NASA TECHNICAL MEMORANDUM

NASA TM X-52045

NASA TM X-52045

N64-28081
(ACCESSION NUMBER)
20
(PAGES)
TMX-52045
(NASA CR OR TMX OR AD NUMBER)

(THRU)
/
(CODE)
27
(CATEGORY)

FACILITY FORM 602

EFFECT OF THRUSTOR ARCING ON ION ROCKET SYSTEM DESIGN

OTS PRICE

XEROX $ 1.60ph.

MICROFILM $

by John B. Stover
Lewis Research Center
Cleveland, Ohio

TECHNICAL PREPRINT prepared for Electric Propulsion Conference sponsored by the American Institute of Aeronautics and Astronautics
Philadelphia, Pennsylvania, August 31 - September 2, 1964

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1964

TECHNICAL MEMORANDUM

EFFECT OF THRUSTOR ARCING ON ION ROCKET SYSTEM DESIGN

by John B. Stover
Lewis Research Center
Cleveland, Ohio

TECHNICAL PREPRINT prepared for

Electric Propulsion Conference
sponsored by the American Institute
of Aeronautics and Astronautics
Philadelphia, Pennsylvania, August 31 - September 2, 1964

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

E-2669

EFFECT OF THRUSTOR ARCING ON ION ROCKET SYSTEM DESIGN

by John B. Stover

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

28081

Arcing between the electrodes of an ion rocket thrustor is investigated for the effect it will have on the overall design of ion rocket systems. The effect of generator, transformer, and inserted impedances on system stability and efficiency, and on operating lifetime of thrustor components are considered. Rate of arcing, preferential arc paths, speed of arc interruption, and response of thrustors to voltage transients are also discussed. The study indicates that arcing is a system hazard and that arcing rates are of prime importance in the design and development of thrustors, thrustor arrays, and system components. Two system models for reducing the hazard are proposed, based on principles developed herein, published data, and experience available from operation of a nine-module electron-bombardment thrustor array. Experimental investigation of these models is presently underway.

AUTHOR

INTRODUCTION

Significant parameters for comparing ion rocket systems are weight, efficiency, and operating life. These parameters are affected by interactions between thrustors and connected electrical equipment.

It is therefore necessary to consider entire systems in order to guide research and development on system components. The purpose of this paper is to discuss the influence of arcing on the integration of an electric power system with a number of electrostatic thrustor modules, with particular reference to the characteristics and requirements of the electron-bombardment thrustor.

Experience indicates that the occurrence of short-circuit arcs between thrustor accelerating electrodes can be a hazard to the entire electric power system as well as to the thrustors. A total of 100 to 1000 such arcs may occur during a 200-day mission. Short-circuit current, which exceeds normal load current, can cause overheating of electrical winding insulation and abnormally high electromagnetic bending forces between conductors. Rectifiers can be overheated and erosion will occur at the foot of the arc. Furthermore, short-circuits can lead to unstable operation of both the powerplant and the thrustors. Elimination of the arcing hazard is feasible, but can exact penalties in weight and efficiency. It appears that the arcing hazard will be dominant in determining the design of the electric power system.

In this paper the characteristics of thrustors and power system elements will be considered first. Next, system problems that arise because of thrustor arcing will be illustrated by discussion of a rudimentary ion rocket system. Finally, two system models that overcome these problems will be proposed.

SYSTEM ELEMENTS

Thrustors

An ion thrustor acts upon a low-mass-flow stream of vaporized propellant to produce a high velocity exhaust jet. Figure 1 is a diagram of the parts of an electron-bombardment thrustor connected to the required power supplies. Voltages and currents are shown for a jet (beam) power of 2 kilowatts at a specific impulse of about 5000 seconds (with mercury propellant). Vaporized propellant is introduced into a manifold. From there it flows through a distributor baffle into a chamber which contains a hot filament and a cylindrical anode. An electron current, constrained suitably by an axial magnetic field (provided by permanent magnets, not shown), flows between the filament and anode and ionizes a portion of the propellant stream by collision. Propellant ions diffuse downstream to an electrode system. This electrode or extraction system is composed of a positive screen electrode and a negative accelerator electrode, which are spaced and proportioned so that the electric field accelerates the ions in a substantially axial direction without appreciable interception by the electrodes. Electrons emitted from a heated neutralizer mix with the accelerated ions to form an electrically neutral high-velocity exhaust jet.

When a short-circuit occurs between thrustor screen and accelerator electrodes, ion acceleration, and hence thrust, is reduced drastically. Reference 1 shows that should the high-voltage positive screen electrode or thrustor body be short-circuited to ground, a large fraction of the positive ion beam current would be intercepted by the high-voltage negative accelerator electrode. If the accelerator electrode short-circuited to ground most of the electrons emitted by the neutralizer would backstream to the screen electrode. This electron current is a nonthrust producing power load on the positive high voltage supply that can exceed the thrust producing power of the ion beam.

The general features of breakdown and arcing between thrustor electrodes have been described in reference 2. Two types of arcing were observed. The more frequent type was a self-extinguishing, or "chopped" arc. This was a low-current arc which extinguished because the rate of metal vaporization at the negative electrode was not sufficient to maintain a minimum metal vapor density between electrodes required for conduction. The less frequent type of arc persisted and operation of a circuit interrupter was required to extinguish the arc and re-establish normal electrode potentials. It was concluded that films of contaminants present on the electrodes probably provided the additional material required in the interelectrode gap to sustain these arcs. The total rate of arcing of both types was not established, but was at least twice the rate of sustained arcing which was between 0.04 and 4.0 arcs per hour during operation in vacuum facilities. Data with other vacuum and electrode conditions, summarized in reference 3, show that more than 30,000 volts is required to break down a 2-millimeter vacuum gap. From this, it might be assumed that there would be no thrustor breakdown during operation in the "hard vacuum" of space. This is not necessarily true because the material and conditioning of the electrodes are as important in determining breakdown strength in vacuum as is the background pressure. Reference 4 shows that breakdown can occur from micrometeorite impact during space flight; however, the rate of breakdown occurrence from micrometeorites has not yet been determined. Therefore, the total rate of thrustor arcing in space from all causes is not yet predictable.

Reference 5 shows that arc erosion is proportional to arc current magnitude and duration. Based upon this reference, calculation of arc erosion of a molybdenum accelerating electrode of a 20-centimeter electron-bombardment thrustor shows that surprisingly large arc currents may be tolerated. For example, it is estimated that an 840-ampere arc persisting for 0.1 second would erode 0.05 percent of the electrode material in a 20-centimeter-diameter electron-bombardment thrustor. Arc erosion will therefore probably not be a major problem in space flight.

Reference 6 shows that for many proposed ion rocket missions, jet power on the order of hundreds of kilowatts, at a specific impulse of about 5000 seconds, is desired. Present electron-bombardment thrustors produce about 2 kilowatt jet power at this specific impulse. If beam power remains limited to a few kilowatts, or even tens of kilowatts per thrustor, ion rocket missions can still require arrays of hundreds of thrustor modules.

Figure 2 is a graph of the arcing rate of an array of 2 kilowatt jet power thrustors plotted against total jet power. Curves are shown for an individual thrustor arcing rates of 0.04 arcs per hour (the present minimum rate experienced in the laboratory and reported in ref. 1) and assumed reductions of this rate by factors of onetenth and one-hundredth. A reduction of two orders of magnitude would result in between 0.02 and 0.2 short-circuits per hour on the array, depending upon the total jet power. For a 200-day mission, the total number of short-circuits would be between 100 and 1000.

Power System

A nuclear-turboelectric system capable of hundreds of kilowatts power output could have a single generator delivering three-phase current, alternating at 1000 cycles per second, at a phase voltage of 1000 volts. During a period of short-circuit, and also after current interruption, the power output of the generator would be abnormal; consequently, there could be fluctuations in angular speed of the turbogenerator. Also, if the generator magnetic field current were supplied through rectifiers from the main generator terminals, generated voltage would tend to decrease. Whether or not the powerplant would remain stable during periods of large output power fluctuation is not yet known.

For the specific impulse range of interest, a major part of the generator output must be transformed to higher voltages and rectified before it can be converted to jet power by the thrustors. Much of the remaining power must be transformed to lower voltages for use in the thrustor ion chambers, cathodes, and neutralizers. Consideration of transformer weight variation with power rating shows that a minimum number of power supplies will be essential for a lightweight high-power ion thrustor system. Figure 3 shows the effect of transformer output on transformer specific weight based upon well-known similarity relationships. For example, two hundred 2 kilowatt transformers would weigh at least four times as much as one 400 kilowatt transformer and, because loss per unit weight is assumed constant, transformer losses would be four times as large. Assuming a ratio of 10 to 1 between powerplant and transformer specific weights and equal transformer losses, use of a multiplicity of transformers could result in a total transformer weight as high as one-half of the powerplant weight.

Alternating or direct current circuit breakers required to interrupt short-circuit current probably will be of the sealed vacuum type, similar to those now being developed. Ideally a-c short-circuit current can be interrupted after one period of current alternation; actually the current may not be interrupted until several cycles have been completed. Direct current short-circuit current, up to 10 amperes, can be interrupted after a comparable period. A period of at least 0.01 second will be required to reclose the circuit breaker.

Rudimentary System

Figure 4 shows a rudimentary ion rocket system. It consists of an array of thrustors connected in parallel to a minimum number of power supplies. Consideration of this system will illustrate the problems of ion rocket system design that arise because of the occurrence of short-circuits.

For simplicity, accelerator electrode potential has been chosen equal to the thrustor screen potential, contrary to the case shown in figure 1. Common ionization power supplies will interconnect the screen electrodes and anodes of the thrustor modules. Therefore a common propellant manifold, which will also interconnect the screen electrodes may be used.

The initial result of short-circuit arcing between electrodes of any thrustor module will be that total beam current (which was originally divided among the thrustors) will flow between the arcing electrodes. Maximum a-c current will flow during the first cycle after short-circuit, and estimates of impedances indicate it will probably be about four-times rated current. The d-c current will rise correspondingly to about four-times normal total beam current. Estimates of impedances also indicate that generator terminal voltage will decrease to less than half its normal value, with the result that the ionization discharges in all thrustors will tend to extinguish. Opening of either circuit breaker I or III (fig. 4) to extinguish the arc current will drop almost all generator load which may result in the entire powerplant becoming unstable. In addition, opening of circuit breaker I will extinguish the ionization discharges in all thrustors and require restarting, which will tend to shorten thrustor operating lifetime. Opening of circuit breaker III will result in over-voltages which will also tend to shorten thrustor operating lifetime. Opening of circuit breaker II will result in a backstreaming current of electrons between the neutralizer emitters (not shown on fig. 4) and the screen electrodes of all thrustors. It is also possible that short-circuit arcs may occur between a screen electrode and a neutralizer emitter and require operation of either circuit breaker I or III. It is obvious that the short-circuit current magnitude should be limited - if possible to only a few percent above normal load current - to protect the generator, transformer, and rectifiers from the effects of excessive current, and to prevent over voltages that will tend to shorten thrustor component operating lifetimes.

Short-circuit current could be limited by inserting a resistor in the positive d-c circuit. However, this would result in excessive power loss during normal operation of the array. A series resistance equal to the load resistance of the array would be required to limit short-circuit current between the positive d-c circuit and ground to two-times total beam current. During normal operation, power loss in the resistor would equal the jet power of the array. Even greater power loss would result from inserting sufficient resistance to limit short-circuit current between electrodes to two-times normal beam current. (Insertion of inductors to limit short-circuit current would require a large increase in kilovolt-ampere rating of the main transformer and/or the generator, and therefore a large increase in equipment weight.)

Insertion of individual resistors between thrustor modules and the d-c positive circuit could limit thrustor short-circuit current to the total array beam current with continuous power loss of 1 percent of jet power. However, individual resistors cannot be effective with either a common anode power supply for all thrustors, or with a common propellant manifold. A common anode supply will connect thrustor bodies and screen electrodes together through the plasma of the thrustor modules while a common propellant manifold will connect them directly.

It follows that it will be desirable to limit short-circuit current between electrodes by insertion of resistance in the negative d-c circuit. Furthermore, because positive circuit to ground short-circuit current can be limited only at the expense of continuous power losses, the array should be designed to prevent this type of short-circuit.

Normal accelerator impingement current is about 1 percent of beam current. Therefore, a resistance of 50-times load resistance of the array inserted in the negative d-c circuit would result in a continuous power loss of about a half percent of jet power. For a 400 kilowatt, 4000 volt thrustor array this resistance would be 2000 ohms and would limit power system current to 100 amperes normal beam current plus 4 amperes resistor current during a short-circuit between electrodes. However, when the accelerator electrodes are disconnected, following short-circuit, they will float near ground potential and upon reconnection the ion interception current will be several times normal. The voltage drop across the series resistor would then be several times normal and the accelerator potential will not be re-established because of excessive interception current. Thus, too many accelerator electrodes connected to a single current-limiting resistor can result in failure to re-establish normal electrode potential following a short-circuit interruption. In addition, following interruption, electron backstreaming could possibly occur from the neutralizer emitters to a large number of screen electrodes.

This would seem to increase the risk of arcing between the positive d-c circuit and ground, which is undesirable.

Proposed System Models

The system models shown in figures 5 and 6 are consistent with the principles developed thus far. Both have sufficient resistance inserted between the accelerator electrode of each thrustor module and the negative d-c circuit to limit current in the power system to within a few percent of total beam current. In figure 5, d-c vacuum circuit breakers are also inserted to interrupt short-circuits between thrustor electrodes. In figure 6 the inserted resistance is large enough to limit current to a small value which will be unstable and will chop rapidly in the gap between thrustor electrodes thus not requiring d-c circuit breakers.

Both system models have negative potential shielding interposed between positive potential parts of the array and ground for the purpose of favoring short-circuits between the positive and negative d-c circuits and avoiding short-circuits between positive d-c circuit and ground. Both system models minimize the exposure of the positive electrodes to electron backstreaming, and therefore to arcing between the positive electrodes and neutralizer emitters, by permitting only the faulted accelerator electrode to rise to positive d-c potential following a short-circuit.

The principal problem presented by these system models is whether or not they will be compromised by electron backstreaming from the neutralizer emitters following short-circuit. In both models a faulted accelerator electrode will rise to positive d-c potential during short-circuit. All other thrustor electrode potentials will remain normal. If neutralization of the ion beams of the unfaulted thrustors continues, electron backstreaming to the faulted thrustor electrodes can be about equal to its normal beam current. However, if the remaining ion beams do not demand neutralization, the entire electron emission current would flow to the positive accelerator electrode of the faulted thrustor. Thrustor arc current would then be approximately equal to total beam current even though current through the current-limiting resistor was only a few percent of total beam current. In such a case the system model shown in figure 6 might not work. Arc current between thrustor electrodes could be too large to be self-extinguished rapidly. If the remaining ion beams will not demand neutralization, then the success or failure of the system model shown in figure 6 depends upon the rate of increase of backstreaming current to the positive accelerator electrode. A 2-ampere vacuum arc between refractory metal electrodes can chop after only a few microseconds which may be fast enough to prevent buildup of arc current to a magnitude that would be relatively stable.

The system model in figure 5 does not depend upon a low arc current magnitude between thrustor electrodes for successful operation. The d-c circuit breaker is required to interrupt only resistor current and reconnect the negative potential to the accelerator electrode. Nevertheless, backstreaming may increase the arc current (as described above) during the period between breakdown and reconnection of the negative potential to the accelerator electrode. Experimental investigation of both system models is currently being conducted at Lewis Research Center with a nine-module array of 20-centimeter-diameter electron-bombardment thrustors. Figure 7 is a photograph of the nine-module array.

CONCLUDING REMARKS

A lightweight ion rocket system for primary propulsion will probably require the paralleling of a number of thrustors on a minimum number of power supplies. Arcing in any thrustor module can affect the entire power system and all thrustor modules. Because it is estimated that several hundred short-circuit arcs may occur between thrustor electrodes during a 200-day mission, it will be necessary to protect system equipment and thrustors. For proper protection the system short-circuit current will have to be limited to within a few percent of total beam current and arc current in a single thrustor module will have to be interrupted with minimum disturbance to the other modules.

Two system models are proposed which will limit short-circuit current and interrupt arcs with minimum disturbance throughout the system. The first system model has a resistance and a d-c vacuum circuit breaker inserted in series with the accelerator electrode of each module. The second system model would limit thrustor arc current to a value that would be unstable between refractory accelerating electrodes. A d-c circuit breaker would not be required with the second system. The effect of electron backstreaming, from neutralizer emitters to accelerating electrodes, upon these system models is being investigated experimentally.

REFERENCES

1. Kerslake, William R.: Accelerator Grid Tests on an Electron-Bombardment Ion Rocket. NASA TN D-1168, 1962.

2. Stover, John B.: Electric Breakdown and Arcing in Experimental Ion Thrustor Systems. Paper 63057-63, AIAA, Mar. 1963.

3. Hawley, R.: Vacuum as an Insulator. Vacuum, vol. 10, no. 4, Sept. 1960, pp. 310-318.

4. Anon.: Final Report on Micrometeorite Impact Studies. Space Technology Labs., June 1964. (Contract NAS3-3569.)

5. Wilson, W. R.: High-Current Arc Erosion of Electric Contact Materials. Trans. AIEE, vol. 74, pt. III, no. 19, Aug. 1955, pp. 657-664. (See also Eng. Digest, vol. 16, no. 10, Oct. 1955, pp. 473-476.)

6. Mickelsen, William R., and Kaufman, Harold R.: Status of Electrostatic Thrustors for Space Propulsion. NASA TN D-2172, 1964.

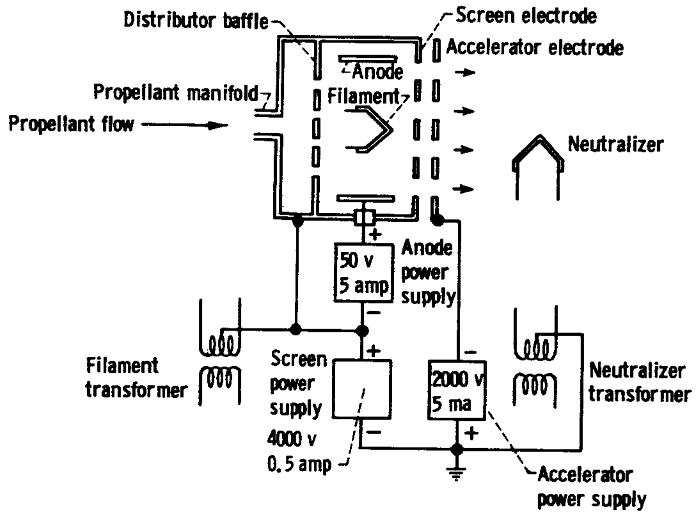


Figure 1. - Electron-bombardment thrustor and power supplies, 2 kilowatts.

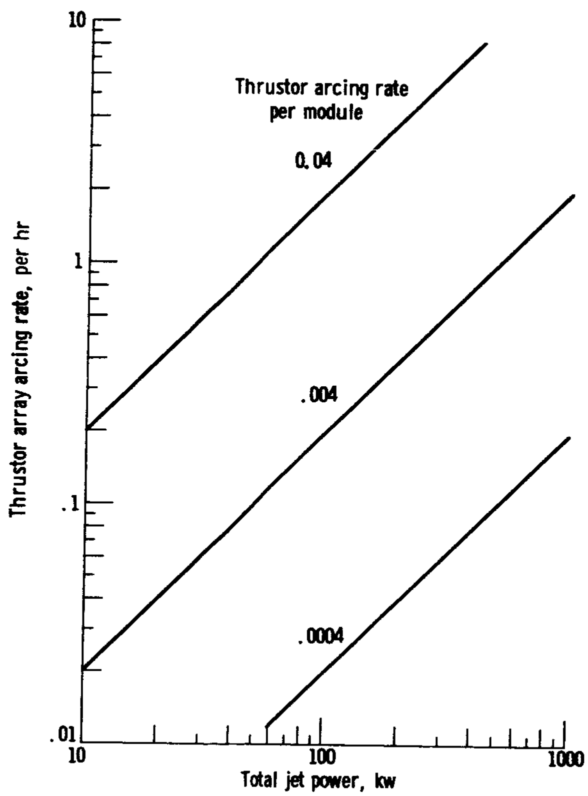


Figure 2. - Effect of total array jet power on system arcing rate for several thrustor arcing rates, 2 kilowatts jet power per module.

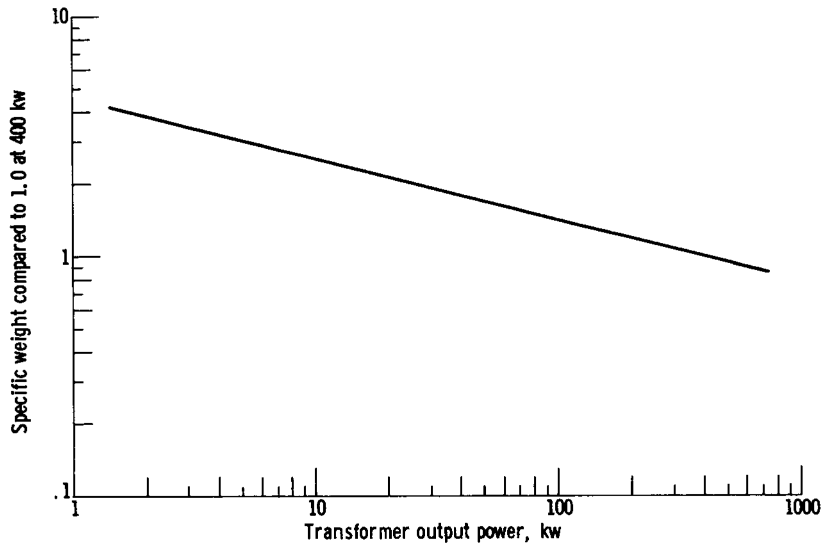


Figure 3. - Variation of transformer specific weight with power output.

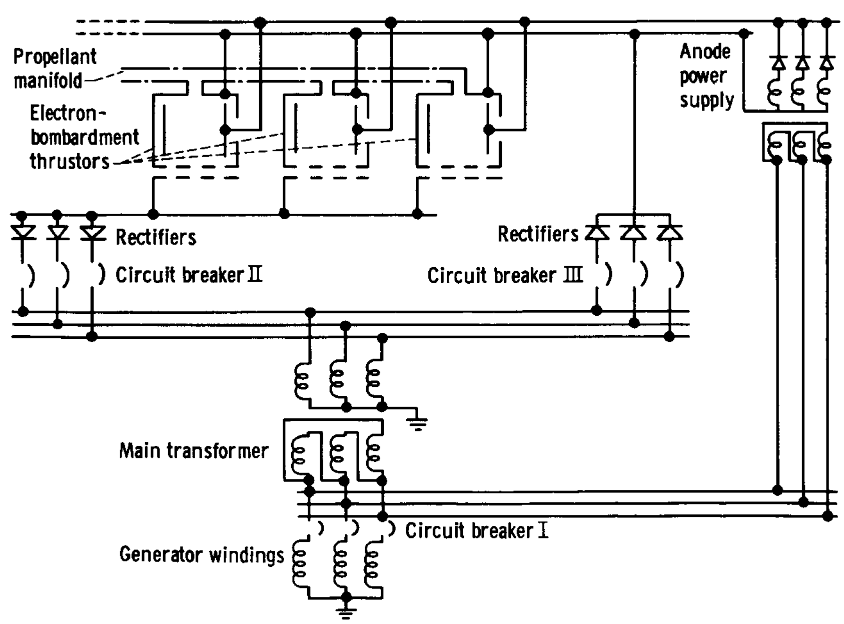


Figure 4. - Rudimentary ion rocket system.

E-2669

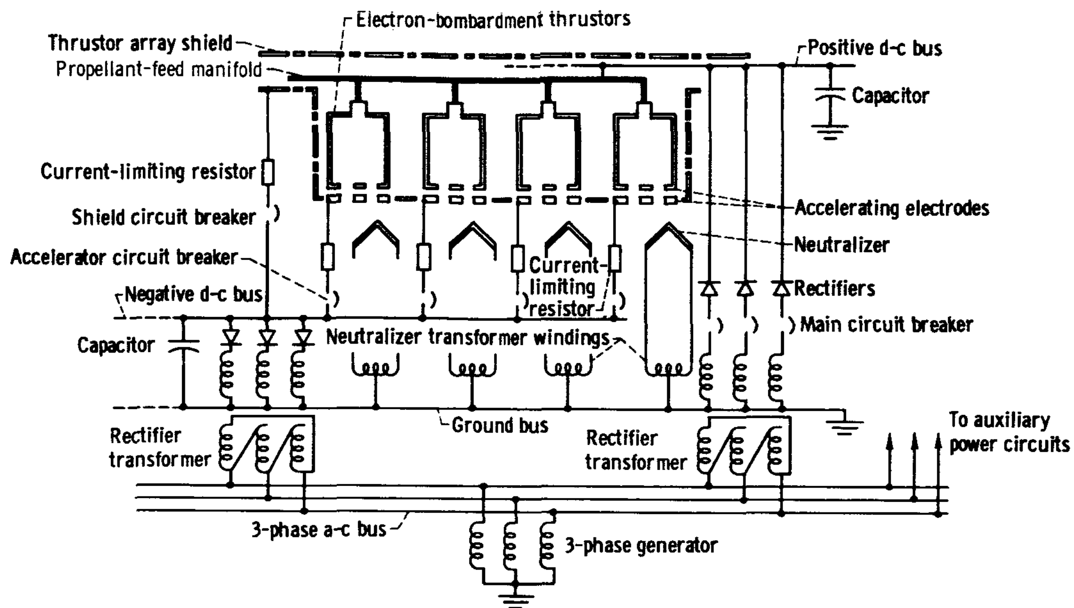


Figure 5. - Electron-bombardment ion rocket electrical system with current-limiting resistors and accelerator circuit breakers.

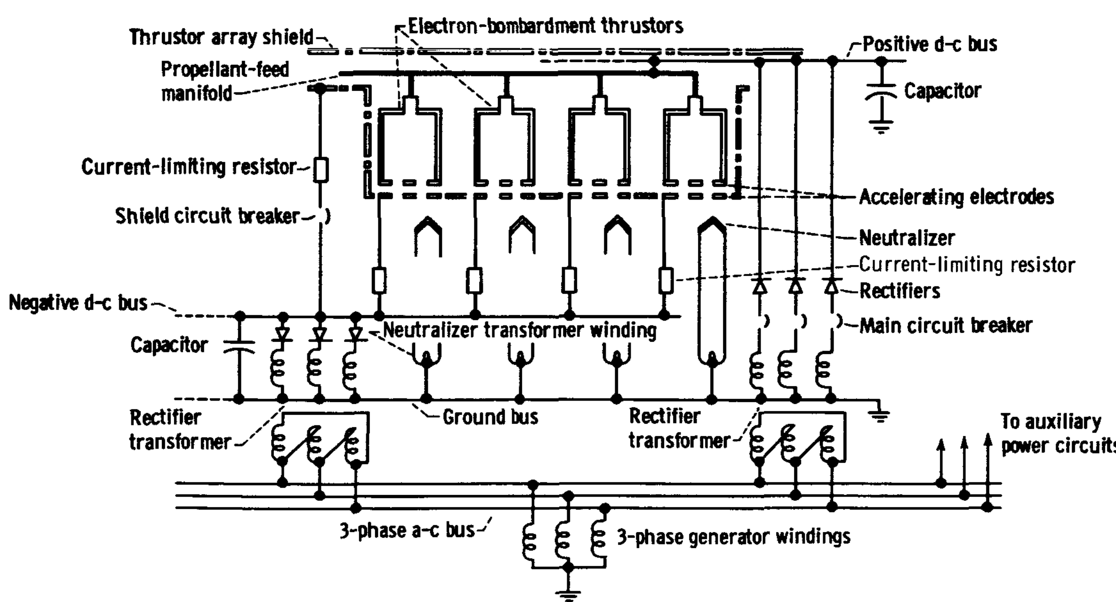
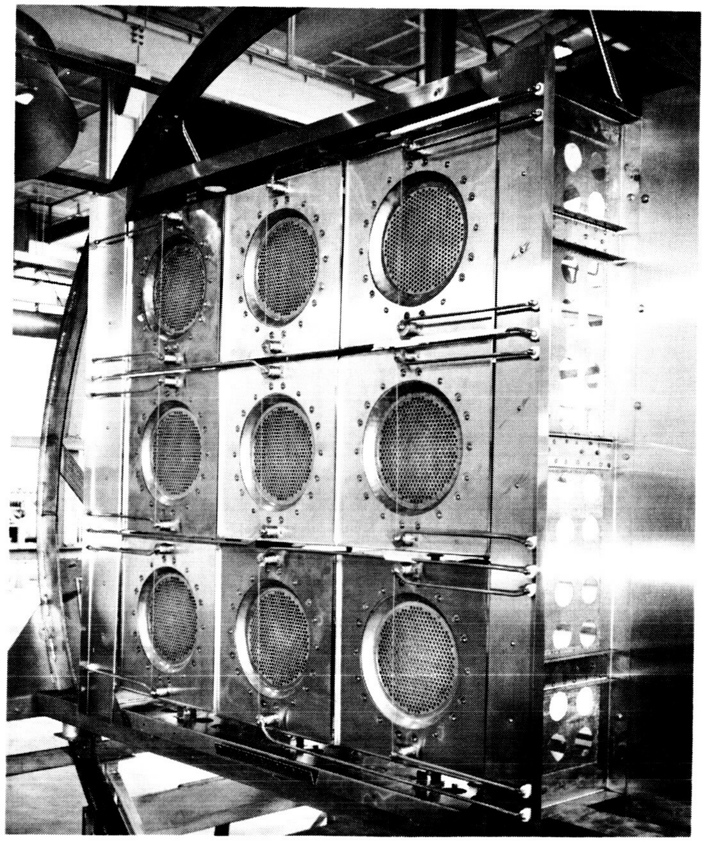


Figure 6. - Electron-bombardment ion rocket electrical system with high resistance in accelerator circuit to prevent stable arcs.



C-66676
Figure 7. - Nine-module array of electron-bombardment (Mercury) thrustors operated in a 25-foot-diameter vacuum facility at Lewis Research Center.