of the CIV assembly were in functional order, but the test was terminated to make way for a second generation CIV assembly designed to operate at 1600 v.

Conclusions

Durability tests of a structurally integrated 5-cm-diam ion thruster system have been conducted at the Lewis Research Center. The Hughes SIT-5 thruster modified for specific tests has operated over 8000 hr. A history of the test and performance mapping at widely separated intervals showed that the cathode, ion chamber discharge, and accelerator drain current characteristics remained essentially constant throughout the test. Restarts were reliable and easy even after 7900 hr of operation. The neutralizer keeper voltage and the thruster floating potential showed a slight rise with time. A translating screen thrust vector grid showed minimal erosion after 2023 hr. In situ examination of the electrostatic thrust vector grid showed some erosion due to charge exchange and possibly direct impingement ions. Grid shorting was a recurrent problem, but all shorts were cleared to permit continuation of the test. An independent test of the SIT-5 propellant feed system conducted for 5400 hr has demonstrated its reliability. The test was terminated to make way for a second generation cathode-isolator-vaporizer assembly designed to operate with 1600 v across the isolator.

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Forced Motion of Lumped Mass Systems Including the Effect of Axial Force

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Nomenclature

p	= scalar parameter
$(p_{cr})_j$	= critical buckling loads $j = 1, \ldots, N$
$(p_{cr})_{min}$	= minimum critical buckling load

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