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OPERATIONAL COMPATIBILITY OF 30-CENTIMETER-DIAMETER ION THRUSTER WITH INTEGRALLY REGULATED SOLAR ARRAY POWER SOURCE

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16. Abstract

System tests were performed in which integrally regulated solar arrays (IRSA's) were used to directly power the beam and accelerator loads of a 30-cm-diameter, electron bombardment, mercury ion thruster. The remaining thruster loads were supplied from conventional power-processing circuits. This combination of IRSA's and conventional circuits formed a "hybrid" power processor. Thruster performance was evaluated at 3/4- and 1-A beam currents with both the IRSA-hybrid and conventional power processors and was found to be identical for both systems. Power processing is significantly more efficient with the hybrid system. System dynamics and IRSA response to thruster arcs were also examined.

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SUMMARY

System tests were performed in which integrally regulated solar arrays (IRSA's) were used to directly power the beam and accelerator loads of a 30-centimeter-diameter, electron bombardment, mercury ion thruster. The remaining thruster loads were supplied from conventional power-processing circuits. The experiment was performed to demonstrate the feasibility of powering major ion thruster loads directly from regulated solar arrays and to evaluate the effects of such operation on thruster steady-state and dynamic performance.

Thruster performance was measured under several operating conditions at 1-ampere beam current with conventional and IRSA power systems, and steady-state electrical waveforms were recorded. Performance was also measured at 3/4-ampere beam current. Thruster performance was independent of the power-processing system used. Steady-state waveforms were also essentially the same. Perveance of the thruster grids was measured with the conventional and the IRSA systems. Again, no significant differences were found between the two.

The single difference observed between thruster operation with a conventional power-processing system and an IRSA system lies in the electrical efficiency of the power system. The conventional power circuits for the beam supply are very efficient - approximately 95 percent. However, IRSA efficiency is about 99.9 percent. This loss reduction yields a direct reduction in thermal control system mass, and the reduced power loss also implies a reduction in needed solar array area.

INTRODUCTION

Arrays of silicon solar cells are the major source of electrical power for spacecraft. In conventional power systems, the solar array output is conditioned by power-processing equipment to match the current and voltage requirements of the various spacecraft loads. For large electrical loads such as ion thruster and high-power radio-frequency amplifiers, the necessary power processors are heavy, complex, and expensive to design and build and are a substantial burden on the spacecraft thermal control system. Considerable work is being done on alternate power-processing concepts to reduce these spacecraft penalties.

One of the most promising concepts is the integrally regulated solar array (IRSA), an implementation of which is the high-voltage solar array (HVSA). The IRSA system provides regulated direct-current power from a controlled solar array directly to the using load without an intervening power processor. References 1 and 2 describe some results obtained with prototype IRSA systems operating lower power active loads. Typically, the solar array is subdivided into a number of series and/or parallel blocks, some of which are paralleled by shorting switches. The array output is regulated by closed-loop, digital control logic that selectively actuates the shorting switches. The switchable blocks are usually binary weighted in voltage to minimize the number of switches, but this is not a concept requirement. Figure 1 is a block diagram of a typical IRSA system consisting of the solar array, regulation switches, control logic, a sensor, and a direct-current load. As can be seen from the diagram, the IRSA system offers a number of advantages over a conventional power processor. Heavy power switches, transformers, rectifiers, and filters are replaced by digital logic and solid-state shorting switches. Instead of the 5- to 15-percent power dissipation of conventional power processors, the IRSA system approaches zero dissipation at maximum loading when all the shorting switches are off. Overall system reliability improves from two factors: the reduced number of parts and the absence of series elements between the power source and the load. IRSA has one further advantage - adaptability. A single regulator design can be employed to regulate any solar array; for example, 30 volts at 10 amperes, 1000 volts at 2 amperes, or 10 kilovolts at 100 milliamperes. The switch ratings and the solar array configuration change, but the regulator design does not. This adaptability can represent major design cost savings.

A program is currently underway at the Lewis Research Center to develop and test IRSA systems on actual spacecraft loads, such as ion thrusters and high-power radio-frequency amplifiers. A series of experiments has been performed to establish the feasibility of powering major ion thruster loads directly from integrally regulated solar arrays, to evaluate the effects of such operation on thruster steady-state and dynamic performance, and to provide an experimental data base for the assessment of overall system benefits from the inclusion of IRSA's in a spaceflight power-processing system for ion thrusters. The specific thruster power-processing system discussed in this report is a hybrid of conventional power-processing circuitry and two IRSA's that supply power to the high-voltage (beam and accelerator) loads of the thruster. A preliminary test of the operation of an 8-centimeter-diameter ion thruster beam and accelerator loads from unregulated solar arrays is reported in reference 3. Those test results showed that the thruster performed essentially the same with unregulated solar array operation as with conventional laboratory power supplies. Although the solar arrays and the ion thruster were both operated manually, this work formed the basis for proceeding with the 30-centimeter-diameter thruster tests. The test reported herein involved closed-loop operation of a 30-centimeter-diameter mercury ion thruster with flight-typical power processors of both the conventional type and a hybrid combination of conventional and IRSA power-processing systems.

SYMBOLS

J_A	accelerator impingement current, A
J_B	beam current, A
J_E	emission current, A
J_{NK}	neutralizer keeper current, A
V_A	accelerator voltage, V
V_g	neutralizer coupling voltage, V
V_I	beam (screen) voltage, V
ΔV_I	discharge voltage, V

TEST EQUIPMENT

A 30-centimeter-diameter, electron bombardment, mercury ion thruster, two integrally regulated solar arrays, and two different conventional ion thruster power processors were employed in this test. Electrical interface circuits provided easy and rapid conversion between conventional and hybrid thruster operation.

Thruster

A 30-centimeter-diameter, electron bombardment, mercury ion thruster (#501) was used for this test. This 400-series thruster was originally built by Hughes Research Laboratories and was modified at the Lewis Research Center to be essentially equivalent to a 700-series engineering model thruster (EMT) described in reference 4. These modifications included the neutralizer assembly, the dished grids of the EMT geometry, 800-series main- and cathode-isolator vaporizers, an increased magnetic field, and a $10\frac{1}{2}$-turn magnetic baffle. Both cathode and neutralizer had 900-series impregnated inserts. In addition, the discharge chamber was lined with tantalum foil and stainless-steel mesh to reduce internal erosion and the subsequent spalling of deposited material.

Solar Arrays

Two integrally regulated solar arrays were assembled in the 1-kilowatt laboratory solar array facility (described in ref. 5). The facility consists of nine independent modules, each of which contains an array of 2560 solar cells (2 cm by 2 cm), a tungsten-iodide lamp bank, an infrared filter, and water and air cooling for the cells and lamps, respectively. Each module array contains two subpanels of 40 series strings that are 32 solar cells long. Figure 2 shows one of the modules opened to display the solar array and its lamp bank. Depending on the internal wiring, each module can produce approximately 120 watts at voltages from 12 volts to 1.2 kilovolts. The modules can be interconnected in any series-parallel arrangement.

Accelerator Integrally Regulated Solar Array

One subpanel (half of one module array) was used to form the accelerator array. The 40 strings were connected in series to produce an array with an unregulated open-circuit voltage of approximately 700 volts. Three lamp-bank operating points were established to produce array short-circuit currents of 100, 50, and 10 milliamperes. As shown in figure 3, taps for the regulation switches were placed at nominal voltages of 5, 10, 20, 40, 80, and 160 volts. These taps were placed at the negative end of the accelerator array, which for ion thruster operation is about 500 volts below facility ground. For convenience, the regulator was floated at the negative end of the accelerator array.

Beam Integrally Regulated Solar Array

The remaining eight solar array modules were used to form the beam array. In each module, the two subpanels were paralleled to produce nominal 600-volt, 0.25-ampere solar array sections. The modules were interconnected to form two groups of four modules in parallel that were then placed in series, to produce 1200 volts at 1 ampere. As shown in figure 4, all solar array sections, including the switchable sections, were isolated by blocking diodes. For simplicity, the individual subpanels are not shown in the figure. The four lowest voltage (closest to thruster common) modules were tapped and paralleled to provide regulation sections of 8, 15, 30, 60, 120, and 180 volts at 1 ampere. The regulator for this beam array was floated at thruster common, which is about 15 volts below facility ground.

Regulators

The regulators for the beam and accelerator solar arrays, which were identical to that described in reference 2, consisted of control logic, switches, and switch drivers. As shown is figure 5, the control logic was basically a three-state voltage comparator that drove a binary up-down counter. The counter in turn opened and closed the regulation switches by means of the switch drivers. When a null between the sensed and reference voltages (within an adjustable deadband) was detected, the up-down counter was disabled. Likewise, an "end stop" disabled the counter if all switches were on and the array voltage remained too high or if all switches were off and the array voltage was too low. This feature was necessary to prevent the counter from continuously cycling through all switch on-off combinations when the array was unable to produce the required reference value. The regulation switch was a transformer-isolated, solid-state relay that was basically a switching transistor with parallel and series rectifiers for transient protection. The switches used in this test were higher current rating versions of the hybrid circuit switches described in reference 6. The beam switches were rated for 2.2 amperes, and the accelerator switches were rated for 125 milliamperes.

For convenience, since the regulators were floating, the logic power for both regulators was obtained from two small solar array sections within the modules. Each of these sections contained 32 solar cells in series, two cells in parallel. The sections were zener diode regulated to 12 volts and floated at beam and accelerator negative, respectively (figs. 3 and 4). For transient protection, in addition to that provided by internal isolation in the switches, the control logic was isolated from the switch drivers by optical couplers. Drive power for the two sets of regulation switches was also derived from two small sections of zener-diode-regulated solar array. These switch-drive power supplies were allowed to float with respect to the rest of the systems. However, it was found during testing that this double layer of isolation was unnecessary. That is, the 2.5-kilovolt isolation capability of the regulation switches was adequate for all observed transients.

The two regulators, consisting of control logic, drivers, and switches, were assembled on printed circuit cards that were mounted within two of the modules. The external connections for the two regulated solar arrays were the two pairs of power leads, plus two potentiometers that were used to set the regulation voltages. The available regulation ranges were 1200 to 800 volts for the beam array and 600 to 400 volts for the accelerator array. In addition, the control logic could be disabled by means of a switch. When disabled, the sorting switches were locked into the last on-off configuration established by the regulator.

Conventional Power-Processing Systems

Two different 30-centimeter-diameter, ion thruster power-processing systems were used during this test. The transistor-bridge-converter test console, which is described in reference 7, was employed for the major part of the testing. Although this unit is a laboratory test console, it does incorporate all the controls necessary for closed-loop thruster operation and is thus functionally representative of a flight-type power processor. The inverters supplying the beam, accelerator, and discharge loads operate at a switching frequency of approximately 10 kilohertz. The inverter that supplies the remaining thruster loads operates at 5 kilohertz. Abbreviated performance tests were also made using an SCR series-resonant-converter power processor, which is described in reference 8. The maximum switching frequency of the inverters is 10 kilohertz. This unit is a breadboard of a flight-type 30-centimeter-diameter thruster power processor. Both power processors were operated with all three thruster control loops closed for both conventional and IRSA-hybrid power-processing system operation.

Interface Console

Figure 6 is a schematic diagram of the interconnection circuits between the thruster, the beam and accelerator IRSA's, and the conventional power processor. The thruster heaters, vaporizers, cathode keeper, and magnetic baffle power supplies have been omitted. The interface circuits were used to provide rapid conversion between conventional and hybrid power-processing system operation without shutting down the thruster. The interface console also included switches to short out each of the two solar arrays. The switches shown in the diagram were actually a series combination of a mechanical contactor and a vacuum relay. The contactors permitted separate, individual control (connect-disconnect and shorting) of the IRSA's and the two conventional supplies. The vacuum relays controlled both IRSA's simultaneously. This combination of switches provided a high degree of operational flexibility. The interface console also contained metering for the beam and accelerator voltages and currents.

EXPERIMENTAL PROCEDURES

Three types of tests were made. Thruster steady-state performance data and oscillograms of selected electrical waveforms were obtained during operation with both conventional and IRSA-hybrid power-processing systems. The thruster grid system perveance was also determined. And, during IRSA operation, transient waveforms were recorded during spontaneous recovery from thruster beam short circuits.

Steady-State Operation

Thruster. - The thruster was operated in a 1-meter-diameter port (E63) of the 7.6-meter-diameter by 21.4-meter-long vacuum facility at the Lewis Research Center. Tank pressure was maintained at approximately 3×10^{-4} pascal (2×10^{-6} torr). The thruster neutralizer and main discharges were started under manual control using the conventional power processor. The beam and accelerator loads were powered by either the IRSA's or the power processor. The thruster beam current was established at 0.75 or 1.0 ampere, and the three thruster vaporizer control loops were closed. Three to four hours were allowed to elapse before performance measurements were taken to ensure that the thruster and propellant feedlines had reached thermal equilibrium. Brief stabilization periods (15 to 30 min) were also used when the thruster operating point was changed.

Solar array. - For thruster operation with the IRSA-hybrid power-processing system, the 1-kilowatt laboratory solar array facility was activated, the regulation control logic was enabled, and power was applied to the thruster by means of the interface console. It was unnecessary to wait for the facility cooling system to come to thermal equilibrium since the array regulators automatically compensated for changes in the solar arrays' electrical characteristics. The array outputs were periodically checked and the lamp-bank input power was raised, as necessary, to compensate for lamp aging effects. The short-circuit current of the beam IRSA was maintained between 1.1 and 1.25 amperes. The short-circuit current of the accelerator IRSA was generally held at 100 milliamperes but was decreased by means of the lamp-bank setting to 10 milliamperes during the transient tests.

Performance. - Thruster performance (all electrical parameters and propellant flow rates) was measured at a number of representative operating points to confirm stable and efficient thruster operation with the IRSA-hybrid power-processing system and to compare hybrid with conventional power-processing system operation. Table I shows the matrix of operating points at which thruster performance measurements were made with various power-processing systems. The beam current was restricted to 1 ampere (full throttle for an EMT is a 2-ampere beam) by the power limitation of the solar array facility. The selected ranges of emission current, which varies the discharge losses, and magnetic baffle current, which alters the ratio of cathode to main vaporizer flow, are representative of normal thruster operation. At any single operating point, the interface console was used to rapidly convert between conventional and IRSA-hybrid operation without perturbing the thruster's internal or external operating conditions. In addition, to control hysteresis effects, the magnetic baffle current was briefly reversed whenever the baffle current set point was changed. Thruster electrical parameters were recorded from calibrated, floating digital meters. Propellant flow rates for the three vaporizers were measured by timing the flow of mercury to the thruster through calibrated glass pipettes. Simultaneous oscillograms of the steady-state voltage and current waveforms were obtained for the beam, accelerator, and discharge over the full test-point matrix.

Perveance Limit

Thruster operation too near the perveance limit voltage causes control stability and noise problems, as well as increased grid erosion. To ensure that IRSA operation does not degrade the operating margin, the perveance of the thruster grid system was measured for both conventional bridge and IRSA/bridge hybrid power-processing system operation. For this test, the beam and accelerator voltages were lowered simultaneously while the accelerator impingement current was monitored. The ratio of beam voltage to total grid (beam plus accelerator) voltage was maintained at approximately 2:3. The onset of a rapid increase in accelerator current indicates that the perveance limit of the grid system has been reached and that the ions are no longer focused through the grids. For the purpose of power-processing system comparison, the perveance limit voltage was defined as the 45° tangent point (slop of 10^{-6} A/V) on a plot of accelerator impingement current versus total grid voltage. Following several trial runs to clean and condition the grids, the perveance limit was determined for both power systems at all nine combinations of emission and magnetic baffle currents at a beam current of 1.0 ampere.

Integrally Regulated Solar Array/Thruster Transients

Spontaneous beam short circuits (arcs) in a well-conditioned thruster are infrequent, but do occur. Arcs usually are initiated by a brief surge in the accelerator impingement current that is sufficiently large to overload the accelerator power supply, causing the accelerator voltage to decrease. As a result, electrons from the neutralizer backstream into the discharge chamber and overload the beam power supply, causing its voltage to decrease. If the two overloaded power supplies "stabilize" at a total grid voltage less than the perveance limit voltage but greater than the minimum voltage needed to maintain the arc, the arc will be maintained. At lower total voltages, the arc will self-extinguish.

The purpose of this test was to examine the behavior of the IRSA's during recovery from arcs when both beam and accelerator solar arrays are loaded to nearly their short-circuit current points. Since spontaneous arcs occur with insufficient frequency for test purposes, three methods of inducing arcs were employed. The accelerator IRSA was briefly shorted out or disconnected from the thruster to establish neutralizer backstreaming into the discharge chamber. Arcs were also induced by deliberately putting the thruster into low mode. In low mode, the propellant vapor density in the discharge chamber is excessive, and ions can no longer be produced efficiently by the discharge. This results in a substantial decrease in beam current. The excess mercury vapor available in low mode will produce excessive accelerator impingement current and result in a continuous arc. As the thruster is brought out of low mode by reducing propellant flow, one or more spontaneous arcs and recoveries can usually be observed. This technique probably simulates truly spontaneous arcs more closely than interruption of the accelerator voltage. Simultaneous oscillograms of the beam and accelerator currents and voltages, the neutralizer keeper current, and the neutralizer coupling voltage were recorded during recovery of the IRSA's from arcs that were induced by all three methods. The effect of decreasing the current capability of the accelerator solar array from 100 milliamperes to 10 milliamperes was also examined, to assess the thruster's sensitivity to the location of the operating point on the solar array voltage-current curve.

RESULTS AND DISCUSSION

Steady-state thruster performance was measured, and selected electrical waveforms were recorded during thruster operation with conventional and IRSA-hybrid power-processing systems. Thruster grid system perveance was also determined for both power systems. Transient excursions of the beam IRSA and accelerator IRSA were examined during spontaneous clearing of arcs.

Steady-State Performance

The thruster was operated with satisfactory propellant utilization over the selected operating ranges shown in table I. Table II lists representative sets of measured and derived thruster parameters at 3/4- and 1-ampere beams. Thruster steady-state performance is independent of the type (bridge converter, IRSA/bridge, series-resonant converter, IRSA/series resonant) of power-processing system employed. The single performance difference between the various power systems is the electrical efficiency of the power system. For instance, at a 1-ampere beam current, the conventional series-resonant-converter power processor had an efficiency of 87.8 percent and the IRSA/series-resonant hybrid had an efficiency of 91.5 percent. A common rule of thumb projects a 1-percent increase in the delivered mass capability of an electric propulsion system for each 1-percent improvement in power-processing efficiency. For the proposed solar electric propulsion (SEP) missions, the scientific payload is typically about 1 percent of the total delivered mass. Therefore, the improved efficiency (plus the removal of massive power components) of an IRSA-hybrid power-processing system can directly expand the scientific capabilities of proposed and contemplated SEP missions.

To further examine thruster steady-state operation, the waveforms of six major electrical parameters were recorded. These are beam voltage V_I and current J_B, accelerator voltage V_A and current J_A, discharge voltage ΔV_I, and emission current J_E. These parameters are indicated in figure 6. The waveforms were recorded simultaneously during steady-state operation over the range of thruster operating points for all four (conventional and hybrid) power-processing systems. The interface console was used to rapidly convert between hybrid and conventional power-processing system operation at a given operating point without perturbing the thruster.

Figures 7 and 8 are representative waveforms for conventional and hybrid operation with the bridge- and series-resonant-converter-based power systems, respectively. Separate examinations of the two figures show no major differences between the waveforms under conventional power supply and IRSA-hybrid operation. For the bridge-converter-based power systems (fig. 7), all waveforms except the accelerator voltage show substantial, rapid, but aperiodic fluctuations. Under IRSA operation the peak-to-peak variations of the beam voltage and current were somewhat reduced - perhaps about 20 percent. Also, while the J_B waveform was somewhat smoother with the hybrid power system, the V_I fluctuations appear to be more rapid. This is thought to be the combined effect of the very low-energy storage capability (nearly zero internal capacitance and inductance) of the solar array and the attempt of the array regulator to maintain a constant beam voltage with consequent over- and undershoot. However, regulator action had the lesser effect on the waveforms, as was determined by disabling the control logic and permitting the thruster beam to follow the unregulated solar array voltage-current characteristic. The fluctuations of the accelerator current were substantially increased for IRSA operation, by nearly a factor of 2, peak to peak, over the conventional power-processing system operation. Again, this is the result of the nearly zero energy storage capability of the solar array. The discharge current and voltage waveshapes were unaffected by the type of power system used. The thruster operating point (over the range examined) did not affect the waveforms with either power-processing system.

For the series-resonant-converter-based systems (fig. 8), the waveforms are considerably more regular and of smaller amplitude than those observed with the bridge-based system. Comparing the discharge and beam currents for the conventional and hybrid power-processing systems shows that the beam oscillations are driven by the discharge characteristics. The substantial differences between the bridge- and series-resonant-converter-based systems' waveforms are the result of the output impedance characteristics of the two discharge supplies. The bridge-converter discharge supply has a capacitive output. The inductive output of the series-resonant-converter discharge supply is the cause of the relatively smooth waveforms observed with this power-processing system (ref. 9). Comparing series-resonant-converter conventional and hybrid operation shows that the amplitude of the beam current oscillations was decreased and the amplitude of the beam voltage oscillations was increased with hybrid operation, by about a factor of 2 in each case. The accelerator voltage was very smooth for both power-processing systems. Close examination of the hybrid beam current waveform discloses a number of rapid (10 to 20 μsec), irregularly spaced transients toward zero beam current. These appear with IRSA operation because the solar array lacks the energy storage capability to maintain current flow. Similar transients can also be found in figure 7 but are far less obvious. These brief transients, which appear throughout the operating range examined, did not in any way affect operating stability or thruster performance.

One additional area of interest in the steady-state operating of hybrid power-processing systems was explored. This is the sensitivity of thruster performance and stability to the location of the operating point on the solar array voltage-current curve. For this purpose, the tests were performed at a 3/4-ampere beam current, which is well "above" (toward open-circuit voltage) the solar array maximum power point, and at 1-ampere beam current, which is closed to the maximum power point. The solar array facility itself introduced an additional variable in the 1-ampere-beam data. Seasonal variation in the temperature of the available cooling air and water and aging effects of the lamp bank served to alter the solar array voltage-current curve, so that the 1-ampere operating point gradually shifted from above to below the maximum power point. These changes in solar array characteristics are illustrated in figure 9, where the circular symbols denote the normal thruster operating points with the regulated solar array. The operating stability, electrical waveforms, and thruster performance were completely insensitive to the location of the operating point on the solar array curve. To further confirm this result, oscillograms were taken with the regulator control logic disabled, which allows the thruster to directly follow the array voltage-current curve. The beam current was slightly increased so that the thruster would operate well "below" (toward short-circuit current) the solar array maximum power point. These test points are also indicated in figure 9. Again, the thruster was completely insensitive to the location of its operating point on the solar array voltage-current curve.

Perveance

The perveance of the thruster grid system was examined, and the perveance limit voltage was determined for the conventional bridge and IRSA/bridge hybrid power-processing systems. To maintain satisfactory ion focusing, the operating total grid voltage should be well above the perveance limit. Therefore, it is important that the power system and the thruster do not interact in such a manner that the perveance limit voltage is increased. Perveance limit voltage were determined at discharge losses of 185, 200, and 215 electron volts per ion. At a given thruster operating point, the perveance curves were taken alternately with both systems. A full set of perveance curves is shown in figure 10, which plots accelerator impingement current as a function of total grid voltage difference. The perveance limit voltages (defined at the 45° tangent point, which corresponds to a slope of 10^{-6} A/V) are listed in table III. As can be seen in the table, the perveance limit voltage is slightly, but consistently, lower for the IRSA-hybrid power-processing system.

Integrally Regulated Solar Array/Thruster Transients

The behavior of the beam and accelerator IRSA's was examined during recovery from induced beam short circuits (arcs). Spontaneous arcs in a well-conditioned thruster are infrequent. However, they do occur and the power system must be able to tolerate and extinguish them to prevent both damage to the power supplies and excessive erosion of the thruster grids. A solar array is inherently tolerant of load arcs. The single difference between operating at maximum power and working into a direct short is a slight (2° to 3° C) rise in solar cell temperature. In addition, the array's lack of energy storage capability protects other system elements from large, possibly destructive, current surges. The maximum current available is the solar array short-circuit current, which is approximately 10 percent larger than the solar array maximum-power-point current. Based on the known characteristics of solar arrays, it was considered possible that thruster arcs would automatically extinguish without external intervention in short enough periods of time to protect the thruster grids.

Throughout the entire test sequence, arcs were very infrequent regardless of the power-processing system used. Arcs that did occur were generally associated with off-normal operating conditions: excessive tank pressure, cleanup of condensates during thruster startup, or thruster operation in low mode. The conventional power-processing systems possess circuitry that intervenes and attempts to interrupt and extinguish arcs. With the IRSA-hybrid power-processing systems, the arrays were simply allowed to "collapse" toward short-circuit current. Depending on the precipitating cause, the arc either cleared immediately or continued at a beam voltage of approximately 150 volts. Continuous arcs were generally attributable to one of the off-normal operating conditions. Interrupting the high voltages and/or briefly decreasing the discharge current may possibly speed the arc recovery. However, the usual procedure was to leave the solar arrays collapsed until the precipitating cause had been removed, at which time the arrays returned to their normal operating voltages. Operation with collapsed arrays for periods in excess of 5 minutes has produced no discernible damage in any system element. Arc susceptibility, duration, and recovery appear to be independent of the nearness of the normal operating current to the solar array short-circuit current for both the beam and accelerator IRSA's. This was confirmed by the use of the two beam current levels and by the reduction of the current capability of the accelerator IRSA to 10 milliamperes.

Since spontaneous arcs are infrequent, the behavior of the beam and accelerator solar arrays during arc recovery was observed with induced arcs. The arcs were induced by three different methods, but the observed behavior was not influenced by the method. Simultaneous oscillograms of six waveforms were recorded: beam current and voltage, accelerator current and voltage, neutralizer keeper current, and neutralizer coupling voltage. Figure 11 shows two sets of typical transient waveforms. The sweep was triggered on the rise of the accelerator voltage as the arrays recovered from the induced arc. In both sets shown, the initial recovery was followed by a second spontaneous arc and recovery. These spontaneous arcs initiated at points A in figure 11, where the beam and accelerator voltages dropped to zero, as is seen in the left-hand oscillograms. The arc durations of 2.7 and 3.4 milliseconds, for the upper and lower sets, respectively, were typical of all spontaneous arcs observed. The recoveries of V_I and V_A occurred at points B. The effect of the arc on the neutralizer keeper current and the neutralizer coupling voltage are shown in the right-hand oscillograms. The sole effect on V_g was a single, very rapid transient at arc initiation. The J_{NK} waveform also showed a large spike at arc initiation, which was followed by a steady increase in keeper current to the maximum current capability of the power supply. The high keeper current remained for the duration of the arc. The keeper current returned abruptly to normal at B when the arc extinguished. Two additional transient phenomena can be observed in these oscillograms. In the upper set, at point C the beam voltage dropped to a continuous low value (≈200 V), but the accelerator voltage had remained high and thus effectively prevented neutralizer electrons from coupling into the discharge chamber. The neutralizer keeper current remained low at this point. This condition persisted for less than a millisecond and then was followed by full arc initiation at A. In the lower set, an initial, brief transient of the accelerator voltage was sufficient to trigger the sweep, but recovery from the induced arc was delayed about a half a millisecond. This provided a good view of a slightly different type of arc recovery. In this event the beam recovered quite smoothly, but the accelerator voltage displayed a large number of rapid transients. However, even during this period the accelerator voltage had recovered sufficiently to decouple the neutralizer electrons, and the arc extinguished at D. For all arcs observed during this test, the recovery of the IRSA's to near normal operating voltage required between 200 and 300 microseconds.

CONCLUDING REMARKS

System tests were performed in which two integrally regulated solar arrays (IRSA's) were used to directly power the beam and accelerator loads of a 30-centimeter-diameter, electron bombardment, mercury ion thruster. Two different conventional thruster power-processing systems were used to supply the remaining thruster loads, in effect forming two types of IRSA-hybrid power-processing system. The steady-state performance of the thruster was measured at 3/4- and 1-ampere beam currents for both the hybrids and the totally conventional power-processing systems over a range of emission and magnetic baffle currents. Steady-state waveforms of the major electrical parameters were recorded for all four power-processing combinations: transistor bridge converter, IRSA/bridge hybrid, series-resonant converter, and IRSA/series-resonant hybrid. The perveance limit voltage of the thruster grid system was determined for the hybrid and conventional power-processing systems. Transient behavior of the IRSA's during recovery from induced beam short circuits (arcs) was examined.

Throughout the testing sequence, the thruster operated efficiently under closed-loop vaporizer control with any of the four power-processing systems. The following conclusions were drawn from these tests:

1. Thruster steady-state performance (thrust, specific impulse, and propellant utilization efficiency) are independent of power-processing system type.

2. The IRSA/ series-resonant hybrid system at a 1-ampere beam current has a power efficiency of 91.5 percent, as compared with the 87.8-percent efficiency of the

conventional system. At the normal power level of the 30-centimeter-diameter engineering model (2-A beam current, 1100-V voltage), the conventional series resonant power-processing system used in these tests has an efficiency of 90.8 percent. Extrapolation of IRSA-hybrid system efficiency shows an increase to 95.8 percent at the 2-ampere beam current level. If the power level of the thruster beam were to be increased further (high voltage and/or current), the efficiency of the thruster hybrid power-processing system would gradually approach that of the IRSA beam power supply itself, 99.9 percent.

3. Only minor differences between the hybrid and conventional systems were observed in the steady-state waveforms of the major electrical parameters. The striking differences observed between the bridge- and series-resonant-converter-based power-processing systems were traced to significantly different output impedance characteristics of the two discharge power supplies.

4. Comparing the perveance limit voltages for the hybrid and conventional power-processing systems shows a slight, but consistent, improvement in operating margin with the hybrid systems.

5. Examining the transient behavior of the beam and accelerator IRSA's during induced arc recovery shows that the solar arrays recover to normal operating voltages in approximately 200 microseconds after the precipitating cause of the arc is removed. Continuous arcs at a beam voltage of about 150 volts can be produced under off-normal operating conditions, such as low mode or excessive tank pressure.

In conclusion, the basic characteristics of mercury ion thrusters and solar arrays are extremely compatible. Using appropriately designed solar arrays to directly power major thruster loads will produce stable, highly efficient power-processing systems for ion thrusters.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 23, 1977,
506-23.

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TABLE I. - MATRIX OF OPERATING POINTS EXAMINED WITH VARIOUS POWER-PROCESSING SYSTEMS DURING STEADY-STATE PERFORMANCE TESTING

Beam current, A	Emission current,[a] A	Magnetic baffle current,[b] A	Power-processing system			
			Transistor bridge converter		SCR series-resonant converter	
			Conventional	IRSA hybrid	Conventional	IRSA hybrid
0.75	3.95	2.0	X	X		
		2.5	X	X		
		3.0	X	X		
	4.30	2.0	X	X		
		2.5	X	X		
		3.0	X	X		
	4.60	2.0	X	X		
		2.5	X	X		
		3.0	X	X		
1.00	5.30	2.0	X	X	X	X
		2.5	X	X	X	X
		3.0	X	X	X	X
	5.70	2.0	X	X	X	X
		2.5	X	X	X	X
		3.0	X	X	X	X
	6.15	2.0	X	X	X	X
		2.5	X	X	X	X
		3.0	X	X	X	X

[a]Discharge voltage was maintained at 35 V throughout.
[b]Magnetic baffle has $10\frac{1}{2}$ turns.

TABLE II. - 30-CENTIMETER-DIAMETER THRUSTER PERFORMANCE DATA

[Magnetic baffle current, 2.5 A]

Parameter	Beam current, A					
	0.70			1.00		
	Discharge loss, eV/ion					
	185	200	215	185	200	215
Beam (screen) voltage, V	1100	1100	1100	1100	1100	1100
Neutralizer coupling voltage, V	-11.5	-11.6	-12.6	-11.2	-11.0	-10.7
Accelerator voltage, V	-500	-500	-500	-500	-500	-500
Accelerator current, mA	3.6	3.4	3.2	2.8	2.8	3.0
Discharge voltage, V	35	35	35	35	35	35
Emission current, A	[illegible].95	4.30	4.60	5.30	5.70	6.15
Cathode keeper voltage, V	7.9	7.5	7.2	7.0	6.9	6.7
Cathode keeper current, A	1.0	1.0	1.0	1.0	1.0	1.0
Neutralizer keeper voltage, V	16.0	16.8	16.8	16.0	15.7	15.6
Neutralizer keeper current, A	2.12	2.13	2.10	2.12	2.12	2.12
Main vaporizer flow rate, A	0.807	0.683	0.648	0.960	0.960	0.949
Cathode vaporizer flow rate, A	0.137	0.154	0.169	0.163	0.169	0.174
Neutralizer vaporizer flow rate, A	0.043	0.048	0.045	0.043	0.040	0.043
Ideal thrust, mN	[a]50.7	47.4	47.4	67.7	67.7	67.7
Ideal specific impulse, sec	[a]2523	2626	2696	2849	2839	2849
Measured propellant utilization efficiency	[a]0.760	0.791	0.812	0.858	0.855	0.858

[a]Beam current, 0.75 A.

TABLE III. - PERVEANCE LIMIT VOLTAGE FOR IRSA-HYBRID AND CONVENTIONAL POWER-PROCESSING SYSTEMS

Discharge loss, eV/ion	Perveance limit voltage, V	
	IRSA hybrid	Conventional
185	880	900
200	910	920
215	900	930

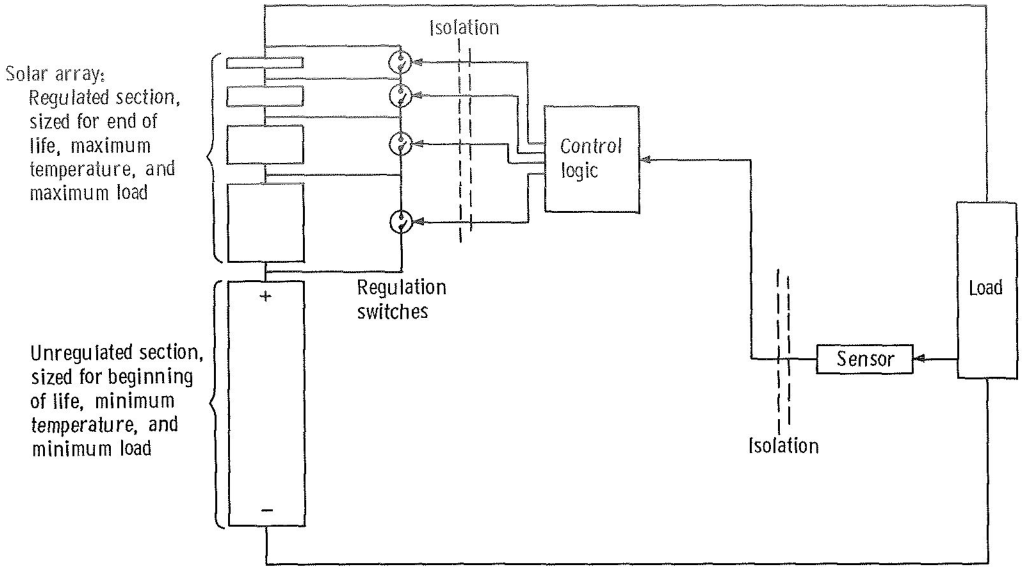


Figure 1. - Block diagram of an integrally regulated solar array.

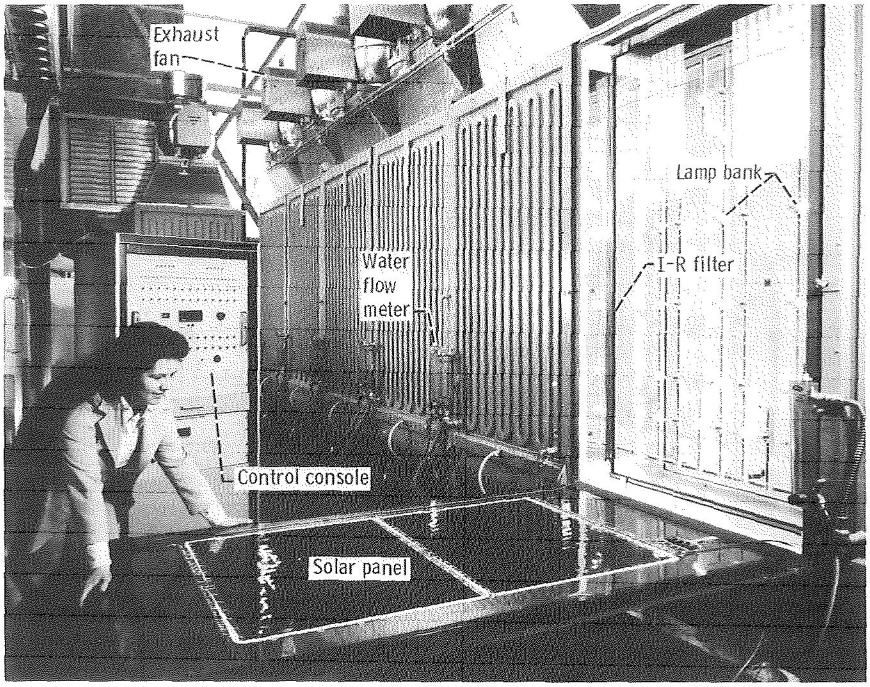


Figure 2. - 1-Kilowatt laboratory solar array facility with one of the nine modules opened to display array panel and lamp bank.

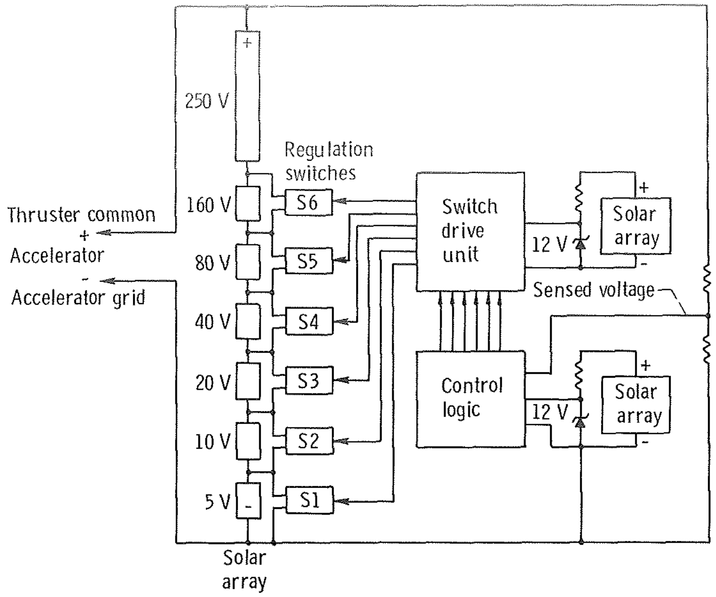


Figure 3. - IRSA accelerator supply (-500 V/100 mA).

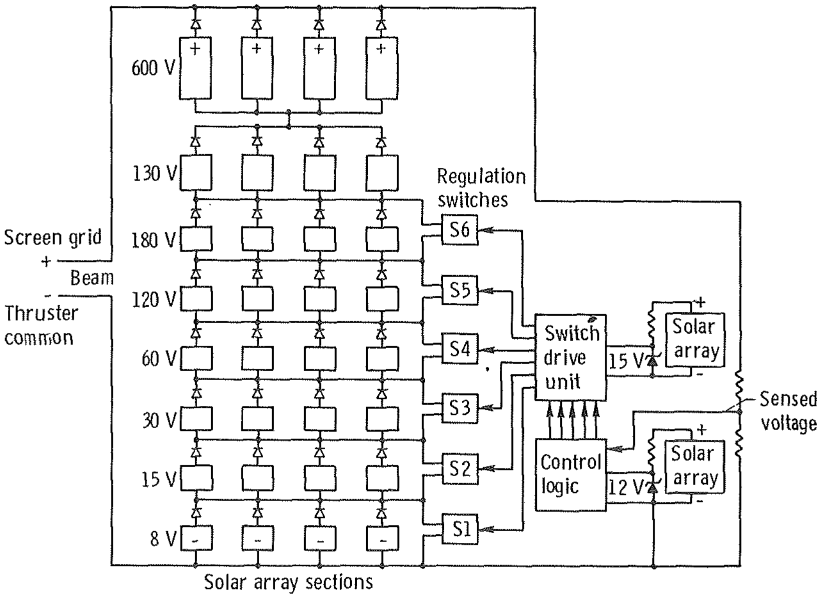


Figure 4. - IRSA beam supply (1100 V/A).

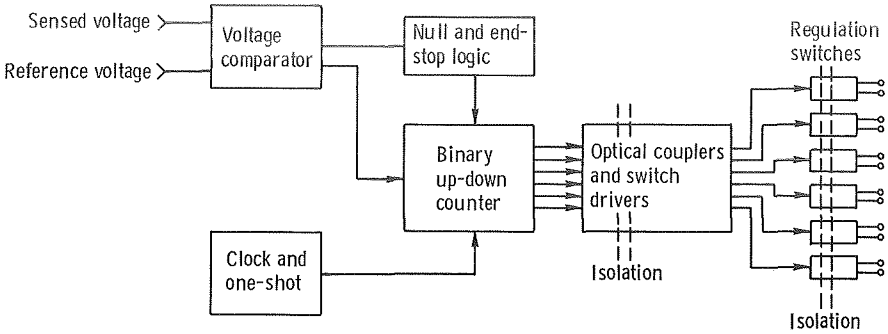


Figure 5. - Regulator block diagram.

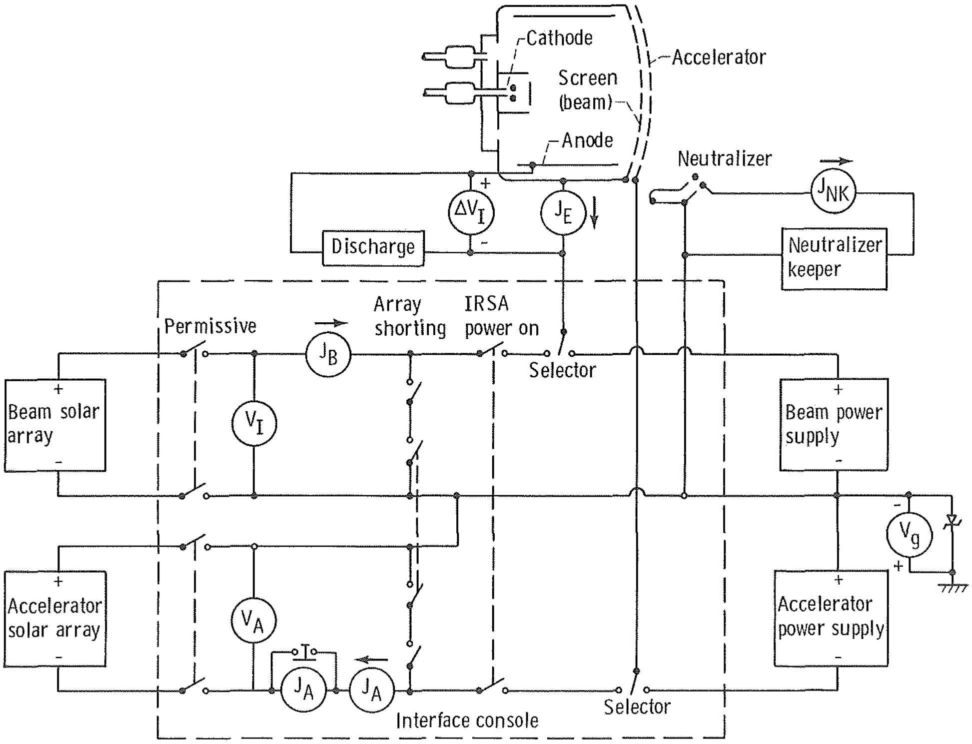
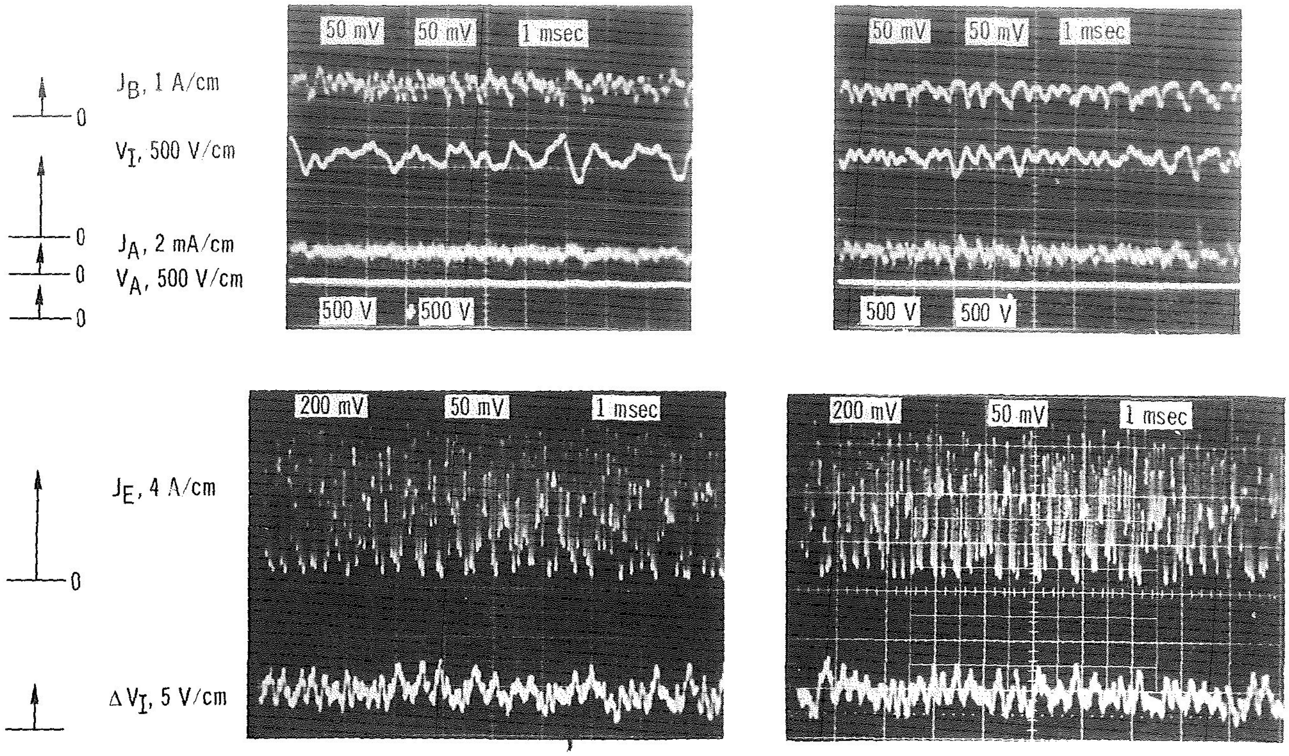
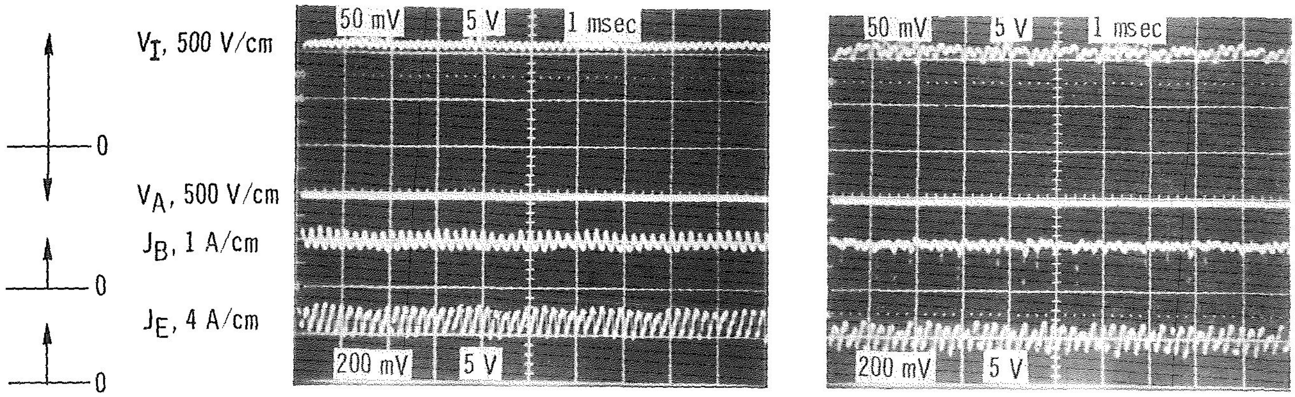


Figure 6. - Interconnection circuits between thruster, solar arrays, and conventional power supplies.



(a) Conventional (b) Hybrid.

Figure 7. - Selected steady-state waveforms for conventional bridge and IRSA/bridge hybrid power-processing system operation.



(a) Conventional. (b) Hybrid.

Figure 8. - Selected steady-state waveforms for conventional series-resonant and IRSA/series-resonant hybrid power-processing system operation.

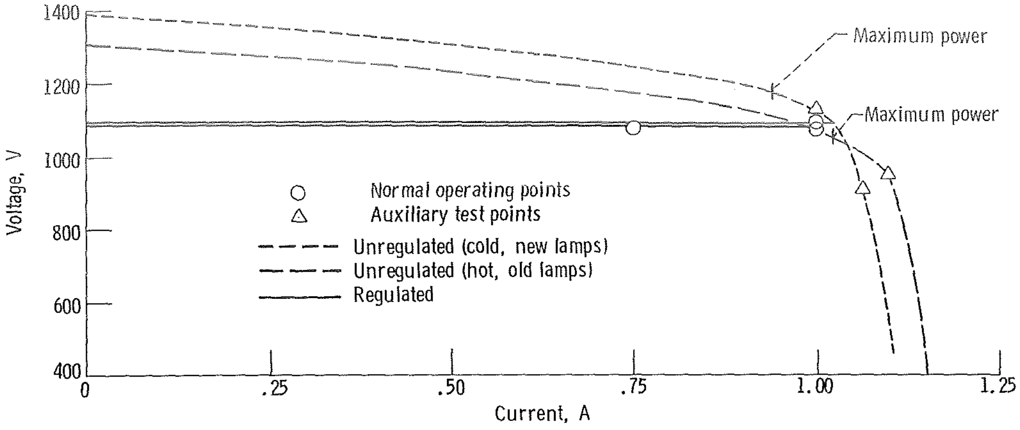


Figure 9. - Unregulated and regulated solar array voltage-current curves.

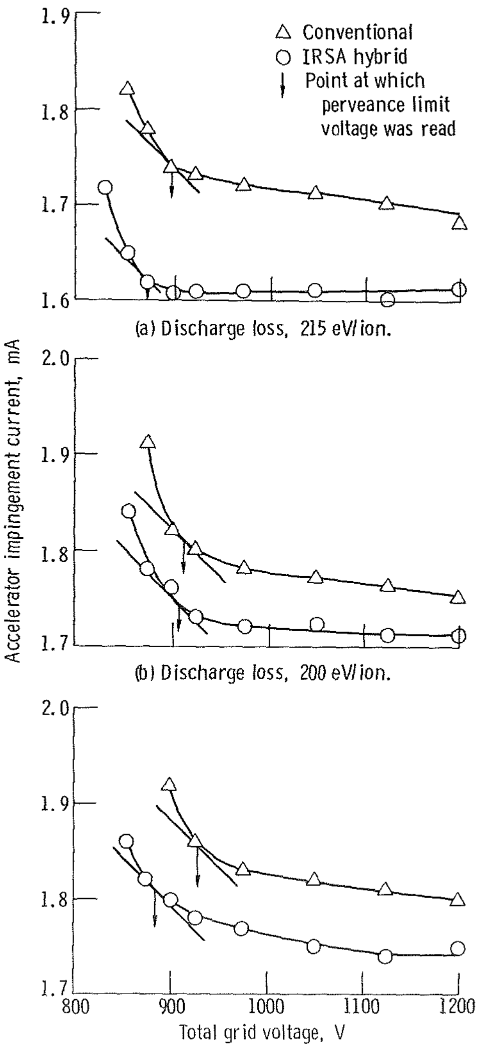


Figure 10. - Thruster grid perveance current-voltage curves (at 1-ampere beam current).

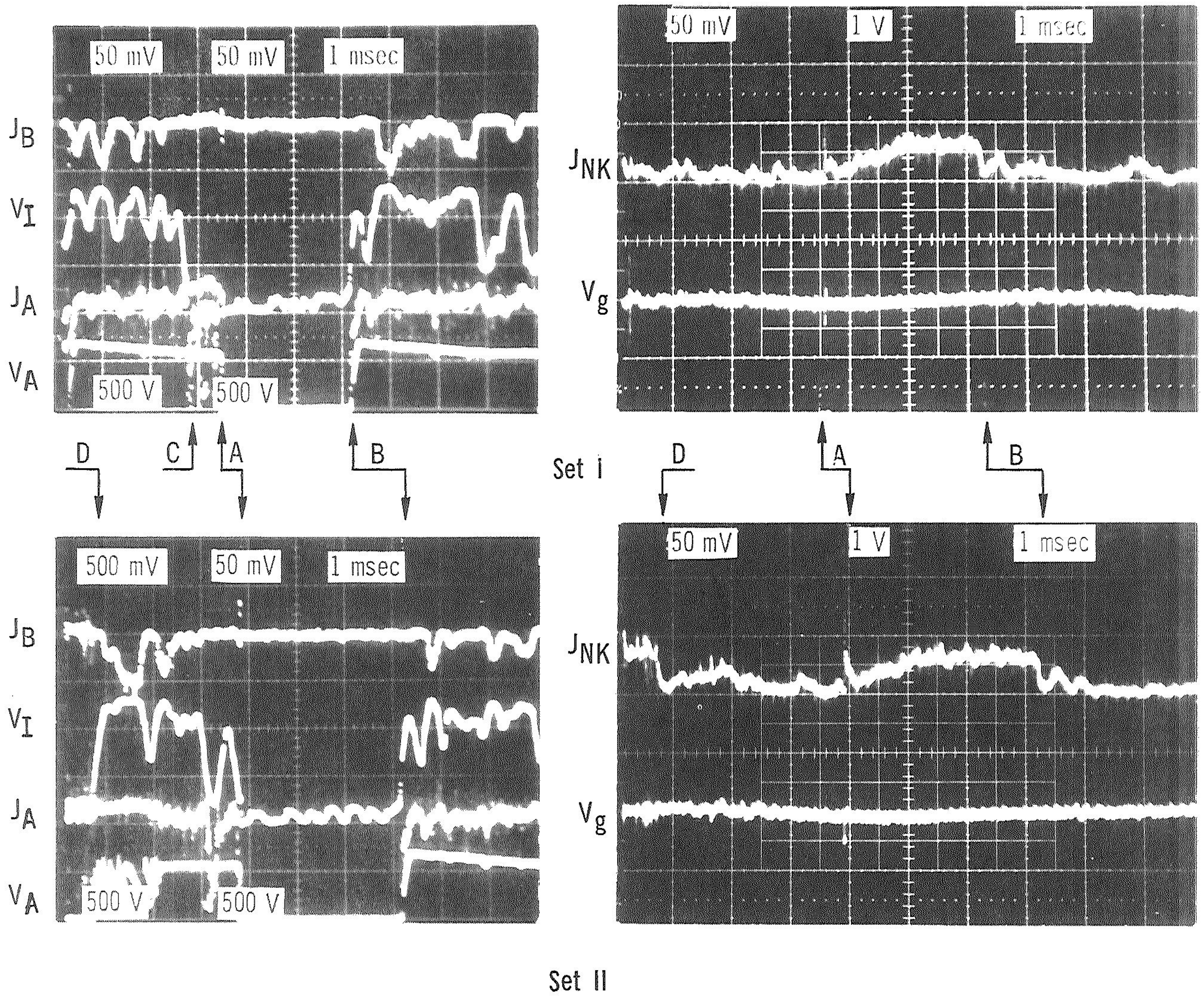


Figure 11. - Transient waveforms during induced thruster arcs.

NASA-Langley, 1977

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