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REVIEW OF SERT II POWER CONDITIONING

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16. Abstract

The SERT II power conditioner was required to meet severe operating conditions. These conditions include operation in vacuum, potential differences of 4000 volts, and frequent and unavoidable thruster arcs. Techniques intended to provide satisfactory, reliable performance for a period of at least 6 months are discussed. The techniques described include "open-to-vacuum" construction of magnetic components, automatic overload protection, conformal coating, and aluminum-coated insulating sheets as barriers. The performance of the successful power conditioning system to date is discussed.

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SUMMARY

This report covers those areas of the SERT II power conditioning development considered most important for the containment of high voltages for the long-term, space operation of an ion thruster. Current limit and output interruption techniques for protection from thruster arcs are discussed. The extent to which open-to-vacuum construction techniques were used is described.

Internal arcing problems occurred late in the development of the power conditioner. These problems were ultimately solved by the addition of insulation inside the power conditioner. Both conformal coating and aluminized insulating barriers were used. Based on the application of these insulations and their success in solving the arcing problems, certain recommendations are possible for future designs: (1) insulation in addition to that provided by the vacuum and (2) separation of low and high voltages by a barrier which may be part of the structure.

The successful operation of the power conditioner in running a thruster both on the ground and in space has proved the effectiveness of the open-to-vacuum construction and of both the internal and external arcing protection.

INTRODUCTION

The power conditioning system development program for SERT II incorporated concepts that proved valuable in assuring the system's long-term performance for a 6-month mission operating an electric thruster. The power conditioning system described herein was developed to power a 1-kilowatt mercury ion thruster on the orbital SERT II spacecraft. Information about the SERT II program and its results can be found in related reports (refs. 1 to 3) covering the design and description of the SERT II spacecraft and the performance of the ion thruster. A brief description of the power conditioner is included in this report, but the reader is directed to the more detailed coverage provided by reference 4.

The power conditioning system used for the 1964 SERT I mission incorporated a sealed, pressurized enclosure to ensure proper operation during its 1-hour useful mission life. The SERT II system was specifically designed to perform a 6-month mission. The techniques used should be of interest to those who must decide between open or sealed construction and to those who must deal with the generation and use of high voltages in a confined volume. Those acquainted with the arcing and startup problems of ion thrusters should find the SERT II techniques particularly informative.

The information gained from the development and application of this power conditioner covers several design areas. Protection of the power conditioner from both external and internal arcs is covered in detail. Current limiting and momentary supply shutdown were two techniques used successfully in the power conditioner design. Open-to-vacuum construction was selected from the several techniques available as the most likely to achieve success for a long-term space mission. The extent to which open-to-vacuum construction techniques were used is described.

Late in the development program, failures due to internal arcing began occurring. This was particularly frustrating because of the precautions already taken. The subsequent investigation showed that outgassing was not the cause of the failures. Success was achieved only after the addition of insulation inside the power conditioner. Although the effects of our corrective techniques are still under investigation, some design guidelines are drawn. The success of the design is further demonstrated by its performance in flight.

POWER CONDITIONER DESCRIPTION

The power conditioner converts solar-cell electrical power into power required to operate a mercury ion bombardment thruster. The SERT II solar-cell array provides a nominal dc voltage output of 60 volts during full-beam thruster operation. The power conditioner converts this into nine different electrical outputs totaling approximately 860 watts for the thruster. The major amount of electric power is delivered at 3000 volts, 0.25 ampere dc. Nominal conversion efficiency is 87 percent.

Mechanical Description

The power conditioner with and without cover is shown in figures 1 and 2. It is a rectangular box 20.5 inches (52 cm) long, 10.5 inches (26.7 cm) wide, and 5.5 inches

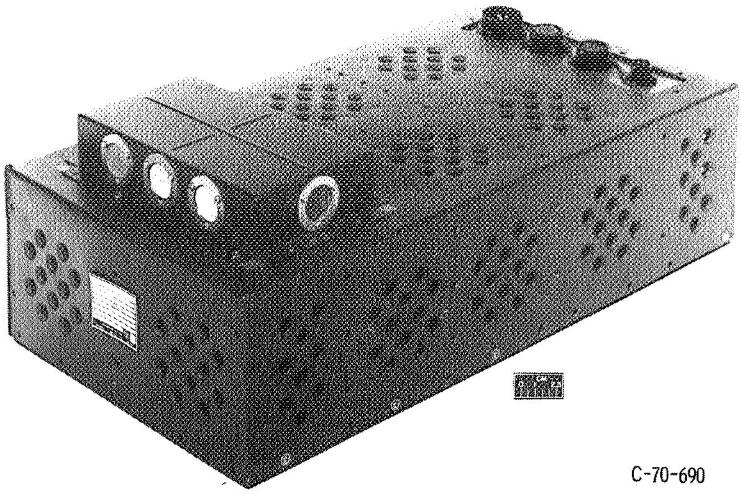

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Figure 1. - Power conditioner with cover installed.

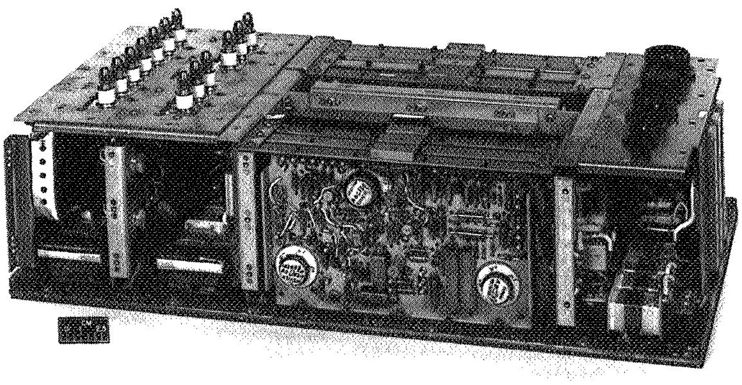

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Figure 2. - Power conditioner without cover.

(14 cm) high and weighs 32 pounds (14.5 kg). The nine electrical outputs are terminated on 13 ceramic feedthroughs. The power conditioner is bolted to the spacecraft radiator. The radiator is sized to maintain a temperature less than 120° F (322 K) at rated operating conditions.

Electrical Characteristics

Table I lists the rated electrical power output from the power conditioner for each of the nine supplies. Also listed in this table are the typical operating values for each electrical supply. Some of the power supplies (V5, V6) have outputs that vary proportionately with input voltage. The neutralizer bias supply (V9) is an experiment and is not required to operate the thruster. Telemetry outputs are provided to indicate the condition of individual supplies.

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.

Description of Supplies

Master inverter. - The master inverter, which provides power to all supplies except V5 and V6 high voltages, is a modified Jensen inverter (ref. 5) that operates at a nominal 8 kilohertz.

Heaters (V2, V3, and V7). - These supplies receive power from the master inverter. All three heater supplies, main vaporizer (V2), cathode heater (V3), and neutralizer heater-vaporizer (V7), use magnetic amplifiers to control output power by pulse width modulation. Control of these supplies is by feedback signals, as shown in figure 3.

High voltage (V5, V6). - The screen (V5) supply consists of three modified Jensen inverters (ref. 5). Each provides one-third of the output voltage. The rectified outputs are connected in series to obtain the required +3000 volts. A fourth redundant inverter

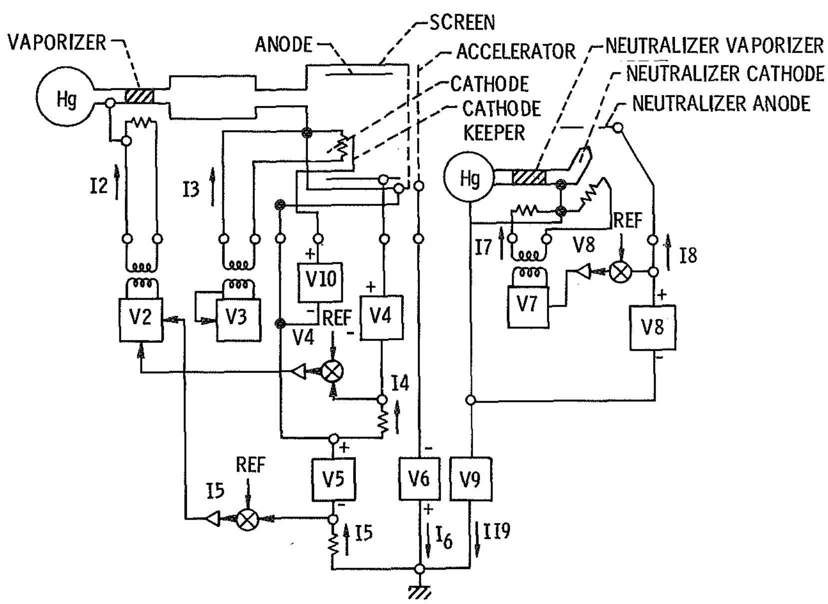

Figure 3. - Power conditioner block diagram.

can be commanded to operate in the series string if one of the other inverters fails. The accelerator supply (V6) is similar to the individual V5 inverter module except the output is -1800 volts dc.

Floating dc (V4, V10). - The anode supply (V4) consists of a transformer and full wave bridge rectifier powered by the master inverter. It uses magnetic amplifier control to provide voltage regulation and current limit. The voltage can be set at any of three values by ground command. The cathode keeper supply (V10) consists of a transformer and a series inductor powered by the master inverter with a full wave diode bridge for rectification. Open-circuit voltage is nominally 400 volts. This drops to approximately 15 volts when the thruster keeper fires. Both the V4 and V10 supplies float at the V5 potential, +3000 volts dc.

Neutralizer keeper supply (V8). - The neutralizer keeper supply (V8) consists of a transformer and a series inductor powered by the master inverter. The output is rectified by a full wave diode bridge. The series inductor limits the current.

Neutralizer bias supply (V9). - The neutralizer bias supply (V9) provides both positive and negative biases. For positive bias, neutralizer emission current flows through zener diodes to cause a 25- or 50-volt bias. For negative bias, an auxiliary circuit consisting of a transformer powered by the master inverter is used. The bias level is selected by ground command.

Operating Modes

The thruster requires a sequential turnon of supplies. This is provided by using interlocked command relays. First, a preheat command is given to start the master inverter, thus energizing the V3, V4, V7, V8, and V10 supplies. Second, the propellant command applies power to the thruster vaporizer by activating the V2 supply. Finally, the operate command allows V5 and V6 inverters to start by removing shorts from stop windings and activating a base drive pulse generator.

Control Circuits

Main discharge ($I2 \propto I4$). - A voltage proportional to the anode current (I4) is applied to the input of a comparator operational amplifier. This signal controls the V2 magnetic amplifier to provide a controlled discharge in the thruster. This control is connected only in the propellant mode.

Beam ($I2 \propto I5$). - A 10-ohm resistor in the ground return of the V5 high-voltage supply provides a feedback signal proportional to beam current. This signal is compared with a fixed reference at the input of a comparator operational amplifier. This signal causes the V2 magnetic amplifier to control the beam current. Command relays select the three reference values for beam control at 75, 200, or 250 milliamperes.

Neutralizer ($V8 \propto I7$). - A signal proportional to the V8 voltage is compared to a selectable reference potential This signal causes the V7 magnetic amplifier to control the neutralizer keeper voltage (V8). The threshold voltage at which control begins is set by command relays which select specific reference potentials. Two V8 control points are available, 28 volts and 22 volts.

Overload integration and shutdown. - The power conditioner overload integrator provides for an automatic shutdown when it reaches its peak value. Resumption of operation must be by ground command through the normal startup sequence. This shutdown function can be disabled from the ground.

OPERATION OF SYSTEM DURING THRUSTER ARCING

Probable Location of High-Voltage Breakdowns in a Thruster

Any system which uses high voltage provides a possibility for voltage breakdown or arcing. The ion thruster has a combination of close spacings and a plasma which is highly conducive to periodic arcing. Some of these arcs will self-extinguish, but many

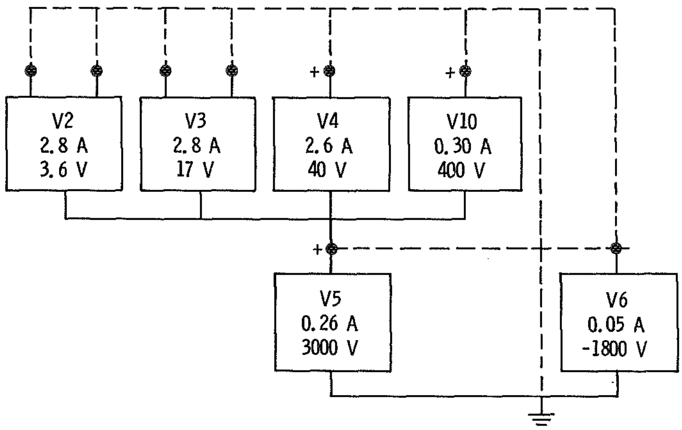

Figure 4. - Possible arc paths in ion thruster. (Dashed lines show arc paths.)

will continue until the power source is interrupted. This is covered in detail in reference 6.

Figure 4 is a block diagram indicating some of the arc paths possible in a thruster. There are two high-voltage supplies (V5 and V6) plus four more supplies (V2, V3, V4, and V10) which float at high voltage. This combination of supplies can result in a variety of overload conditions due to arcing. An arc from either the V5 or V6 supply to ground results in an overload or short on a single supply. An arc from any of the floating supplies to ground results in an overload on that supply plus one on the V5 supply. Also, both supplies will be subjected to the current from the supply with the highest current rating. As seen in table I, three of the floating supplies have current ratings at least 10 times larger than the V5 supply. An arc from one of the floating supplies to the negative V6 supply results in an overload on three supplies. Again, the high current rating problem is present. The supplies in the power conditioner must be protected from all the aforementioned overloads.

Possible Approaches to Handling Breakdowns

Breakdowns across a supply. - There are a number of possible approaches to protect a power supply from shorts caused by arcing. First, the supply could be designed to support short-circuit current. However, this would require that the circuit components be rated for much higher current than they normally supply. Also, the arc or short would be reflected back to the solar array. This could result in a very large drop in the input voltage. Thus, a short on one supply could severely affect all supplies. This is not a desirable approach.

The second approach would be to provide some type of current limiting within each supply. A simple way would be to insert a series resistance. However, this causes a power dissipation and results in a lower efficiency. An inductance can also be inserted in the ac portion of the circuit and provide current limiting with a much lower power loss. Circuits which require control of their outputs - either voltage or current - use a control device such as a magnetic amplifier or a series regulator. This control device can be used to limit the current besides providing the control function for which it was originally intended.

A third approach would be to turn the supply off in the event of an overload. The supply is then not required to either supply arc current or to limit it. Turning off the supply also allows the arc to extinguish.

Breakdowns between supplies. - There are a number of approaches to protect a high-voltage, low-current supply when a high-current supply floating on the high voltage is shorted to ground. First, those components which are subjected to the high current of the floating supply could be sized to withstand it. However, this would require components of very large wattage rating to withstand the current of the floating supply and the voltage of the high-voltage supply. In the case of rectifiers, there would be either higher leakage currents and/or higher forward drops, which result in poorer efficiency.

A second approach would be to place a series resistance in the low-current supply to limit the current during the arc. While this does result in added losses, they need not be prohibitive since the high-voltage supplies operate at low-current levels.

A third possibility is to provide a bypass path for the higher currents obtained during the arcs. While this means added components, it has very little effect upon the circuit during normal operation.

Successful Methods Used for SERT II

Because so many types of arcing conditions can occur, the SERT II power conditioner protection was designed on the following basis:

(1) Each supply must be capable of withstanding a short circuit across its terminals for an indefinite period of time.

(2) Each supply must be capable of having either of its output terminals shorted to ground.

(3) Each supply must be capable of being shorted to any other supply.

In addition, all supplies except the neutralizer supplies have 6000-volt isolation between primary and secondary circuitry.

Current limiting. - The heater supplies (V2, V3, and V7) use magnetic amplifier control to provide a constant power to a fixed resistive load. Therefore, they have built-in current limits and can operate into a short circuit indefinitely.

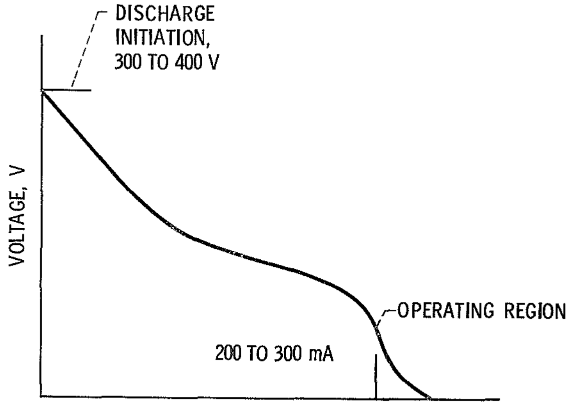

Figure 5. - Keeper supply voltage-ampere characteristic.

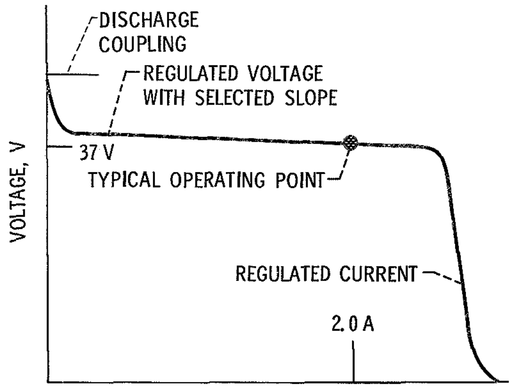

Figure 6. - Anode supply voltage-ampere characteristic.

The two keeper supplies (V8 and V10) are required to provide either a few hundred volts at low currents (5 mA) or a few tens of volts at higher currents (200 to 300 mA). To provide this drooping type of characteristic, shown in figure 5, an inductor is placed in series with the primary. This provides built-in current limiting for these supplies.

The anode supply (V4) uses a magnetic amplifier to provide controlled voltage to the load. By the addition of an extra control loop, this same magnetic amplifier is used to provide current limiting as well. The resulting characteristic is shown in figure 6. The anode supply has the highest current rating of any of the supplies in the power conditioner. This causes additional problems, particularly during a V4-to-ground arc. As shown in figure 4, the path for the arc current is through the V5 supply as well as through the V4 supply. While the V4 supply has its built-in protection due to the current limiting of the magnetic amplifier, the V5 supply is not protected for this high value of current. The output of the V5 supply consists of four bridge rectifiers in series with a current-sensing resistor. The protection from the V4 arc current was initially provided by a bypass diode across each V5 bridge. This results in a very efficient system since the only power loss, under normal operation, is due to the bypass diodes leakage current. The current-sensing resistor was only 0.25 ohm, which also kept the losses quite low. The current-sensing resistor was increased to 10 ohms in the final design. This was done to provide a better signal-to-noise ratio and a more accurate sensing of beam current. It was then decided to add 25 ohms additional series resistance. This resistance along with the voltage in the bridge rectifiers provides the current-limiting protection from the V4-to-ground arc. While this approach is less efficient than the original one, it is felt to be more reliable and to provide for more accurate beam current sensing. A series resistance was also used in the V6 supply to limit currents during arcs such as V5-to-V6 or V4-to-V6. Since the normal load current of V6 is only 1 or 2 milliamperes, this can be done with little effect on efficiency.

The protection of the high-voltage supplies from arcs is accomplished by turning the supplies off momentarily (blink-off technique). As discussed in Stover's paper (ref. 6), many high-voltage arcs which occur in a thruster will not be extinguished until the power source is turned off. Therefore, besides providing protection for the supply, the blink-off technique causes the arc to be extinguished. While the high-voltage supplies are off, there is no beam coming from the thruster and the ions are no longer focused by the two high-voltage plates. However, ions (in excess of full beam levels) are still being produced in the thruster chamber since the other supplies are still on. (V2 is turned off with V5 and V6, but the thermal lag is much too long for any reduction in mercury flow during a single blink-off cycle.) When the high voltages are turned back on, the excess and defocused ions cause an overload in the V5 supply for a short period of time. Figure 7 illustrates what a cycle would be like with an overload on the V5 supply. The supply turns off very rapidly (1.0 msec) upon the occurrence of the arc. The supply remains off for 100 milliseconds. (The off-time was evaluated with a thruster from 10 msec to 5 sec with no noticeable difference in operation.) Upon turnon there is an overload on the screen current (I5) for a few milliseconds. A delay of approximately 10 milliseconds has been placed in the trip-off circuit to overcome this overload. If this delay were not present, the trip-off circuit would continuously cycle until the thermal lag in the vaporizer (V2 load) had reduced the mercury vapor level in the thruster to a low enough value so that I5 would no longer overload upon turnon. This phenomenon is much more likely to occur with V5 than V6 since the accelerator current (I6) trip level is approximately 25 times the normal operating level while the I5 trip level is only 1.2 times its normal operating level. Since these are protective trip levels, the overdesign of the V6 supply is apparent.

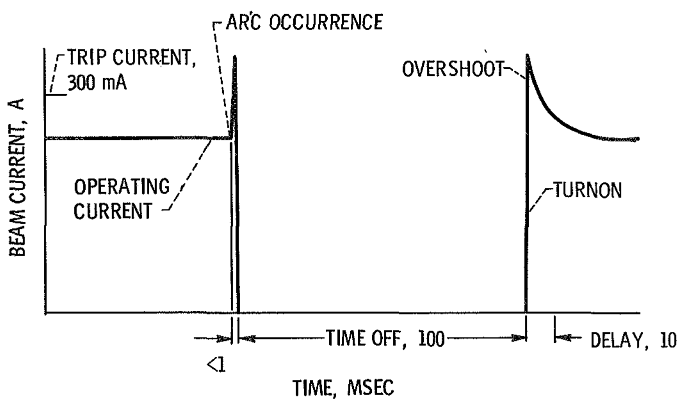

Figure 7. - Beam current overload cycle.

OPEN-TO-VACUUM DESIGN

Purpose and Objectives

The voltage between various components and terminals mounted within the power conditioner can vary over a wide range. Some circuits are at a few kilovolts, positive or negative. Others have alternating voltages, with peak values ranging between a few volts and a few kilovolts. The current capability can also vary over a wide range. One high-voltage circuit will deliver only 50 milliamperes. Another, at less than 100 volts (the power input circuit) will deliver up to 20 amperes. It is plain that we must provide a dielectric medium within the power conditioner to prevent breakdown and arcing between circuits.

We chose the insulation system to meet the following requirements:

(1) It must prevent breakdown and arcing during 6 months in orbit (at 10^{-14} torr) and during preflight testing both in air (760 torr) and in vacuum tanks (10^{-6} torr).

(2) The insulation system must prevent breakdown and arcing over a range of temperatures from -30° to 120° C, for example, in cyclic thermal-vacuum testing.

(3) It must continue to prevent breakdown and arcing after the power conditioner has been subjected to vibration and shock during preflight tests and launch.

Possible Insulating Techniques

One type of insulation method could be to fill the power conditioner with potting compound. Another could be to fill the power conditioner with either a gas or a liquid (at about 760 torr). A third possibility is to use the insulating properties of vacuum.

Potting. - The power conditioner filled with potting compound would probably be heavier than any of the other insulation methods. It could contain voids, possibly like those illustrated in figure 8. Either a high dielectric constant or low insulation resistance of the potting compound can result in overstressing the gas within a void. During

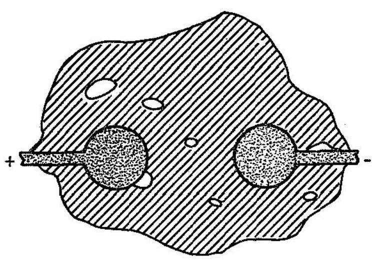

Figure 8. - Voids within a potted assembly.

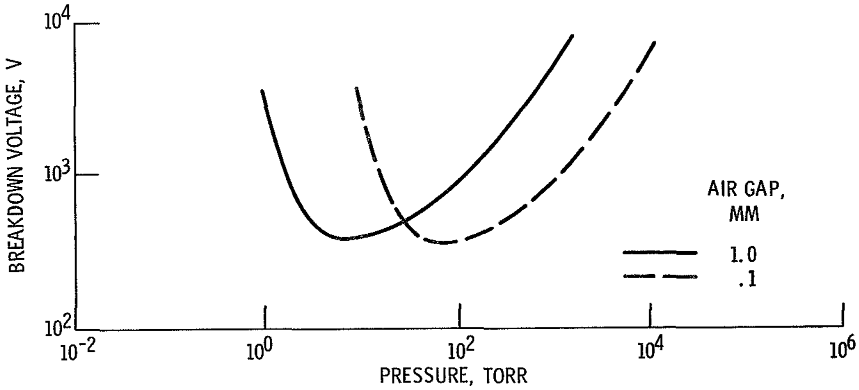

Figure 9. - Paschen breakdown voltage for small air gaps.

6 months operation in orbit, or perhaps during thermal-vacuum testing, a void could leak to lower pressure. Figure 9 shows curves based on the Paschen breakdown curve for small gaps in air. This figure shows that leakage of a void to a lower pressure could result in destructive breakdown.

Liquid or gas filled. - A second type of insulation system could be the power conditioner containing either a liquid or a gas. A liquid-filled power conditioner would be heavier than a gas-filled one and would require pressure relief from thermal expansion of the liquid. The liquid-filled power conditioner would be of interest in an extremely compact design where conductors would be closely spaced. But it seems to be less attractive than the gas-filled type, which would have at least a small positive pressure (e.g., 760 torr at 20° C), enough to detect leakage and to gain confidence in the gas seal during preflight testing. Loss of gas pressure could be disastrous, either in orbit or in vacuum-tank testing. Figure 10 shows curves based on the Paschen breakdown curve for large gaps in air. They show that breakdown would occur within the power conditioner

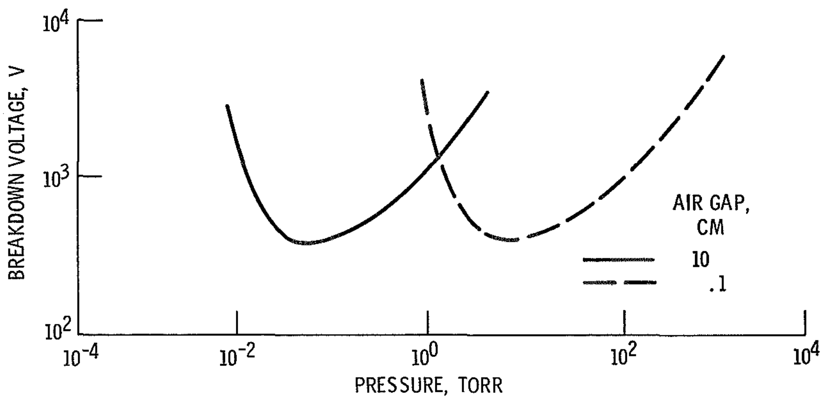

Figure 10. - Paschen breakdown voltage for large air gaps.

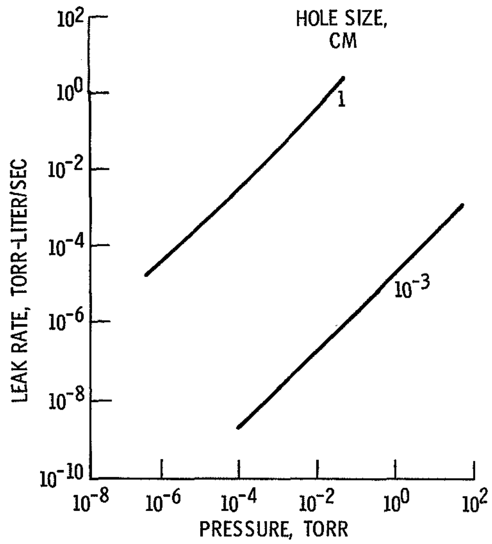

Figure 11. - Airflow rate for two leak-hole sizes.

if its pressure fell into a critical range. Shown in figure 11 are airflow-rate curves for two hole sizes. The leak rate through a 10^{-3}-centimeter hole from 760 torr is about 10^{-3} torr-liter per second. In 200 hours the power conditioner would lose about a tenth of its total gas charge through this size hole; that is, the pressure would fall to about 690 torr in 200 hours. This assumes no temperature variation. An acceptable leak rate would be smaller than the one just discussed. To validate the existence of an acceptably low leak rate for a number of power conditioners would take excessive test time. To be sure those leak rates would remain low through launch, thermal cycling, and 6 months in orbit would be extremely difficult.

Open to vacuum. - The third insulation system is the power conditioner open to vacuum. During some preflight tests the power conditioner would be at room ambient pressure. Under vacuum conditions the power conditioner interior would vent down to a pressure near that of the outside environment. Vacuum dielectric strength is excellent; it can be as high as 10^5 volts per centimeter. Possible problems with this system are diffusion of mercury plasma or vapor into the power conditioner and local pressure concentrations within it. But whether or not the power conditioner is vented to vacuum, some of the output potentials must be exposed to the vacuum environment. They will be exposed at the feedthrough terminals, or if those are insulated, at the thruster. Therefore, somewhere within the spacecraft we could expect similar problems whether or not we chose this insulation system.

An open-to-vacuum insulation system was chosen for the SERT II power conditioner. Space qualified encapsulation and potting compounds would be used only where absolutely necessary.

Package Design

Layout. - In figure 12 the partially assembled power conditioner is shown resting on its baseplate. At the left, mounted on the baseplate between vertical brackets, are four high-voltage transformers. (Only three of these can be seen in the figure.) Between the transformers are tubular high-voltage filter capacitors. And on the second vertical bracket from the left, between the transformers, are mounted four pair of power transistors.

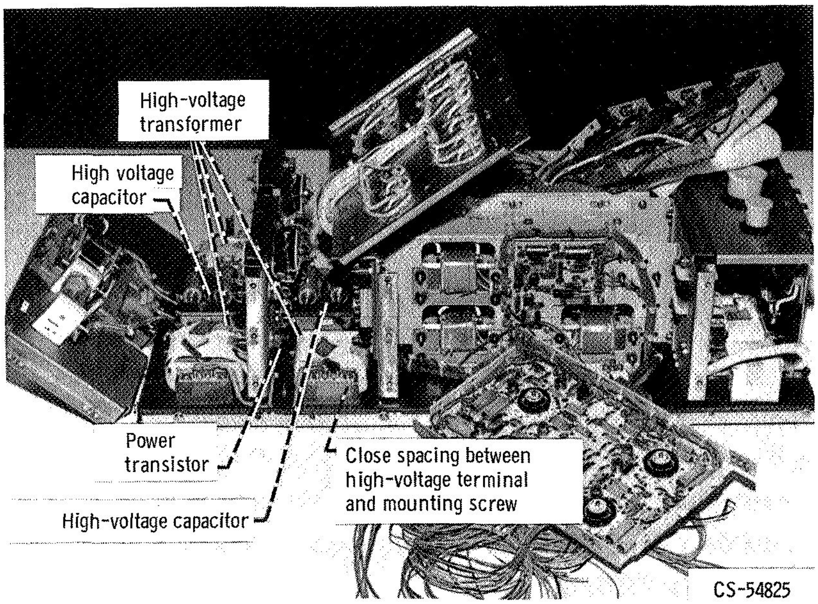

Figure 12. - Partially assembled power conditioner.

There is a direct-line-of-sight spacing between high-voltage transformer terminals and low-voltage transistor terminals. There is also a direct line of sight between these terminals, which are at spacecraft potential, and the power conditioner baseplate. A minimum spacing between terminals and the baseplate of 1 centimeter is maintained in the layout of the power conditioner. In these locations the insulation strength of vacuum is relied upon entirely to prevent breakdown and arcing.

Venting. - Referring back to figure 1, the vented, high-voltage terminal cover can be seen at the left. The main cover is vented with about 200 3/8-inch- (0.95-cm-) diameter screened holes. These holes are made in double wall panels, with either nine or 12 holes per panel. A cross section is shown in figure 13. About 3.5 percent of the cover surface is open through these holes. These vents were designed to carry the outgassing load from inside the power conditioner at about 1×10^{-4}-torr pressure drop. This

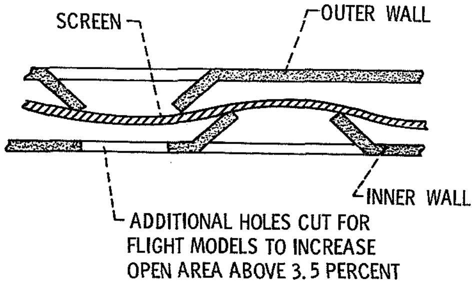

Figure 13. - Cross section at vent holes through double wall cover of power conditioner.

pressure is low enough to provide good dielectric strength in orbit and during tests in vacuum tanks. Figure 14 (curves of pressure against time) shows the measured performance of these vents. (Although the performance was adequate, this is not the way the system was flown. As explained later, arcing problems, believed to be caused by inadequate outgassing, prompted making one-half of the holes extend through the double wall.) Obviously, local pressure within the power conditioner will be affected by location of the vent holes and the major sources of outgassing. Also flow restrictions and entrapped gasses can affect local pressure.

Materials. - In general, the outgassing characteristics required of materials used in the power conditioner are (1) low volatile content, (2) rapid release of volatiles, and

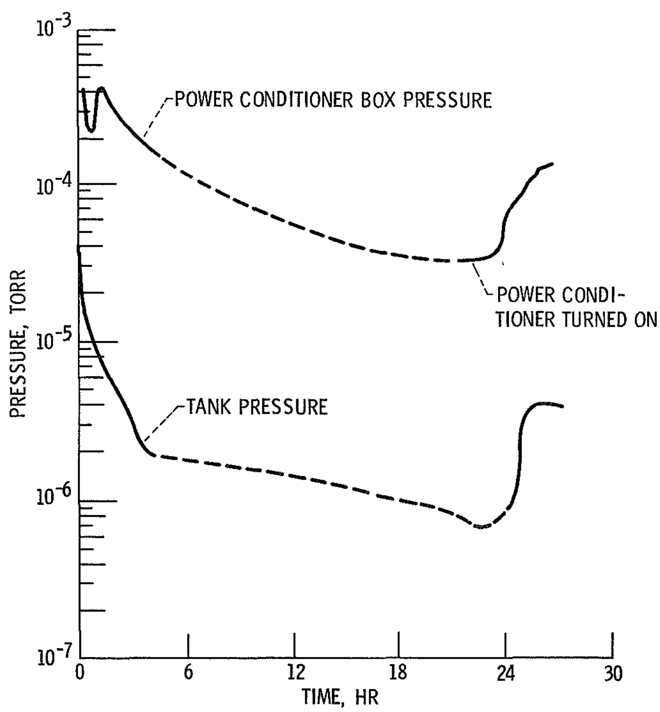

Figure 14. - Venting tests on experimental model.

TABLE II. - OUTGASSING OF MATERIALS USED IN

SERT II MAGNETIC COMPONENTS

Material	Weight loss at 130° C and 2×10^{-6} to 6×10^{-6} torr			
	Percent loss	Days on test	Percent loss	Days on test
G-7 Fiberglas laminate	0.013	1	0.026	14
Silicone-Fiberglas tubes	.021	1	.015	11
Isomica 4350, postcured	.016	3	.023	10
Nomex fiber	3.39	1	3.33	3
Silicone-Fiberglas sleeving	.043	↓	.054	11
MgO-coated laminations	.002	↓	.002	11
DC 2104 silicone resin	.025	↓	.047	7
Mass spectrometer tests - material	Loss rate, percent/100 hr after 1 day[a]			
ML wire insulation	0.09 at 160° C and 10^{-6} torr			
Kapton H-film	.018 at 200° C and 10^{-6} torr			

[a]Samples previously under vacuum of 10^{-6} torr at room temperature for 20 hr.

(3) low long-term outgassing rates. These factors were considered in the careful selection of materials. High-voltage wire is silicon rubber insulated with a semiconductive coating between the wire and its insulation. Low-voltage wire is Teflon (trademark of DuPont) insulated. Components are bonded to circuit boards and the baseplate with RTV (DC3145). Circuit boards are glass melamine coated with epoxy varnish. Table II shows the outgassing rates of some materials used in the transformers.

Open-to-vacuum transformer construction. - Figure 15 shows the transformer for

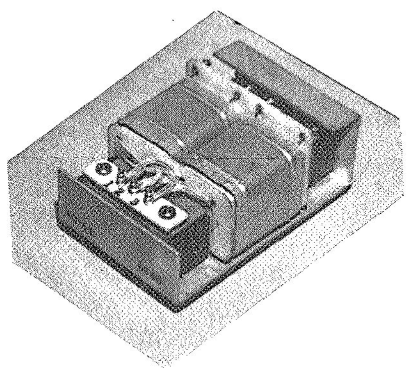

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Figure 15. - High-voltage transformer used in power conditioner.

a high-voltage, high-power inverter module which is representative of all high-voltage magnetics. It consists of two coils wound on fiber-glass-laminate bobbins, which are fitted over stacked core laminations. Each coil has a bifilar primary winding of three layers of number 22 insulated wire. Insulation between layers is 0.005-inch (0.0127-cm) synthetic mica. Over the primary is a 0.005-inch (0.0127-cm) copper shield, and over that is a 0.035-inch (0.0889-cm) silicone - fiber-glass bobbin for the secondary winding. The secondary winding has six layers of number 29 insulated wire separated by 0.005 inch (0.0127-cm) synthetic mica insulation.

Holes in the flanges of the fiber-glass bobbins vent the space between the windings. In the critical space around high-voltage windings, no potting materials were used.

INTERNAL ARCING

Having considered the significant design features of the power conditioner, we now move into a discussion of the lessons learned from the testing program and its associated problems.

Manifestation of the Problem of Internal Arcing

The internal arcing problem was elusive because of the way it gradually manifested itself. It caused failures in first one area of the power conditioner and then another. These failures are discussed in approximately the same order in which they occurred.

Screen supply fuse failures. - The screen supply (V5) modules are each equipped with a 10-ampere fuse in their input. The purpose of this fuse is to remove any defective module from the dc input bus. These screen supply fuses began to fail during tests in vacuum. The failures usually occurred at the time of high-voltage startup or during a thruster arc. These failures occurred randomly throughout the development phase in both experimental and prototype power conditioners. We suspected that current surges at high-voltage turnon could be the cause of the failures. It was also possible that the V5 fuses used were defective. Laboratory tests later showed that neither suspicion was right. Startup transients were gentle and well within the rated fuse capacity. Likewise, the fuses were found to meet the manufacturer's specifications for current ratings and opening times. Though investigations continued for the next few months, these failures of the V5 screen supply fuses remained unexplained until later in the investigation.

Anode supply rectifier failure. - As the prototype test program continued, the power conditioner was plagued with another recurring component failure, this time of the rectifying diodes in the anode supply (V4). As stated earlier, the anode supply produces about

40 volts dc at 1 to 3 amperes, and is floated at the V5 screen potential. Again, these failures usually occurred during startup or during arcs. Two parallel supporting test programs were initiated to find and cure these failures. The smaller of the two programs was to continue investigating the V5 fuse problem and the larger was to investigate the anode supply diode failures.

Arc propagation to low-voltage bus. - In the course of the anode failure testing, a power conditioner was run in a small vacuum tank where it could be viewed by test personnel and its electrical parameters measured and recorded. Because arcs were seen, we installed a camera aimed at the area of interest, opened the shutter, and operated the power conditioner. When an arc indication appeared on the telemetry, the film was advanced and developed. The location of most of the arcs could be determined from the photograph. It was during this testing that the last and most fearsome manifestation of the internal arcing problem occurred (see fig. 16). A power conditioner was being tested

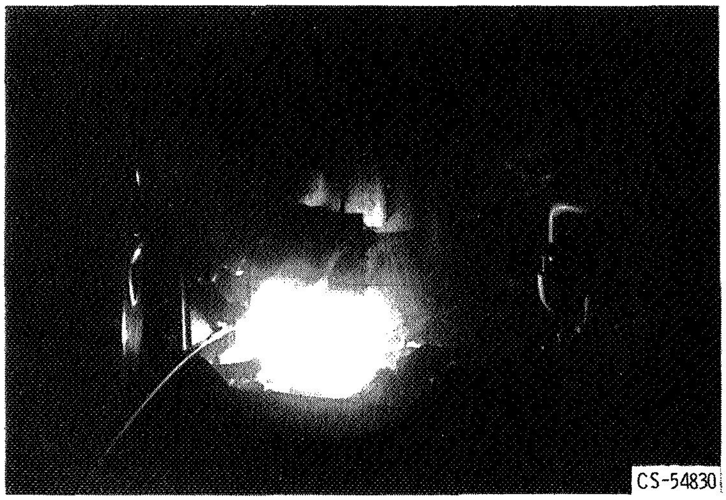

Figure 16. - High- to low-voltage transfer arc on V4 anode supply.

under high-vacuum conditions. The startup was normal through preheat and propellant mode. When high-voltage turnon was attempted, a large current transient was recorded on the input bus and an immediate automatic shutdown occurred. When we later opened the power conditioner, we found serious damage to everything in the anode supply area. It was apparent that the primary side of the anode supply transformer had arced to ground.

Investigations and Solutions

To make our investigations as systematic as possible within the time allowed, we first attempted to list the suspected causes of the failures. Apparently, the failures were associated with a phenomenon that was most evident at high-voltage startup and provided a momentary conduction path. The following were considered as possible causes:

Outgassing. - The outgassing theory was the leading contender early in the investigation. Theories as to the source of the outgassing ranged from leaking components to gas trapped on the many surfaces of the power conditioner. To determine the outgassing rate, tests were run measuring gas pressure inside and outside the power conditioner during a pumpdown. The curve in figure 14 shows that the inside pressure remained about 10^{-4} torr above the tank pressure. We tried to track down a specific source of the gas by placing baffles in the suspected areas inside the power conditioner to isolate these areas. We were not able to locate any specific source by this technique.

In another attempt, helium gas was forced into a power conditioner in the hope that the helium would permeate the gas trap and then later be detected by a helium leak detector. Again the results were negative and no "trap" was found.

Various hermetically sealed components such as electrolytic capacitors and encapsulated devices were tested for material leakage. No leaking devices were found.

Attempts were made to identify the products exuded by a power conditioner while it was heated in a vacuum. A scanning mass spectrum analyzer was used. The analyzer output showed the presence of nitrogen, water, and some heavier molecules believed to be associated with RTV polymers. These gases are normally expelled during curing and, with time, reduce to very low concentrations. To reduce the postcure outgassing we therefore increased the high-temperature bake in vacuum to 240° F (389 K) for 100 hours. Some substances in the power conditioner could reabsorb gases when exposed to atmosphere, so we modified the test procedures to include a 12-hour vacuum bake at 140° F (333 K) prior to each startup. Also, the flight spacecraft was modified to include heaters to warm up and outgas the power conditioner in orbit prior to operation. We also increased the venting rate by redesigning the cover vent holes for straight-through flow (Postlaunch testing showed that while the added cover holes increased the venting rate they were not necessary for successful operation.)

Magnetic fields. - It was the primary terminals of the anode supply transformers that received the most damage during the internal power arcs, as shown in figure 7. These transformers are powered by a single 8-kilohertz oscillator and their secondaries are at high voltage.

A theory was advanced that possibly the stray magnetic flux from these transformers could cause charged particles in the area to be accelerated, thus promoting secondary ionization. This could cause breakdown of the low-voltage bus to ground. Magnetic surveys showed that the ac fields were approximately 3 gauss rms. The dc field in the area of the V4 anode supply inductor was 80 gauss. We thought we had finally found the cause of the failures until it was demonstrated that the failures still occurred with the inductor removed.

It might be mentioned that magnetics also were a candidate in the search for the cause of the screen supply fuse failures at the opposite end of the power conditioner. Our testing demonstrated that a fuse could be made to fail at well below its rated current. This was not a melting of the link but a fatigue fracture caused by placing the fuse in a strong dc magnetic field and then tuning the ac current (through the fuse) to the link's resonant frequency, as depicted in figure 17.

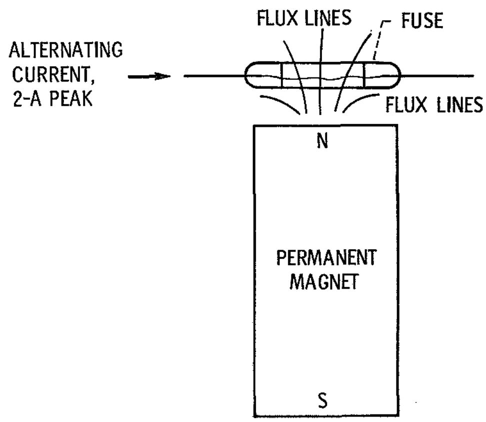

Figure 17. - Diagram of setup of fuse failure test.

The V5 screen supply transformers were also found to have low stray magnetic fields and therefore were an unlikely cause of the fuse failures.

Corona. - The third theory offered to explain the internal arcs was based on the presence of corona at or near some of the high voltage terminals. (Corona is particle ionization due to local high field gradient.) A low voltage arc-over could occur if the amount of corona (or plasma) were sufficient.

To identify the locations of corona discharge, we operated a power conditioner in an evacuated darkened tank. At the highest input voltage (75 V and above), we did observe a corona-like glow on the windings of a V4 (anode) transformer. This transformer was removed and replaced with another of the same type. No evidence of corona was observed upon energizing the replacement. The apparently faulty transformer was returned to the manufacturer but he was unable to find anything wrong with it.

The standard cure for corona is to increase the radii of any sharp corners in order to reduce the electric field gradient. In some places where corona was seen, such as on the V4 transformer windings, it was judged impossible to reduce corona without a major transformer redesign. Since most of the high-voltage terminals and connectors were free of sharp corners, there was not much that could be done in this area.

The techniques described in the next section (Electric fields) also served to reduce the corona. This is reasonable since the corona is caused by high field gradients.

Electric fields. - In the open-construction design, the empty space between components has a certain dielectric strength. The electric-field failure theory speculated that, under "real" conditions, a combination of field gradient, spacing, and pressure environment may combine to permit arcing. This theory was considered in spite of the fact that our present gas discharge knowledge predicted that our high-voltage-component spacing was adequate.

The first response to this theory was to make fine-wire-mesh electrostatic shields to cover the high-voltage terminals. We reasoned that if the fields could be terminated away from the low-voltage bus, any breakdowns occurring would be extinguished before they caused secondary arcs. Initially, little success was achieved because it was hard to make the complex shapes necessary to provide shielding while avoiding shorting out the critical terminals.

Conformal coating had been considered for the power conditioner circuits and components, but its use had been limited to the back side of the printed circuit boards. Conformal coating had not been applied to all exposed terminals because we thought that its application would be hard to control and could even become a source of gas if it contained bubbles. Now we became willing to accept the coating problems if the added dielectric would reduce the internal arcing. All high- and low-voltage exposed terminals in the power conditioner were coated in an attempt to completely solve the arcing problem.

We attempted to apply the coating thickness of 5 mils (0.0127 cm) to provide 18 000 volts of dielectric protection. When the power conditioner was operated in the test chamber, the problem did not reoccur in the V4 area, but further testing revealed continued arcing in the V5 area. Close examination of this area revealed spots where no coating had been applied or where sharp edges thinned the coating to an inadequate thickness. We concluded that the geometry of the parts in the V5 area prevented complete coating and adequate thickness buildup on points and edges.

In looking for something that could overcome these failings, we decided on aluminized Kapton (trademark of DuPont) film. The 5-mil (0.0127-cm) film would give 36 000 volts of dielectric protection when used in double thickness. The material was folded with the aluminized sides facing inward. This film was used in several other applications on the SERT II spacecraft. The Kapton proved to be relatively easy to work with and filled the dual function of terminating the electric field on the grounded conductive side and providing additional insulation in the Kapton film. The Kapton was used only where close and line-of-sight spacing existed between high- and low-voltage terminals.

In the course of disassembling the power conditioners to conformally coat the inner circuits, we noticed that there were evidences of arcing on the inner circuit boards. The arcs occurred between high-voltage transformer terminals in the center of the power conditioner and the screen supply V5 control board. Arcs on this board accounted for V5 fuse failures. Conformally recoating these inner circuit boards and adding a double layer of Kapton barrier between the offending terminals stopped the breakdowns in this area. Based on the positive results of the conformal coating and Kapton barrier tests, these two techniques were incorporated into the flight power conditioners.

Anode supply diode reconfiguration. - Although conformal coating and Kapton barriers can prevent breakdowns, as an extra precaution further corrective measures were taken. A circuit analysis indicated that the two-diode full wave configuration we were using could be subjected to excessively high peak inverse voltages (PIV) if an arc occurred.

A straightforward solution to this problem was to reconfigure the V4 diodes to a full wave bridge which has inherent inverse voltage protection. No more failures occurred after going to the bridge configuration. See figure 18 for schematic of the two bridge configurations.

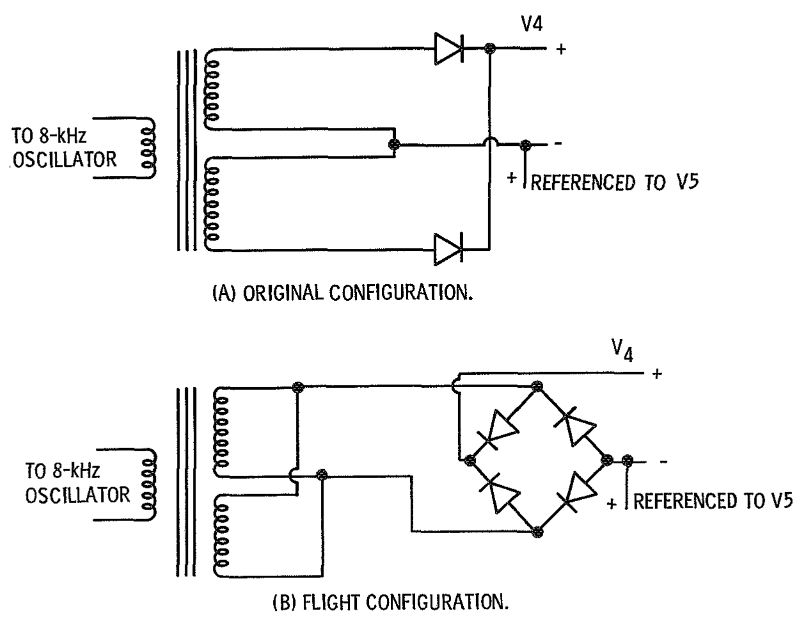

Figure 18. - Configuration of V4 anode supply output circuit (both original and flight designs).

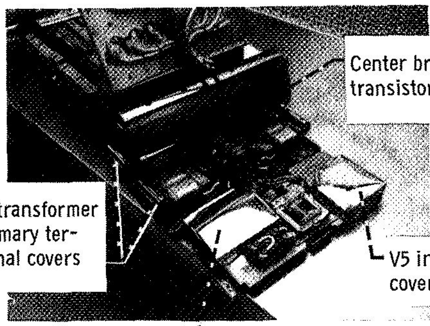

Figure 19. - Power conditioner with barriers installed.

Flight configuration. - The final power conditioner configuration is shown in figure 19. Kapton barriers were used to cover each of the V5 module transformer primary terminals. Also the V5 inductors located on the vertical end bracket and the 8-kilohertz capacitors and fuses on the same bracket were housed in small Kapton enclosures. The V5 transistors mounted on the middle vertical bracket in the high-voltage end of the power conditioner were covered by a piece of Kapton draped over the bracket and secured by the terminal plate. The last barrier used was the one installed between the center section supplies and the screen supply printed circuit board.

DESCRIPTION OF SOLUTIONS

Conformal Coating

The conformal coating added to the power conditioner was Magna Coating and Chemical Corporation's Laminar X500 3C-23, a clear polyurethane. The properties of this material include a dielectric constant of 2.7 and dielectric strength of 3700 volts per mil ($146\ V/m{\times}10^{-6}$).

The effectiveness of the conformal coating was tested by preparing two identical circuit cards with only solder terminals and leads. One card was coated, the second was not. When tested under the same conditions in a bell jar, an arc was ignited on the uncoated card and no arc could be started on the coated card.

Conformal coating is a good method of improving the reliability of vacuum insulation at both high and low voltages. Conformal coating is recommended for new power conditioning designs. Although the material used was satisfactory, it is possible that better materials and application methods can be developed.

Aluminized Insulating Barriers

The aluminized plastic barriers installed in the high-voltage supplies were fabricated from two materials: first, polyimide H-film (DuPont Kapton) 5 mils (0.0127 cm) thick with evaporated aluminum on one side; second, Kapton tape $1\frac{1}{2}$ mils (0.0038 cm) thick including adhesive. The properties of Kapton include a dielectric constant of 4.0, dielectric strength of 3600 volts per mil (142 $V/m \times 10^{-6}$) and tensile strength of 20 000 psi (29 000 N/cm^2) at 20° C.

The barriers were designed to separate high- and low-voltage supplies. The high- and low-voltage supplies were separated electrically by grounding the aluminized coating of the barriers. The barriers were carefully designed to vent freely.

The effectiveness of barriers was tested in combination with conformal coating by a number of thermal-vacuum tests of complete power conditioners at high input voltage. The combined techniques were completely successful in preventing vacuum insulation failures under combined worst-case testing.

The use of barriers was a successful solution to the vacuum insulation problem, but the materials used are not recommended for new designs. Problems with the barrier materials included

(1) Kapton has poor tear resistance. Special stress-relief methods are required to prevent tears from starting.

(2) The adhesive of the tape can develop carbon tracks at voltages well below the Kapton breakdown voltage.

(3) The adhesive of the tape tends to trap air bubbles.

(4) The thin aluminum coating of the Kapton can be easily damaged by scratches and sharp folds.

For new designs it is recommended that metal barriers coated with insulation be used.

Rationalization of the Methods Used to Reinforce Vacuum Insulation

Apparently, vacuum alone is not sufficient insulation in high-voltage applications such as this. Similar phenomena have been experienced as reported in references 7 and 8, but their test conditions do not agree with our configuration. Large separations between high-voltage and ground or low-voltage circuits does not necessarily improve vacuum insulation.

Conformal insulation coating of all high- and low-voltage conductors is believed to be effective for the following reasons:

(1) Ambient plasma is isolated from bare terminals.

(2) The coating suppresses photoelectric and secondary electron emissions.

(3) Surface contamination breakdown from such causes as solder flux is prevented.

(4) The coating may inhibit field emission by space charge effects.

(5) The coating prevents shorts caused by metal chips.

Vented and grounded compartments around each high-voltage supply are believed to be effective for the following reasons:

(1) Grounded shielding keeps high-voltage breakdowns from occurring and/or starting low-voltage arcs.

(2) Outgassing effects are kept localized.

Tests are currently being conducted to ascertain which of these factors, if any, affected the performance of the power conditioner. To date, no conclusions can be drawn from the test results.

SPACE OPERATION IN COMPARISON WITH GROUND TESTING

The power conditioner performance in space has been perfect to date, without exception. All supplies are powering their thruster loads well within their specified ranges. Thruster arcs are occurring on an average of four per day and the power conditioner is safely handling these overloads with no apparent adverse effects. All control loops are stable and the measured operating parameters are constant within the telemetry resolution. The passive thermal design of the spacecraft is allowing the power conditioner to operate with its baseplate at 98.6° F (310 K) and its internal area at 110° F (317 K). The anticipated operational limit was 120° F (322 K) and the test limit was 140° F (333 K). The input voltage to the power conditioner, highest at no load, at the beginning of the mission, did not reach the maximum anticipated level. It was expected to reach 78 volts but never exceeded 72 volts. Therefore, voltage stress, especially on the unregulated high-voltage supplies, was less than planned and qualified for. The power efficiency calculated from measured values in flight is 87.5 percent, compared to a design goal of 87 percent.

Flight performance compares very well with ground testing. All operating values equal those obtained during ground testing where the power conditioner and the thruster were mounted in their flight configuration on the spacecraft in a vacuum tank. Although certain test conditions on the ground resulted in more frequent thruster arcs, the arcs during long uninterrupted tests compare favorably with the number recorded in flight.

CONCLUDING REMARKS

The development of a reliable power conditioner for SERT II was not undertaken with the idea of advancing the state-of-the-art in electronic power conversion equipment. Nevertheless, development within the flight constraints resulted in some advances worth noting. The design of a power conditioner to operate an ion thruster is a difficult task, and the handling of high voltages with their resulting arcs posed some design problems. Current limit protection proved adequate in all areas where it was used. The interruption of the high voltages when an arc occurs and their subsequent reapplication to restart the beam, although simple in concept, proved very successful.

Although its adequacy was questioned at times, the open-to-vacuum construction of the power conditioner proved to be quite satisfactory. It also made disassembly and repair during development much easier. Our results show that it is not difficult to design components and their layout to get good venting.

The internal arcing problems that did occur during development could not be attributed to a failing of the open-to-vacuum design. On the contrary, our testing only tended to show that outgassing was not the cause. Ultimately, the use of conformal coating and aluminized insulating barriers was all that was needed for successful performance. We concluded that the existence of a good vacuum and spacing were not enough to prevent breakdowns. A better insulating medium must be provided. Conformal coating can provide this insulation, as well as surface protection. But if surface geometry is complex and sharp corners exist, conformal coating may not be adequate in itself. Insulating sheets provide the added protection. Although the techniques used to solve power conditioner problems for SERT II are not recommended for new design, the principles employed are recommended. To this end, the low and high voltages must be physically separated by a barrier. Wherever possible, this barrier should be a part of the structure.

Investigations are currently proceeding in an attempt to more fully explain the phenomena that caused the breakdowns. Even without a full explanation, the techniques to be used for success are clear from this discussion.

Lewis Research Center,
National Aeronautics and Space Administration,
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