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THE ADVANTAGES OF THE HIGH VOLTAGE SOLAR ARRAY FOR ELECTRIC PROPULSION

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THE ADVANTAGES OF THE HIGH VOLTAGE SOLAR ARRAY FOR ELECTRIC PROPULSION

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ABSTRACT

The high voltage solar array (HVSA) offers improvements in efficiency, weight, and reliability for the electric propulsion power system. The basic HVSA technology involves designing the solar array to deliver power in the form required by the ion thruster. This paper delves into conventional power processes and problems associated with ion thruster operation using SERT II experience for examples. In this light, the advantages of the HVSA concept for electric propulsion are presented. Tests conducted operating the SERT II thruster system in conjunction with HVSA are discussed. Thruster operation was observed to be normal and in some respects improved.

INTRODUCTION

The intent of this paper is to point out the advantages of the High Voltage Solar Array (HVSA) for Electric Propulsion. The basic HVSA technology involves designing the solar array to deliver its power in the form required by the ion thruster directly without intermediate power processing. In the conventional power system approach, the solar array provides power at rather low voltage. This makes power processing necessary for electric propulsion since ion thrusters require power in many forms but primarily at high voltage. The prime impetus of the HVSA concept lies in eliminating the losses, weight, and unreliability associated with conventional power processing. In any ion thruster mission, improvements in the specific weight, efficiency and reliability of the total power subsystem (source

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plus power processing) will enhance system performance. There have been several studies[1,2,3] sponsored by NASA-Lewis Research Center, of the HVSA concept. They were concerned primarily with investigating the HVSA with power conditioning integral with the panel which can provide regulated high voltage (2 kV to 16 kV) at rather high power levels (15 kW). They were studied in the framework of a hypothetical direct broadcast TV satellite using ion thrusters to raise itself from a low earth injection orbit to a synchronous altitude. The solar array could be configured to operate the ion thrusters as required and be reconfigured to power the TV broadcast transmission tube when on its synchronous station. In general these studies have concluded that HVSA's are feasible and that they can out perform conventional power processing systems operating from low voltage arrays. However the scope of these investigations were limited to the realm of high voltage and high power aspects typical of the beam requirements of an ion thruster system. The imposed limitations of these studies will be pointed out along with additional consideration of the other requirements of electric propulsion. In addition to these studies there has been experimental investigations of the basic regulation concepts of HVSA at NASA-Lewis Research Center[4] and Hughes Research Laboratories[5]. This work further substantiates the merits and feasibility of this technology and will be briefly reviewed in order to present an overall prospective of the HVSA status.

A new solar cell, the multiple junction edge illuminated solar cell (M-J Cell), will be described[6]. The M-J Cell was devised for high voltage, low current requirements such as the ion thruster's accelerator and keeper electrodes and will also find application for sensor and control power.

A principle advantage of the HVSA for electric propulsion lies in that the characteristics of the solar cell and the requirements of the ion thruster are ideally matched. The solar cell is inherently a dc power source that is ripple free and current limited while the ion thruster requirements are primarily for dc power of low ripple with limited current for protection. It is necessary to realize the short comings and problems associated with conventional power processing to obtain these requirements or the disadvantages of conventional power processing, in order to fully appreciate the advantages of the HVSA for electric propulsion. Because of the author's experience and familiarity with the SERT II program it will be the basis for this discussion. In early 1970 a "quick and dirty" test was conducted in operating the SERT II ion thruster system in conjunction with solar array power. Thruster operation was observed to be normal and in some respect improved by the ripple free nature of the solar array power. These tests and observations will be discussed.

ION THRUSTER - POWER PROCESSING SYSTEM ASPECTS

The block diagram of the SERT II ion thruster and power conditioning (p/c) system is shown in Fig. 1. A complete description of the SERT II ion thruster system was given by Kerslake, et al.[7] and the power conditioning system was described by Hoffman, et al.[8]. However for completeness, table I lists the rated electrical power outputs from the SERT II P/C for each of the nine supplies. Also listed are the typical operating values for each supply for the nominal solar array input of 60 V during full beam thruster operation. The solar array operating characteristics will be influenced by the P/C loads, radiation damage, temperature, and sun line orientation. This imposes an input variation of 54 to 75 V that the SERT II P/C must satisfy the thruster requirements.

From a power processing viewpoint, ion thrusters present an unusual combination of characteristics that make the creation of a design for low weight, efficient, and reliable operation difficult. The heaters (V_2, V_3, and V_7) are low impedance designs and undergo rather large impedance changes from cold to hot. The keeper discharges (V_8 and V_{10}) require a peak high voltage for initiation and a smooth transistion to a lower voltage operating condition. The bulk of the power is required in the form of high voltage (V_5). Both positive (V_5) and negative high voltages (V_6) are present. Breakdowns and arcing within the ion thruster (V_5 to V_6 and V_5 to ground) occur with extremely fast rise times. Many supplies must float at the positive high voltage potential (V_2, V_3, V_4 and V_{10}). In addition the plasma associated with the discharge will couple and effectively short supplies together. To bring a thruster up to operating temperatures requires that the supplies be turned on in a certain sequence; called the preheat, propellant and operate modes. Last, but not least, is the physical nature of the ion thruster in a highly complex process system. From a control viewpoint its control elements are quite nonlinear, with long time constants, transport lags, and strong interactions between processes. For example, the vaporizer heater power and flow rate are quite nonlinear with long thermal time constants. The propellant flow is subject to transport lags in the plumbing and thruster chamber thereby creating delays within the control loops. And ripple in the anode discharge current, I_4 reflects strongly in the beam current ripple, I_5 [9]. This broad brush treatment of the "nature of the beast" is to set the tone for discussion of problems associated with the conventional power processing for ion thrusters.

CONVENTIONAL POWER PROCESSING

Conventional power processing for ion thrusters involve many basic power processing functions. The processes utilized in the SERT II power conditioning and control system shown in Fig. 2 are typical and were primarily:

(1) Inversion - The process of converting dc power to ac power by switching devices.

(2) Transformation and dc Isolation - The process of converting ac power from one level to another either step up or step down and/or providing dc isolation between input and output.

(3) Rectification - The process of converting ac power to unfiltered dc power.

(4) Filtering - The process of suppressing frequency on input and/or output by passive energy storage devices.

(5) Power Modulation - The process of controlling power from the source such that the output is maintained within desired limits.

For SERT II power modulation was accomplished by PWM of an unregulated ac power by magnetic amplifiers. In addition, there are the command control. feedback control and overload protection processes.

As shown in Fig. 2 each of these power process functions are essentially series operation as far as efficiency and reliability are concerned. Each process, being imperfect, compounds the overall electrical efficiency and reliability. For example, if the process associated with V_5 are each 98 percent efficient the overall efficiency would be approximately 90 percent. In a similar manner the overall reliability is effected by the reliability of each series function. In practice the efficiency and reliability of each process will not be the same, with the inversion process usually the less efficient and reliable. The reported efficiency of the SERT II P/C was 87 percent under rated conditions.[8]

In the following discussion of the SERT II P/C outputs, a rather in-depth treatment of some of V_5 supply design problems will be given. In no way is this discourse intended to reflect a criticism of the SERT II P/C design that has been proven successful in its space mission. The rational for this being to make the reader aware of typical design problems encountered in power processing for ion thrusters. These functional design subtleties encountered are difficult to explain in the conventional concise manner of technical papers and reports and thus are normally glossed over in most circuit descriptions. This leaves the uninitiated reader with a vastly oversimplified technical picture. By realizing the short comings and problems associated with conventional power processing, one gains further appreciation of the advantages of the HVSA concept for electric propulsion. The HVSA concept does not involve power processes such as inversion, transformation, and rectification.

Screen (V_5) Supply

The screen (V_5) supply consists of three modified Jensen inverters[10] where each provides one third of the output power. The inverter transistors alternately switches each half of the primary winding so generating an alternation current (ac) voltage across the primary winding. This is transformed to the high voltage (1000 V ac/module), rectified and filtered. The rectified outputs are connected in series to provide the required +3000 V. Protection is simple in sensing when output current exceeds a given amount and quickly shutting off the inverter for a short time interval. This technique interrupts the on set of an arc that very likely may be self-sustaining if not interrupted. For reliability, a fourth inverter can be commanded to operate in the series string, if one of the other inverters fails. This technique of partial redundancy does enhance the overall system reliability with a small weight impact. In principle the operation appears straight forward. However, when one gets down to the nitty gritty of power processing design, things are not so simple. For example, the transistors in the inverter typically turn on faster than they turn off and this overlap appears as a "short" on the dc input line. In the case of SERT II, an inductor filter in series with the dc input limited the input rate of current rise in this interval. Transistors require drive sufficient to handle its worst case extreme demands, that may be typified by starting at low input voltage into its maximum output load while at its lowest operating temperature. Since transistor gain may vary 3:1 over its temperature range, designing for worst case presents problems in normal operation with excess drive currents. Excessive drive in normal operation causes excess minority carriers in the transistor which increases the turn off times and compounds the problem of overlap and efficiency.

The transformer appears on the surface to be a simple device, however, in the design of high voltage transformers for inverters subtle characterisitcs are encountered. Transformers are the heaviest components in the P/C and in order to decrease its size, the frequency must be increased with its attendant increase in losses. Thus, efficiency and weight are opposing design relationships. Also, high voltages requires additional dielectric material between winding and layers making a high voltage transformer weigh more than its same VA capacity low voltage counterpart. In addition, the separation causes additional reduction in mutual coupling of the transformer which decreases its regulation from a strictly turn ratio viewpoint. In order to convert the low voltage to high voltage there must be a large turns ratio between the input and output windings. The large number of turns and usual layer construction form a rather large distributed capacitance in the secondary winding. This with the inherent leakage reactances associated with the primary and secondary windings results in an oscillatory LC circuit that rings when excited with the fast rise and fall times of the transistor. This ringing causes high peak input current and transistor dissipation in this interval along with the possibility of the output filter being charged to the high peak voltages after rectification under light load conditions.

In addition, for self oscillating inverters of the Jensen type where the collector to collector voltage is used for feedback drive, a high frequency inverter operation mode could result under certain overload conditions because of the reflected high frequency characteristics of the transformer. The fast rise times associated with breakdowns and arcs with ion thruster operation requires a grouded shield between any output winding operating at the high voltage potential of V_5. The grounded shield terminates the distributed capacitance in the output winding that would normally be coupled to the input winding and provides an effective shunt for the electrostatic energy being discharged during the transient. Without a grounded shield, these transients would be coupled electrostatically from output winding to the input winding and the possibility of failure in the transient prone semiconductor circuits would be high. This grounded shield also increases the separation between the windings. Low core loss, high permeability magnetic core materials, such as 80 percent iron - 20 percent nickel, exhibit a ratcheting phenomenon where the excercised B-H loop is only conditionally stable around its center but will drift towards on of its stable equilibrium points, B_r, residual flux state.[11] This is caused not only by slight dc unbalance in the circuit due to saturation voltage (Vcesat), turn on (ton), etc. of transistors but switching transients can intiate the phenomenon. A transformer core that has ratcheted to one of its saturation portions of the B-H loop will result in a high current spike in one of the inverter transistor near the end of that half cycle of operation.

Shutting off the transistor under this condition causes high peak power dissipation and undue stress. In SERT II the series input inductor filter effectively limited the rate of rise in current to safe levels during this interval. This fix was necessary even with the use of D-U laminations in the transformer core since the effective air gap was too small to avoid the problem.

In addition, a limited discussion of certain salient problems associated with some of the other supplies follows. This is included for background purposes since it will be shown later that the HVSA concept avoids these characteristic problems.

Accelerator (V_6) Supply

The V_6 supply has its own inverter-transformer similar to that employed in the V_5 supply. This supply's transformer winding ratio is the highest of all and the aforementioned problems of ringing in the transformer results in poor inherent regulation in the rectified output voltage under light load conditions as shown in Fig. 3 for the SERT II preliminary breadboard. In SERT II this problem was endured rather than burden the output with a bleeder to dissipate the transient energy and suffer the attendant losses. As one can see from Fig. 3 to obtain load regulation of approximately 5 percent would require a bleeder of 10 mA with a dissipation of 20 W.

Anode (V_4) Supply

The anode (V_4) supply receives power from the master 8 kHz inverter which also powers the remaining supplies. A magnetic amplifier is employed to modulate the ac power prior to transformation, rectification and filtering as shown in Fig. 2. This supply along V_2, V_3, and V_{10} floats at the positive high voltage (V_5) potential. Normally sensing and controls are done on the input side of the output transformers to minimize circuitry that must operate at the HV potential. This requires circuitry to compensate for temperature and load effects. In instances such as in the V_4 and V_{10} supplies the rectifiers and filters must be on the high voltage side. Here it is necessary to recognize that the V_5 high voltage breakdowns are extremely fast and essentially instantaneous for all practical purposes.

In Fig. 4 the function of the capacitor, C_A across the rectifiers is to absorb the transient energy associated with the distributed capacitance, C_D in the transformer, wiring, and components when the thruster arcs. For instance, without this capacitor a sudden drop in the V_5 potential due to a fast rising arc could result in high inverse voltage stress on the rectifiers. Since the distributed capacitance shown schematically in Fig. 4 would likely maintain its charge at the V_5 potential prior to the arc for some finite interval of time. The added capacitor, C_A is sized to absorb all this distributed capacitance energy while permitting only a safe voltage rise that is well within the rectifier's PIV ratings.

An important requirement for the anode (V_4) supply is low ripple content in its output voltage. There are several paramount reasons for this: (1) voltage ripple modulates the discharge current within the ionization chamber and this modulation can be strongly observed in the main ion beam[9]; and (2) the propellant utilization of the ion thruster is quite sensitive to the potential of the Anode supply.[7]

In the SERT II case, the V_4 supply was set to be a nominal 37.0 V with ±4.5 percent peak ripple allowed. Designing for less ripple is highly desirable, but would require additional filtering and its attendant weight increase. One must recognize the difficulty in designing for low ripple content in a low voltage, high current dc output filter such as V_4's when the power is modulated by PWM techniques, yet is light weight, efficient, and reliable. This discussion is intended to be a brief synopsis of conventional power processing for ion thruster problems. In view of the above remarks about the nature of the ion thruster characteristics and the power processing design problems, it is no wonder that power processing for ion thrusters have proven complex, inefficient, and costly to develop. In fact, many of the advantages of the HVSA concept for electric propulsion are afforded because of the disadvantages associated with conventional power processing. The HVSA concept does not involve many of the basic processes such as inversion, transformation, and rectification that extracts their toll in weight, efficiency and reliability.

INHERENT CHARACTERISTICS OF HVSA FOR ELECTRIC PROPULSION

As mentioned in the introduction, the prime impetus for the HVSA concept lies in eliminating the losses, weight, and unreliability associated with conventional power processing. The basic HVSA technology involves designing the solar array to deliver its power directly in the form required by the ion thruster.

If one examines the physical processes within the ion thruster, all are inherently dc in nature. The thermal flow, discharges, the ionization, acceleration, and neturalization of the ion are all dc processes.

Although the thermal flow for all heater elements are unidirectional, heaters could be ac or dc operated since only electrical heating power to reach thermal conditions are required. In conventional power processing, such as SERT II, ac is applied to the heaters for efficiency reasons. To obtain dc would necessitate the addition of rectifiers with its attendant losses. DC operated heaters have advantages when compared to ac powered heaters. For example, the line inductance of the wiring limits the upper ac operating frequencies that can be used to effectively transmit power and the power factor associated with the line reactances reflected to the inverter effects its efficiency.

In certain instances, operating the inverters at higher frequencies and rectification of the ac to dc power the heaters results in weight reduction that may offset the increase losses. At the present time, Hughes Research Labs is comtemplating the use of dc for heater in the design of the 30 cm ion thruster power processing.[12]

Another factor one can observe is all the supplies for the ion thruster are current limited in one form or another. The heaters employ magnetic amplifiers to limit the current under cold impedances or short circuits. The keeper discharges are current limited by the series inductor on the inverter side of their output transformer prior to rectification and filtering. This provides the soft I-V characteristics for ignition of the discharge and stable operation. The Anode discharge also must be current limited to protect the ion thruster. When the thruster arcs and the HV supplies are momentarily shut off, the plasma currents in the discharge can increase considerably due to the loss of the extraction of ions from the discharge by the field optics associated with the screen and accelerator electrodes. Current limiting the Anode discharge limits the additional heating and possible damage that would occur within the ion thrusters and also makes the plasma less dense and hence easier to re-establish the HV potential to the screen and accelerator. In addition it is necessary to limit current by interrupting the breakdown or arc currents associated with the screen and accelerator. Without this provision an arc occurrence could be self sustaining and continuous. The V_5 and V_6 supplies, however, are necessarily designed for fast shutdown in order to protect the inverter transistors. It is very likely that sensitive and fast acting overload sensing and tripping circuits as used in

SERT II, would give the appearance of more frequent breakdowns and arcing than really exists within an ion thruster.

Now turning our attention to the source of power for all practical electric propulsion missions - the solar cell. This device has ideal characteristics for the type of loads exhibited by the ion thruster. The solar cell is inherently a ripple free dc power source that is current limited. These are the very characteristics that one tries to achieve in the design of conventional power processing for ion thrusters.

The solar cell is rugged and can operate in three I-V quadrants as shown in Fig. 5. Power is delivered by the solar cell while operating in quadrant I which is its normal mode. In addition, the solar cell can safely dissipate transient power, if required, in the forward or reverse bias condition as represented by quadrant II and IV respectively.

In principle the transition from a low voltage solar array to a HVSA is a straight forward task. One connects a large number of solar cells in series to achieve the high voltage and a few in parallel to satisfy the current requirements, instead of the converse as in a conventional low voltage array.

As will be shown later, the preferred method for regulation of a HVSA is by shorting out solar cells in excess of that required to maintain its output. This is essentially a non-dissipative technique in that a "shorted" solar cell dissipates no more power than an unloaded solar cell, thus presents no thermal stress on the array. Figure 6 shows a typical solar cell I-V, power, and temperature relationships in a graphically manner. The solar cell operates at the lowest temperature when it is delivering maximum power which is consistent with the conservation of energy principles. Likewise the temperature of operating in the open circuit or short circuit mode is essentially the same. In essence, the solar cell's inherent characteristics of a rugged dc power source that is ripple free and current limited are ideally matched with the intrinsic requirements of the ion thruster. From a systems viewpoint, if the source and load are compatible then there is no requirement for power processing, per se.

HVSA STUDIES AND LIMITATIONS

In 1969, NASA-Lewis Research Center sponsored three studies of the HVSA Electrical Configuration.[1,2,3] The object of these studies were to define: (1) conceptional designs of electrical configurations for HVSA with integral power conditioning; (2) problems associated with development of such electrical systems; and, (3) efforts associated with the resolution of the problems identified by the studies.

For study purposes, the array application postulated was supplying power to ion thrusters to raise a spacecraft from low orbit to synchronous orbit and then reconfigure to power high frequency electron tubes for TV broadcasting. Briefly the most significant system requirements and study guidelines were:

(1) The array must be capable of delivering 15 kW of useable power at one voltage level or up to six different voltage and power levels in the voltage range from 2 kV to 16 kW.

(2) The electrical configuration should have capability of delivering power to loads over the widest practical range of voltage and current.

(3) The array must be capable of being configured to any of its physically realizable states by ground command.

(4) The load voltage or load current should be regulated to ± 0.1 percent using an on-board computer control.

(5) The array design and electrical configuration should provide a reliability after deployment of 0.99 probability of design power at the end of 5 years with a 90 percent confidence level.

For the basis of these studies, the array construction, assumed for design estimates as to weight and size, is that given in the 30 W/lb Roll-up Solar Array Feasibility Study.[13]

In parallel with these investigations the space plasma environment interactions with the HVSA were being examined;[14,15] however, discussion of these aspects are beyond the scope of this paper.

In general these studies concluded that HVSA's are feasible and can out perform the conventional power processing system operating from low voltage array. However, the scope of these investigations were limited to the realm of regulated high voltage and high power typical of the beam requirements of an ion thruster which represent 0.85 to 0.9 of the total power requirements. For an electric propulsion mission, where reconfiguring is not required, the HVSA can provide regulated power for the main beam with a system performance estimate of 0.6 to 1.0 lb/kW and an efficiency of 0.99 to 1.0.[2] This is highly favorable in comparison to the conventional power processor performance of 8 to 12 lb/kW and an efficiency of 0.9 to 0.94.

The design goals of 0.99 reliability specified for these studies could be met by incorporating a large number of bypass diodes to provide an auxiliary current path in the event of an open circuit solar cell failure. This reliability figure is much higher than presently achieved in the conventional power processing system.

In brief, these studies show distinct advantages that the HVSA concept offers for electric propulsion in weight, efficiency and reliability even if only the main beam requirements were considered.

PRESENT STATUS OF HVSA

The studies identified problem areas and defined the effort necessary to develop the switching, sensing, and control devices required for integral regulation and reconfiguration on the array. It was originally intended that additional NASA sponsored effort to breadboard, develop and verify the design concepts in a system evaluation would follow. Unfortunately this did not materialize as planned but some related activities have evolved that still makes this a viable technology for electric propulsion.

A new photovoltaic device, the Multiple Junction, Edge Illuminated Solar Cell (M-J Cell)[6] was devised to fulfill the need for high voltage, low current loads represented by the accelerator V_6 and the high voltage ignition requirements of the keeper electrodes, V_8 and V_{10}. In addition this cell would find application in providing isolated power for controls and sensors. Devices developed for a flight test in the MINX Experiment (Miniature High Voltage Array Interaction Experiment)[16] in early 1974 on the SPHINX spacecraft have 96 series connected P-N-N^+ junctions in a 2 cm by 2 cm cell, where each individual solar cell junction has an area of approximately 0.04 cm^2. Figure 7 shows the M-J Cell's construction and typical performance compared to a conventional cell. The MINX array shown in Fig. 8 is a series connection of 36 M-J Cells. The total array voltage is 1100 V dc (80° C) with approximately 1 mA output capability. It is likely that the MINX array configuration would be representative of a practical accelerator supply. Also on the MINX experiment a hybrid micro-electronics solid state relay is used to control the output of a group of 4 series connected M-J Cells. The requirements of this solid state relay were quite severe and maybe representative of that required for the HVSA. It is significant that this small device packaged in a T0-116 package provides 5000 V corona free isolation and survives 1000 thermal cycles from -120° C to +80° C[17].

In addition to these new developments, several experimental investigations of the weighted binary digital regulation concept of an actual solar array were pursued by NASA-Lewis Research Center[4] and Hughes Research Labs.[5] This work, utilizing optoelectronics techniques for voltage isolation, further substantiates the merits and feasibility of the HVSA. For high voltage, this technique of regulation appears simple, efficient, and reliable. For completeness a brief description of the NASA tests follows, however, the reader should refer to the referenced material for more detail. In Fig. 9 a schematic of the test array is shown. This array is divided into two sections. A 500 V unregulated section and a 255 V weighted binary regulated section. The 255 V regulated section of the solar array was tapped at voltage levels equivalent to the binary weight system (i.e., 2^0, 2^1, ... 2^7). The variable voltage from 0 to 255 V in 1 V increments is obtained with this binary voltage tap configuration.

The unregulated 500 V solar a-ray section was placed in series with the 255 V regulated solar array section for a total array output capability of 755 V at 50 mA.

Regulation of 0.175 percent was obtained with this arrangement and an I-V plot taken is shown in Fig. 10. Basically any voltage ±1.0 V can be obtained between the two extremes shown for all switches open and all switches shorted. Closed loop control was achieved by an up-down counter operating from the signal derived in comparing the actual voltage output with a reference voltage.

Another experiment, shown schematically in Fig. 11 demonstrated a Pulse-width modulation (PWM) technique. In this configuration, power is modulated in a PWM fashion by the transistor shorting the 300 V and 0.5 A solar array supplying two series connected lamps as a load. This experiment was operated at 100 kHz rate with modulation from 0 to 100 percent, yet the output transistor required no heat sink which is an indication of its efficiency.

A basic switch, employing photo coupled light emitting diodes (LED) and transistors, shown in Fig. 12, was breadboarded and demonstrated as being feasible for computer control and hybrid microminiaturization. Turn on and turn off is accomplished by pulses from the computer output to the LED's coupled to the appropriate photo-transistors. Briefly its operation follows: A turn on pulse into LED_2 drives photo transistor PT_2 on, which in turn pulls current through LED_1 and provides drive to PT_1. PT_1 provides base drive and turns on transistor, Q_1. If Q_1 is driven into or near saturation (full on) current will continue to flow in LED_1 through diode D_2 even after the turn on pulse terminates. Therefore, an on pulse in LED_2 will cause transistor, Q_1 to latch on via LED_1 and PT_1 and remain on until (1) a turn off pulse into LED_3 turns on photo transistor, PT_3 and shunts Q_1 base drive momentarily allowing it to turn off, or (2) for any reason transistor Q_1 pulls out of the saturation region, i.e., due to overload exceeding base drive capability, partial shadowing of the drive solar cells lowing the base drive to insufficient levels, etc. This self protection feature would be necessary to protect a hybrid package because of its limited power dissipation capability and lack of heat sinking on an array. In any tests it is probable that instances of partial shadowing and overloading would be commonplace.

Under contract with NASA-Lewis Research Center, Hughes Aircraft Co. has fabricated a modular high voltage solar cell power generating system(18) that will be a test bed for future HVSA development activities.

OPERATION OF SERT II ION THRUSTER SYSTEM WITH SOLAR ARRAYS

In early 1970 a series of "quick and dirty" tests were conducted using the SERT II ion thruster system (including P/C) in conjunction with solar arrays. This testing was proposed and conducted within a three week period in order to take advantage of SERT II hardware availability and a vacuum chamber prior to being modified for another program. Because of expediency, short cuts were necessary and minimum data was recorded. (Also at the time it was felt that this type of activity would be continued and refined; however this was not the case.) Although the tests and techniques appeared crude, the observations noted are valid and will be discussed.

The solar cell arrays available were: (1) 12-SERT II solar array panels (28 V at 0.5 A each) that could easily be modified to provide a wide variation of voltage and currents up to 168 W maximum; (2) 22-1 ft^2 fiber glass HV panels with 234 series connected 1x2 cm^2 solar cells on each panel (117 V at 35 mA each). An array of lamps was set up and with rectified 3Φ, 60 Hz power controlled by a variac, the "sun" source was created in the lab. Since this was not sufficient solar array power to operate the entire SERT II thruster system, it was done piece-meal as follows:

Vaporizer, V_2 - A section of the array was configured to match its maximum requirements. Since the vaporizer is feedback controlled by Anode current, I_4 during "propellant" mode and the screen current, I_5 during "operate" the simplest technique for control was implemented. The analog signal inside the SERT II P/C mechanized to control the V_2 magnetic amplifier was used to modulate a 10 V pre-focused light bulb instead. This light bulb was optically coupled to a transistor with a hole in its case using black opaque heat shrink plastic tubing. This technique provided the necessary high voltage isolation between the analog signal at ground and the transistor control on the solar array floating at the V_5 potential. The circuit design was such that the $I_2 - I_5$ control loop gain required for stable thruster operation was maintained. Normal operation of the thruster was observed in this test.

Cathode, V_3 - A section of the array was configured to provide its maximum requirements for "preheat" and "propellant" modes and a tap was made in the array to provide normal "operate" power. A high voltage ceramic vacuum relay was used to switch between modes by picking up a control signal from the P/C. Normal operation of the thruster system was observed.

Cathode Keeper, V_{10} - Two arrays were configured and "or" together with diodes to provide the I-V characteristics shown in Fig. 13. The HV modules provided the 400-500 V at 35 mA and the SERT II panels cells are configured to provide 0.5 A which couldn't be easily modified. Therefore, gum backed tape was used to cover some of the cells to provide the 0.3 A required at 30 V.

Neutralizer, V_7 and V_8 - The composite arrays configured for V_{10} was used for the V_8 keeper supply but modified for the 200 mA maximum current requirements and an additional array was configured to provide the maximum V_7 heater requirements. A shunt regulator circuit shown in Fig. 14 was used to provide the proper V_8-I_7 feedback gain relationships. In the test the neutralizer was operated entirely off solar array power and low ripple operation was observed. In Fig. 15 scope photos of neutralizer keeper's voltage and current, V_8 and I_8 are shown for (a) operation with the SERT II power conditioner, and (b) operation directly off the solar array. We can see in (a), the ripple associated with the conventional power processing systems. It is 16 kHz ripple that results by rectification and filtering the PWM 8 kHz master inverter power. To decrease its magnitude additional filtering weight would be required. One should observe the ripple free nature of solar array power shown in (b). The plasma noise however can be observed in these photos and it is quite possible that it can be effectively filtered at the thruster to eliminate conductive propagation of these frequencies along the lines to the source.

Accelerator, V_6 - The high voltage modules were configured to provide the necessary -1800 V. Several by-pass diodes were added to provide transient paths for a V_5 to V_6 arc. For control only on-off operation was required and was accomplished using a high voltage ceramic vacuum relay operated with a control signal from the SERT II P/C. Normal operation was observed and no problems were noted with arcing. However, it should be noted that this direct HVSA hookup provides regulation inherently as good as the solar array, that is not compromised by the power processing idiosyncrasies as was shown in Fig. 3 for the SERT II P/C.

Anode, V_4 - This supply was configured to match the maximum requirements and, for regulation, a weighted binary switching arrangement was introduced. Only three switches were necessary and manually operated high voltage ceramic vacuum relays were employed. The inherent ripple free nature of the solar array power was again observed as one can see in Fig. 16. Here scope photos show, (a) the V_4 and I_4 discharge ripple with the SERT II P/C- and (b) the V_4 and I_4 discharge with solar array. Again the plasma noise of the discharge can be noted. Unfortunately these photos have different time and amplitude scaling that makes direct comparisons inconvenient.

Screen, V_5 - Insufficient solar array was available to operate the entire beam; therefore 300 V at 0.5 A of SERT II arrays were connected in series with the existing V_5 supply within the SERT II P/C. This was connected in place of the standby module and was floated to the normal V_5 potential. It was found that a relay was necessary to "short" this array after an arc to interrupt the I_5 current so that the P/C could reestablish the high voltage. This was done with a high voltage ceramic vacuum relay using the normal overload shutdown signal within the P/C.

In summary these test testify to the feasibility of operating ion thrusters using the HVSA concept. No problems were noted with arcing. In fact, induced arcs and shorts of all combinations normally required for the SERT II P/C design were purposely subjected to the solar arrays. The ripple free power from the solar array is an additional benefit of the HVSA. Low ripple in the discharge supply V_4 should enhance the ion thruster's operation for several reasons: (1) The discharge current modulates the beam current[9] therefore, less ripple is more desireable; (2) the propellant utilization of the thruster system is very sensitive to the discharge potential[7] thus, low ripple may reflect an increase propellant utilization. In addition, (3) the cathode sputtering is sensitive to the discharge potential[7] and low ripple may likely provide an increase lifetime.

ADDITIONAL CONSIDERATIONS AND CONCLUSIONS

The HVSA configurations as discussed here imposes penalties for ion thrusters systems. If one assigns a separate dedicated array for each thruster load requirement then each array as a minimum must be sized to furnish the maximum worse case load condition. In table I, the rated P/C output reflects this maximum requirement for the SERT II ion thruster whereas the typical operating output requirements are considerably less. For SERT II, the maximum rated conditions are 1126 W which represent a 30 percent oversize penalty for a dedicated HVSA when compared to the 860 W typical operating conditions. This would represent a poorly matched HVSA system.

Fortunately there are system tradeoff considerations that would allow one to design a better power matching HVSA system. For example, considering the heaters V_2 and V_3 are operated at their maximum levels only until the discharge V_4 has been established permits the possibility of sharing a portion of the array or a semi-dedicated HVSA system.

There are some functions that conventional power processing techniques can perform better than the HVSA concept as now envisioned. This lies in it being able to provide power conversion. For example, peak power tracking on an array to charge batteries or capacitors is accomplished readily in conventional power conversion but would require an infinite reconfigurable solar array to use HVSA concepts.

Systems studies have not been fully investigated, but a practical HVSA system for an electric propulsion mission would likely be comprised of a combination of HVSA and conventional power processing techniques. One could, for example, take advantage of HVSA concept to supply the main beam, V_5 and discharge, V_4 directly from the array, and likewise using M-J Cells for the accelerator, V_6, while using conventional power processing techniques for the other supplies. For the SERT II example, this would represent approximately 95 percent of the thruster's typical requirements and would substantially improve the systems performance in terms of weight, efficiency, and reliability.

Although considerable study and development remains to be done, the work described in this paper demonstrates the technical feasibility of the HVSA concept for electric propulsion.

CONCLUSIONS

The HVSA offers improvements in efficiency, weight and reliability for the electric propulsion power system. The inherent characteristics of the solar array's ripple free and current limited dc power ideally match the intrinsic requirements of the ion thruster. Tests conducted on the SERT II ion thruster system in conjunction with direct solar array power verify the feasibility of the technology and in some respects the enhanced ion thruster's operation. A practical HVSA system for electric propulsion would likely be comprised of a combination of HVSA and conventional power processing techniques.

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TABLE I. - ELECTRICAL OUTPUT REQUIREMENTS

Output supply	Rated output[a]			Typical operating output[a]		
	Voltage, V	Current, A	Power, W	Voltage, V	Current, A	Power, W
Propellant feed vaporizer, V2	3.6 ac	3.0	10.8	1.78 ac	1.7	3.0
Cathode, V3	17 ac	3.4	57.8	5.2 ac	1.5	7.8
Anode, V4	45 dc	2.6	117	37.4 dc	1.7	63
Screen, V5	3000 dc	.26	780	3000 dc	.255	765
Accelerator, V6	-1800 dc	.05	90	-1550 dc	.0019	3.0
Neutralizer cathode and neutralizer vaporizer, V7	13 ac	3.4.	44.2	5.8 ac	1.9	11.0
Neutralizer keeper, V8	30 dc	.23	7	23 dc	.183	4.2
Neutralizer bias, V9	50 dc	.25	13	0	0	0
Cathode keeper, V10	20 dc	.35	7	11.7 dc	.30	3.5
Total power			1126.8			860.5

[a]For nominal input voltage of 60 V dc.

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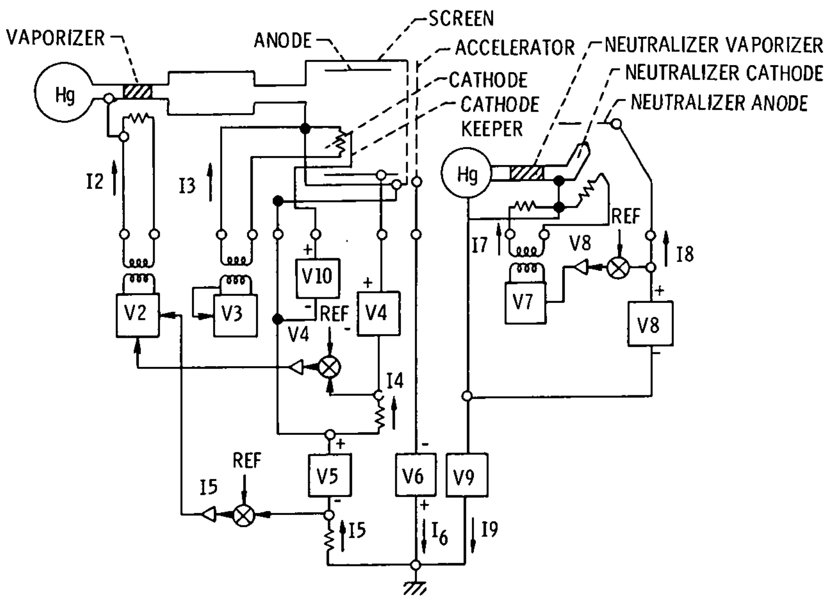

Figure 1. - Power conditioner block diagram.

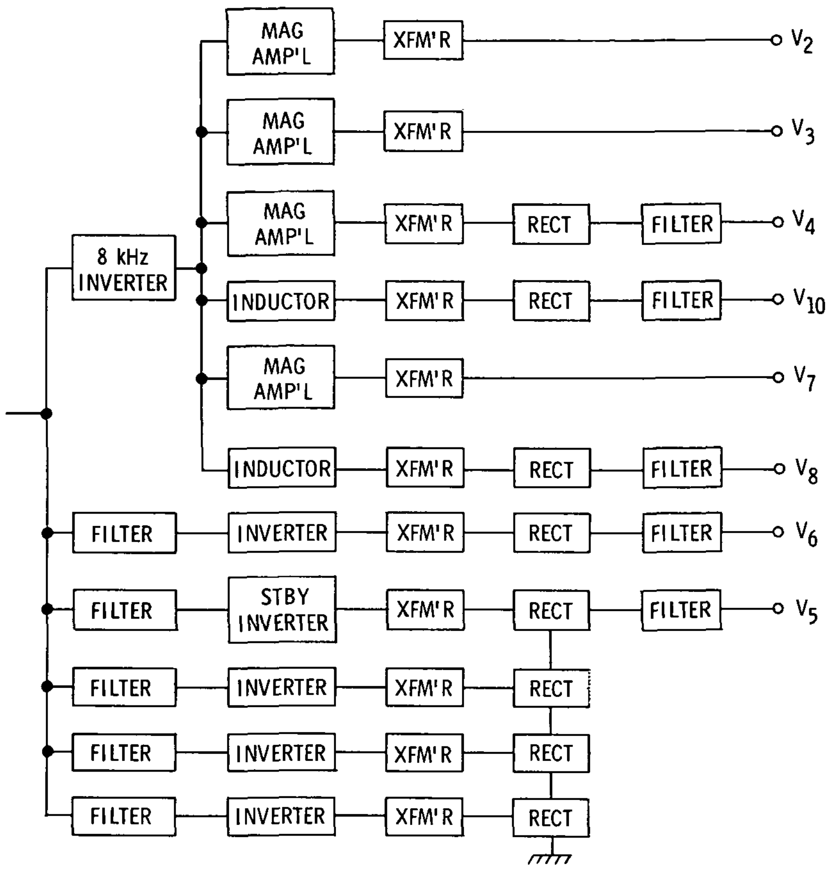

Figure 2. - Basic power processes in SERT II P/C.

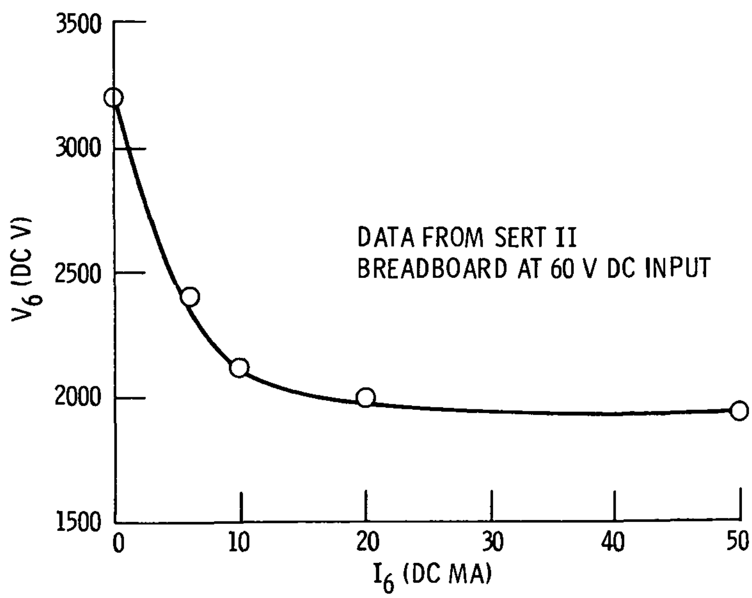

Figure 3. - Typical V_6 output characteristics.

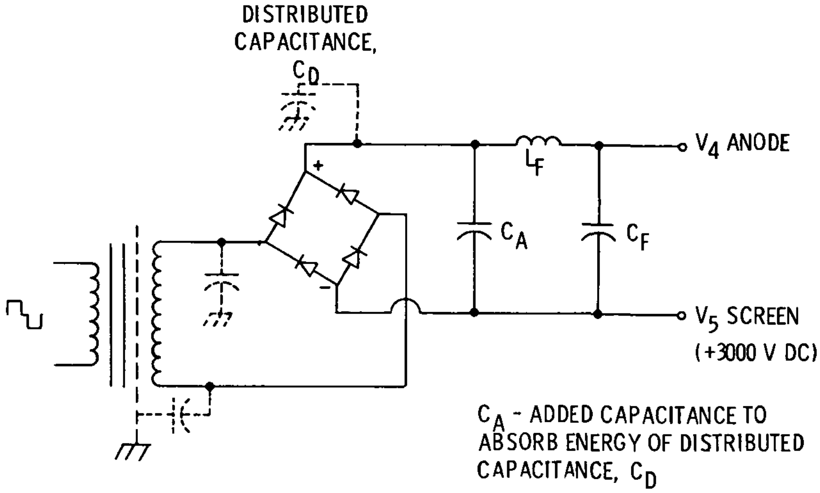

Figure 4. - V_4 - anode supply schematic.

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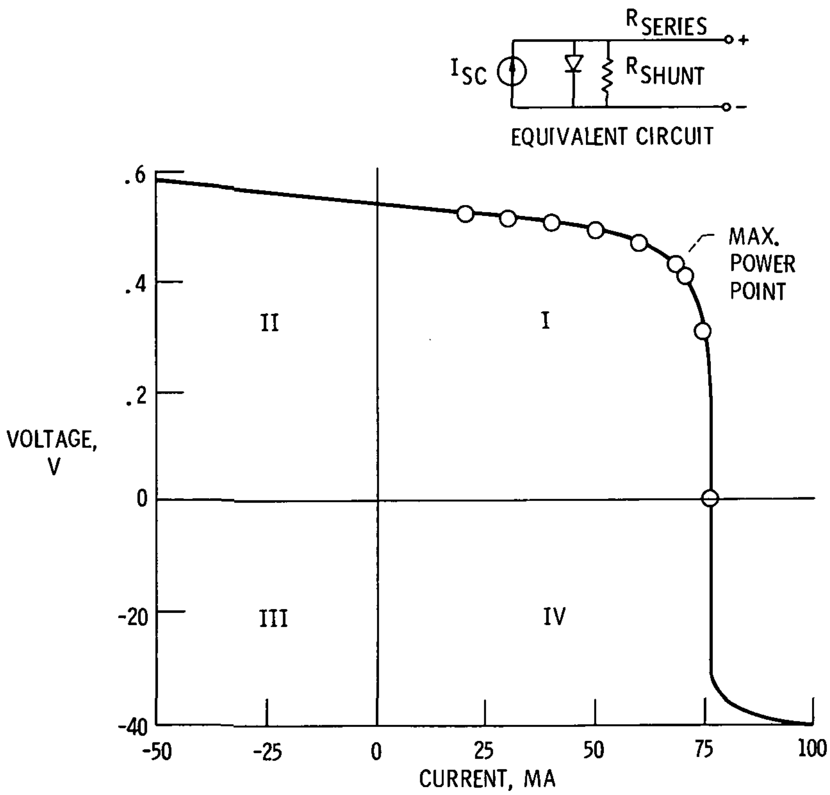

Figure 5. - Typical solar cell I-V relationships.

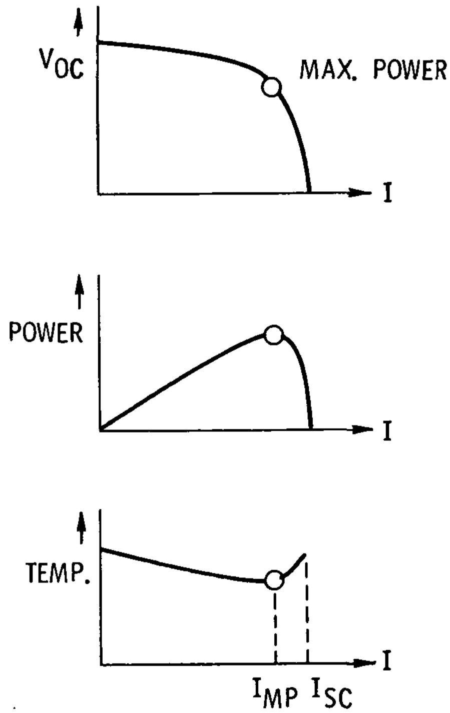

Figure 6. - I-V, power, and temperature relationships of solar cell.

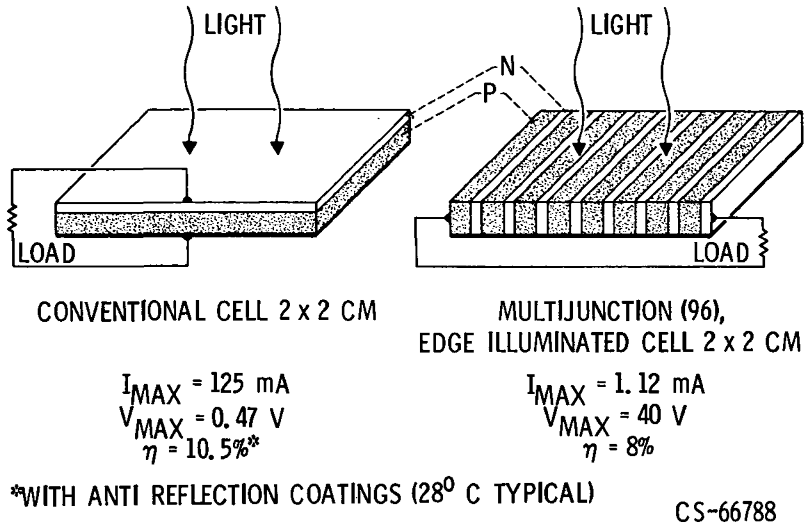

Figure 7. - Multiple junction edge illuminated solar cell.

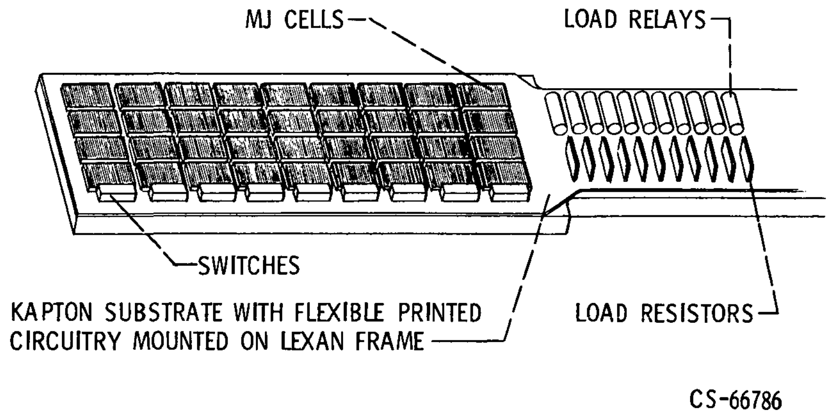

Figure 8. - MINX flight array.

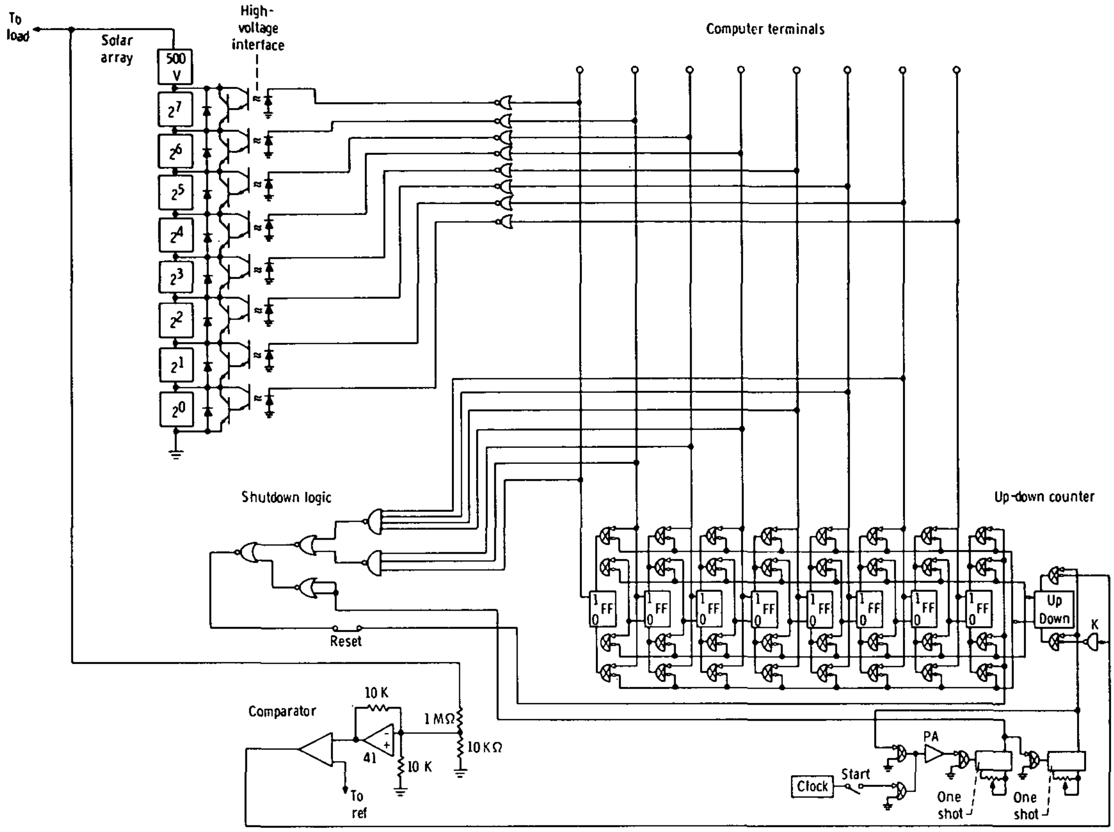

Figure 9. - Digital regulated high-voltage solar array module.

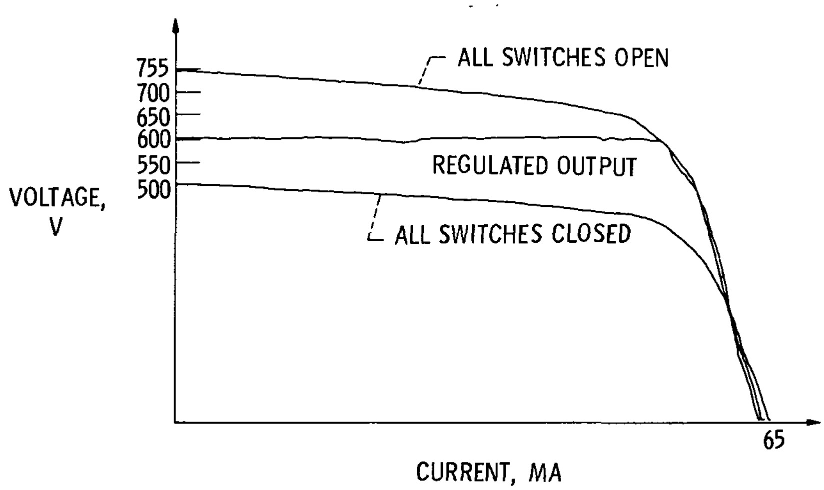

Figure 10. - Regulation at 610 volts of HVSA module under artificial illumination.

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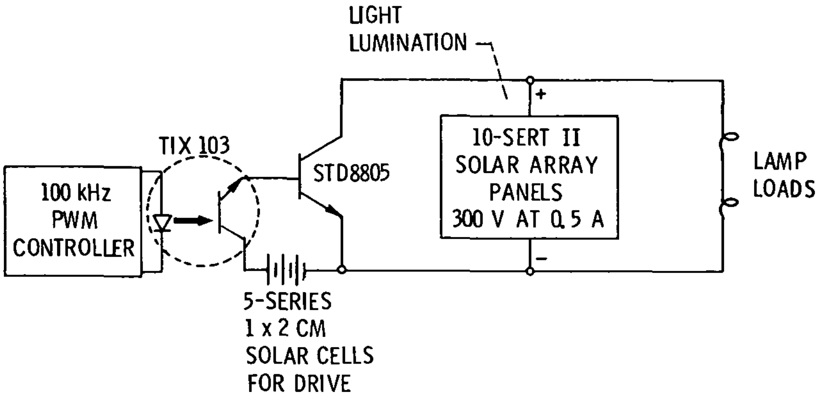


Figure 11. - 100 kHz PWM solar array demonstration.

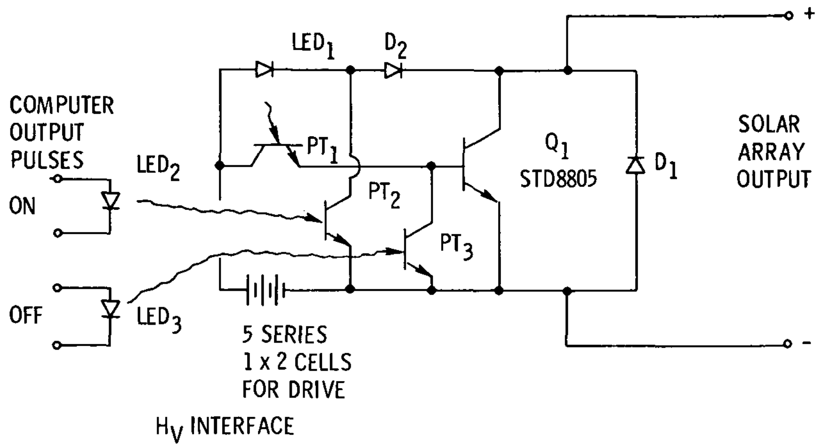


Figure 12. - Computer pulse operated, self-protected H. V. isolated switch concept.

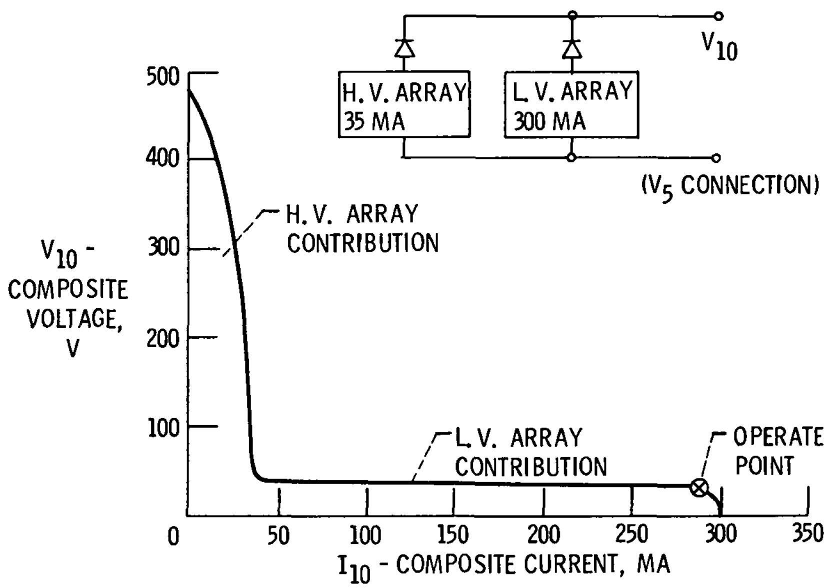


Figure 13. - V_{10}, cathode keeper supply.

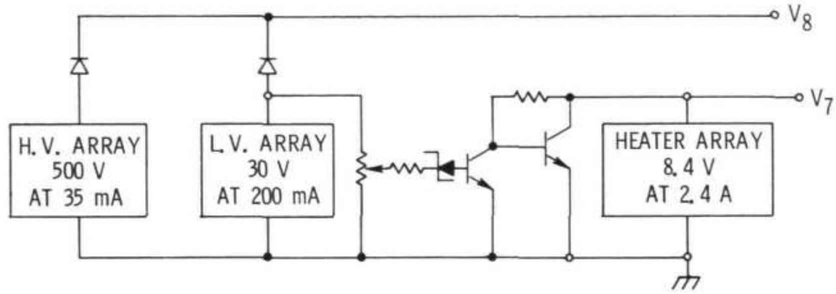
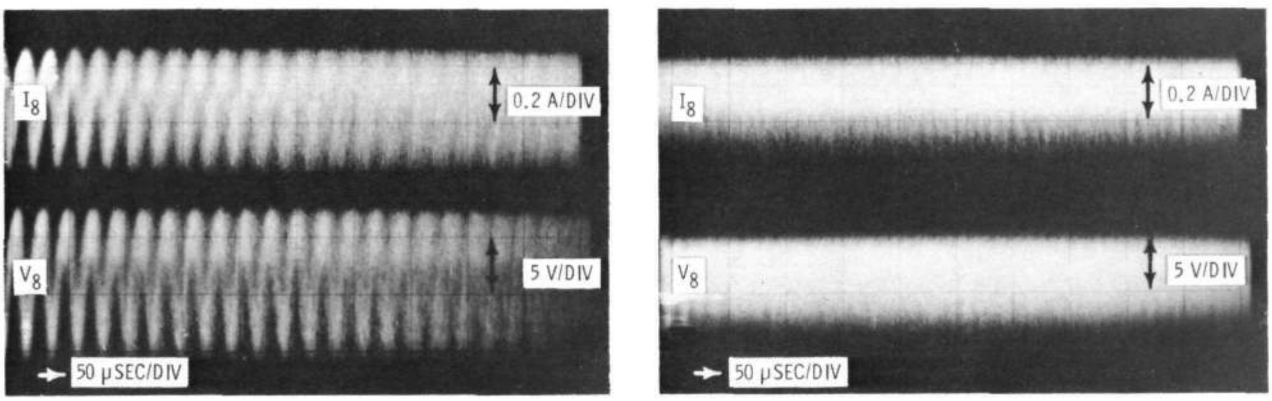


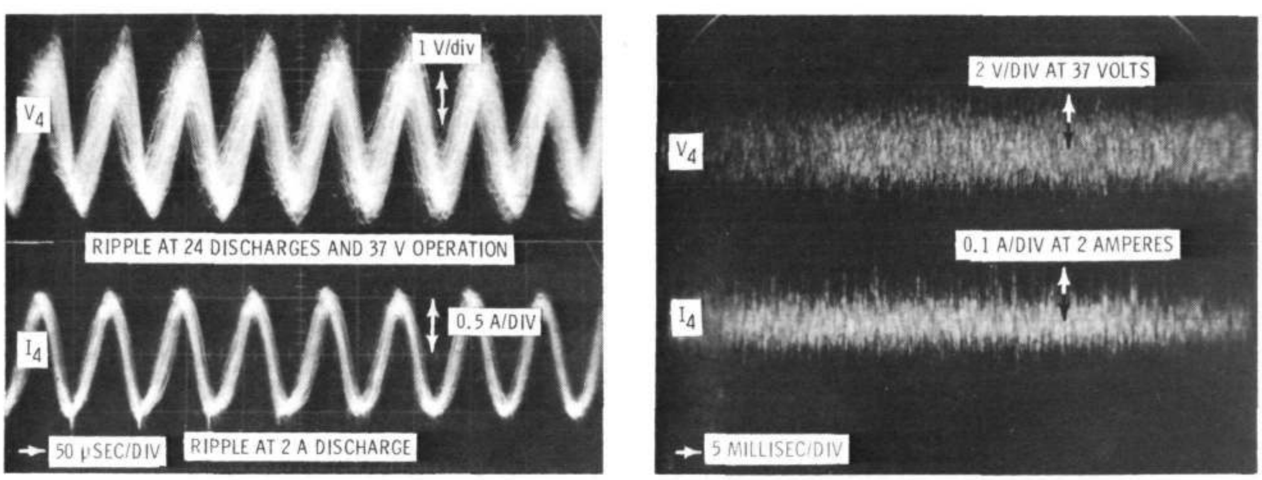
Figure 14. - Schematic of neutralizer-solar array test.



(a) NEUTRALIZER WITH SERT II P/C MODEL EX-5.

(b) NEUTRALIZER WITH SOLAR ARRAY.

Figure 15. - Neutralizer keeper ripple test results.



(a) SERT II P/C MODEL EX-5.

(b) OPERATION WITH SOLAR ARRAY.

Figure 16. - Anode discharge ripple test results.

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