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BOMBARDMENT THRUSTER INVESTIGATIONS AT THE LEWIS RESEARCH CENTER - 1971

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ABSTRACT

The current status of various research programs on mercury electron-bombardment thrusters is reviewed. Future thruster requirements predicted from mission analysis are briefly discussed to establish the relationship with present programs. Thrusters ranging in size from 5 to 150 cm diameter are described. These thrusters have possible near to far term applications extending from station keeping to primary propulsion. Included is a 5 cm thruster having a power-to-thrust ratio of 138 kW/lb; the 15 cm diameter SERT II thruster; and a 30 cm thruster designed to produce a 2.0 ampere beam at 3000 sec specific impulse. Research activities on thruster components are reported in the context of the various thruster programs. These include glass-coated, single accelerator grids that have accumulated 1000 hr operating time; high-current hollow cathodes of over 10 amperes emission; and, beam deflecting grid systems.

INTRODUCTION

It is generally recognized among members of the electric propulsion community that, with a few exceptions, initial applications of electric propulsion probably will be with systems powered from photovoltaic cells. Specific masses of present day solar cell systems dictate that electrostatic thrusters will be required to operate at specific impulses generally below 4,000 sec in order to minimize overall propulsion system specific mass, estimated to range from 30 to 50 kG/kW. Several prospective solar electric missions assume the use of mercury-electron bombardment thrusters (Refs. 1-4). The references in this area are not complete but are only intended to be representative of trends in mission studies reported in the past year or so. The studies detail the requirements for thruster operation at less than 4,000 sec. Because of inherent ion production losses and some unavoidable fixed losses, the efficiency of a bombardment thruster decreases with specific impulse. Continued research is being conducted to ensure optimum performance at the required specific impulse.

The present mercury electron-bombardment thruster research investigations described herein arose from considerations such as those mentioned above. Discussed first is the 15-cm SERT II thruster. Then the 30, 5, and 150-cm thruster programs will be described. Highlights of research activity on glass-coated accelerators, hollow cathodes, and other thruster components are described in the context of these programs. Finally, performance projections of each of the thrusters are summarized.

SERT II FLIGHT

The Space Electric Rocket Test II was launched in February 1970 for the purpose of demonstrating long-life space operation of either one of two 15-cm diameter ion thrusters. A cut-away flight model is shown in Fig. 1. The results of the space testing (Ref. 5) and correlary ground tests indicated excellent agreement of thruster performance in space compared to the same thruster pretested before launch. One flight thruster operated for 5 months while the other for 3 months. The nominal operation of the solar-cell powered thruster was: 0.25 amp. beam current; 4150 seconds specific impulse; total power input, 0.85 kw; overall thruster efficiency, 0.68; thrust, 28 mN (6.3 mlb).

Each flight thruster operated in space with less degradation than corresponding ground tests until a sudden permanent electrical shorting occurred between high positive and negative voltages. All cathodes and feed systems continued to relight and function normally.

After study of post flight failure data, ground endurance test observations, and a number of possible causes, it was concluded that both flight thrusters failed (shorted) for the same reason. Localized wear of the accelerator grid, due to neutralizer ions, caused a few small, metal grid fragments to detach. During ground tests such fragments could fall (by gravity) away from the thruster, but in space a fragment would be drawn by electrostatic force and short between the closed space thruster grids.

There are two possible solutions to the SERT II thruster problem. One is to move the neutralizer to a new location which would reduce the localized accelerator grid wear to a level at which fragments would not form. The other is to provide a high current source to "burn out" such fragments if they should form. This capability, unfortunately, was not incorporated in the SERT II power conditioner. The remaining parts of the accelerator grid are capable of useful life to 10,000 hr or more if the fragments are cleanly removed.

30 cm THRUSTER

Future multi-kilowatt electric propulsion spacecraft, such as the Solar Electric Multiple Missions Spacecraft (SEMMS), requiring on the order of 10 kw power will probably not use the SERT II size (15-cm) thruster system. Instead a larger diameter thruster, such as 30-cm, will be used to reduce the total number of thrusters required. The use of larger thrusters also improves the thruster efficiency (higher propellant utilization and lower ratio of fixed power loss to total power) and provides more beam area (needed for lower specific impulse operation) per unit thruster.

A 30-cm diameter thruster has been experimentally tested both at Lewis Research Center (Refs. 6, 7) Fig. 2 and Hughes Research Laboratory (Ref. 8) Fig. 3 for the past several years. These programs defined critical design problems with increasing thruster size, optimized the discharge chamber geometry and magnetic field shape, and experimentally documented higher propellant utilization efficiencies. A schematic cross section of a 30-cm thruster is shown in Fig. 4. The following paragraphs discuss the present critical design areas and current research programs.

Accelerator Grid System

The design beam current, 2.0a., is eight times that of SERT II, while the accelerator area is only increased four times. The accelerator grid is the present limiting thruster component for maximum beam current and low specific impulse. Two basic grid designs are being tested. One is a conventional, two-grid, system (Fig. 3). The other is a single, glass-coated grid (Fig. 2). The two-grid system, when first tested (Ref. 6), resulted in low performance (low beam current and high discharge losses) and was temporary de-emphasized in favor of the better performing glass-coated grid. The glass-coated grid, however, has shown a dependence on vacuum tank wall sputtering to maintain a high beam current and a lack of proven durability with problems in consistently reaching 1000-hr grid life (Ref. 9). Therefore, the two-grid system has been re-emphasized for immediate applications.

More beam current and lower specific impulse may be obtained by a two-grid system by decreasing the grid spacing and using smaller holes. The limit to decreasing grid spacing is thermal buckling of the grid system and electrostatic attraction of the two grids. The use of small holes will eventually result in web-thickness-between-holes being too thin compared to tolerances of fabrication. Present programs at Lewis Research Center are looking at ways to mechanically design and support the grids to minimize the effects of thermal buckling. Center supports appear to be necessary, if for no other reason, to limit electrostatic movement of the grids. An alternate approach to center supports is the use of support rods between the screen grid and thruster back plate for a 20-cm diameter thruster (Ref. 10). Other methods besides closer-spaced grids are also being pursued to increase the maximum beam current. These are: (1) reduce the radial variation in the discharge-chamber plasma density to more effectively use the outer diameter areas of the grid system; (2) increase the percent open area of the screen grid; and (3) use thinner screen grids. The results of these research areas will be incorporated into flight prototype thrusters when they become proven.

The present state-of-the-art grid fabrication is represented by a 30-cm thruster tested for 450 hr (December 1970) at the Hughes Research Laboratory. Using that data at a beam current of 1.87, an extrapolation to 2.0 a with Child's Law scaling, gives a total accelerating voltage of 2080v. Use of a minimum value of 0.5 for net-to-total voltage ratio, limits the specific impulse to values greater than about 2940 seconds for the 2.0 a beam current. The 0.5 value was assumed to prevent excessive thrust loss due to beam divergence and possible direct beam erosion of the grid. Two-grid lifetime due to sputtering by charge exchange ions will be in excess of 20,000 hr. The adverse effects of thinner grid material and high beam current density are more than offset by lower grid voltages and high propellant utilization efficiencies.

Although a two-grid system is presently recommended for near-term 30-cm diameter thruster flight designs, projections for the glass-coated grid remain promising. A continuing research program is in progress at Lewis Research Center on the glass-coated grids. This program has two paths. First, new grids are being designed to extract high beam currents (2.0 a at 600 to 1000 net accelerating voltage). Second, facilities are being studied to permit valid ground testing of glass-coated grids. The approach for new grids is to use smaller holes to increase the beam extraction capability. These accelerator designs must also prevent self backsputtered coatings which drastically shorten lifetime (Ref. 9). Additional grid beam extraction capability could be obtained by improving the quality of the glass coating such that thinner layers of glass would withstand the operating voltages without breakdown. The grids also must be correctly attached to the thruster or life-limiting wear can occur at the edge termination. Various designed edge terminations seem to be capable of effective solution to this problem (Ref. 11).

As glass-coated grid lifetime and perveance can be strongly influenced by condensed sputtered metal (Ref. 9), thruster endurance tests may not be valid if made in present vacuum tanks. Several alternative approaches are possible: (1) test in space where there is no facility backsputtering; (2) test in an extremely large tank so that the backsputter flux is negligible (less than 100 monolayers for the total test time); (3) test with a facility that backsputters an insulator instead of a conductor; or (4) test with a facility that backsputters a material (mercury) that will not condense on the thruster. The first two alternatives are too costly to be practical. The third alternative is presently being evaluated by operating a 30-cm thruster into a 3-meter square insulator target of an alumina-silica material located 3 meters from the thruster. The initial results show no short term (100 hr) change in grid perveance nor excessive wear when using this target. Long term tests (greater than 1000 hr) have not yet been made. The fourth alternative should be feasible, but will only be used if the insulator target does not prove successful. If used, a frozen mercury target 3-meters diameter (or larger) is required to limit the condensible backsputter to less than 100 monolayers during a 5000-hr test. The mercury target could either be horizontal or vertical and should be at least 3 meters from the thruster. If the target is vertical, some novel means such as freeze spraying must be used to coat the target with mercury.

Main Cathode

Short term endurance tests (up to several hundreds of hours) have indicated acceptable or negligible wear rates (Refs. 7, 9). These low rates result from keeping the hollow cathode tip temperature low. Good designs include larger tip diameter and larger hollow cathode orifice diameter. The most promising design to date contains a chamfered or diverging nozzle shape in the orifice (Ref. 8).

Neutralizer

Hollow cathode neutralizers have been successfully used in 30-cm thruster tests (Refs. 7, 8), but areas still exist for improvement and are the subject of present research programs. One area is the position and angle (to the beam) of the neutralizer cathode to reduce the localized sputtering of the accelerator grid by neutralizer ions. Preliminary investigations of position and angle variables by R. T. Bechtel have indicated an order of magnitude reduction in local neutralizer ion impingement. Another improvement area is reduction of required neutralizer flow.

Present tests use 30 to 200 ma equivalent flow depending on the neutralizer design. Often, 100 ma is required for steady operation. To consistantly operate at 50 ma or less flow requires additional knowledge of present neutralizer designs. A final area of concern is the control of the neutralizer. At the level of 100 ma flow the cathode is in a "spot mode" where the SERT II-type keeper voltage control logic is no longer valid. The keeper voltage is constant over a wide range of flow when the cathode is in the "spot mode." Other possible control parameters, such as, keeper current, thruster (or probe) floating potential, or a spectroscopic technique (Ref. 12) are under investigation.

Throttling and Control

The 30-cm thruster has been throttled over a 2 to 1 range and experimentally controlled well enough to permit unattended endurance operation over weekends (Ref. 6). But the loss of thruster efficiency has been somewhat excessive (a drop from 0.60 to 0.45 with 2:1 throttle range) and the full range of possible flight control has not been verified. Present research programs are studying possible main thruster control loops and ways to improve throttled thruster efficiency. One possibility is a variable magnetic baffle, such as used in Ref. 13. Additional information regarding throttling can be found in the section Supporting Research.

Near-Term Flight Thruster Performance

If the best of the proven existing research data is taken as a starting point for a 2 year development program, and if minor thruster development improvements offset unplanned minor development losses, the following predictions of 30-cm thruster performance could be met for near-term flights. The 2-year development program is assumed to produce a prototype test model (PTM). It should be a flight qualified thruster that has been array tested and is ready to go into the final qualification program of a flight spacecraft.

Figure 5 is a performance plot of a 30-cm PTM thruster efficiency versus effective specific impulse for a 3 to 1 throttling range of beam current. The following assumptions have been used in preparing Fig. 5. (1) Current state-of-the-art grid designs limit the effective specific impulse to the solid portion of the curves. The dashed portion is beyond present technology, but perhaps feasible in the future with closer-spaced accelerator systems. Note that the range of usable effective impulse opens up at lower beam currents where lower accelerating voltages are possible. (2) The chamber propellant utilization (not including neutralizer flow) is 0.93 at maximum beam current of 2.0 a and is reduced to 0.90 and 0.81 at beam current levels of 1.33 a and 0.67 a respectively. (3) The neutralizer flow is constant at 50 ma equivalent flow. (4) A constant value of 220 ev/ion discharge loss for all beam currents is used. (5) A neutralizer coupling loss of 20 v and a 0.6 percent accelerator grid impingement is assumed. (6) The fixed power losses (heaters, keepers, etc.) are 42 w.

The suggested design point is 2.0 a beam current at an effective specific impulse of 3000 seconds. The thruster efficiency is 0.73 at this point. The best manner to throttle to lower power levels is undecided at this time, but will probably include a significant throttling in beam current level and may include some decrease in effective specific impulse. The performance of the SERT II flight thruster is compared with the 30-cm 1973 PTM Thruster and with a far term (1980) thruster in table I.

The lifetime of the PTM thruster is not grid limited. The grid spacing, however, does limit the maximum beam current and the effective specific impulse. The design PTM thruster grid lifetime is well over 10,000 hr and based on a relatively few short time cathode tests, the cathode lifetimes should be similarly long. The problems of the development program should not be those associated with lifetime, but rather those of maintaining thruster efficiency and high beam currents without grid warping or control stability problems occurring.

5-cm THRUSTER

Spacecraft with design lifetimes of several years place severe requirements on attitude control and station-keeping subsystems. The long life and high specific impulse available from low thrust, electrostatic thruster subsystems makes them increasingly competitive for these functions. Thrust levels in the submillipound range, for example, are of particular interest for spacecraft in the 1000-2000 lb class (Refs. 14, 15).

The 5-cm thruster program at Lewis is aimed at both providing an efficient, light weight and durable thruster for the above applications and serving as a test article upon which new component concepts can be demonstrated. The inhouse work is co-ordinated with a contract effort being conducted at Hughes Research Laboratory. The physical characteristics of the 5-cm thruster are given in Table II. Photographs of the Lewis 5-cm prototype thruster subsystem and of the Hughes-developed subsystem are shown in Fig. 6(a) and (b), respectively.

The total discharge chamber propellant flow is fed from the single gas pressurized tank through the cathode. The thruster potentials are separated from the grounded tank by a vapor phase electrical isolator. The neutralizer flow goes direct from the tank to the neutralizer.

Table III lists the performance characteristics of the 5-cm thruster. The best experimental data taken to date with a complete thruster subsystem has been obtained at the Hughes Research Laboratories under Contract NAS3-14129. These data are presented in the first column of Table III. Similar component efficiencies have been obtained at the Lewis Research Center in separate tests. The second column of the table is a reasonable goal for any continued effort on this thruster and was generated by combining the best experimental component performances as the total subsystem goal. The final column of the table is the projected possible performance level achievable by a 5-cm thruster after extended development. Lifetimes greater than 10,000 hr are consistent with all of these performance parameters.

An earlier (1968) summary of the electron bombardment thruster program at Lewis (Ref. 16) described the 5-cm program soon after it had been successfully operated with a hollow cathode. In 1970 the results of a performance improvement program were reported (Ref. 17). In that study it was found that cathode pole piece and baffle position and geometry significantly influenced ion chamber performance and could be used to tailor the discharge characteristics to obtain efficient operational modes (e.g. to change current-voltage characteristics). Enclosed hollow cathodes were chosen for both chamber and neutralizer emitters based on discharge stability, operational range, durability and structural design. Recent results of 5-cm thruster component tests (Ref. 18) indicate that acceptable lifetime cycling (2800 on-off cycles) can be achieved for neutralizer cathodes. Also, neutralizer positioning can be accomplished which is consistent with low coupling voltages, and long accelerator grid lifetime, and does not result in direct erosion from beam ions.

Thrust Vectoring

Thrust vectoring can reduce the number of thrusters required on a spacecraft by combining the function of station keeping and attitude control into a single thruster. Several thrust vectoring methods have been demonstrated both at Hughes Research Laboratories under Contract NAS3-14058 (Ref. 19) and at Lewis Research Center.

A thermomechanical system, in which the screen grid is moved with respect to the accelerator by heating opposite pairs of actuating springs is shown in Fig. 7. The relative movement of the screen and accelerator causes misalinement of the optics and the beam deflects toward the nearer wall of each accelerator hole. Beam deflections of ±15 degrees have been made in two orthogonal directions without significant increase in accelerator impingement. This thermomechanical system is similar in concept but different in implementation to an accelerator displacement beam deflection system developed by the U.S. Air Force at Electro Optical Systems, Inc. (Ref. 20).

A more elegant solution to the beam deflection problem is shown in Fig. 8. This figure is a photograph of a two-axis electrostatic deflecting grid. The beam from each screen hole is accelerated and focused by orthogonal sets of accelerator ribbons. Differential potentials applied across pairs of ribbons causes beam deflection in the same manner as the electrostatic scan systems on cathode ray tubes. Beam deflections of ±9 degrees have been demonstrated without significant increase in accelerator erosion. A 100-hr test with vectoring has been conducted under contract (Ref. 21). Continuing life tests at LeRC are in progress and are aimed at demonstrating the suitability of this beam deflection concept to mission applications.

150 cm THRUSTER

The 150-cm thruster is designed for power levels in excess of 100 kW, which places its potential applications in the category of primary propulsion for large space vehicles, probably using nuclear-electric power conversion systems. Present investigations of thrusters of this size are exploratory in nature, aimed primarily at seeking general information on scaling effects and identifying major component problem areas. A brief discussion of this program is included herein mainly for completeness since no additional data has been reported beyond that reported in Ref. 22.

A representative cutaway view of the 150-cm thruster is shown in Fig. 9. Propellant flows from a distributor manifold into the ion chamber via perforated radial channels located on the chamber rear wall. Ten cathodes are equally spaced on the rear wall and their radial positions may be varied. The ion chamber L/D (length to diameter ratio) is 0.15 and a conventional two-grid accelerator system is used with the exception that it is slightly dished and spacers are used to help maintain uniform grid spacing. Additional details are given in Ref. 23. Performance highlights are listed in Table IV.

SUPPORTING RESEARCH

The energy required in the discharge chamber to produce a beam ion is about 200 ev/ion in present day optimized thruster. High percentage open area grids and divergent magnetic fields are the two major factors contributing to progress in reducing discharge losses. No doubt additional gains will be made in the future, although an increasing degree of sophistication may be required. As an example, one approach recently investigated offers additional insight into present limitations in the discharge chamber.

In this program chamber performance parameters were monitored to determine possible limitations on the propellant utilization of the mercury electron bombardment thruster.

The results of this analytical and experimental study (Ref. 24) show that the loss rate of un-ionized propellant at maximum utilization is nearly a constant over a wide range of propellant flow rate. This constant loss rate strongly effects thruster performance during throttling. The equation below shows the effect of operation at part throttle for a range of maximum utilizations. Neutralizer flow must be included in a separate computation to obtain an overall utilization.

$$\eta_u = \frac{\eta_{max} \times \tau}{\eta_{max} \times \tau + (1 - \eta_{max})}$$

where

η_u = propellant utilization at any given τ (discharge chamber only)

η_{max} = maximum propellant utilization of the discharge chamber

τ = throttled fraction of full beam current

Complete propellant utilization results in no neutral loss and obviously suffers no throttling loss. A one percent neutral loss at 0.99 utilization results in a 0.91 utilization at a 1/10 throttle point. The maximum propellant utilization attainable with a particular thruster therefore can be used to determine the approximate loss penalty for throttling to any reduced flow rate. Other throttling schemes such as variable specific impulse can be used to moderate this constant neutral loss but only over limited ranges due to the net accelerating potential changes required.

In another program a 15-cm SERT II thruster was operated on various gases (Refs. 25, 26). Xenon, krypton, argon, neon, nitrogen, carbon dioxide and helium were tested. These materials are less efficient than mercury for propulsion but have possible ground based applications. Changing the propellant atomic mass while holding geometric and electrical parameters fixed allows a broad view of thruster operation. The correlation of thruster data with a wide range of atomic characteristics has resulted in greater design confidence for mercury thrusters.

PROGRAM SUMMARY

The status of the various thruster programs can be conveniently summarized and discussed within the framework of a thruster efficiency vs specific impulse plot as shown in Fig. 10. Shown for comparison are data points from the thrusters and an "ideal" curve in which all system losses (including un-ionized propellant) are assumed equal to 200 ev/beam ion. The open symbols represent data points while the solid symbols represent design goals.

The 150-cm data point falls significantly below the ideal curve. Problems specifically associated with large thrusters have been investigated and there appear to be no fundamental limits on this size thruster. Hardware initial cost and modification costs along with facility requirements have resulted in a reduced priority effort on this thruster. This decreased emphasis will probably continue until a more specific requirement for this power level thruster becomes apparent.

The increased emphasis placed on the 5-cm thruster over the past few years has resulted in an auxiliary propulsion subsystem with a highly desirable demonstrated power-to-thrust ratio of 138 w/mlb. Values under 100 w/mlb are expected with improved subsystems. The information gained in the 5-cm component and thruster subsystem optimization program with small, relatively inexpensive pieces of hardware has had a significant benefit on the efficient design and rapid optimization of larger components and thrusters. The demonstration of acceptable lifetimes for space application is in progress for the 5-cm thruster subsystem with electrostatic beam deflection capability.

Continued work with glass-coated accelerator grids for 30-cm thrusters has shown a strong dependance of the test facility on both the thruster efficiency and grid lifetime. Therefore, glass-coated grids cannot now be considered for near-term missions. Using conventional (two-grid) accelerators has resulted in 1971 thruster operation at higher specific impulses and somewhat lower thruster efficiencies than compared to 1968 data.

The 30-cm thruster maximum beam current and minimum specific impulse is today limited by physically small grid spacings and not grid lifetime. As better mechanical grid systems are designed, the minimum operating specific impulse should be lowered and the maximum beam current increased. Fixed losses, presently about 80 w per thruster should be able, through development, to be halved. Some improvement in the main discharge losses can also be realized. But the greatest improvements could be obtained by reducing propellant losses at lower beam currents to avoid throttling penalties.

Present 30-cm research thrusters using convention grids have shown good single point performance, ability to operate over a 3:1 throttling range, and good lifetime of all components. Such thrusters, developed through a 2 year program would be capable of performing a variety of near-term space missions.

In the context of the needs of many anticipated missions, mercury electron bombardment thrusters capable of fulfilling a wide variety of applications are already available. Present developments aimed at specific applications should result in increased performance for these applications perhaps without any loss of flexibility.

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TABLE I - THRUSTER COMPARISON

	15-cm SERT II flight	30-cm 1973 PTM*	30-cm 1980 thruster
Input power, kw	0.85	2.7	2.3
Net voltage, V	2900	1090	720
Beam current, A	0.25	2.0	2.5
Utilization efficiency	0.77	0.91	0.94
Thruster efficiency	0.68	0.73	0.74
Thrust, mN	28	135	135
Thrust, mlb	6.2	30	30
Effective spec. imp., sec	4152	3000	2500

*Prototype Test Model.

TABLE II - PHYSICAL CHARACTERISTICS OF 5-cm THRUSTER SUBSYSTEM

7.5-cm diameter, 30-cm long

2.1 kg empty weight

6.2 kg propellant weight

Synchronous orbit thermal design

TABLE III - 5-cm THRUSTER PERFORMANCE VALUES

	Data	Goal	Possible
Input power, W	56.4	59.5	49.5
Net voltage, V	650	1000	750.0
Beam current, mA	35	35	40
Utilization efficiency	0.73	0.78	0.80
Overall efficiency	0.29	0.46	0.48
Thrust, mN	1.8	2.2	2.2
Thrust, mlb	0.41	0.5	0.5
Effective specific impulse, sec	1840	2460	2180
Power to thrust ratio, W/mlb	138	119	99

TABLE IV - 150 cm THRUSTER PERFORMANCE VALUES

Input power, kW	177
Net voltage, V	6000
Beam current, A	25
Utilization efficiency	0.90
Overall efficiency	0.76
Thrust, N	4.0 (0.89 lb)
Effective specific impulse, sec	7000

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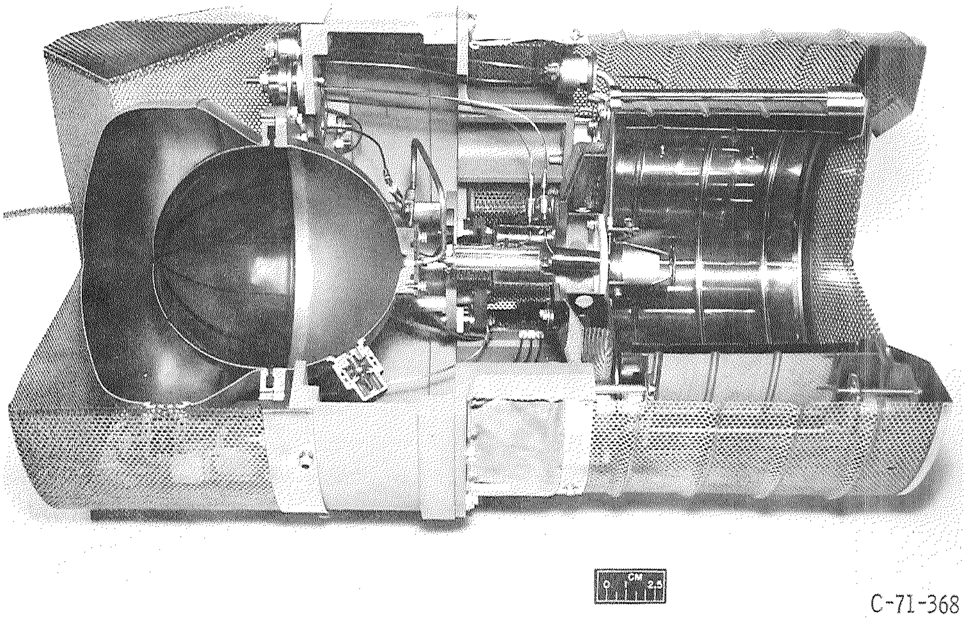

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Figure 1. - Cutaway of 15-cm SERT II flight prototype thruster.

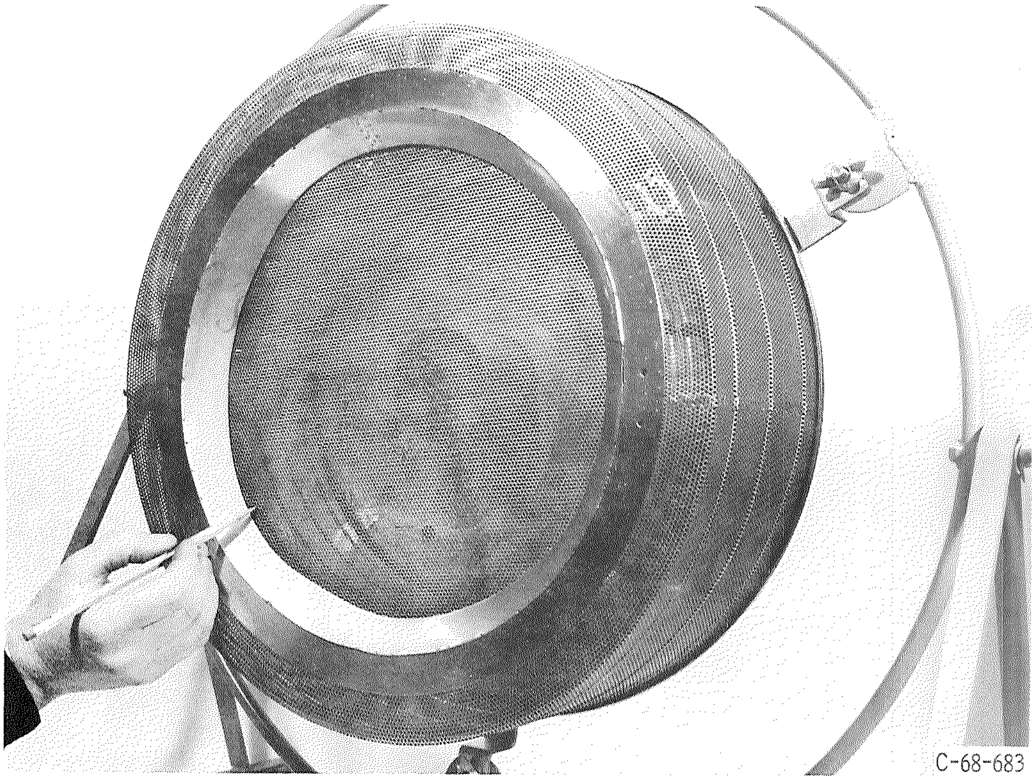

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Figure 2. - 30-cm thruster with glass-coated accelerator grid.

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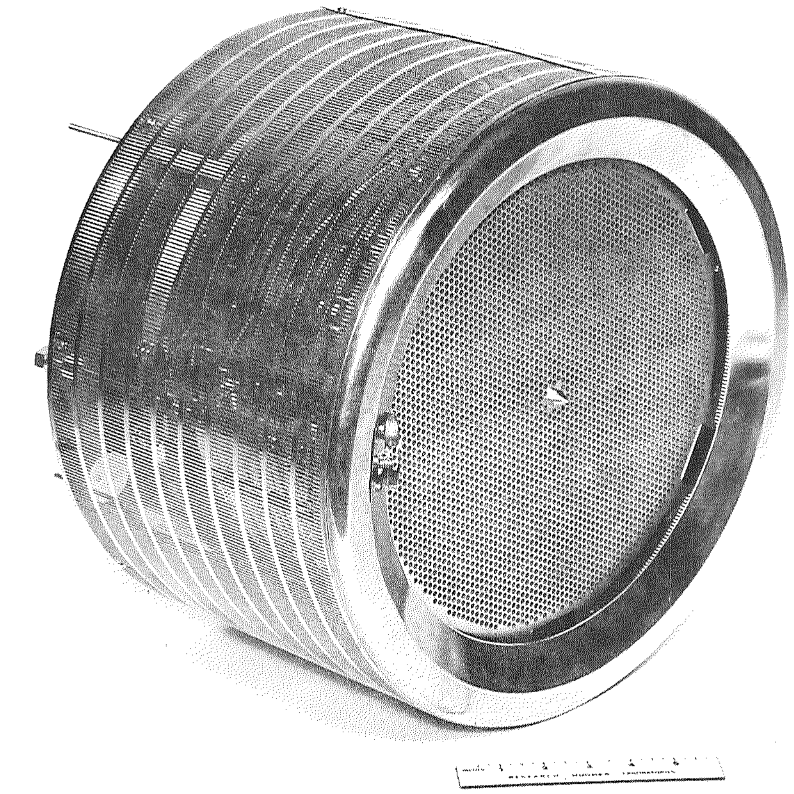

Figure 3. - 30-cm two-grid thruster (contract NAS 3-11523, Hughes Research Lab.).

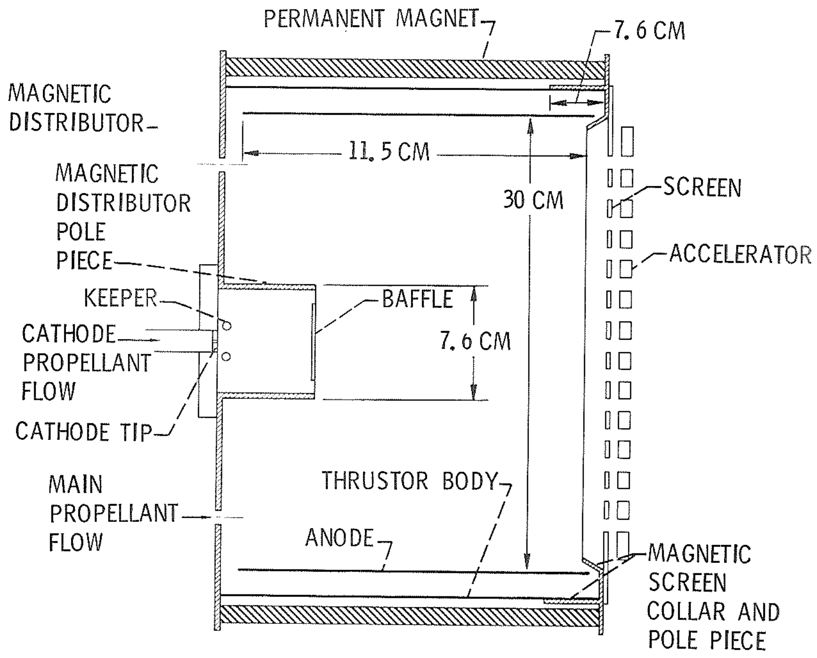

Figure 4. - Section view of a 30-cm two-grid thruster.

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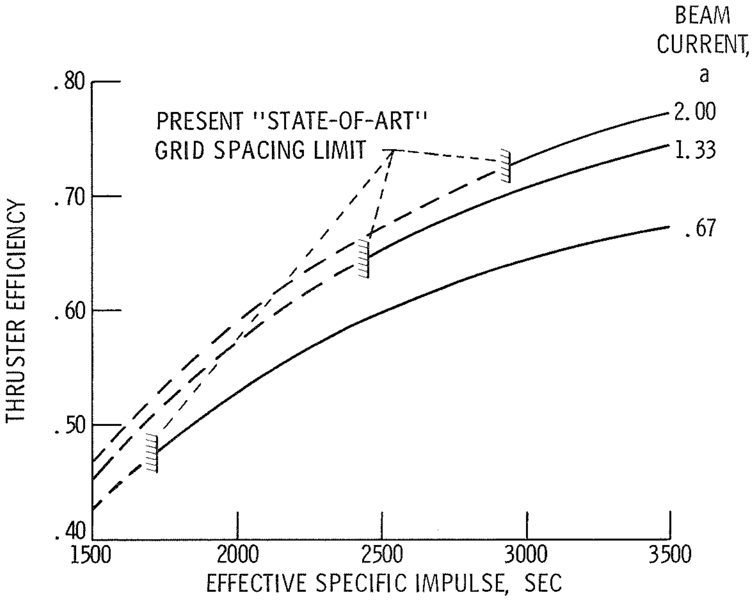
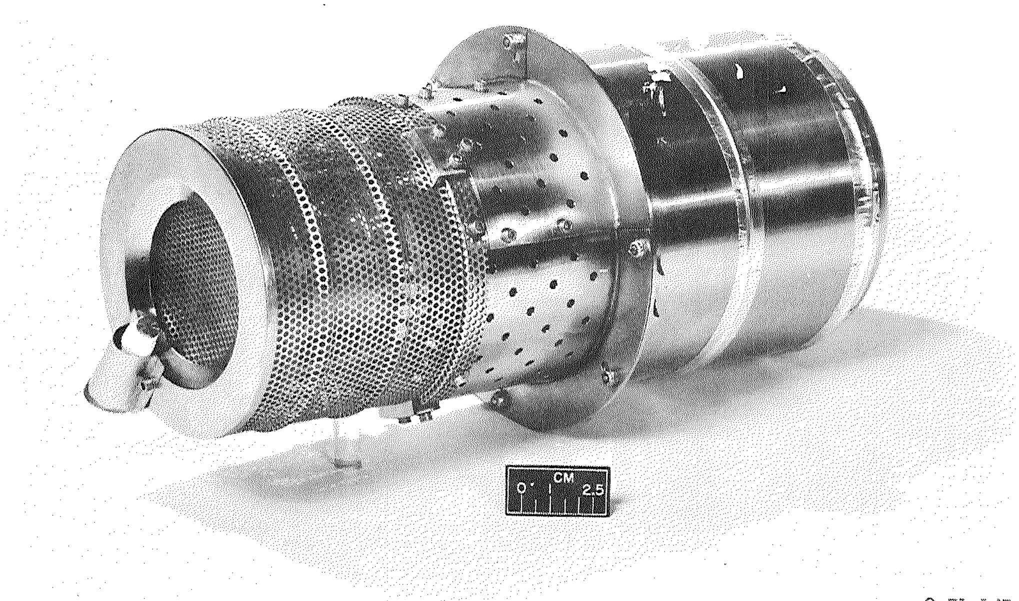


Figure 5. - 30-cm thruster efficiency (1973 PTM) versus specific impulse.



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(a) Lewis prototype.

Figure 6. - 5-cm thruster.

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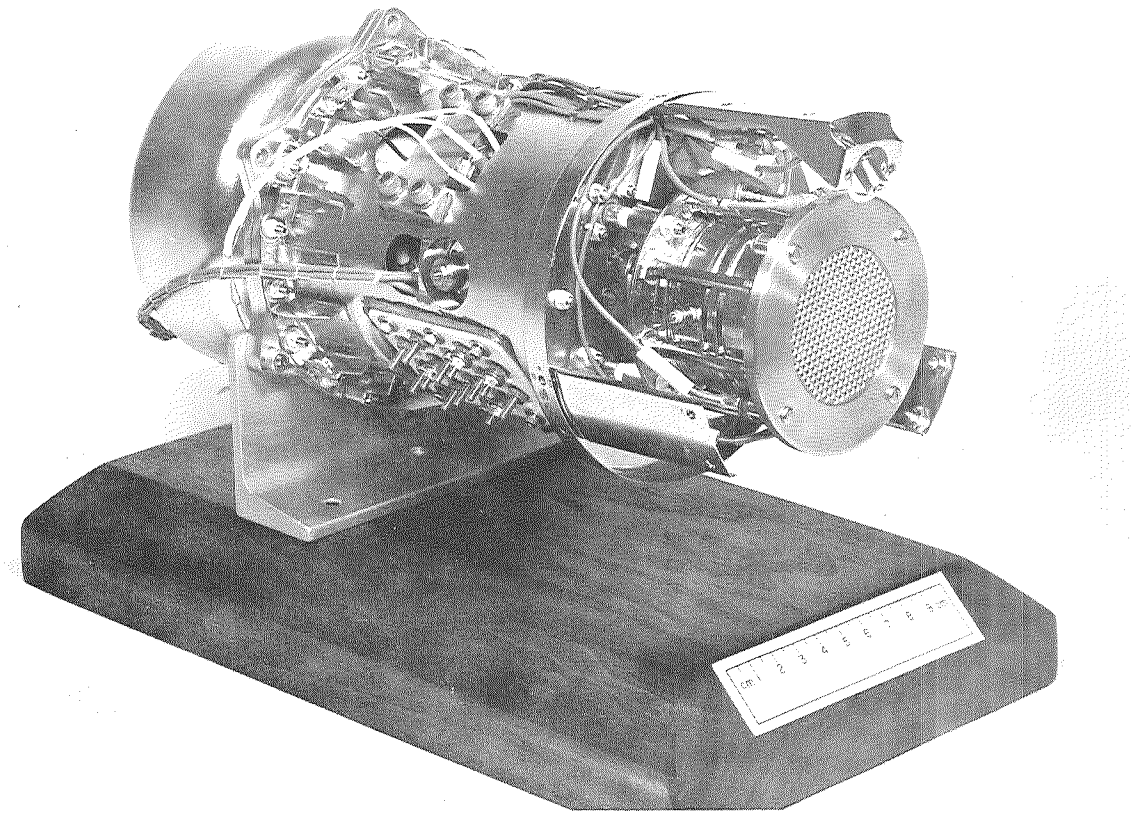

(b) Hughes prototype.

Figure 6. - 5-cm thruster.

E-6315

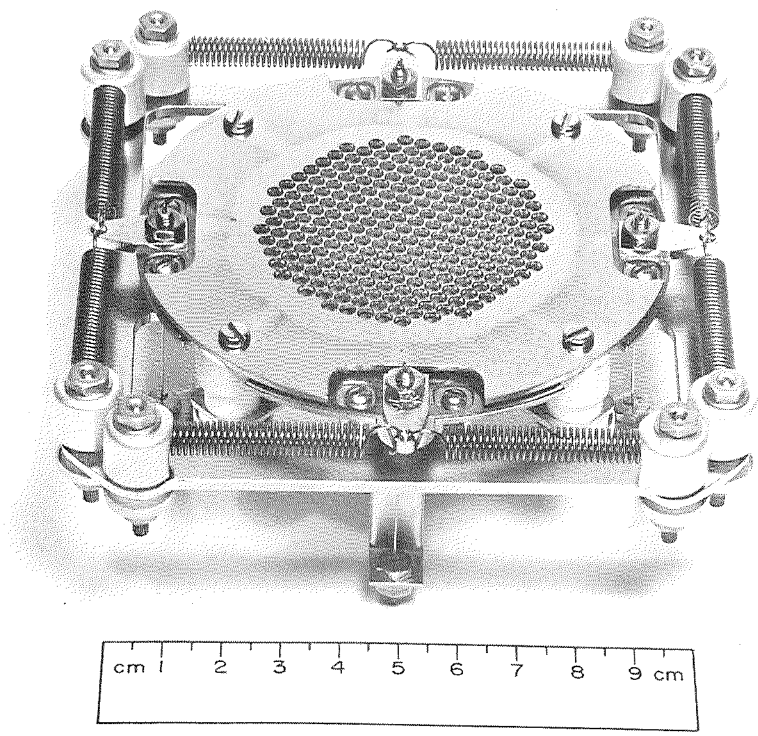

Figure 7. - Thermomechanical 5-cm vectorable grid. (Contract NAS 3-14058, Hughes Research Lab.)

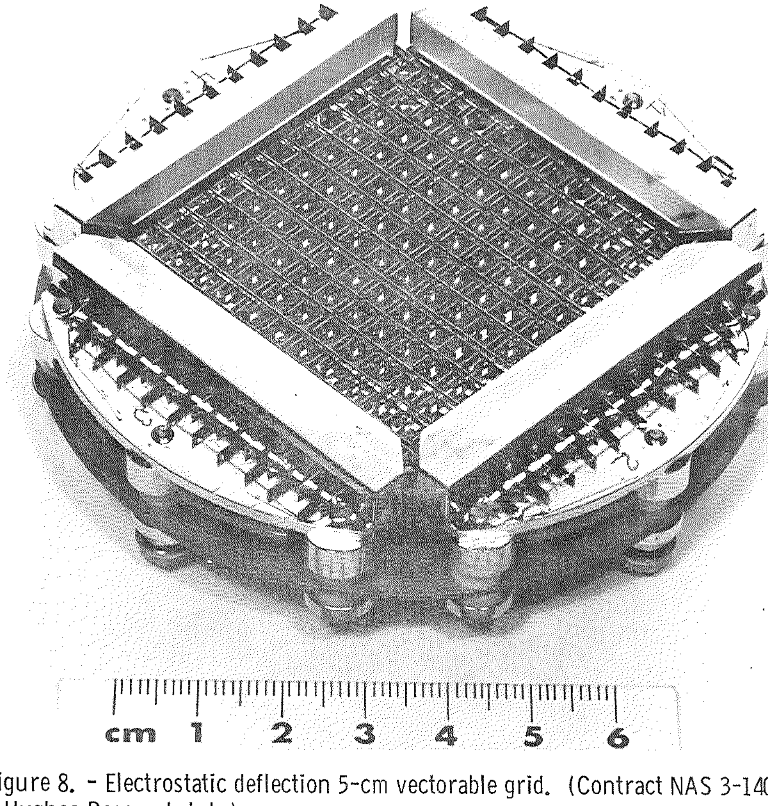

Figure 8. - Electrostatic deflection 5-cm vectorable grid. (Contract NAS 3-14058, Hughes Research Lab.)

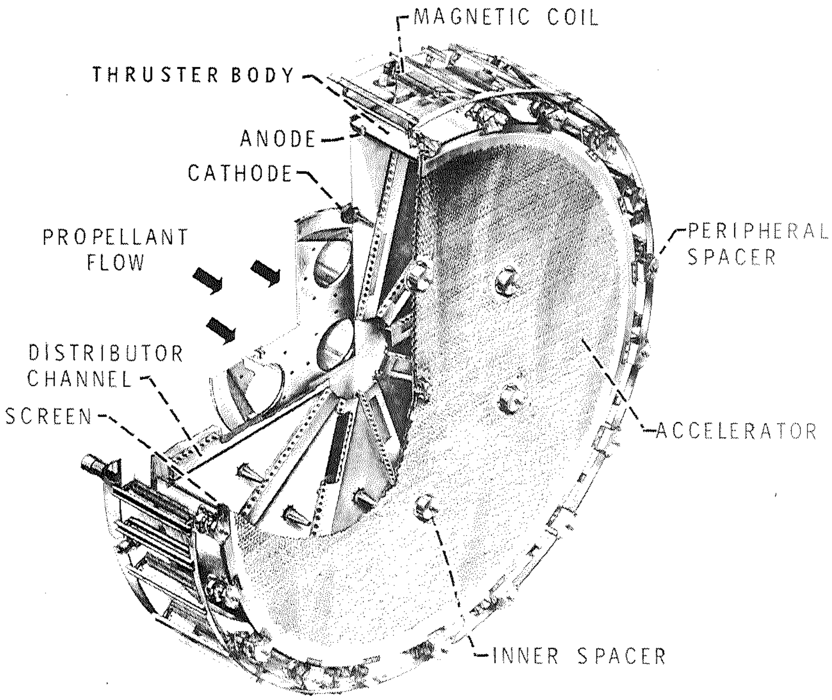

Figure 9. - Cutaway view of 1.5 meter diameter Kaufman thruster.

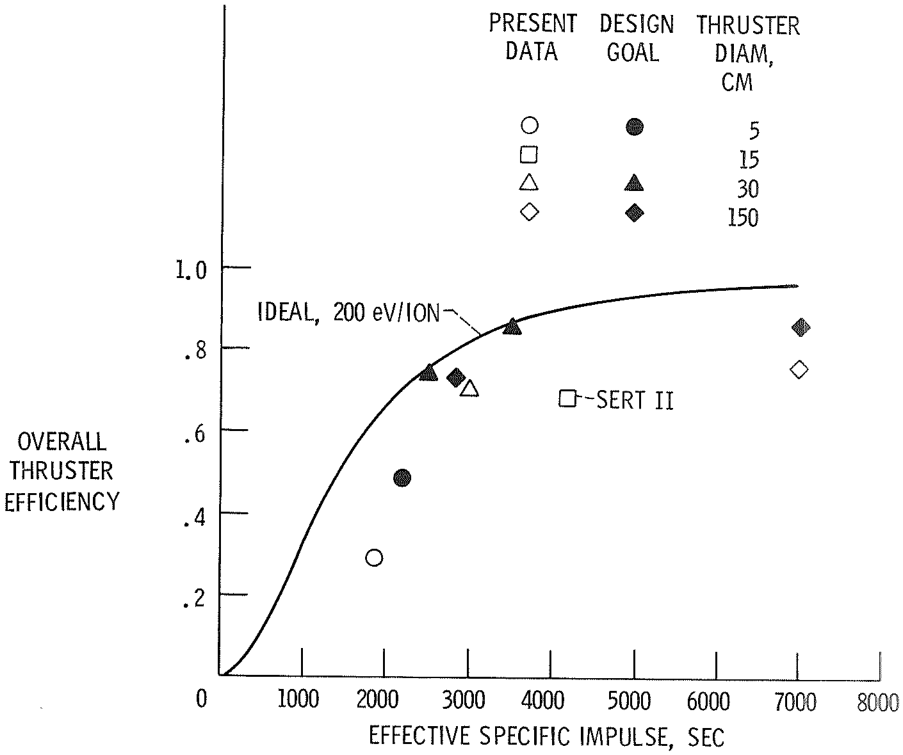

Figure 10. - Comparison of design goals with present data of various size mercury bombardment thrusters at maximum beam currents.