N73-20828
NASA TM X-68202

NASA TECHNICAL MEMORANDUM

NASA TM X-68202

REVIEW OF KAUFMAN THRUSTER DEVELOPMENT AT THE LEWIS RESEARCH CENTER - 1973

by W. R. Kerslake
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER proposed for presentation at
Electric Propulsion Conference sponsored by the
Institution of Electrical Engineers
Culham, England, April 10-12, 1973

ABSTRACT

Major effort is divided between two thruster sizes. One, a small 5-cm or 8-cm size is for spacecraft station keeping. The other, 30-cm (130 mN thrust), is for a thruster array to do primary solar electric propulsion. A 5-cm thruster (1.8 mN) has recently completed 9715 hr of life testing. Use of dished grids in the 30-cm thruster has increased beam current from 2 to 5 A. The total thrust system mass is compared for present small thrusters at different operating conditions for station keeping of synchronous satellites.

REVIEW OF KAUFMAN THRUSTER DEVELOPMENT AT THE LEWIS RESEARCH CENTER - 1973

W. R. Kerslake

INTRODUCTION

Previous papers written on Kaufman thruster development at the Lewis Research Center (LeRC) have summarized work prior to 1971.[1,2] This paper deals primarily with work completed in the subsequent two years. Thrusters tested have ranged in size from 2.5-cm to 150-cm diam; thrust, 0.4 to 4300 mN; and power, 0.03 to 203 kW. A 2.5-cm thruster was briefly tested and found to have surprisingly high thruster efficiency, but as no distinct present application exists, further work is not planned.[3] The 150-cm thruster has not been tested for the last 4 years because of the unavailability of near term spacecraft having megawatt-level power sources. A 15-cm thruster was operated on various gases for possible ground-base application.[4] Presently, the major research and development efforts are directed into two areas of thruster size. One is a small size, 5- or 8-cm diam, to be used for station keeping and attitude control of synchronous spacecraft.[5-12] The other is a 30-cm diam thruster to be used for primary propulsion in a 3- to 7-thruster array for solar electric propulsion of interplanetary or orbit raised spacecraft.[13-16] Emphasis is placed on thruster system reliability and lifetime as previous work has increased thruster efficiency to a high level.[13,16] Work also proceeds on definition of thruster-spacecraft interactions.[17-19]

5-CM THRUSTER

A 5-cm diam thruster has been developed over the past several years for station keeping of synchronous satellites.[5-12] This effort, conducted both at LeRC and by contract with the Hughes Research Laboratory, resulted in the efficient, lightweight, reliable thruster system shown in Fig. 1. LeRC has emphasized thruster component and thruster system reliability through extensive life testing. A 5-cm thruster life test was terminated in December 1972 after accumulating 9715 hr of total operation with a structurally integrated thruster (SIT-5). Two different accelerator grid systems were evaluated in this test. One, a thermomechanical misalinement vector grid was tested for the first 2027 hr, and the other, a two-axis electrostatic deflection grid was then tested for 7688 hr.[20] The thermomechanical grid was tested for an additional 3000 hr on another but similar thruster to raise its total test time to 5000 hr.[21] At 5000 hr the test was stopped by plan. Post-test grid erosion measurements indicated a minimum projected grid lifetime of 20 000 hr. The electrostatic deflection grid test was stopped at 7688 hr (9715 hr total on thruster) when a grid element eroded through. This anomalous erosion was caused by a loose flake of metal which fell on a screen grid hole, causing its beamlet to be distorted and eventually erode through the failed grid element. Other elements of the grid were sufficiently worn (not caused by flakes) that the design life of this grid is probably close to the actual test time of 7688 hr. By redesign of

Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135.

the worn elements, however, the grid life could be 10 000 to 15 000 hr. The balance of the thruster components were operating correctly at 9715 hr when the grid element failed. The main cathode showed little wear and the propellant isolator resistivity showed no change. The neutralizer cathode tip face was eroded, however, to a beveled shape, which precluded lifetime projection significantly beyond 10 000 hr.[20] There was slight-to-moderate erosion of the discharge baffle assembly accounting for the flake formation described above. There was no appreciable grid erosion due to neutralizer ions. Such erosion was apparent on SERT II thruster configurations. Other thruster components have been separately endurance tested in bell jars. A propellant feed system, propellant flow isolator, and main cathode was operated for 5400 hr with successful feed system operation and no electrical leakage in the isolator. The test was stopped to replace the components with prototype hardware. The subsequent test has been run for 4200 hr and is continuing at this writing. In four other bell jar tests 5-cm thruster cathodes have been tested for 3700 to 8700 hr and up to 580 cycles.

Analysis of the rate of baffle assembly mass wear for the 9715-hr test and sputtering yields predict an ion arrival flux of either 70 mA/cm^2 of Hg^+ or 5$\mu A/cm^2$ of Hg^{++}. As the local plasma density can only deliver several mA/cm^2 (Boehm criteria for stable sheath) and the self-heating from 70 mA/cm^2 would be higher than the observed surface heating, it is theorized that the major part of discharge chamber (and perhaps hollow cathode) erosion is caused by a relatively small flux of impinging Hg^{++} ions. If such a theory is correct, the effective control of chamber sputtering must be through a reduction of Hg^{++} density rather than a lowering of impinging ion energy (discharge voltage). The rate of change of sputtering yield is much less near the Hg^{++} energy of 80 V, than at the near threshold energy of 40 V for a Hg^+ ion.

8-CM THRUSTER

The 8-cm thruster reduces the duty-cycle requirement on small spacecraft applications, as well as produces enough thrust to station keep large spacecraft without resorting to multiple thrusters. Its use offers significant advantages of (1) higher propellant utilization through use of a larger discharge chamber,[22] (2) increased reliability due to a shorter duty cycle, and (3) a shorter preflight verification program because of lower required thruster lifetime. Initial operation of the 8-cm thruster is proposed at 72 mA beam current and 2800 sec specific impulse using dished, misalinement vector grids.[6,15] As dished grids are capable of running at beam current density of 3.5 mA/cm^2, future 8-cm thrusters may be capable of operation at 140 to 150 mA beam current. Early component tests using 5-cm thruster hardware run at 8-cm thruster conditions corresponding to 72 mA beam current indicate equal or improved performance at the 8-cm thruster conditions. Since 5-cm thruster component (cathodes, isolator, vaporizer, grid design) technology will be used in the 8-cm thruster, the reliability and confidence gained through 5-cm component endurance tests will apply to the 8-cm thruster design.

15-CM THRUSTER

No testing is presently being performed with 15-cm thrusters at LeRC. The SERT II spacecraft (with two, 15-cm thrusters on board) has been inactive since February 1972. Repeated attempts with both thrusters on the spacecraft to clear the high voltage short between grids were unsuccessful.[23] During each attempt, however, the thruster cathodes restarted readily. The total number of cathode (both main and neutralizer) restarts in space since launch has been 23 for thruster 1 and 67 for thruster 2. Because future missions may possibly require a thruster size between the 8-cm and 30-cm thrusters, which presently receive major emphasis, a research grant was awarded to Colorado State University to further study the 15-cm thruster.[24] One suggested application would be N-S station keeping using shared power from an on-board battery.[25] If high power levels (800 to 1000 W) were available, a 15-cm thruster could be operated for approximately 1 to 2 hr per day and N-S station keep a 1500 kg synchronous satellite. Efficient (high depth of discharge) batteries capable of many recycles (2000 in 5 yr) would be required.

5-, 8-, 15-CM THRUSTER COMPARISON

To compare the relative advantages of thrusters and define ranges of required thruster operation, the following analysis has been done. A single size satellite (1364 kg/3000 lb) was picked and three sizes of thrusters were used to perform N-S station keeping for 5 yr. The total system mass and required thruster lifetime were calculated for each size thruster and plotted as a function of specific impulse (I_{sp}) on Fig. 2. The total system mass includes thrusters, individual propellant and tank for each thruster, a power processor unit (PPU) for each thruster and the chargeable solar cell mass. Two extremes of chargeable solar cell mass were assumed. One, no power sharing, includes the full mass of solar cell required to run each thruster. No switching or sharing of solar cells is assumed. The other extreme was ideal solar cell power sharing in which the mass of solar cell was multiplied by the fraction of thrust on time. In this extreme when the thruster is off, some other spacecraft function will be using the solar cells. Other assumptions made in computing Fig. 2 were: (1) A N-S station-keeping velocity requirement of 46 M/S per year at zero duty cycle and increasing to 72 M/S per year at unity duty cycle.[26] (2) Thrusters placed to fire directly north or south (on tips of solar arrays, for example) and no loss of thrust due beam divergence of Hg^{++} ions. (3) No redundant thrusters used. (4) A PPU electric efficiency and specific mass as shown in Fig. 3. (5) A solar cell specific mass of 23 kg/kW. (6) Dished grids for 8-cm and 15-cm thrusters operated at 2.8 mA/cm^2 beam current density above 2700 sec I_{sp}.[15] Below 2700 sec the beam current drops due to a grid perveance limit at an assumed constant grid spacing. (7) Electrostatic deflection grid for the 5-cm thruster, operated at grid perveance limit with fixed grid spacing lower than 3000 sec I_{sp} and with increased spacing higher than 3000 sec I_{sp} (constant field, 3×10^6 v/m). (8) Respective values for 5-, 8-, and 15-cm thrusters of: chamber propellant utilization, 0.75, 0.86, and 0.90; neutralizer flow, 3, 6, and 15 mA; EV/ion loss (including beam coupling loss), 400, 300, and 235; fixed power loss, 30, 13, and 30 W; thruster shell, gimbels and mounts, 2.2, 2.3, and 4.0 kg; propellant tank and structure, 0.19 fraction of propellant mass for every thruster size.

Figure 2 indicates that for a 1364 kg satellite, six 5-cm thrusters, two 8-cm thrusters or one 15-cm thruster would be required. Total system mass varies from 24 to 85 kg with large mass savings possible if ideal power sharing is possible. The required thruster life varies from 22 000 hr (unity duty cycle limit, 12 hr north or 12 hr south thrusting at 3.1 mN) down to 1300 hr. The 5-cm thrusters are unsuitable for this spacecraft because more thruster units are required, and their total system mass is significantly higher with higher individual thruster life also required. The choice between 8-cm and 15-cm thrusters, however, is close with only 5 kg system mass difference. The major drawback to the lighter mass 15-cm thruster system is the need for high power (~800 W) from the solar panel or an on-board battery.[25] If power sharing or an on-board battery is available (solid curves of fig. 3), the optimum I_{sp} is very broad and shifted to high (4000 to 6000 sec) I_{sp}. The propellant flow isolator has been developed only to 3000 sec I_{sp} and would need further research to achieve isolation at high I_{sp} voltages. With no power sharing, the two 8-cm thruster system has optimum system mass of about 45 kg over a range of 2000 to 3500 sec I_{sp} and a required thruster life of 4000 to 6000 hr. Because of a significant trade-off between beam current, total system mass and required thruster life, Fig. 4 was computed. The same assumptions used in Fig. 2 were also used in Fig. 4. Figure 4 indicates a 5 to 10 kg lower total system mass is possible at beam currents of 50 or 72 mA instead of 142 mA for the no power sharing curves. Also the optimum I_{sp} is spread over a wider range for the lower beam currents. The required thruster life, however, is higher for 72 mA and 50 mA beam current, respectively, than for the 142 mA beam current. With ideal power sharing, there is only 5 to 9 kg saving in the 3000 sec I_{sp} region.

30-CM THRUSTER

The 30-cm thruster is planned to support multikilowatt solar electric propulsion (SEP) future spacecraft. This size thruster has been research tested since 1969 at both LeRC and Hughes Research Laboratory and is presently in an advanced state of devlopment.[13-16] Contractual effort is on-going to make an engineering model thruster, lightweight, vibration and thermal-vacuum qualified. A major advance has occurred in grid technology through the use of dished grids.[15] With dished grids beam currents of 4 to 5 A have been obtained at 3300 sec I_{sp}. Two other approaches to grid design using multiple points of support across the grid were unsuitable because of excessive charge exchange ion sputtering wear on the downstream portion of the support structure.[27] The other design, flat grids with radial tension, achieved 2 A beam current at 3000 sec I_{sp}. The radial tension in the grid needed to overcome thermal buckling, however, was near the material limit of the molybdenum grid. Another major advance has been made in the position of the neutralizer cathode which eliminates any significant impingement of neutralizer ions on the accelerator grid.[13,14] Improvements continue to be made in the discharge chamber by refining the magnetic field and baffle design. Present discharge losses are 190 eV/ion with 2 A beam and 95 to 97 percent discharge propellant utilization (uncorrected for double ions). Short term (~1000 hr) life tests at 2 A beam current are on-going to look for endurance problems with cathodes, grids, insulators, or condensed sputtered metal. Also, bell jar tests to 4000 hr are on-going to test cathodes at both present thruster operating conditions and at high emission levels (>10 A).

REFERENCES

1. RICHLEY, E.A. and KERSLAKE, W.R.: 'Bombardment Thruster Investigations at the Lewis Research Center,' J. Spacecraft Rockets, 1969, 6, pp. 289-295.
2. KERSLAKE, W.R. and READER, P.D.: 'Kaufman Thruster Development at Lewis Research Center (LeRC),' NASA TM X-67915, 1971.
3. COHEN, A.J.: 'Experimental Investigation of a 2.5-Centimeter-Diameter Kaufman Microthruster,' NASA TM X-2708, 1973.
4. BYERS, D.C. and READER, P.D.: 'Operation of an Electron-Bombardment Ion Source Operation Using Various Gases,' NASA TN D-6620, 1971.
5. HYMAN, J., Jr.: 'Design and Development of a Small Structurally Integrated Ion Thruster System,' Hughes Research Labs., NASA CR-120821, Oct. 1971.
6. KING, H.J., COLLETT, C.R. and SCHNELKER, D.E.: 'Thrust Vectoring Systems. Part I - 5-cm Systems,' Hughes Research Labs., NASA CR-72877, 1971.
7. NAKANISHI, S., et al.: 'Status of a Five-Dentimeter-Diameter Ion Thruster Technology Program,' AIAA Paper 71-690, June 1971.
8. *BYERS, D.C. and BANKS, B.A.: 'Beam Focusing Characteristics of Various Shaped Grid Holes,' NASA TM X-67922, 1971.*
9. HUDSON, W.R., LATHEM, W.C., POWER, J.L. and BANKS, B.A.: 'Optimization of Electrostatic Dual-Grid Beam-Deflection System,' NASA TM X-68096, 1972.
10. WEIGAND, A.J.: '5-cm Diameter Ion Thruster Development Program Summary, June 1972,' NASA TM X-68110, 1972.
11. LATHEM, W.C.: 'A Single-Axis Electrostatic Beam Deflection System for a 5-cm Diameter Ion Thruster,' NASA TM X-68133, 1972.
12. NAKANISHI, S.: 'Durability Tests of a Five-Centimeter Diameter Ion Thruster System,' AIAA Paper 72-1151, Nov. 1972.
13. KING, H.J.: 'Low Voltage 30-cm Ion Thruster,' Hughes Research Labs., NASA CR-120919, Feb. 1972.
14. BECHTEL, R.T.: 'Performance of a Neutralizer for Electron-Bombardment Thruster,' AIAA Paper 72-207, Jan. 1972.
15. RAWLIN, V.K., BANKS, B.A. and BYERS, D.C.: 'Design, Fabrication, and Operation of Dished Accelerator Grids on a 30-cm Ion Thruster,' AIAA Paper 72-486, Apr. 1972.
16. BECHTEL, R.T.: 'A 30-cm Diameter Bombardment Thruster with a Variable Magnetic Baffle,' AIAA Paper 72-489, Apr. 1972.
17. MILDER, N.L. and SOVEY, J.S.: 'Star Tracking through the Exhaust Beam of Mercury Bombardment Thrusters,' J. Spacecraft Rockets, 1973, 1, pp. 47-51.
18. WEIGAND, A.J. and MIRTICH, M.J.: 'Change in Transmittance of Fused Silica as a Means of Detecting Material Sputtered from Components on a 5-cm Ion Thruster,' NASA TM X-68073, 1972.
19. REYNOLDS, T.W. and RICHLEY, E.A.: 'Contamination of Spacecraft Surfaces Downstream of a Kaufman Thruster,' NASA TN D-7038, 1971.
20. NAKANISHI, S.: 'A 9715-Hour Durability Test of a 5-cm Diameter Kaufman Thruster.' (NASA TM to be published.)
21. LATHEM, W.C.: '5000-Hour Test of a Grid-Translation Beam-Deflection System for a 5-cm Diameter Kaufman Thruster,' NASA TM X-68185, 1973.
22. KAUFMAN, H.R. and COHEN, A.J.: 'Maximum Propellant Utilization in an Electron-Bombardment Thruster,' NASA TM X-67921, 1971.
23. KERSLAKE, W.R., GOLDMAN, R.G. and NIEBERDING, W.C.: 'SERT II: Mission, Thruster Performance, and In-Flight Thrust Measurements,' J. Spacecraft Rockets, 1971, 8, pp. 213-224.
24. WILBUR, P.J.: 'Experimental Investigation of a Throttlable 15-cm Hollow Cathode Ion Thruster,' Colorado State Univ., NASA CR-121038, Dec. 1972.
25. FREE, B.A.: 'Battery Powered Electric Propulsion for N-S Station Keeping,' COMSAT Tech. Rev. (to be published 1973).
26. LOVELL, R.R. and O'MALLEY, T.A.: 'Station Keeping of High Power Communication Satellites,' NASA TM X-2136, 1970.
27. BYERS, D.C.: 'A Preliminary Investigation of Charge-Exchange Erosion of Accelerator Grid Supports,' NASA TM X-67842, 1971.

E-7369

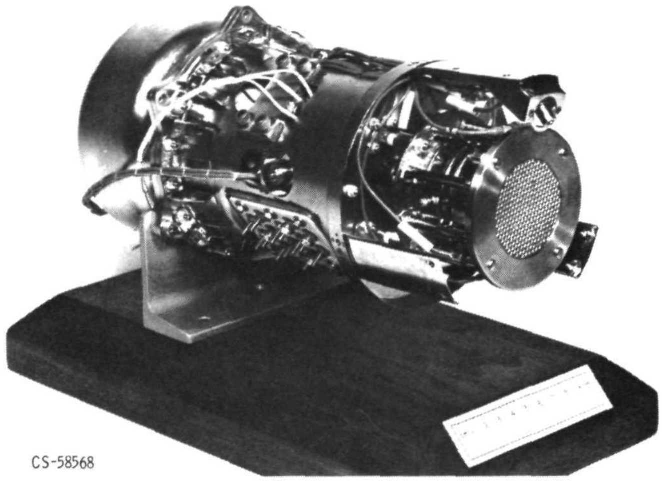

Figure 1. - 5-cm thruster system.

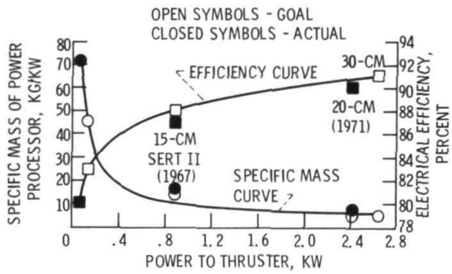

Figure 3. - Power processors for ion thrusters, 1973 estimated performance.

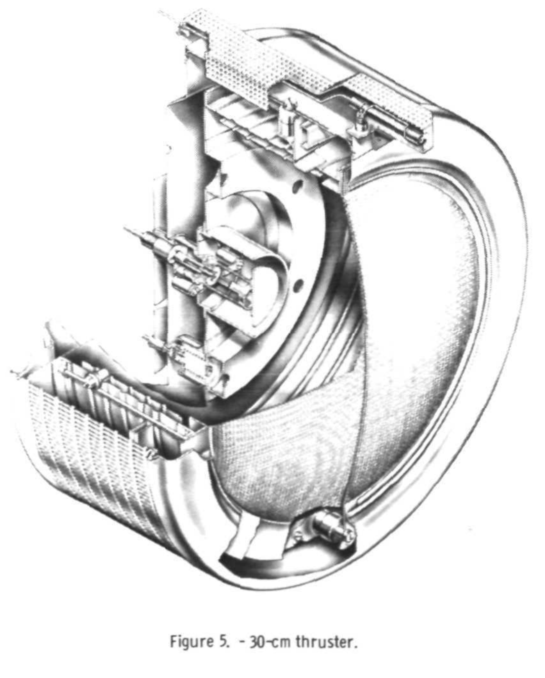

Figure 5. - 30-cm thruster.

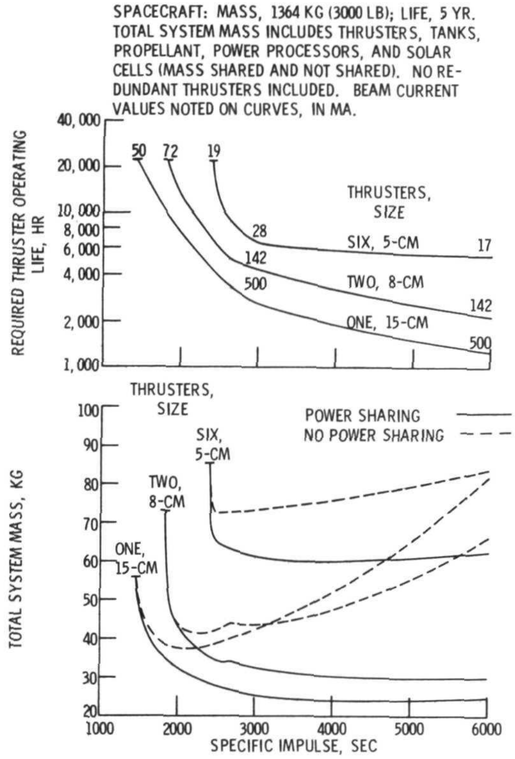

Figure 2. - N-S station keeping system requirements with various size thrusters.

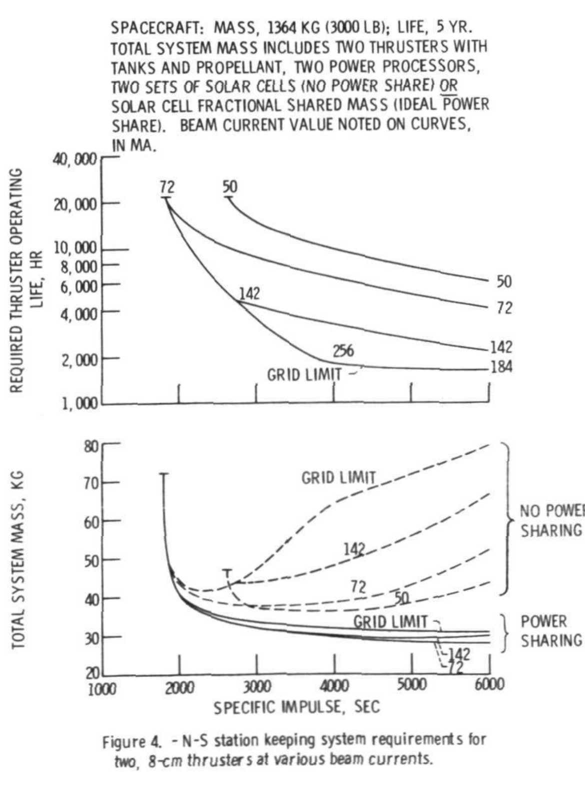

Figure 4. - N-S station keeping system requirements for two, 8-cm thrusters at various beam currents.