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GRID-TRANSLATION BEAM DEFLECTION SYSTEMS FOR 5-CM AND 30-CM DIAMETER KAUFMAN THRUSTERS

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Abstract

A 5-cm grid translation mechanism has been developed capable of 10° beam deflection. A 2026-hour endurance test was run at a preset 10° deflection angle and an extrapolated lifetime of better than 10 000 hours obtained. Response time data for grid translation are presented. Preliminary results for a 30-cm diameter system are given and results of a theoretical analysis of a dished grid system are discussed.

Introduction

A number of operational advantages can be realized if the beam from an ion thruster can be deflected about the nominal thrust axis. For example, the deflected beam of a station keeping thruster could provide attitude control for the satellite. For primary propulsion application, corrections would be possible for the thrust deflection caused by mechanical misalinements or for the shutdown of one module of a thruster array. Mission analysis indicates that beam deflection capability up to about 10 - 15° might be desirable.

Under a recent contract to Hughes Research Laboratories (NAS3-14058) a number of techniques for using the ion extraction system to control the direction of thrust from a mercury bombardment ion thruster were evaluated, the most promising systems were fabricated, and their performance experimentally documented and compared with that predicted from analytical models.[1,2] The basic goal of the contract was to design an ion extraction system for a 5-cm thruster that would provide up to 10° deflection of the thrust vector at all azimuths. From a number of different designs two were chosen as having the highest probability of success--the electrostatic dual grid and the grid-translation system. Functional 5-cm hardware was fabricated and tested. Both systems met the design goals. The electrostatic system was given primary emphasis under a follow-on contract because of its high speed of response and lack of moving parts. Continuing effort has been expended, however, on the 5-cm grid-translation system at the Lewis Research Center for the following reasons. Because the system uses standard match drilled parallel plate accelerator grids, it is inherently simple in design. Also, a larger beam deflection angle was demonstrated for this system than for the electrostatic system before the beam was intercepted by the accelerator grid.[1,2] Finally, this system was chosen for the 30-cm thruster because of problems involved in constructing electrostatic grids in 30-cm size. This continuing program on the grid translation system is the subject of this report.

5-cm Program

Design

The grid-translation system was suggested as a possible deflection technique in reference 3, which analyzed the effects of grid misalinement for the SERT II thruster.[4] Additional analysis and experimental results of this type system are described in references 5 and 6. A photograph of the grid-translation system for a 5-cm diameter thruster is shown in figure 1 as it was delivered to LeRC by the Hughes Research Laboratories under contract NAS3-14058, Thrust Vectoring Systems. Grid aperture dimensions are shown in Table I. The accelerator grid is stationary with respect to the discharge chamber. The screen electrode is supported slightly away from the end of the discharge chamber and the position is maintained by four thin flexible columns which provide the necessary axial support without constraining the transverse flexibility. The screen grid is held in static equilibrium by stretched coil springs (numbered 1 - 8 in fig. 1) with the spring axes perpendicular to the supporting columns. The outer ends of the springs are electrically isolated and four power supplies are connected so that the springs are heated in pairs. For example, current is passed through spring 1, through the screen grid, and then through spring 6. Heating springs 1 and 6 cause them to lose tension and springs 2 and 5 pull the screen grid to the right. The other four springs are flexible enough to allow this motion over small distances. By proper heating of the pairs, the screen grid can be misalined with respect to the accelerator grid in any azimuthal direction. This misalinement causes the ion beam to be deflected in the same direction as the screen grid is translated (i.e., to the right for the above example).

Beam deflection capability

The system shown in figure 1 was given preliminary tests on a 5-cm thruster at Hughes and then delivered to LeRC for additional testing. The deflection angle as a function of spring heating power is shown in figure 2 for one axis. Similar data was obtained for the other axis. The solid lines represent data taken by the contractor[1,2] and the symbols were the check points taken at LeRC. In both cases the deflection angles were obtained by beam probe techniques.[7] Briefly, the beam is scanned at some known distance downstream of the thruster with a matrix of planar probes and values of current density are obtained. These data are reduced by computer techniques to obtain the centroid of the beam. By comparison of the centroid position for deflected and undeflected beam conditions, the deflection angle is obtained.

Figure 3 shows the effect of deflection angle on the accelerator drain current. The beam current was 25 mA, the net voltage was 1000 volts, and the total voltage was 2000 volts. Note that deflection angles of over 10° were obtained before a marked increase in the drain current was obtained. This increase is believed to result from direct interception of primary beam ions by the accelerator. The base level of accelerator current is believed to be largely due to charge-exchange ion impingement.

Figure 4 shows the effect of total voltage on accelerator current for three values of accelerator voltage. A minimum voltage of about 1800 volts is required to maintain a well-focused beam without direct ion interception by the accelerator. Only small changes in accelerator current result from variations in accelerator voltage for a given total voltage.

Response time tests

Contractor tests indicated a relatively long response time for translation of the screen grid by thermal heating of the springs.[1,2] Approximately 1.1 watts of power was sufficient to hold a 10° beam deflection angle. At that power level, approximately 10 minutes was required to go from 0 to 10°. Longer times (about 30 minutes) were required for cool-down to return to zero beam deflection. Preliminary tests at Hughes indicated that these times could be reduced by overpowering the heaters. Zero to 10° deflection was achieved by initially applying 4 watts, then reducing to the 1.1 watt holding power. It was suggested that the beam could be returned to zero deflection by heating the opposite pair of springs to the same temperature and then removing power to all four springs. The grid would then remain stationary with all four springs cooling at the same rate.

Additional thermal/vacuum tests were performed at LeRC on the same grid after delivery. The results of these tests are shown in figure 5 and were initially reported in reference 8. Figure 5 shows the response time as a function of screen translation distance for various spring heating power levels. Opposite directions of motion are represented by the two parts of the figure.

The data were taken as follows: Starting at either 16.4 degrees or -16.4 degrees, the holding power was removed from one pair of springs, and a preselected power applied to the opposite pair of springs. The times required for the grid to translate to various other preselected position were recorded. As a result, the response times shown in figure 5 are dependent on the cooling rate of one pair of springs and the heating rate of the opposite pair. Note that deflection times as short as a minute can be obtained from +15° to -15°. Tradeoffs can be made between desired response time and heating power available.

Life test

Preliminary experimental results indicated that a 10° vector angle could be obtained without increasing the erosion rate of the accelerator grid. The grids were life tested on a 5-cm thruster to better determine wear rates. The thruster employed was developed under contract NAS3-14129 and is described in reference 9. The thruster operating conditions were set at 25 mA beam current and 2000 volts accelerating voltage. The screen and accelerator voltages were of equal magnitude. The screen and accelerator were misalined by 0.32 mm and mechanically locked in position. This condition gives approximately a 10° beam deflection angle which represents a severe test for the grid.

During the test, the accelerator drain current was typically 100 microamperes, which represents less than one-half of 1 percent of the 25 mA beam current. Post-test photographs of the downstream and upstream surfaces of the accelerator grid are shown in figure 6. Three general observations can be made about the results of this test. First, there was no neutralizer-caused erosion groove on the face of the accelerator such as the one reported for the SERT II thruster. An optimized neutralizer position and orientation had been chosen based on results of 30-cm thruster testing.[10] Second, the circular pattern of erosion pits shown on the grid in figure 6 about one-half centimeter outside the hole pattern is of minor importance. The maximum depth of these pits, which were caused by a focusing effect of the ground screen mask, was only 0.1 mm or 8 percent of the grid thickness after better than 2000 hours of testing. Finally, grid erosion directly attributable to beam deflection was small. The beam was deflected 10° in one direction for the entire 2000 hours and a faint erosion pattern was noticed on the inside walls of the accelerator holes in the direction of beam deflection. This erosion was less than 10 percent of the width of the grid webbing. Because a constant 10° deflection in one direction should result in maximum wear rates, the grid should last about 20 000 hours. Charge-exchange pits normally found on the downstream surface of the accelerator grid in the center of the webbing area common to any set of three holes were not observed on this grid. One theory is that deflection of the beam causes a shift in the downstream plasma boundary so that these ions are focused toward the holes instead of toward the webbing. The ions striking the downstream surface would therefore be spread out more uniformly, reducing erosion significantly. In addition, some ions strike the interior hole walls and some even loop to the upstream surface of the accelerator. Some evidence of the last two types of erosion was found by examination of the grid. A more complete analysis of grid damage will be performed and results reported in a future publication. An extension of the endurance test of this grid is also planned. In conclusion, a conservative extrapolation of the results of this test indicates that the accelerator system should certainly yield an operational lifetime of 10 000 hours and possibly as much as 20 000 hours.

30-cm Program

Design

The contract previously mentioned (NAS3-14058) also produced a design for a 30-cm size grid translation mechanism. It was physically designed to mount to the 30-cm thruster developed under contract NAS3-11523 described in reference 11. In addition, operational specifications were chosen to match those of that same contract. These are shown in table II.

Operational hardware has been fabricated under a follow-on Thrust Vectoring System contract NAS3-15385 which is in progress. Figures 7(a) and 7(b) show photographs of the 30-cm extraction system. There are six springs in this system in contrast to the set of eight used for the 5-cm. This yields a more complicated control problem because of the three-fold symmetry. An orthogonal system as used for the 5-cm would be simpler to operate.

However, the six spring configuration was chosen because the 30-cm thruster used had 12 support points for grid attachment. These 12 locations were used to mount the grid translation system with identical supports to those described earlier for the 5-cm thruster. Stiffer rods were used to support the larger mass of the 30-cm screen grid. A single center support (which eliminated seven extraction holes) was used to maintain grid to grid spacing.

Vectoring capability

Preliminary bench tests were performed by the contractor to determine the lateral motion of the screen grid as a function of heater power as applied to various combinations of the six springs. As shown in figure 8, best results in terms of movement per unit power input is obtained by heating two adjacent springs.

As yet, no thruster testing of this system has been performed. However a theoretical analysis was performed which indicates that for the motion obtained in the preliminary tests, displacement angles of 10° or more will be obtained.

Dished grid analysis

Recent developments in 30-cm grid design at Lewis include the use of dished sets of screen and accelerator grids.[12] Several advantages are gained by this technique. First, the grids become more rigid and resistant to failure under vibration and shock loading and elimination of the center support is possible. Second, the grids have a preferential expansion direction under thermal load so that the direction of movement of the grids can be predicted. This allows the grids to be spaced closer and more evenly without grid-to-grid shorting. This closer spacing allows higher beam current extraction.

The interest in dished grid systems created a special problem for the designer of the grid-translation beam deflection system. A theoretical analysis was performed to determine if the two concepts were compatible. Results of this analysis were reported in detail in reference 13 and selected results are repeated here.

Basically, no problems were uncovered which would preclude the use of the grid translation technique with a dished grid set. In fact, results were quite encouraging, indicating that deflection angles as high as 20° could be obtained by proper electrode optics design. Results for a variety of theoretical and experimental programs[1,2,3,11,13] are shown in figure 9. Note that a 10° deflection angle can be obtained by translating the screen grid a distance approximately equal to 10 percent of the accelerator hole diameter. For the 30-cm system discussed here, which has 1.9 mm diameter holes, a translation distance of 0.19 mm should yield approximately 10° deflection

Concluding Remarks

A 5-cm grid-translation accelerator system has been developed which is capable of deflecting the beam of an ion thruster up to 10° from its normal direction with no appreciable rise in accelerator currents. Beam deflection up to 15° is possible if a small increase in accelerator current can be tolerated for short periods of time. A 2026-hour endurance test was run and an extrapolated lifetime of better than 10 000 hours was obtained for a fixed 10° deflection angle. Data indicate that for a more realistic test with less vectoring an ultimate grid lifetime of 20 000 hours might be possible. Response time data indicate that the beam deflection angle can be changed from 16° to -16° in about 1 minute. About 1.1 W of power is required to hold a 10° deflection angle. Preliminary tests results for a 30-cm system show that the amount of grid-translation obtainable is comparable to the 5-cm system. A theoretical analysis has shown that for the motion obtained in the preliminary tests deflection angles greater than 10° should be expected.

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13. Lathem, W. C. and Adam, W. B., "Theoretical Analysis of a Grid-Translation Beam Deflection System for a 30-cm Diameter Kaufman Thruster," TM X-67911, 1971, NASA, Cleveland, Ohio.

Table I. - 5-cm System Grid Aperture Dimensions

	mm
Screen thickness	0.6
Screen aperture diameter	2.4
Accelerator thickness	1.3
Accelerator aperture diameter	2.4
Aperture center-to-center spacing	2.9
Grid to grid spacing	1.2

Table II. - 30-cm System Operational Requirements

Beam vectoring: Continually variable through ±10° about each of two orthogonal axes
Net accelerating voltage: 1000 V
Total accelerating voltage: 1500 to 2400 V
Thrust: 26 mlb
Beam current: 1.8 A

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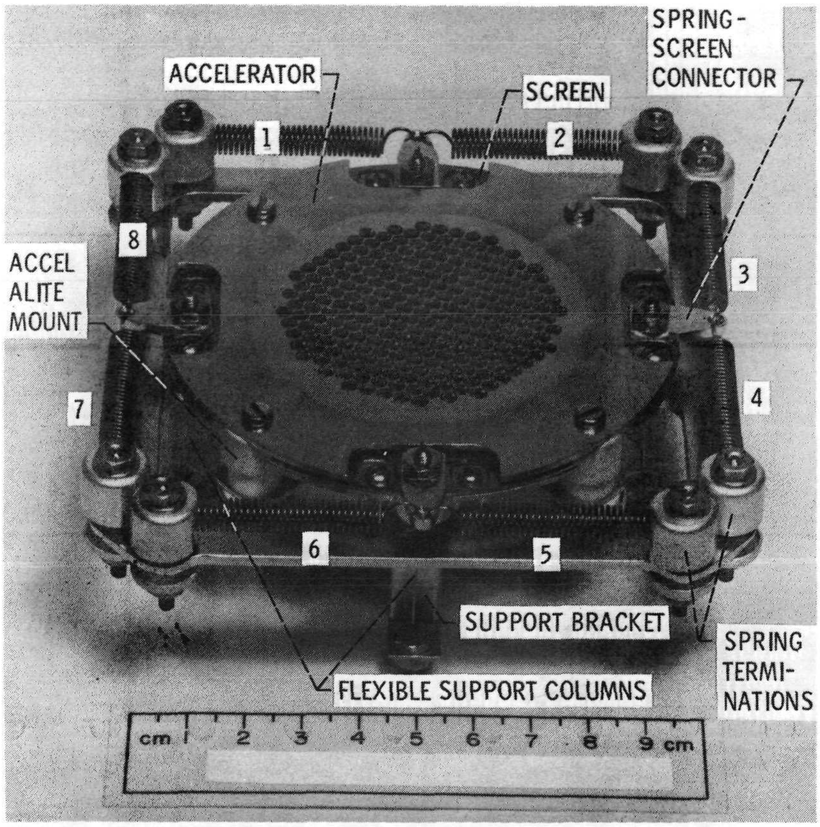

Figure 1. - Thermomechanical 5-cm vectorable grid. (Contract NAS 3-14058, Hughes Research Lab.)

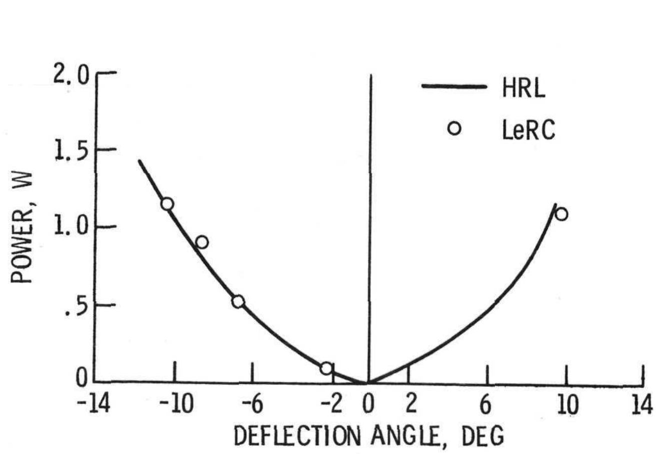

Figure 2. - Beam deflection angle versus spring heating power. (Beam current 25 mA.)

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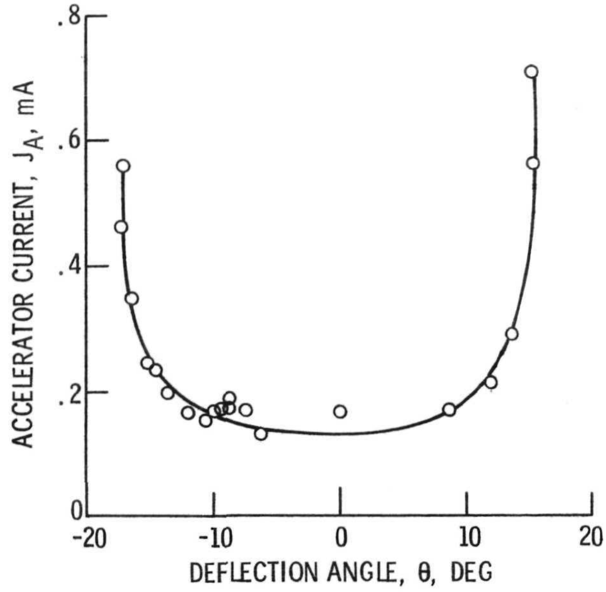

Figure 3. - Accelerator drain current versus deflection angle (total voltage - 2000 V, beam current - 25 mA).

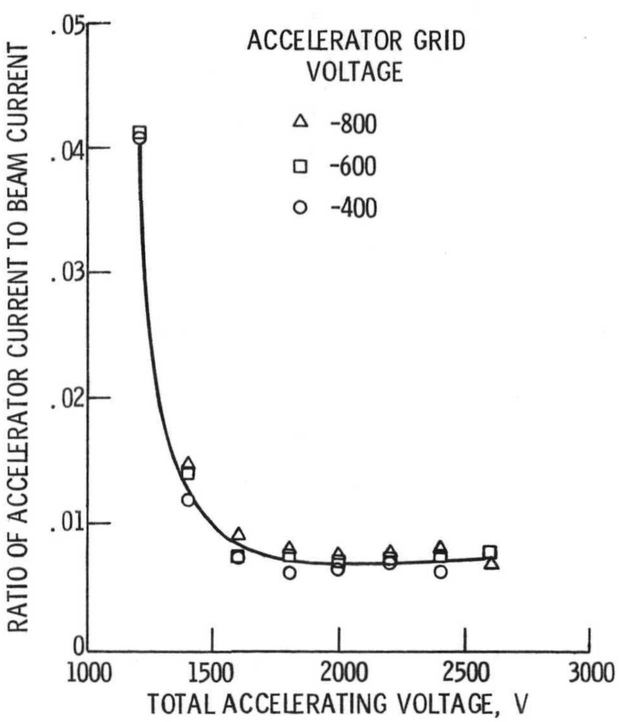

Figure 4. - Ratio of accelerator current to beam current versus total accelerating voltage for various accelerator voltages. (Undeflected 25 mA beam.)

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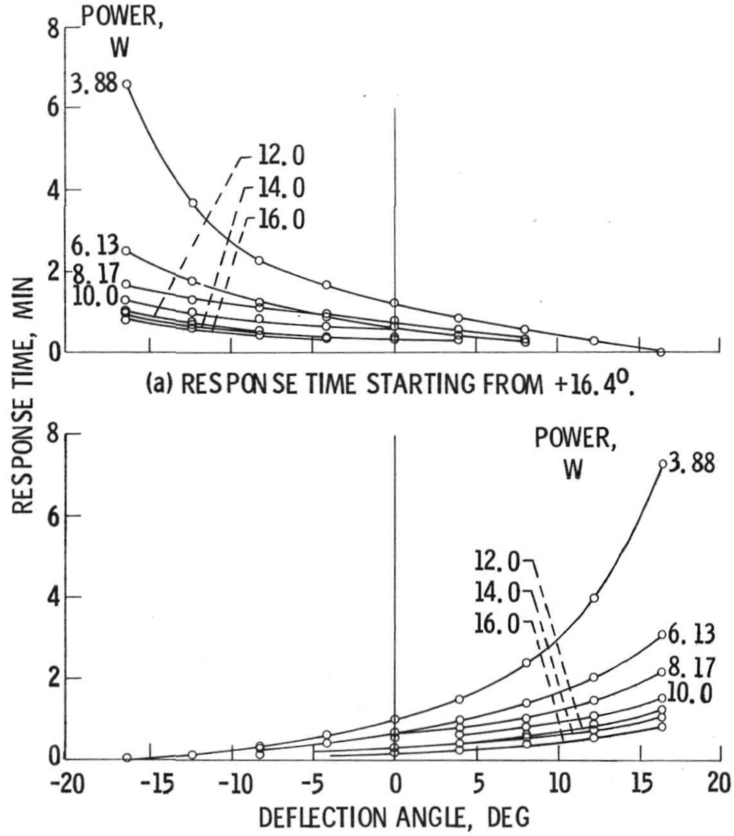

(b) RESPONSE TIME STARTING FROM -16.4°.

Figure 5. - Translational vector grid response time for various spring heating powers.

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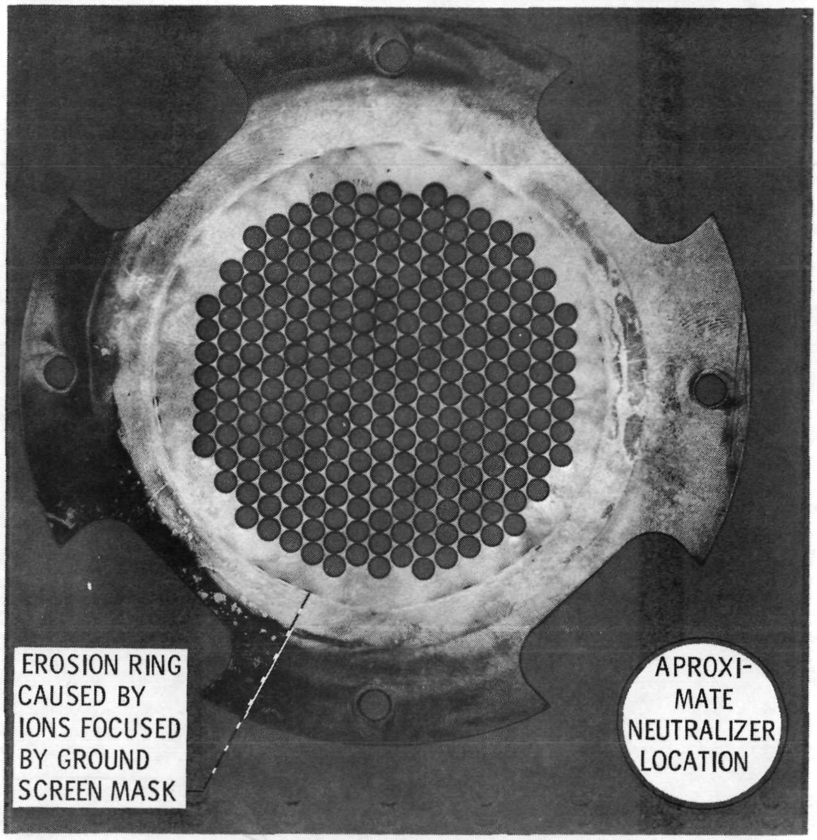
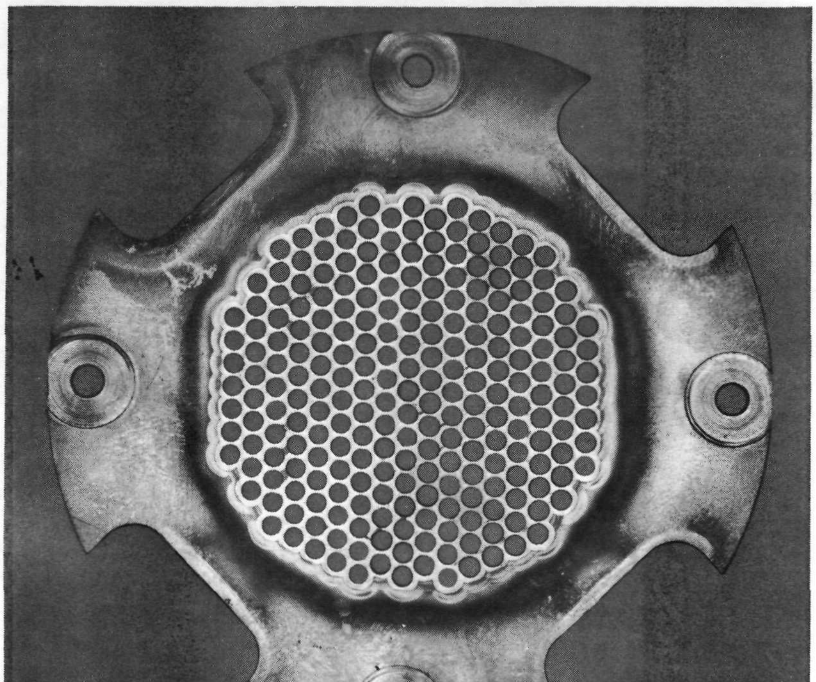


(A) DOWNSTREAM SURFACE.



(B) UPSTREAM SURFACE.

Figure 6. - 5-Cm accelerator grid after 2026 hours at 25 mA beam current.

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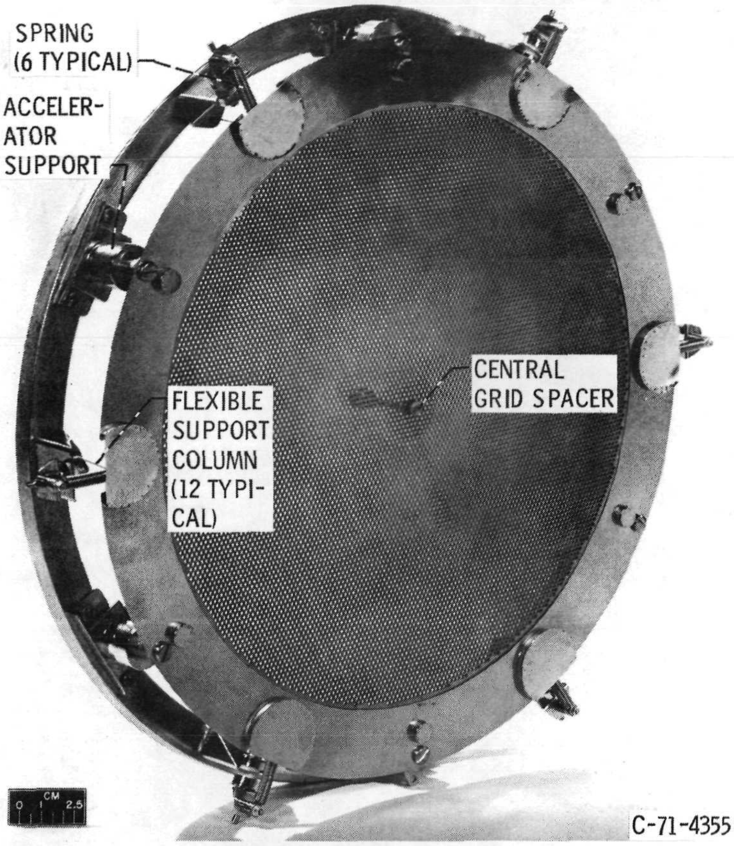
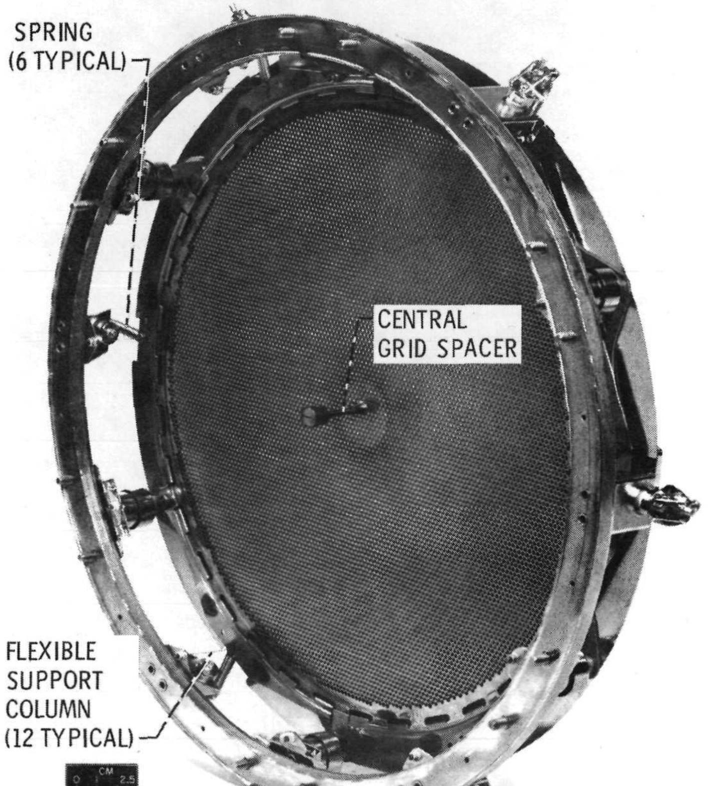


(A) ACCELERATOR GRID VIEW.



(B) SCREEN GRID VIEW.

Figure 7. - 30-Cm grid translation system.

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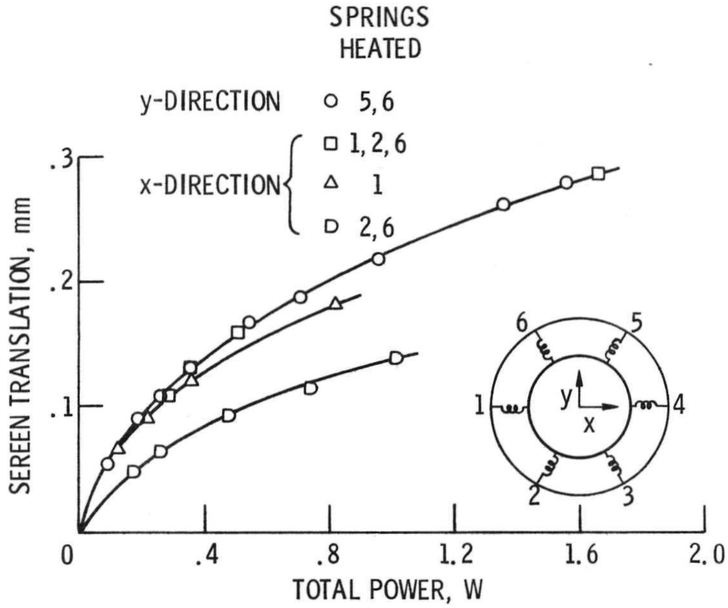

Figure 8. - Sereen translation versus total power for various spring orientations.

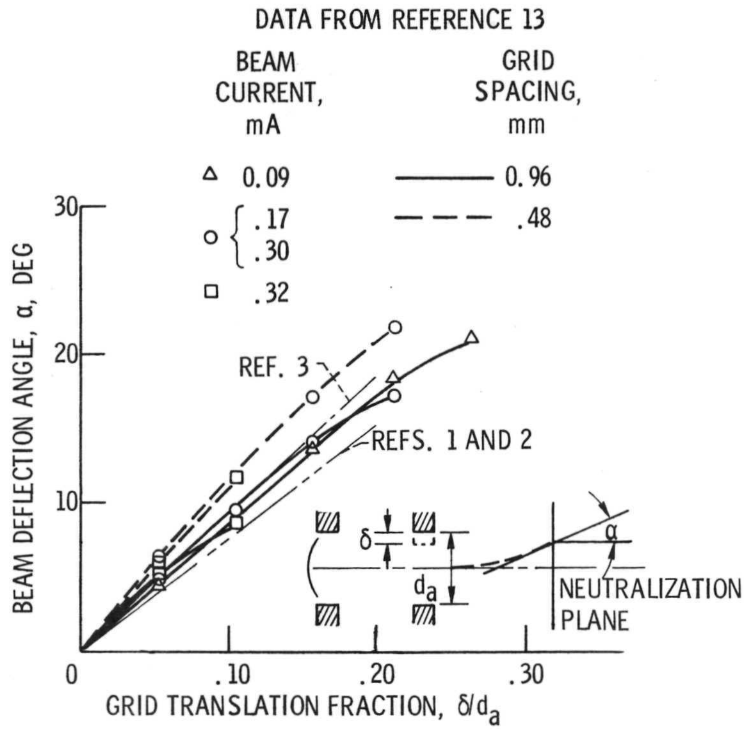

Figure 9. - Ion beam deflection angle α as a function of grid translation fraction δ/d_a (grid displacement/hole diameter).