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EOS Report 7028-Final

Final Progress Report

# PROGRAM TO DEVELOP AND DEMONSTRATE METHOD TO DEFLECT BEAM FOR ION THRUSTOR

by R.M. Worlock

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-7936



EOS

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26 June 1966

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ABSTRACT

A program to demonstrate a method for deflecting the ion beam from an ion thrustor is described. Beam deflections of zero to six degrees relative to the thrustor axis of symmetry were produced in each of three equally spaced azimuthal directions by means of potentials applied to an array of electrostatic deflection electrodes. Two ion thrustor systems each consisting of thrustor, propellant feed, beam deflection electrodes and console for supplying, controlling, and measuring all power to the thrustor were fabricated and operated to demonstrate beam deflection. Selected environmental tests were successfully conducted on one of the thrustors.

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## FOREWORD

This report covers the work performed under Contract NAS3-7936 during the period 6 December 1965 to 6 June 1966. The principal objective of the program was to demonstrate a method for deflecting the ion beam from a contact ion thrustor. Beam deflections of zero to six degrees relative to the thrustor axis of symmetry were produced in each of three equally spaced azimuthal directions by means of potentials applied to an array of electrostatic deflection electrodes. Two ion thrustor systems each consisting of thrustor, propellant feed, beam deflection electrodes, and console for supplying, controlling, and measuring all power to the thrustor were fabricated and operated to demonstrate beam deflection. Selected environmental tests were successfully conducted on one of the thrustors.

The program manager was Dr. Robert M. Worlock. Thrustor development and testing was carried out by Mr. Eugene Caplinger, Mr. William Ramsey and Mr. John Hayes. Mr. Al Kosky supplied the propellant feed systems, Mr. Terence Dillon was responsible for the power supply consoles and Mr. Sid Zafran assisted with the quality assurance portions of the program.

## 1. INTRODUCTION

This report describes a program carried out to accomplish the following tasks:

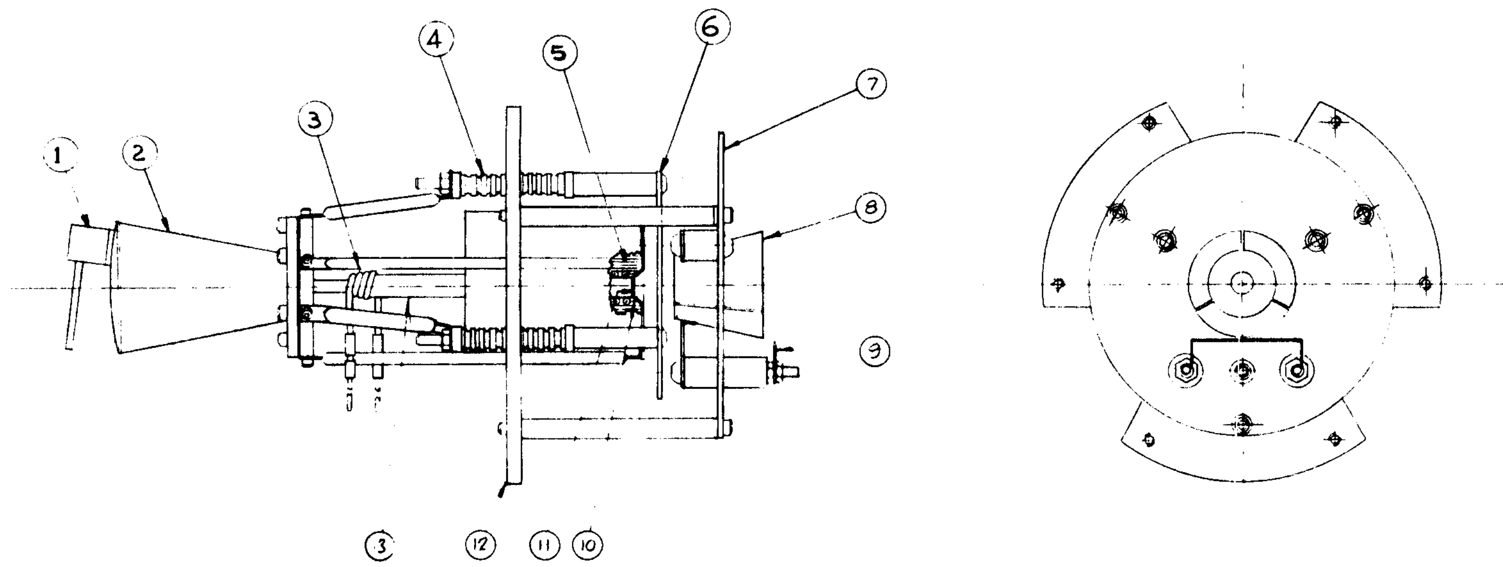
1. Develop a method of electrostatically deflecting an ion beam
2. Fabricate as deliverable hardware two ion thrustor systems each consisting of thrustor, propellant feed, and power supply controls and incorporating the beam deflection electrode developed under (1) above.
3. Test and performance map the thrustor systems
4. Conduct selected environmental tests on one of the thrustors
5. Deliver the two thrustor systems to the NASA Lewis Research Center.

Subsequent sections of this report describe in more detail the work accomplished.

## 2. ION THRUSTOR SYSTEM DESCRIPTION

### 2.1 Thrustor

The thrustor is a single source contact type; its configuration is shown in Fig. 1. The ionizer is a flat porous tungsten button electron-beam welded to one end of a molyrhenium cesium vapor feed tube. Ionizer heater power is supplied by a sheathed heater brazed to the tube near the ionizer button. Ion beam focusing is provided by a conical focusing electrode which surrounds the ionizer button in an approximation of the Pierce geometry. The high temperature end of the molyrhenium tube is thermally insulated with alternate layers of Fiberfrax and metal foil. The cooler end of the molyrhenium feed is brazed to a stainless steel feed tube which is attached to a flange used both for mechanical support and for mating to the cesium reservoir. The ionizer assembly is shown in Fig. 2.




1 RESERVOIR RELIEF VALVE
2 CESIUM RESERVOIR
3 VAPORIZER HEATER
4 ALUMINA INSULATOR
5 THERMAL INSULATION
6 ACCELERATOR ELECTRODE
7 DEFLECTOR MOUNTING PLATE
8 DEFLECTION ELECTRODE
9 NEUTRALIZER FILAMENT
10 FOCUS ELECTRODE
11 POROUS IONIZER
12 THRUSTER MOUNTING PLATE
13 FEED TUBE

**FIG. 1 MICROTHRUSTOR, DEFLECTION PLATES AND NEUTRALIZER ASSEMBLY**

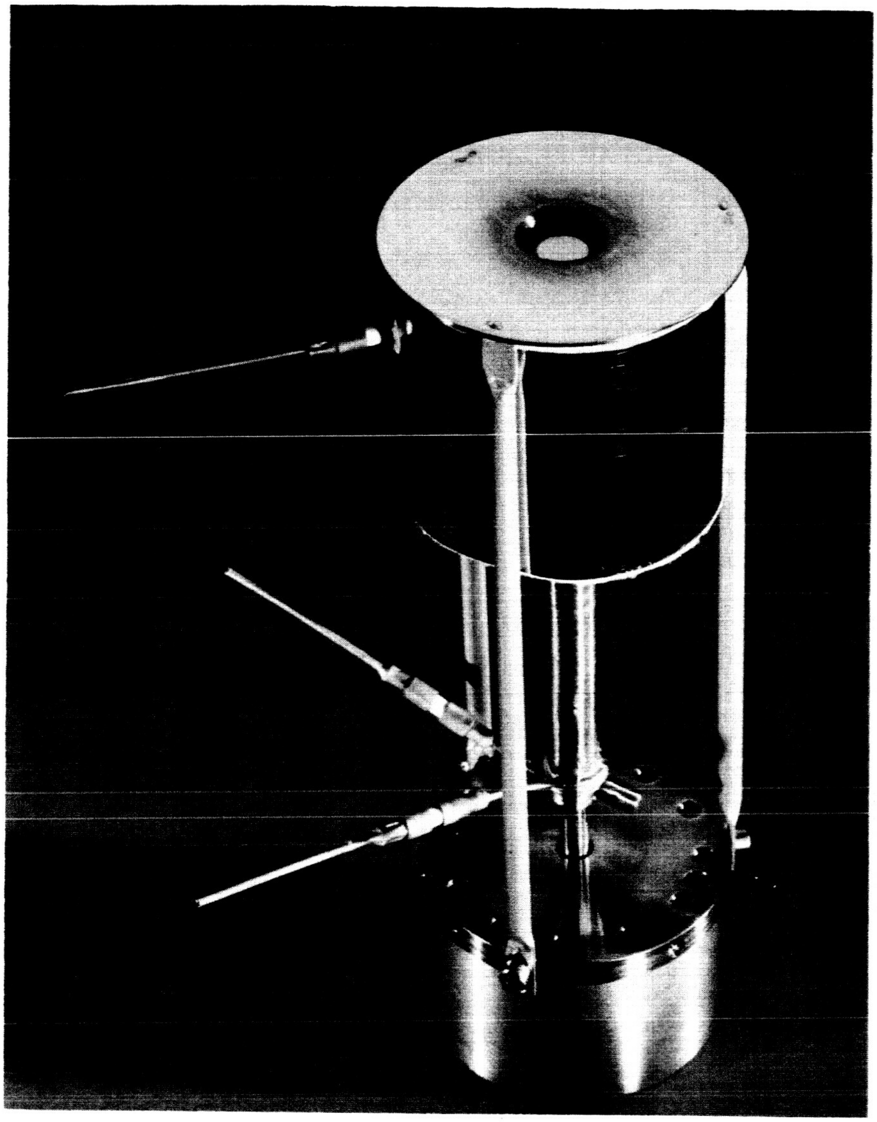


FIG. 2 IONIZER ASSEMBLY

Cesium is stored in the conical reservoir shown in Fig. 1. Capacity is approximately 50 grams. In its intended zero-g configuration a porous nickel wick extends along the axis and a set of nested coaxial cones surround the wick and provide the capillary pumping required to keep the liquid in contact with the porous rod. The wick extends out of the reservoir and up the feed tube to the vaporizer heater shown surrounding the feed tube in Figs. 1 and 2. When power is applied to this heater, the end of the wick is heated and cesium is vaporized.

In the laboratory or one-g version of this propellant feed system the nested coaxial cones are left out and the reservoir end of the porous rod is bent down to contact the liquid cesium in the bottom of the reservoir.

The valve on the rear of the reservoir is a relief valve provided for evacuation of the reservoir during vacuum chamber pump-down. If the reservoir is not vented the gas trapped inside the reservoir must escape through the ionizer and often carries liquid cesium along with it.

The thrustor is supported by a mounting ring. The ionizer assembly and feed system are supported by means of three alumina insulators attached to the mounting rings by clamps around the middle of the insulators. The other end of the insulators are used to support the accelerator electrode. A ground potential plate is supported from the main mounting ring; this plate serves both as a decelerating electrode and as a mounting for the deflection plates and neutralizer. Front and rear views of the assembled thrustor are shown in Figs. 3 and 4. Operation of the thrustor is covered in Section 6, Thrustor System Operational Procedures.

2.2 Power Supply Console

To operate the thrustor the power supply console shown in Fig. 5 was designed and built. The console consists basically of seven modular units. Master Power Control controls and distributes

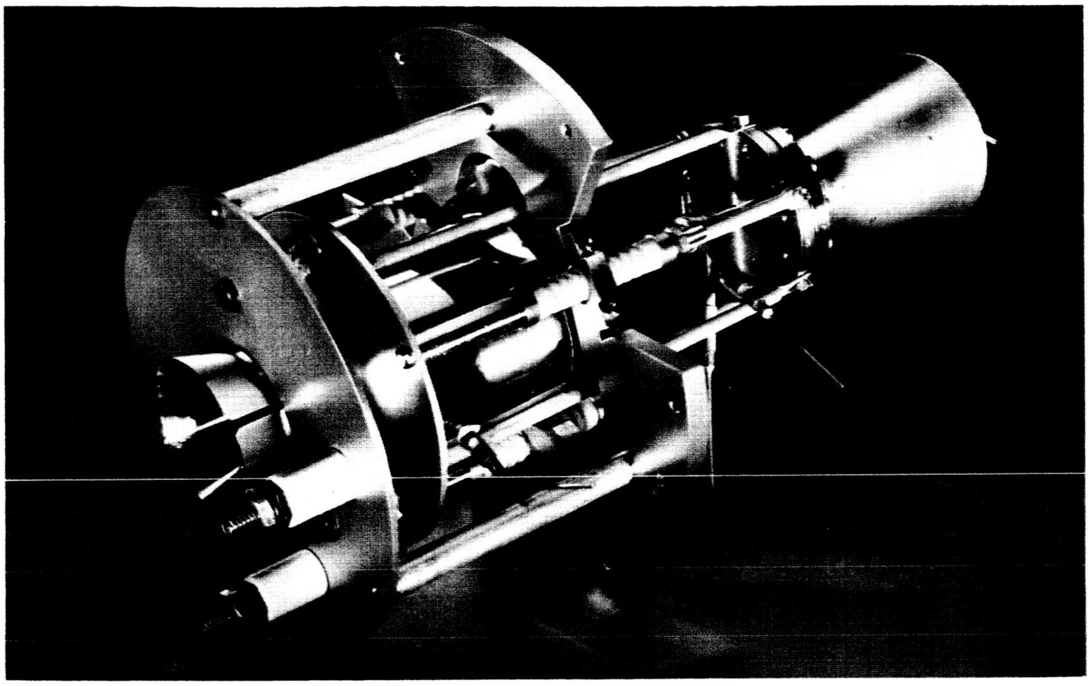


FIG. 3 MICROTHRUSTOR, FRONT VIEW

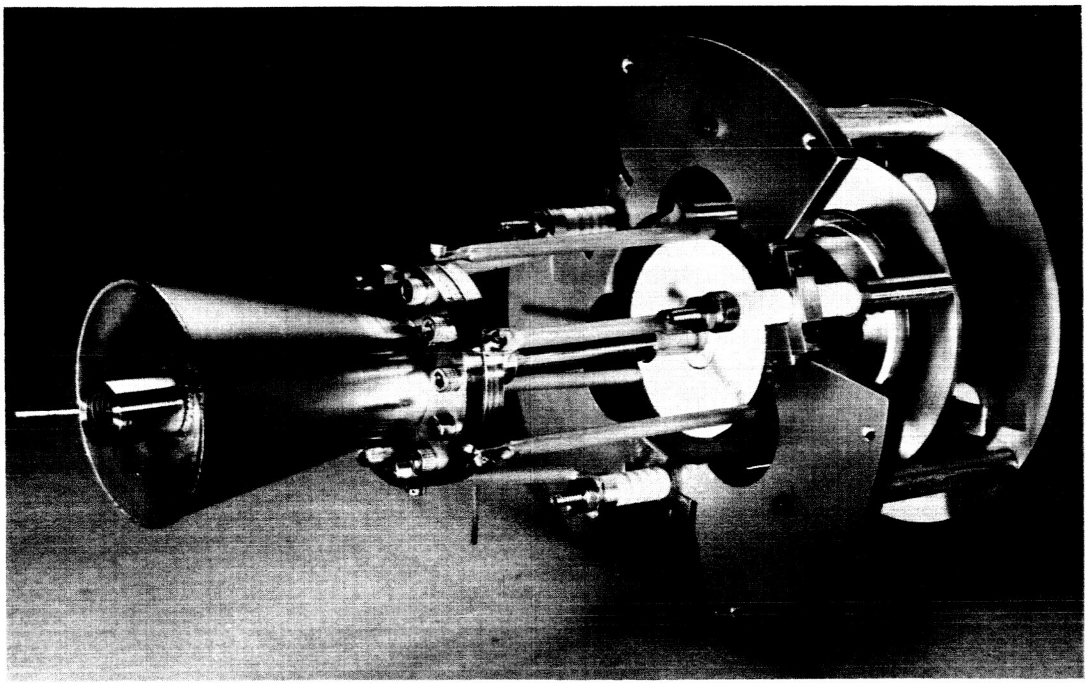


FIG. 4 MICROTHRUSTOR, REAR VIEW

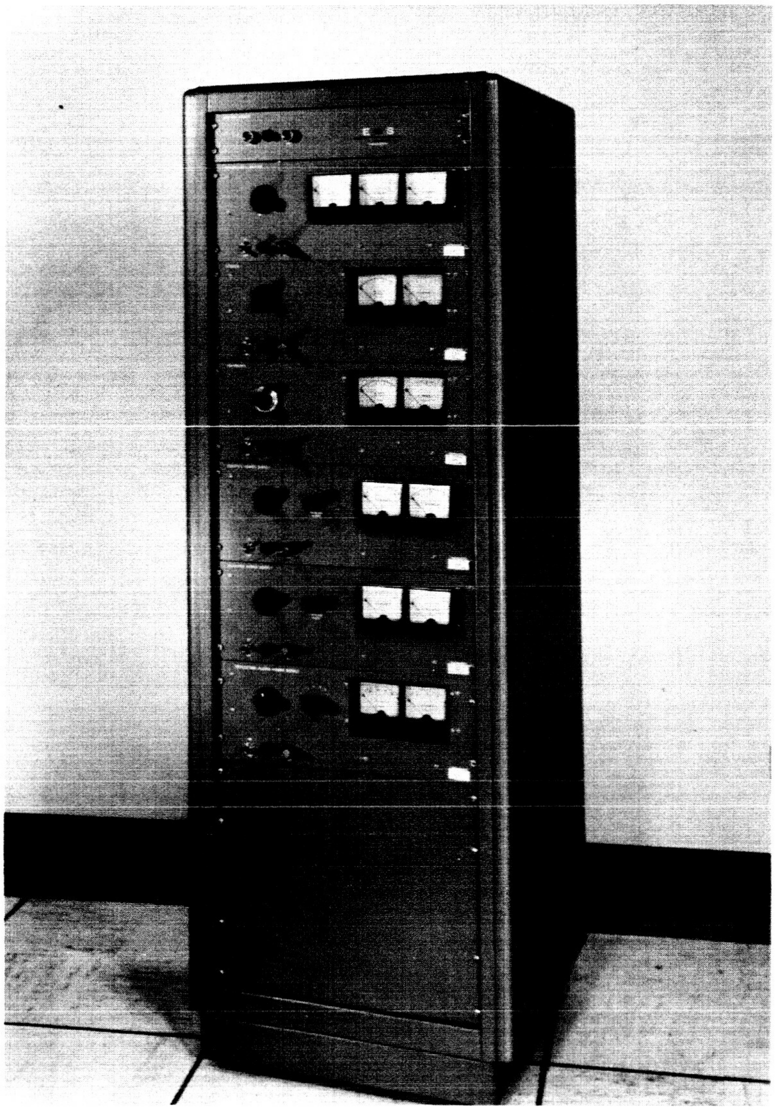


FIG. 5  POWER SUPPLY CONSOLE

110 Vac power to all other modules. The Neutralizer Heater module provides variable heater power and meters for measuring heater voltage, heater current and electron emission current. The Ionizer Heater module provides variable ionizer heater power and meters for measuring heater voltage and heater current. The Vaporizer module provides vaporizer heater power, meters for measuring heater voltage and heater current, and circuitry for feedback control of vaporizer heater power to maintain the desired ion beam current. The Positive Power Supply provides variable ionizer assembly high voltage and meters for measuring voltage and current. Overload circuitry is provided which turns off the supply momentarily when a current overload is sensed. The Negative Power Supply is similar but provides variable negative potential for the accelerator electrode. The Deflection Plates Power Supply provides variable negative potential and meters for measuring voltage and current. A front panel switch switches the output to any one of four output terminals and grounds the other three.

More detailed information on voltage and current ranges, interlocking arrangements, zero-start feature, etc. may be found in Section 6, Thrustor System Operational Procedures and Section 7, Power Supply Functional Test Procedures.

### 2.3 Deliverable Hardware Fabrication

Two complete systems as described above were fabricated and assembled for test and ultimate delivery. In the fabrication and assembly of the thrustors, procedures were followed as specified in Quality Assurance Plan, EOS Report 6954-QAP-1, the quality assurance document used on other electric propulsion programs conducted for the NASA Lewis Research Center by EOS. Quality Assurance on the power supply consoles were handled by considering the console modular units as the component parts of the system and by subjecting the modules to the functional test procedures described in Section 7, Power Supply Console Functional Test Procedures.

## 3. THRUSTOR SYSTEM OPERATING DATA

The two deliverable thrustor systems were performance mapped for ten hours each. Typical operating data are presented in Tables I and II. Beam deflection data are presented in Section 4.

## 4. BEAM DEFLECTION MEASUREMENTS

The technique used for observation of beam deflection is a visual one previously developed at EOS on an ion microscopy project. An assembly drawing of the instrument is shown in Fig. 6. Ions arrive from the left and are partially collected on a 50 percent transparent stainless steel converter grid (5) which is maintained near zero potential. Secondary electrons produced by the ion bombardment are accelerated to an aluminized phosphor screen (1) maintained at approximately 10 kilovolts positive. Those ions which penetrate the converter grid are energetically incapable of reaching the phosphor and are returned to the converter grid where more secondary electrons are produced. If the ions do not pass through the converter grid along a line perpendicular to the grid plane, they will not return to the grid at the point through which they originally passed. The loss of resolution caused by this lateral motion is not serious in the present application, however. The light intensity produced by the phosphor is directly related to the incident ion current density and may be observed from outside the vacuum chamber through the transparent Plexiglas flange (7). A reticle was mounted with the phosphor screen to aid in making deflection measurements.

Electrical leads could have been brought out through the Plexiglas flange, but in the present application it was considered more convenient to bring them out through a separate flange. Operation of the instrument was quite satisfactory and ample light for either visual observation or photography was produced with an incident ion current density of 1 microampere/cm$^2$ and phosphor potential of 5 kilovolts. Although phosphor light output is proportional to electron current density, this instrument should probably be regarded as

TABLE I

THRUSTOR OPERATING DATA

The following table lists a set of operating data for the two EOS $\mu$-3d microthrustors. These data were taken while the engines were being performance mapped according to the contractual requirements of NAS 3-7936, Exhibit A.

| PARAMETER | SYMBOL | THRUSTOR 1 | THRUSTOR 2 |
|---|---|---|---|
| Ionizer heater voltage | $V_{ih}$ | 7.8 volts | 7.0 |
| Ionizer heater current | $I_{ih}$ | 2.7 amps | 2.4 |
| Vaporizer heater voltage | $V_{vap}$ | 2.8 volts | 3.2 |
| Vaporizer heater current | $I_{vap}$ | 1.5 amps | 1.4 |
| Ionizer high voltage | $V_+$ | 2.0 kilovolts | 2.0 |
| Ionizer current | $I_+$ | 1.18 milliamps | 1.35 |
| Accelerator voltage | $V_-$ | 2.0 kilovolts | 4.0 |
| Accelerator current | $I_-$ | 0.18 milliamp | 0.32 |
| Ionizer temperature | $T_{ion}$ | 1150$^\circ$C | 1060 |
| Vaporizer temperature | $T_{vap}$ | 310$^\circ$C | 292 |
| Chamber Pressure | P | $2.5(10)^{-6}$ | $1.5(10)^{-6}$ |

## TABLE II

## NEUTRALIZER DATA

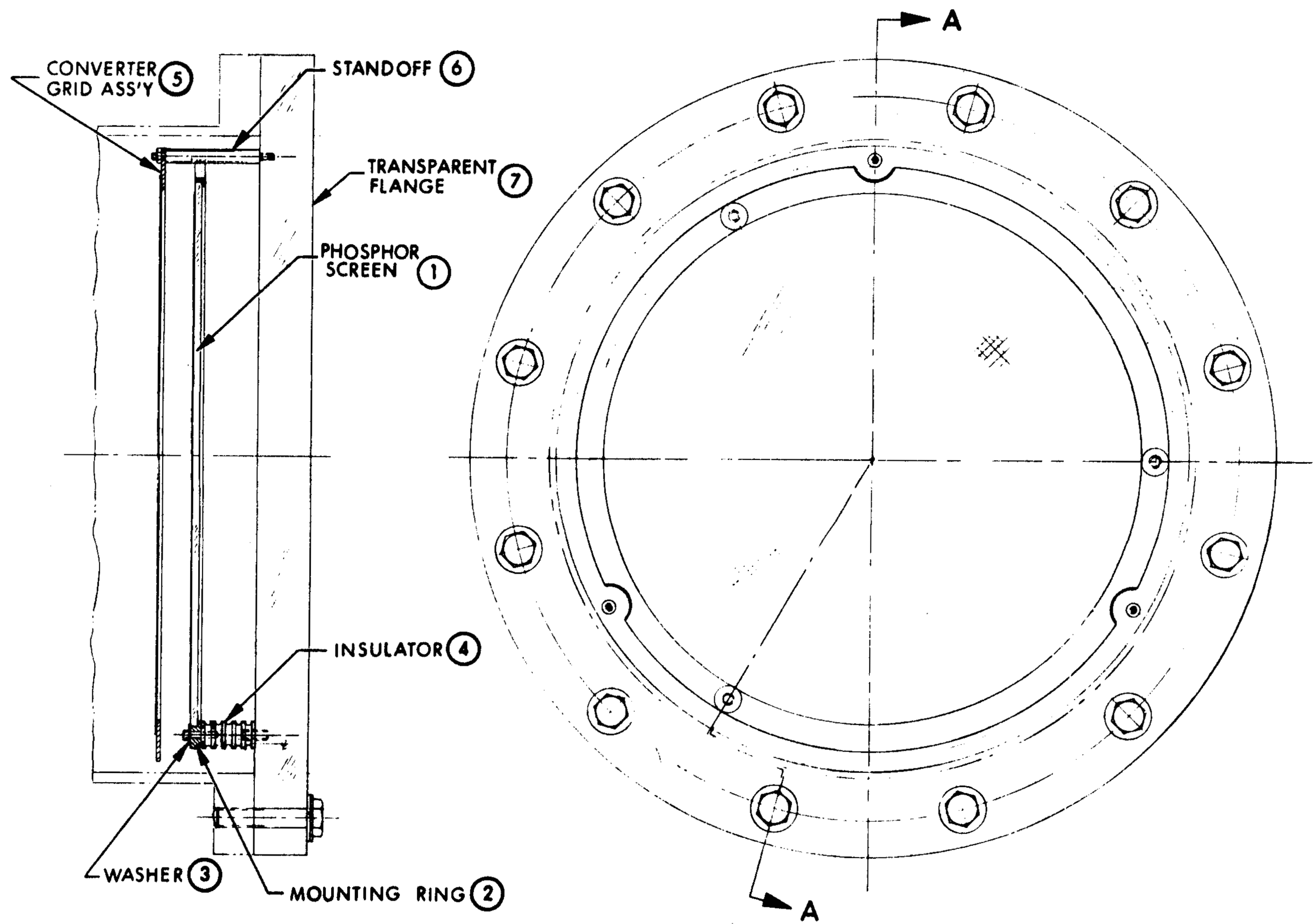
The following table shows the operating characteristics of the neutralizer operating on a 2 kV, 1 mA ion beam. The data were taken in a vacuum chamber which had an electrostatic liner which could "float" above ground. (The dc voltage recorded corresponds to the liner potential.)

<u>ENGINE 1</u>

| $V_{nh}$ (volts) | $I_{nh}$ (amps) | $I_n$ (mA) | $V_{dc}$ (volts) |
|---|---|---|---|
| 4.0 | 3.9 | 1.2 | 16 |
| 4.0 | 3.9 | 0.9 | 30 |
| 3.8 | 3.8 | 0.7 | 95 |
| 3.7 | 3.7 | 0.5 | 170 |
| 3.5 | 3.55 | 0.3 | 400 |
| 0 | 0 | 0 | 600 |

<u>ENGINE 2</u>

| $V_{nh}$ (volts) | $I_{nh}$ (amps) | $I_n$ (mA) | $V_{dc}$ (volts) |
|---|---|---|---|
| 3.7 | 4.0 | 0.73 | 110 |
| 3.6 | 3.95 | 0.6 | 260 |
| 3.55 | 3.88 | 0.5 | 530 |
| 3.45 | 3.80 | 0.38 | 700 |
| 3.40 | 3.75 | 0.30 | 780 |
| 3.25 | 3.60 | 0.20 | 880 |
| 3.00 | 3.45 | 0.10 | 980 |
| 0 | 0 | 0 | 1200 |




SECTION A-A

FIG. 6 MICROTHRUSTOR, DEFLECTION DISPLAY ASSEMBLY



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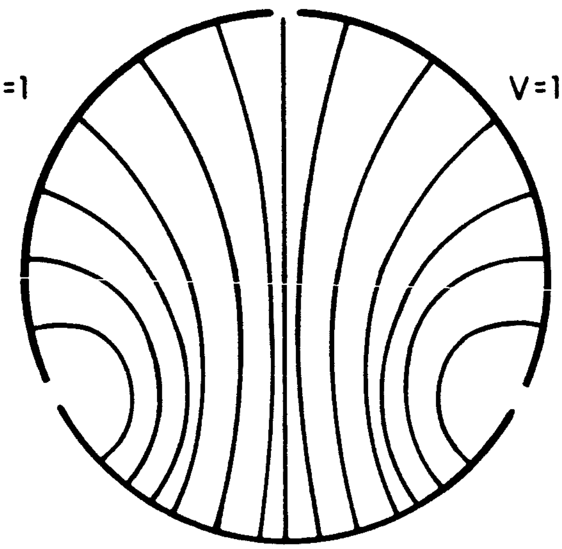
providing a qualitative indication since effects such as change of secondary electron emission coefficient with cesium coverage and change of phosphor characteristics as cesium and sputtered stainless are deposited could change the ion current density-light output relationship.

In operation it was found desirable to operate the converter grid at approximately 100 volts negative to keep neutralizing electrons in the beam and to prevent stray electrons from reaching the phosphor and distorting the display.

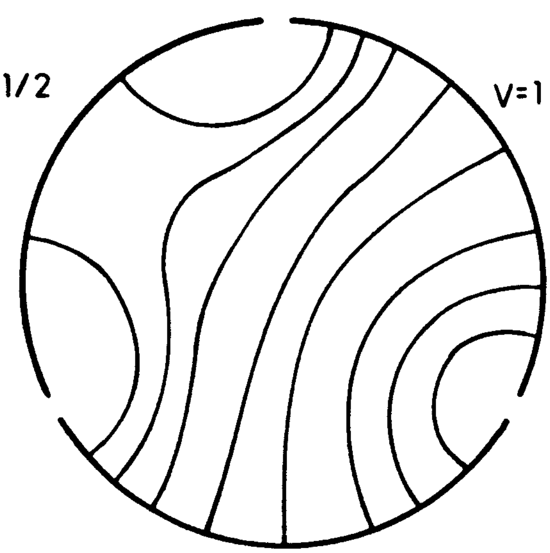
The deflection electrodes used on the thrustor are shown in Figs. 1 and 3. Slightly different versions were also tried with similar results. To avoid collecting neutralizing electrons from the beam, negative (or zero) potentials were applied to the deflecting electrodes. In general it was found that beams were distorted as well as deflected by the applied fields. At least two effects contribute to this distortion. The first is the nonuniformity of the electric field in the deflection region. Figure 7 shows qualitatively the electric field configuration produced by two arrangements of electrode potential. In Fig. 7a, two of the three electrodes are at zero potential while the third is at a negative potential. In Fig. 7b, one electrode is at zero potential, the second is at some negative potential and the third is at half that potential. In each case it is readily apparent that significant distortions will be produced if beam size or beam motion is comparable to the radius of the deflection array.

In experimental operation both configurations were tried. Different beam deflection patterns were produced but one was not significantly better than the other so the simpler one of Fig. 7a was adopted.

For beams with perveance of $10^{-8}$ amp/volt$^{3/2}$ or higher the more important distortions appear to be produced by space-charge forces. Application of negative voltage to one of the deflection plates




(a)




(b)

FIG. 7 ELECTRIC FIELD CONFIGURATIONS

creates a region of negative potential. This potential tends to exclude electrons from the beam which, before application of the deflecting potential, was fully space-charge neutralized. Exclusion of the electrons leaves a region with net positive charge. Enough net charge is created to terminate all the field lines leaving the negative electrode. The result then is that the applied electric field affects the side of the beam nearer the negative electrode while the far side is shielded by the plasma. This qualitative explanation agrees with observed beam deflection displays. A quantitative study would involve extensive analysis and numerical computation and is outside the scope of the present project.

In interpreting the beam displays the assumption was made that current density was constant over the fairly well defined beam pattern. Measurements of light intensity could have been made, but stability of the display instrumentation did not warrant it.

The procedure in making a beam deflection measurement was to photograph both the undeflected and deflected beam displays. Measurements were than made on each photograph to determine the pattern centroid. From the centroid shift and the distance from the midpoint of the deflection electrodes to the converter grid, the beam deflection angle was calculated.

In performance mapping Thrustor 1, measurements were made with deflection potentials of 50, 75, 100, 130, 150 and 200 volts. Corresponding beam deflection angles are plotted in Fig. 8. A linear fit to the first five data points is also shown. The 200-volt point was disregarded in making the linear fit since nonlinear terms appear to be important in this region. Typical display photographs and measurement patterns are shown in Figs. 9 and 10. In performance mapping Thrustor 2, deflection potentials for deflections in one-degree increments were taken from the straight line fit of Fig. 8; each deflection in each direction was held for 10 minutes. Measured deflection electrode currents are listed in Table III.

Table III

DEFLECTION ELECTRODE CURRENT

Thrustor 1

| Electrode Potential (Negative) | Electrode Current Microamperes | | |
|---|---|---|---|
| | $60^{\circ}$ | $180^{\circ}$ | $300^{\circ}$ azimuth |
| 50 | 12 | 18 | 12 |
| 75 | 16 | 15 | 12 |
| 100 | 10 | 18 | 8 |
| 130 | 12 | 15 | 15 |
| 150 | 10 | 55 | 12 |
| 200 | 17 | 24 | 20 |

Thrustor 2

| | | | |
|---|---|---|---|
| 18 | 5 | 6 | 6 |
| 37 | 5 | 3 | 6 |
| 56 | 7 | 4 | 8 |
| 73 | 10 | 6 | 8 |
| 93 | 12 | 8 | 10 |
| 112 | 20 | 9 | 13 |

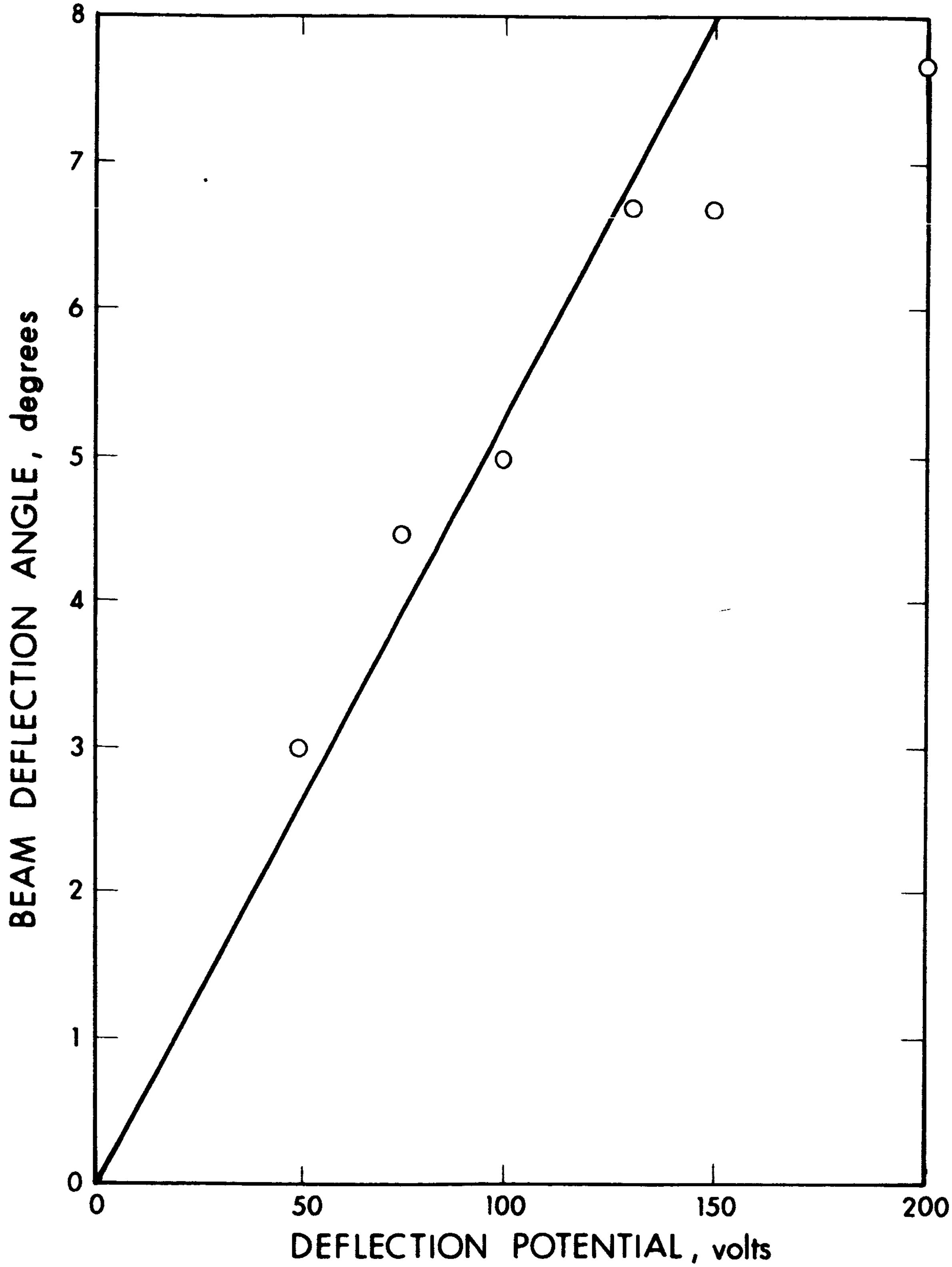
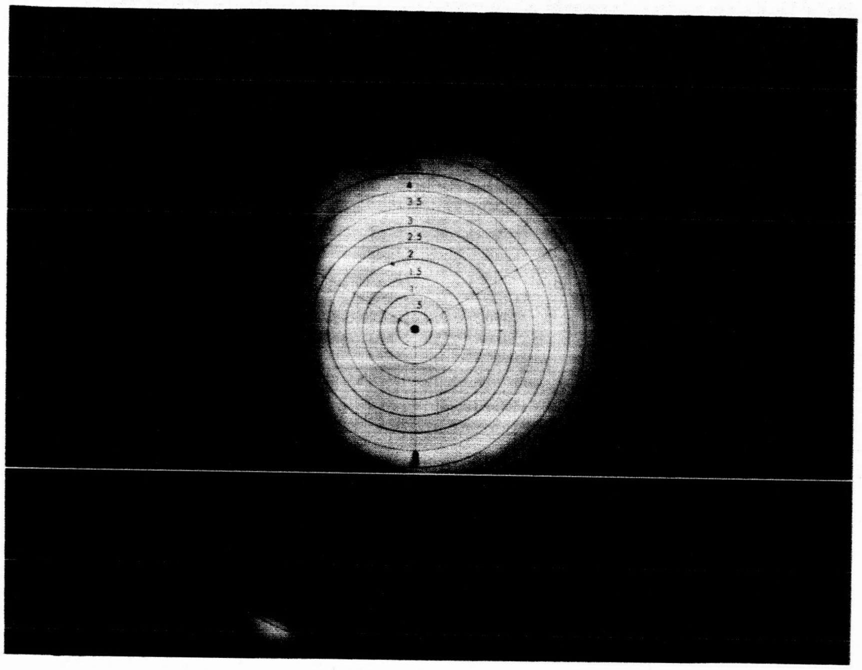
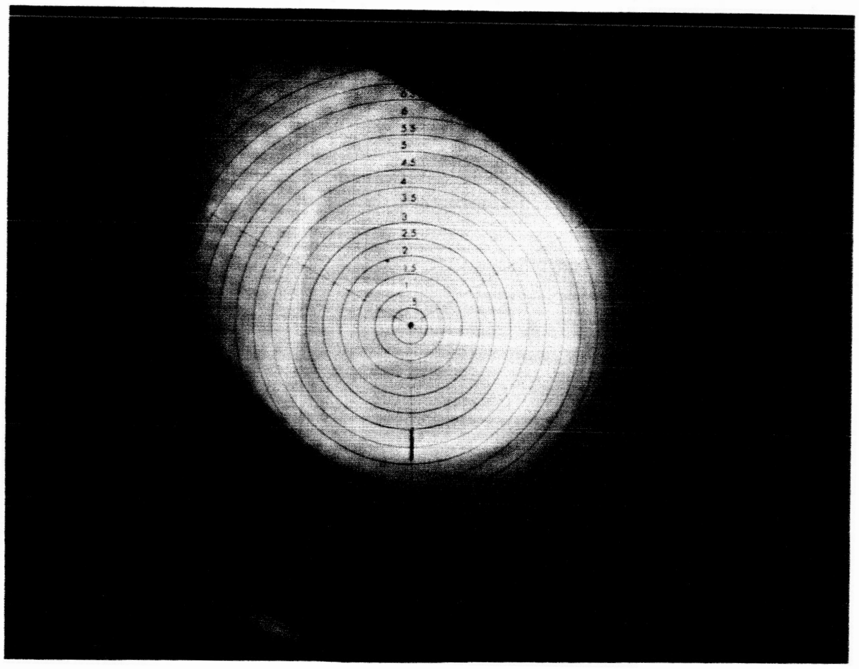



FIG. 8 BEAM DEFLECTION VERSUS DEFLECTION POTENTIAL



A. Undeflected Beam



B. Deflected Beam

FIG. 9 PHOTOGRAPHS OF FLUORESCENT BEAM DISPLAY

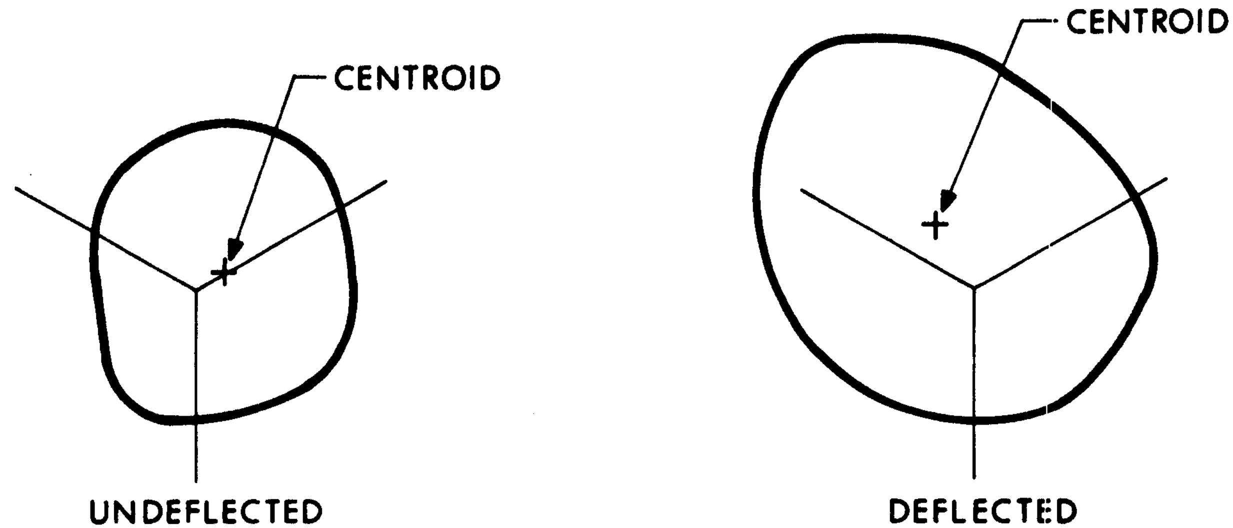



FIG. 10 BEAM DEFLECTION, MEASUREMENT

## 5. THRUSTOR ENVIRONMENTAL TESTING

In accordance with paragraph II.C. of Exhibit "A" of Contract NAS3-7936, a μ-3d microthrustor (number 2) was vibrated as specified in Tables I and II of Goddard Space Flight Center Specification No. S2-0102, Revision C, dated 8-6-65. These specifications are reproduced in Appendix A of this report. The tests were begun on 23 May 1966 with exploratory sweeps in each axis to look for resonant modes. (The thrustor was the same as that shown in EOS drawing 706130, except that there was no porous rod in the reservoir and the rear half of the reservoir valve was left off.)

During this preliminary test the internal engine assembly exhibited a strong resonance at a frequency of approximately 60 Hz. (In the following statements the z-z axis is the thrustor axis of symmetry.) Specifically, the engine survived the schedule of Table I in the z-z and y-y axes. It also survived a sweep in the x-x axis with only 4 g programmed in the 17-150 Hz range. When the g force was increased to 7.5 in accordance with Table I, the amplitude of resonance was so severe that the feed tube-seal fitting weld (706125) fractured. Since visual observation of the resonant mode indicated that the internal engine assembly flexed considerably with respect to the ground ring, it was decided that the support assembly needed stiffening. This was accomplished by the strut assembly which remains on the engine. A tendency for the heat shielding to migrate along the feed tube during the z-z shake was observed. This was minimized by spot welding strips from the outermost shield to the support tubes. The feed tube was rewelded to the seal fitting and the engine reassembled. The modified engine was then given a full test (both Tables I and II) on 1 June 1966.

The sinusoidal vibration showed that the resonance had been increased in frequency (appearing at about twice the original frequency) and essentially eliminated (no deleterious effects occurred). The deflection plates have strong resonances but there is no change in their relative geometry after the vibration ceases. (The resonances occur at 130 Hz in the y-y and x-x axes, and at about 100 and 400 Hz in the z-z axis.)

The random frequency test (Table II) produced no new results except that 2 of the 3 restraining straps on the heat shield fatigued and broke off. Although it is not clear that these are really needed, they could easily be strengthened.

In summary, the $\mu$-3d microthrustor (number 2 modified as described above) successfully passed the referenced vibration tests.

## 6. THRUSTOR SYSTEM OPERATIONAL PROCEDURES

### 6.1 Reservoir Filling

Since the thrustor assemblies are shipped from EOS with dry (unfilled) reservoirs; it will be necessary to fill these with enough cesium to permit operation for the anticipated period of thrusting. (The capacity of a reservoir is about 30 grams of cesium. One gram of cesium can provide about 0.2 amp-hour of ion beam.)

The following operation should be done in an inert-gas (e.g., argon, nitrogen) atmosphere. The reservoir is rather simply filled by placing the engine in a horizontal position, unscrewing the rear half of the valve assembly, and introducing cesium through the hole in the valve body. The rear half of the valve is then rethreaded onto the reservoir and the engine is ready for mounting.

The porous nickel wick can be wetted with cesium at this point if desired. Care must be taken in subsequent handling of the engine, since only surface tension forces keep the cesium from migrating into the feed tube and up to the ionizer. The process for wetting the wick is as follows: With the reservoir in a horizontal position, a thermocouple connected to the vaporizer, and still in an inert-gas atmosphere, heat is applied to the reservoir until the vaporizer temperature, $T_{vap}$, reaches 200°C. It is held at this temperature for approximately one-half hour and then allowed to cool to room temperature before mounting the engine. Experience at EOS suggests that the wick wetting procedure is best carried out after the engine is mounted in the vacuum system in which it is to be run. For that procedure see Section 6.2, Engine Mounting.

### 6.2 Engine Mounting

The μ-3d microthrustor is provided with a ground ring which is to be used for mounting the engine in a vacuum system. (For mounting bolt center diameter, see EOS drawing C705818.) The engine should be mounted in a horizontal position, with the reservoir valve at the top and the heater leads toward the bottom.

After the engine is physically located, the electrical leads should be connected. It is suggested that at least No. 18 AWG size copper be used for this purpose--certainly for the heater leads, and preferably for the others.

The thermocouple terminal located on the vaporizer provides a mechanical connection for the thermocouple leads which are necessary for determining the vaporizer temperature, $T_{vap}$. This permits all leads to be broken at the engine. Since one end of the ionizer heater is brazed to the engine, it is necessary to connect a lead to the engine itself to complete the ac circuitry. This lead will be referred to as the engine common. It is normally fastened under one of the bolts on the engine-reservoir flange.

Means should be provided at this time for operating the reservoir valve. This valve is provided so that during chamber pump-down, the reservoir may be evacuated through it rather than through the porous wick. (Evacuation through a wet wick usually leads to pumping out some quantity of cesium through the ionizer. This can result in complete engine failure.) The valve has an actuating arm which extends approximately 1 inch toward the centerline of the engine. Moving this arm about 0.2 inch toward the reservoir moves a spring-loaded ball away from its seat in the valve and vents the reservoir.

This actuation can be accomplished by a rod projecting through a sliding shaft seal in the vacuum flange. (If a metal rod is used care must be taken that it does not short any leads or the ionizer power supply.)

Means should also be provided for wick wetting if this was not done earlier. A simple technique used successfully at EOS is that of electron-bombardment heating. A thermionic emitter is mounted below the reservoir and the ionizer power supply is used to provide the bombardment energy. The same procedure is followed as outlined in Section 6.1, Reservoir Filling.

All connections should be checked for tightness and electrical continuity at this same time. Cold heater impedances should be measured (if desired) and the location of all engine elements recorded. After the vacuum flange is closed, it is wise to check connections again for shorts to ground, to each other, etc. Open the reservoir valve (by pushing the arm toward the reservoir) before pumping down the system. While the system is pumping down, the console connections should be made.

### 6.3 Console Connections

There are twelve 15-foot leads which come from the power supply console. The six ac leads have an average impedance of 0.1075 ohm per lead. This resistance should be considered when determining the power delivered at their ends. All leads are labeled and color coded and should be connected to the engine according to the following table.

| Label | Color | Number | Connect to |
|---|---|---|---|
| ION. | Blue | 2 | Ionizer heater and engine common |
| VAP. | Yellow | 2 | Vaporizer heater and engine common |
| NEUT. | White | 2 | Neutralizer filament |
| POS. | Red | 1 | Engine common |
| NEG. | Green | 1 | Accelerator electrode |
| DEF. | Black | 4 | One to each deflection plate, one spare |

A comment on the last item is in order here. The DEFLECTION PLATE POWER SUPPLY is designed with four outputs. This permits operation of a deflection assembly as supplied on the present thrustors and also allows for operation of an array of four deflection plates.

The console provides a male twist-locking connection for accepting input power (115 Vac) which is then switched to all the modules when the ON button is pressed on the SYSTEM POWER panel. The console also provides an interlock which is activated by the door of the console and/or remotely by means of the plug so marked on the rear of the console. The plug has four pin connections. If pins 1 and 2 are disconnected, the high voltage circuit is opened. Opening the door on the console also opens this circuit by releasing the door-mounted switch connected in series with pins 1 and 2. If pins 3 and 4 are disconnected, the SYSTEM POWER circuit is opened and the entire console is shut down. The plug is supplied with pins 1 and 2 and 3 and 4 connected. Remote interlocking will necessitate breaking these connections and attaching the remote connections.

The console contains six modules which are labeled from top to bottom: NEUTRALIZER HEATER, IONIZER, VAPORIZER, POSITIVE POWER SUPPLY, NEGATIVE POWER SUPPLY, and DEFLECTION PLATES POWER SUPPLY. Each one is fused for 2 amps, has controlled variable output, and meters for current and voltage.

The NEUTRALIZER HEATER will supply about 50 ac watts and permits monitoring neutralizer heater voltage, $V_{nh}$, current, $I_{nh}$, and filament emission, $I_n$.

The IONIZER power supply will provide about 50 ac watts and permits monitoring ionizer heater voltage, $V_{ih}$, and current, $I_{ih}$.

The VAPORIZER power supply will provide about 25 ac watts and permits monitoring the vaporizer heater voltage, $V_{vap}$, and current, $I_{vap}$. Unlike the preceding power supplies, this one has an output which is a function of the dial setting plus a derived signal. This derived signal is taken from the net current flowing from the positive and negative high voltage supplies and is used as a measure of the ion beam current. This current flows through a resistor, developing a voltage which is balanced against the reference voltage created by the dial setting; the difference or error signal determines the output of the supply.

The POSITIVE POWER SUPPLY provides up to 5 kilovolts (at 3 mA) above ground and includes meters for monitoring the ionizer voltage, $V_+$, and current, $I_+$.

The NEGATIVE POWER SUPPLY provides up to 10 kilovolts (at 1 mA) below ground and includes meters for monitoring the accelerator electrode voltage, $V_-$, and current, $I_-$.

Each of the high voltage supplies has an OVERLOAD ADJUST which determines the maximum (3-15 mA) steady-state current flowing through that supply. If the current exceeds this maximum, the high voltage and vaporizer supplies are momentarily turned off. These supplies are then automatically turned back on. If the current overload still exists, the supplies will again be turned off. This cyclic operation will continue until the overload is cleared or a fuse is blown. Operating experience with the μ-3d thrustors at EOS indicates that this cyclic operation should rarely occur.

The DEFLECTION PLATES POWER SUPPLY provides about 750 volts at any one of four switched outputs, the other three being grounded. It also provides meters for monitoring the deflection voltage, $V_d$, and current, $I_d$.

All variable controls must be returned to zero before operating any power supply. This safety feature is provided on all modules except the vaporizer supply which is protected by being interlocked with the high voltage supplies. On the current supplies, it prevents burning out heaters due to flipping the ON switch while the control is set for high output. On the voltage supplies it prevents inadvertent application of immediately high voltages to (possibly) exposed electrodes.

If, for one reason or another, the line voltage is lost these variable controls must first be turned to zero and then returned to the previous value. (This is not true of the vaporizer control, however. It will function again as soon as the high voltages are reapplied.)

This description of the power supply console now allows for a discussion of some preliminary checks to be made before actual engine operation.

## 6.4 Preliminary Checks

The vacuum system should be down to $10^{-6}$ torr or better at this point. The reservoir valve should now be closed by removing the force from the actuating arm. Putting an ohmmeter between engine common and the sliding metal shaft (if one is used) permits determining when the valve is closed. Retract the shaft sufficiently to prevent sparking of the ionizer high voltage.

The positive and negative high voltages should now be set to the maximum values expected during operation. Any faulty wiring or leaks should show up at this time. Return the voltage to the values desired for initial operation--nominal values of $V_+ = V_- = 2$ kV are reasonable.

The neutralizer heater could be outgassed at this time. Simply heat until no pressure increase shows in the vacuum system. Return to zero.

The ionizer heater should now be turned on. Conservative operation suggests that the variable control be increased gradually, compensating for the change in resistivity as the rhenium conductor gets hot. For complete surface ionization, the temperature should be $1000^{\circ}C$, or better, on the ionizer. It is suggested that this temperature be monitored by pyrometer readings. However, operation at EOS suggests that an indicated input power of 14 watts or greater will be sufficient. Again, outgassing can be accomplished by going to slightly higher temperatures than normal operation dictates. The temperature should not go above $1500^{\circ}C$ in any case, since there are several engine materials which degrade above this temperature. Return to normal operating temperature and turn on the vaporizer power supply.

Again, conservative operation suggests that the vaporizer control dial be increased gradually. It only takes a few watts to heat the vaporizer to 300$^{o}$C, which will result in a beam current of about one milliamp. Since the vaporizer is controlled by a feedback loop, mild fluctuations in the current, $I_{vap}$, and voltage, $V_{vap}$, will indicate steady-state beam levels.

6.5 Engine Operation

Normal operation of the engine will consist of selecting a beam level with the vaporizer control, neutralizing (if needed) by varying the emission from the neutralizer, and deflecting the beam by applying voltage on one of the three plates. With a beam of a nominal 1 mA, 2 kV, the deflection sensitivity is approximately 0.05 degree/volt for this assembly. If other means of detecting deflection are not available, increasing the pressure momentarily to $10^{-5}$ torr with argon permits visual observation. Operating ion engines in metallic vacuum tanks usually results in self-neutralization of the beam. This is due to the copious supply of secondary electrons which are produced by beam bombardment of the metallic surfaces.

6.6 Shutdown Procedure

To terminate engine operation, the vaporizer control dial should first be turned to zero. The ionizer heater should not be turned off until the vaporizer temperature is below 150$^{o}$C. The reason for this is to ensure that all the cesium fed to the ionizer leaves it rather than collecting in the pores, as happens if the ionizer cools. This is not particularly harmful if the engine remains in the vacuum system, for the cesium will be driven off the next time the ionizer is first heated. But if the ionizer is exposed to the atmosphere while saturated with cesium it will probably be destroyed by the exothermic reactions cesium initiates.

After the vaporizer has cooled, the ionizer should be turned off, the neutralizer (if used) turned off, and all dc voltages turned off.

## 6.7 Engine Removal

Certain procedures should be followed in removing the engine from the vacuum system and from its mounting. First, good vacuum practice suggests that the system be "let up" to atmospheric pressure by admitting dry nitrogen or argon. Before letting in gas check that the actuating rod does not open the reservoir valve. An open valve at this point creates a pressure gradient along the wick which causes cesium to migrate into the (lower pressure) feed tube volume. This can lead to the same deleterious effects mentioned in Section 6.2, Engine Mounting.

Removing or replacing the engine on the mounts is rather simple, since all connections may be broken at the engine. Care should be exercised in manipulating the heater connections. These are rather delicate and become more so after being at elevated temperatures for long periods of time.

If the engine is being removed with cesium remaining in the reservoir, care should be taken to handle it in the horizontal position. If it is not to be returned to the vacuum system for some time, it should be stored in an inert gas atmosphere. An engine with a dry reservoir may be handled without regard for these precautions.

# 7. POWER SUPPLY CONSOLE FUNCTIONAL TEST PROCEDURES

## 7.1 System Power Panel

1. Make a point-to-point continuity check of the completed chassis with an ohmmeter.
2. Connect a jumper wire between TB500-9 and -10 and between TB500-11 and -12.
3. Depress ON button (S502). Indicator light (1501) should be lit.
4. Measure 115 Vac between TB500-3 and -4, between TB500-5 and -6, and between TB400-7 and -8.
5. Momentarily interrupt 115 Vac line. Indicator light should be off, and voltage measurements in step 4 should be zero.

6. Repeat step 3.
7. Depress OFF button (S501). Indicator light should be off.

7.2 Neutralizer Panel

1. Make a point-to-point continuity check of completed chassis with an ohmmeter.
2. Set Variac (VT-601) to ZERO and place power switch (S-601) to off position.
3. Connect a 1Ω, 25W resistor to output leads.
4. Connect line cord to 115 Vac.
5. Place power switch to ON. Indicator light (I601) should be lit.
6. Slowly increase Variac until voltmeter (M601) and ammeter (M602) read approximately 5 volts and 5 amps.
7. Momentarily interrupt 115V line. Indicator light should be off and voltmeter and ammeter should read zero.
8. Return Variac to zero; indicator light should be lit.
9. Place power switch to OFF.
10. Remove 1Ω, 25W resistor.
11. Connect a 1.5V battery in series with a 1.8KΩ, 1W resistor. Connect positive lead to either output lead and the negative lead to the chassis.
12. Read approximately 0.75 milliampere on ammeter (M603).

7.3 Ionizer Panel

1. Make a point-to-point continuity check of the completed chassis with an ohmmeter.
2. Set Variac (VT701) to ZERO and place power switch (S701) to the OFF position.
3. Connect a 1Ω, 25W resistor to the output leads.
4. Connect line cord to 115V.
5. Place power switch to ON. Indicator light (I701) should be lit.
6. Slowly increase Variac until voltmeter (M701) and ammeter (M702) read approximately 5 volts and 5 amps.

7. Momentarily interrupt 115 Vac line. Indicator light should be off and voltmeter and ammeter should read zero.
8. Return Variac to zero; indicator light should be lit.
9. Place power switch to OFF.

7.4 Vaporizer Panel

1. Make a point-to-point continuity check of the completed chassis with an ohmmeter.
2. Connect a jumper wire between K401 pin 1 and TB400-1.
3. Place power switch to OFF, set front panel dial (R404) to zero, and set R415 fully counterclockwise.
4. Connect line cord to 115V.
5. Place power switch (S401) to ON. Indicator light should be lit, and voltmeter (M401) should read approximately 5 volts.
6. Adjust R414 clockwise until voltmeter reads zero.
7. Connect a 1Ω, 25W resistor between output leads.
8. Connect a 0-10 volt dc power supply in series with a 10 KΩ, 1W resistor. Set output voltage at zero. Connect positive lead to TB400-1 and the negative lead to TB400-2.
9. Adjust front panel dial until voltmeter and ammeter (M402) read approximately 3 volts and 3 amps.
10. Adjust 0-10V power supply until voltmeter and ammeter read approximately 2 volts and 2 amps.
11. Place power switch to OFF.

7.5 Positive Power Supply Panel

1. Make a point-to-point continuity check of the completed chassis with an ohmmeter.
2. Set Variac (VT201) to zero, set overcurrent adjust (R201) fully clockwise and place power switch to OFF.
3. Place a jumper wire between TB200-3 and -7, between TB200-6 and the chassis. Connect a 1 megohm, 10W resistor from the output lead to the chassis.
4. Apply 115V between TB200-1 and -2.

5. Place power switch to ON. Indicator light should be lit.
6. Slowly increase Variac until voltmeter (M201) and ammeter (M202) read approximately 3000 volts and 3 milliamperes.
7. Turn overcurrent adjust counterclockwise until power supply oscillates between on and off condition.
8. Momentarily interrupt 115V line. Indicator light should be off, voltmeter and ammeter should read zero.
9. Return Variac to zero. Indicator light should be on.
10. Place power switch to OFF.

7.6 <u>Negative Power Supply Panel</u>

1. Make a point-to-point continuity check of the completed chassis with an ohmmeter.
2. Set Variac (VT301) to zero, set overcurrent adjust (R301) fully clockwise, and place power switch (S301) to OFF.
3. Place a jumper wire between TB300-5 and -7, between TB300-6 and the chassis. Connect a 4 megohm, 4W resistor between output lead and the chassis.
4. Apply 115V between TB300-1 and -2.
5. Place power switch to ON. Indicator light should be lit.
6. Slowly increase Variac until voltmeter (M301) and ammeter (M302) read approximately 4000 volts and 1 milliampere.
7. Momentarily interrupt 115V line. Indicator light should be off, voltmeter and ammeter should read zero.
8. Return Variac to zero. Indicator light should be lit.
9. Place power switch to OFF. Remove 4 megohm, 4W resistor.
10. Connect voltohmmeter between output lead and chassis. Set to 12 milliampere scale.
11. Repeat step 5.
12. Slowly increase Variac until meter reads approximately 3 mA.
13. Turn overcurrent adjust counterclockwise until power supply oscillates between on and off condition.
14. Place power switch to OFF.

7.7 Deflection Plate Power Supply Panel

1. Make a point-to-point continuity check of the completed chassis with an ohmmeter.
2. Set Variac (VT101) to zero, set selector switch (S102) to 1, and place power switch (S101) to OFF.
3. Connect four 4.7 megohm, 2W resistors from TB101-1, -2, -3, and -4 respectively to the chassis.
4. Connect line cord to 115 Vac.
5. Place power switch to ON. Indicator light (I101) should be lit.
6. Slowly increase Variac until voltmeter (M101) and ammeter (M102) read approximately 500 volts and 95 microamperes.
7. Rotate selector switch from 1 through 4. Voltmeter and ammeter should read approximately the same on the four positions.
8. Momentarily interrupt 115 Vac line. Indicator light should be off, voltmeter and ammeter should read zero.
9. Return Variac to zero. Indicator light should be lit.
10. Place power switch to OFF.

7.8 Console Interlock System

1. Make all chassis interconnections per print No. 706180.
2. Set all power switches to OFF, set all front panel controls to zero or fully counterclockwise position.
3. Connect the positive power supply and the negative power supply output leads to the chassis.
4. Apply 115 Vac to J502, console input power.
5. Depress ON button on the system power panel. Indicator light should be lit.
6. Set power switches to ON on the vaporizer, positive and negative power supply panels. Indicator lights should be lit.

7. Remove short between P501-3 and -4. All indicator lights should be off. Replace short.
8. Repeat step 5.
9. Remove short between P501-1 and -2. Vaporizer, positive and negative power supply indicator lights should be off.
10. Replace short between P501-1 and -2. Indicator lights should be lit.
11. Open door of console; indicator lights should be off.
12. Close door of console; indicator lights should be lit.
13. Slowly increase Variac on negative power supply to approximately 1 mA on the ammeter.
14. Slowly increase Variac on the positive power supply until it oscillates between on and off conditions. Vaporizer indicator light and negative supply should also oscillate between on and off conditions.
15. Decrease positive supply Variac until ammeter reads approximately 1 mA on ammeter.
16. Increase negative supply Variac until it oscillates between on and off conditions. Vaporizer indicator light and positive supply should also oscillate between on and off condition.
17. Depress OFF button on system power panel. All indicator lights should be off.

## 8. CONCLUSIONS AND RECOMMENDATIONS

It has been concluded that small angle deflection of low perveance (approximately $10^{-8}$ amp/volt$^{3/2}$) ion beams is feasible although the information presently available on ion beam deflection could best be described as semiquantitative. If ion microthrustors are to be used in satellite attitude control and station keeping systems, it would be desirable to have more detailed information in several areas:

1. Beam deflection mechanisms and space-charge limitations
2. Spreading of deflected and undeflected beams

3. Beam deflection versus deflecting potential relationship
4. Correlation between direct measurements of axial and lateral thrust components and electrical measurements of beam deflection and thrustor operating parameters

APPENDIX A

Tables I and II of Goddard Space Flight Center Specification No. S2-0102, Revision C, dated 8-6-65, entitled "Applications Technology Satellite Project Technical Requirements".

Table I

Sinusoidal Vibration Schedule
Component Design Qualification

| Frequency | Axis | Level (0-Peak G) |
|---|---|---|
| 10-25<br>25-250<br>250-400<br>400-2000 | Thrust<br>Z-Z | $\pm$ 2.3<br>$\pm$ 11.5<br>$\pm$ 18.5<br>$\pm$ 7.5 |
| 10-17<br>17-250<br>250-400<br>400-2000 | Lateral<br>X-X<br>and<br>Y-Y | .50 in. double ampl.<br>$\pm$ 7.5<br>$\pm$ 15.0<br>$\pm$ 7.5 |

Table II

Random Excitation Vibration Schedule
Component Design Qualification

| Frequency | Acceleration (g-rms) | Test Duration | PSD Level ($g^2$/cps) |
|---|---|---|---|
| 20-150 | 9.2 | 4 Min. per axis | 0.0225 |
| 150-300 | | | Increasing from 150 cps at a constant rate of +3.0 db per octave. |
| 300-2000 | | | 0.045 |