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Advanced Power Conditioning for an Ion Propulsion System

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ADVANCED POWER CONDITIONING FOR AN ION PROPULSION SYSTEM

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Summary

Space programs proposed for the period 1970 to 1980 include plans for transporting large payloads to the near planets, such as Mars, and to even greater interplanetary distances. The accomplishment of these missions in a reasonable travel time will require a specially designed, continuous-thrusting propulsion system. Three types of systems are envisioned: chemical, nuclear, and electrical. Of the three, the electric propulsion system is certainly the most advanced and by far the most attractive in terms of potential development. The electric systems, which have the highest specific impulse, provide a maximum payload in terms of propulsion system weight.

In any electric propulsion system, the engine and power conditioning must be developed as an integral unit. Ion engines are small, lightweight devices and the weight and size of the power conditioning often detracts from them. Furthermore, while space operation of ion engines has been successfully demonstrated by both the Air Force and NASA in short ballistic flight tests, their ability to operate in space for extended periods of time under actual mission conditions has yet to be demonstrated.

Electro-Optical Systems, in designing the advanced ion propulsion system discussed in this paper, had three prime objectives: reliability, low weight, and extended operational life. A study program was first undertaken to determine the optimum size of the thrusting system for a specific Mars mission; the results indicated 3 kW systems to be optimum based on state-of-the-art electronic devices.

One of the most significant problems with any ion engine power conditioning system is the containment of the high voltages while operating in a vacuum. This problem was successfully solved in the next phase of the program when a system was built which was capable of extended operation in vacuum, although not packaged for flight.

Introduction

Electro-Optical Systems set out in June 1965 to design and build a breadboard prototype power conditioning system to power a 2-3 kW cesium contact ion engine. This breadboard prototype, while not a flight configuration, would nevertheless have flight qualified components. Because of the high potentials involved with ion engine operation, the problem of high-voltage containment in vacuum would have to be solved; the heat rejection from the breadboard would have to be by radiation since this will be the primary heat rejection mechanism in outer space.

The breadboard prototype had to demonstrate the potential long life capability of an ion propulsion system and more specifically, of the system power conditioning. While this program involved only one type of ion thruster, the cesium contact ion thruster, similar work was going on with the cesium bombardment ion engine.

This paper will describe the operation of the ion engine, the power conditioning system, the system testing and the problems encountered.

Ion Engine Operation

Ion engines are basically low-thrust, high-specific impulse devices. They develop thrust by accelerating ions to extremely high velocities (as compared to gas molecule velocities in chemical thrusters). While the thrust of an ion engine is small, on the order of 10⁻² pounds, fuel consumption is also small, and the engine can operate for approximately 150 hours on a pound of fuel at the 10⁻² pound thrust level.

The engine used in the series of tests described in this paper is a cesium contact 10 mlb high-performance ion engine operated at a power/thrust ratio of 175 kW/lb and a specific impulse of 5500 seconds. Fig. 1 shows the engine with a 20-pound cesium fuel reservoir which contains enough fuel for 3000 hours of operation. A typical ion engine schematic is shown in Fig. 2. (This figure is of an orbital flight engine but is typical of the 10 mlb engine described here.)

The contact ion engine generates cesium ions from a hot porous tungsten surface. The ionizer is a continuous surface of porous tungsten, with periodic contours or indentations to focus ion beams. This type of ionizer is called the "sastrugi", named for its similarity to a wind-eroded snowfield. Such ionizers are made from spherical powdered tungsten, with grains between 2 and 10 microns. A backing plate or "crucible" is joined to the ionizer by electron beam welding. The crucible is heated by a sheathed heater powered by the breadboard electronics system.

Ion beams are accelerated through a copper electrode; copper is used because sputtered electrode material must not damage the ionizer.

Cesium is supplied to the engines from a zero-g feed system (Fig. 3), which uses surface tension force to pump and deliver liquid cesium to a vaporizer. Cesium, like any wetting liquid, tends to migrate to the narrow end of a tapered enclosure since surface tension acts to minimize the free surface area and maximize the wetted surface. The cesium flows to the rod through the tapered channels between the radial fins; after arriving at the rod it is transported to the vaporizer by the same wick-type action. The vaporizer is heated, by a specially controlled vaporizer heater power supply, to a temperature of approximately 300°C, which vaporizes the cesium. The flow of cesium is controlled by the temperature of the heater which is controlled, in turn, by the vaporizer heater power supply. Response time for flow adjustments is a few seconds. The
feed system thus provides propellant storage and control without valves or other moving parts.

For every positively charged ion that leaves the engine an electron must also be ejected to keep the spacecraft electrically neutral. If this were not done the positive ion beam would be attracted to the negatively charged spacecraft and engine thrust would be cancelled out. The neutralizer system designed to provide neutralizing electrons is a small cesium gas discharge which supplies electrons to the ion beam. A hot cesiated surface supplies 100 to 500 times as many electrons as neutral cesium atoms to a confined discharge. Slow ions are also generated; these overcome the space charge forces which inhibit coupling to the beam. Neutralizer and beam are connected by a plasma "bridge". From the gas discharge, the positive ion beam acquires the precise number of electrons needed for neutralization.

**Power Conditioning System**

While the ion thrustor is rather basic in design and operation the associated power conditioning system is often quite complex. The power conditioning system weight must be kept to a minimum to be consistent with the weight advantages of ion engines. The goal for a power conditioning system weight ratio for a mission to Mars is on the order of 25 lb/kW, that is, twenty-five pounds of power conditioning weight for each kilowatt of input power. This goal is being exceeded by a projected weight ratio of 15 lb/kW. Constant improvements in this weight/power ratio are moving this figure downward. The figure of 15 lb/kW is for a 2 kW system; as the power level increases the weight/power ratio improves.

The 2000 watt power conditioning system needed to operate the ion engine is shown in the block diagram of Fig. 4.

The power necessary to operate the ion engine can be categorized as follows: (1) electrical power that translates directly into power in the beam, or thrust, and (2) power which is necessary for engine operation but which has no relation to thrust and is thus treated as a loss.

The major portion of the power in category (1) is the positive high voltage which supplies all the useful power to the beam and is directly related to thrust. The positive high-voltage potential on the engine is 2200 Vdc and the amount of current supplied the beam is approximately 650 ma (approximately 1430 watts). The negative potential necessary to accelerate the ions away from the ionizer surface is -7,000 Vdc. This negative high voltage potential on the accelerator electrode is such that the ions are accelerated through the apertures in the electrode with very few ions striking the electrode. Ions which do strike the accelerator are not ejected from the engine as part of the ion beam and must be subtracted from the positive high-voltage current to obtain the correct beam current value. Currents from the accelerator electrode are generally below 1% of the positive high voltage current (approximately 70 watts).

In the thrust equation it can be seen that the thrust is a direct function of the beam current and the square root of the positive high voltage.

\[ T = 11.9 \frac{I_b}{V^{1/2}} \]

Where \( T \) = Thrust in mlb, \( I_b \) = \( \frac{T_f}{V} - I^- \) (Positive high voltage current - negative high voltage current), and \( V \) = Positive high voltage potential in kilovolts.

It should be noted that the negative high voltage potential on the ionizer electrode does not contribute directly to the thrust. The ions are initially at an energy level equal to the positive high voltage. The ions are accelerated from the high positive potential through a high negative potential and then decelerated to zero potential (the potential of the ion beam as it leaves the spacecraft); therefore, the net potential difference the ions see traveling through this accelerating/decelerating mechanism is that of the positive high voltage potential and zero.

The major portion of the power in category (2), that is, power necessary for proper engine operation but which does not contribute to thrust, is the power needed to heat the ionizer to 1200°C. When the ions come in contact with the hot porous tungsten surface they are almost completely ionized. Of the remaining power of 500 watts approximately 450 watts are required to heat the ionizer. Other power requirements are relatively small; the vaporizer heater requires approximately 25 and the neutralizer approximately 15 watts and 10 watts miscellaneous.

The power conditioning system is divided into two sections, similar to the division of categories (1) and (2) for engine power. One section is the low-voltage inverter which includes the ionizer heater power supply and the neutralizer heater power supply. The other section is the high-voltage inverter which includes both the positive and negative high-voltage power supplies and the vaporizer heater power supply.

Power is first applied to the ionizer heater (and the neutralizer); after the ionizer has reached operating temperature the high voltage inverter is turned on. When the high voltage is first turned on there is no beam present since the vaporizer has not had time to reach operating temperature. Since there is no power going into the beam at this time the power capability of the supply can be used to bring the vaporizer up to temperature very rapidly. During this interval the power to the vaporizer is approximately four
times the normal steady-state power needed to maintain the full beam current (approximately 100 watts). As the ion beam starts to increase, the power to the vaporizer is decreased, and when the ion beam has reached full thrust the power to the vaporizer has been cut back to just sustain the full thrust point; a beam current regulation control circuit then takes over to maintain the beam current at ±1% of the full thrust level.

The incorporation of the vaporizer heater power supply as part of the high-voltage inverter has the advantage of using the excess power capability of the supply to heat the vaporizer to temperature very rapidly and yet pay nothing for this increased power capability.

One of the problems associated with ion engines is the sparking that occasionally occurs between the ionizer and the accelerator electrode. The potential difference between these two electrodes is 9 kv and the spacing is less than 1/4 of an inch. To prevent damage to the engine and/or the power supplies during these periods of sparkover, overload protection is incorporated in both the positive and negative high-voltage supplies. Overload current sensors are used in each supply to assure that if an overload causes an increase in current on the positive high-voltage supply above 1 amp or an increase in current on the negative high-voltage supply above 200 ma, a signal is sent to the high-voltage inverter which turns off the inverter for approximately 50 milliseconds. After this time the inverter is turned back on but will again shut off if the overload is still present. This procedure is repeated until the overload has cleared. Regardless of which supply experiences the overload, both high-voltage outputs are turned off, since both are driven from a common inverter.

During overload periods the vaporizer power is also off; this is desirable since the cesium flow should stop whenever the high-voltage potentials are off. This is another advantage gained automatically when the vaporizer heater is part of the high-voltage inverter.

Another unique technique used with this power conditioning system is the use of a high-voltage relay in the accelerator high-voltage lead. Generally, when an overload occurs, it is necessary to interrupt the current path between ionizer and accelerator which is accomplished by this high-voltage relay. An even greater advantage is realized, however, when the power supply turns back on from an overload; full negative high voltage is applied to the engine.

The negative high-voltage current or drain current is a double-valued function. During normal operation the negative accelerating voltage is adjusted to minimize the drain current. This has to do with the fields set up between ionizer and accelerator; if the accelerator potential is either greater or less than the optimum value a defocusing of the ion beams takes place and more ions strike the accelerator electrode causing an increase in the drain current. After an overload has occurred and the power supplies are turned back on the voltages increase to normal in a few milliseconds. While the accelerator voltage is increasing it is going through this region where the current will be high and possibly trip the overload circuit again; this makes it very difficult to recover from an overload.

However, with the high-voltage relay in the accelerator lead the following action takes place. When an overload is sensed a signal is sent to shut off the high-voltage inverter and also to open the relay. Since the response of the inverter is faster than the relay the inverter shuts off first. After the 50 millisecond period has elapsed the inverter turns back on but the relay remains open. After a few milliseconds full positive high-voltage is back on the engine and normal negative voltage is present at the relay input but not yet connected to the engine. The relay then closes and the proper negative voltage is applied to the engine. In this manner the engine is prevented from going through the region of high drain currents.

The neutralizer system is powered from the low-voltage inverter and is on as soon as the power is applied to the engine. However, until an ion beam is present no electrons are emitted from the neutralizer. As the ion beam increases, the potential of the beam also increases in a positive direction. When the beam voltage has reached approximately 80 volts an arc is struck in the neutralizer gas discharge region and electrons are generated and supplied to the beam. The beam potential then drops to a level of three to five volts, just enough so that the exact number of electrons may be drawn off as needed by the beam. If more electrons are needed, the beam potentials increase slightly and more electrons are extracted. If less electrons are needed the beam voltage drops. This is a self-regulating process and no outside control is necessary. A telemetry sensor is incorporated that measures the electrons being supplied to the beam. If perfect neutralization is accomplished the neutralizer beam current will match the current being supplied by the positive and negative high voltage supplies.

**Ion Engine Control**

The control of the engine system is rather complex. In an actual mission the engine control will be from a centralized computer system in the spacecraft but for these laboratory tests, manual control was exercised from a control console that also had the capability to maintain and record all the ion engine operating functions. Fig. 5 is a picture of the ion engine control console. This console is very versatile and is used to control several types of ion engine systems. All the controls shown are not necessary for the operation of the engine being discussed.
Telemetry Functions

All of the various heater power supplies, and high-voltage power supplies contain signal conditioning circuitry to convert the operating engine data to 0 - 5 Vdc signals compatible with present day telemetry systems.

Power Conditioning Design

In the design of the power conditioning system two factors were of the utmost importance: the power conditioning system had to be designed to operate for years without failure and the weight had to be compatible with the mission goals.

The power conditioning system was designed to operate with solar panels as the prime power source. The solar panels have a voltage swing of from 50 to 84 volts. In the design no attempt was made to regulate the entire system for this wide voltage swing. A regulated system amounts to a constant power system and as such has the possibility of two operating points on the solar panel characteristics (only one of which is stable). The power conditioning system only regulates the accelerator high voltage and the ionizer heater voltage (or ionizer temperature). The engine requires close control of these two parameters for proper operation. With the majority of the power conditioning system being unregulated the load line on the solar panel characteristic is a straight line with only one operating point, which is stable.

High Voltage Inverter

The preliminary converter design choices concerned the switching devices, operating frequency, and basic circuitry.

Choice of Switching Devices

The types of switching devices considered were:

1. Silicon Controlled Rectifiers
2. Gate Controlled Switches
3. Germanium Transistors
4. Silicon Transistors

Silicon Controlled Rectifiers. These devices are available with high forward current and peak inverse voltage ratings. Forward voltage drops are relatively low; on the order of one volt. The switching speed (turn-off) is relatively slow, but the biggest disadvantage is forced on natural commutation, which is required for turn-off. Because of commutation problems that would be encountered at higher frequencies, these devices were not used.

Gate Controlled Switches. These devices have an advantage over the SCR in that they can be turned off with a signal applied at the gate. Therefore, they do not impose the commutation requirements of the SCR. They have a relatively high forward voltage drop.

The main disadvantage of these devices is their relatively low maximum-current rating. For example, the Westinghouse 2422zp is rated at 10 amperes rms. Using a 56 volt bus at the required power level would require paralleling several of these devices which would result in poor reliability. For this reason, gate controlled switches were not used.

Germanium Transistors. Germanium transistors have the advantage of very low forward voltage drops but several disadvantages, including low rated junction temperatures, high leakage currents and relatively low peak inverse voltages, precluded their use.

Silicon Transistors. These devices have relatively low forward voltage drops, good switching speeds, high rated junction temperatures and relatively high peak inverse voltage ratings. Although they require undesirably high drive power it was decided to use silicon transistors for the following reasons:

1. High ambient operating temperature possible
2. No forced commutation necessary
3. Relatively high forward current devices are now available

Operating Frequency and Choice of Power Transistors. It would be preferable to operate at the highest possible frequency to reduce the weight of the iron core components. However, at the time of this design, there was not a large number of high-current, high-speed, high-peak inverse-voltage transistors available. The inverter section must supply three outputs as shown below:

- Ionizer High Voltage Output: 2000 volts at 688 mA or 1375 watts max
- Accelerator High Voltage: 8500 volts at 20 mA or 170 watts max
- Vaporizer Heater: 150 volts at 170 mA or 25 watts

Total Power Output: 1570 watts

To determine the approximate switching current, an overall efficiency of 90 percent was assumed.

The required input power is:

\[ P_{in} = \frac{P_o}{\eta} = \frac{1570}{0.9} = 1740 \text{ watts} \]

The current that must be switched at 56 volts is:

\[ I_{in} = \frac{P_{in}}{E_{in}} = \frac{1740}{56} = 31 \text{ amperes} \]

The transistors were capable of switching 31 amperes plus transients at the frequency at which they are operating.
Table I shows power transistors that were considered in the design of this supply. The table shows maximum collector current, breakdown voltage, switching speeds and current gains (β) on a comparative basis.

Since efficiency and low weight are essential to the design, it is desired to operate the transistors at as high a frequency as possible to reduce the weight of the iron core components. Figure 6 shows the losses of four types of transistors as a function of operating frequency, assuming a 1300 watt load. It is desirable to operate the transistors with a minimum safety factor of two, for current and voltage ratings.

From a safety factor standpoint, it is desirable to use the STC 2N3149 or 2N2501 as shown in Table I. These transistors have high forward current ratings and relatively high voltage ratings. They could be operated safely without paralleling units at the required power level. Since weight is of primary importance, they were not used, due to the losses shown in Fig. 6. As shown by the figure, the transistors would have to be operated at 3 kc or lower to keep power losses down.

The Delco 2N2581 can operate at high frequencies and has the highest peak voltage rating; however, due to its low current ratings, several units would have to be paralleled, thus reducing reliability.

The RCA 2N3265 was the most logical choice for the breadboard design. The switching losses are lower than other transistors and current ratings are relatively high. The main disadvantage is the relatively low peak inverse voltage of 110 volts. The transistors were used in a bridge amplifier and during breadboard tests, the bus voltage was maintained at 56 volts; thus a two to one safety factor was maintained on the voltage ratings. As will be shown later, two bridges are operated in parallel, thus a safety factor on the current rating is also obtained. It is expected that higher-current and higher-speed silicon transistors will soon be available which will further reduce weight and improve reliability.

It was decided to use 6 kc as the switching frequency. Calculations indicate that the transistors would represent a 2 to 3 percent power loss in the system. This was assuming maximum switching speeds.

Circuit Descriptions. Reliability is the key factor in the design of this power converter. Semiconductors and transistors, in particular, are more subject to failure than other components. Diodes are capable of severe overloads for short periods of time. With careful design the transformers and other iron-core components can be very reliable devices as can other components, such as resistors, capacitors, etc.

Redundancy, used in the design of transistor circuitry, will increase the weight of the system, but is necessary to improve reliability.

Driving Oscillators. In the design of the inverter two identical saturating core-oscillators are used to drive the bridge amplifiers. While one oscillator is operating the other is in standby. If the operating oscillator should fail, a relay switches to the standby oscillator.

Overall efficiency of this oscillator is about 85 percent; therefore, the total oscillator loss is approximately:

\[
P_{\text{loss}} = P_{\text{in}} - P_{\text{out}} = 14 - 12 = 2 \text{ watts}
\]

### Table I

<table>
<thead>
<tr>
<th>Transistor</th>
<th>(I_c)</th>
<th>(V_{ce0})</th>
<th>Switching Speed</th>
<th>(H_{F})</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCA 2N3265</td>
<td>25A</td>
<td>110V</td>
<td>(T_{on} = 0.5\ \mu\text{sec})</td>
<td>(H_{F} = 20) at 15A</td>
</tr>
<tr>
<td>RCA 2N3773</td>
<td>30A</td>
<td>160V</td>
<td>(T_{on} = 7.0\ \mu\text{sec})</td>
<td>(H_{F} = 15) at 15A</td>
</tr>
<tr>
<td>STC 2N3149</td>
<td>70A</td>
<td>150V</td>
<td>(T_{on} = 5.0\ \mu\text{sec})</td>
<td>(\beta = 10 - 50A)</td>
</tr>
<tr>
<td>STC 2N2501</td>
<td>150A</td>
<td>150V</td>
<td>(T_{on} = 10.0\ \mu\text{sec})</td>
<td>(\beta = 2 - 70A)</td>
</tr>
<tr>
<td>Westinghouse 2N2771</td>
<td>30A</td>
<td>150V to 250V</td>
<td>(T_{on} = 7.0\ \mu\text{sec})</td>
<td>(H_{F} = 10) at 15A</td>
</tr>
<tr>
<td>Westinghouse 2N2132</td>
<td>30A</td>
<td>150V to 300V</td>
<td>(T_{on} = 14.0\ \mu\text{sec})</td>
<td>(H_{F} = 10) at 20A</td>
</tr>
<tr>
<td>Delco 2N2581</td>
<td>10A</td>
<td>400V to 500V</td>
<td>(T_{on} = 2.1\ \mu\text{sec})</td>
<td>(H_{F} = 25) at 5A</td>
</tr>
</tbody>
</table>

Two to one safety factor was maintained on the current ratings. As will be shown later, two bridges are operated in parallel, thus a safety factor on the current rating is also obtained. It is expected that higher-current and higher-speed silicon transistors will soon be available which will further reduce weight and improve reliability.
Bridge Amplifiers. The minimum dc bus voltage is 56 volts dc. The RCA 2N3265 has a breakdown voltage \( V_{CEO} \) of 110 volts; therefore, a push-pull arrangement cannot be used. The off transistors would have twice the supply voltage applied between collector and emitter or 112 volts; therefore, bridge amplifiers are required in the design of the power amplifiers.

Two bridge amplifiers drive separate primaries on the power output transformer (Fig. 7). During normal operation both bridges are operating simultaneously and each supplies 1/2 the total power to its primary winding. Each primary winding is capable of handling the total required current (approximately 31 amps) at full load.

In case one bridge fails and the other bridge is required to supply the full output power, the RCA 2N3265 will be operating at a high-current level and the two-to-one safety factor on current ratings will not exist. With both bridges operating, the desired safety factor is exceeded.

It is expected that higher-current high-speed transistors will soon be available. One bridge could then handle the required full output power with a large safety factor. In this case, it would be preferable to operate one bridge continuously and have the other bridge as a standby unit, similar to the oscillator modules.

The bridge amplifiers are designed for the most critical operating condition, that is, one bridge supplying full load power. Under this condition each transistor is switching approximately 15 amperes (dc). At this point the RCA 2N3265 has a minimum beta of 25. A base drive of 1.5 amperes will be supplied to insure more than sufficient drive under possible overloads. Two volts rms will drive the base emitter circuitry; therefore, the total base loss is approximately:

\[
P = 4E_b I_b = (4) (2) (1.5) = 12 \text{ watts}
\]

The collector losses at 6 kc are approximately 48 watts. Thus, the total power transistor losses at full load with one bridge operating are approximately:

\[
P_t = P_{base} + P_{collector} = 12 + 48 = 60 \text{ watts}
\]

Overload Sensing. When the ion engine arcs, or in the case of a short circuit at the output, excessive currents flow that will very quickly cause a catastrophic failure of the supply. It is, therefore, necessary to sense output current and to turn off the supply during overloads. Current limiting cannot be used, as the output voltage has to be reduced to zero to extinguish engine arcs. Also, peak currents through the switching transistors would become excessive. During overloads or short circuits, the supplies are turned completely off as described previously. The supply is held off for approximately 50 milliseconds by a time constant built within the overload circuitry. After this period, the supply is turned on again. If the short persists the operation is repeated. When the short is cleared the unit returns to normal operations.

A current transformer is used to sense load current. The output of this transformer is rectified and the dc voltage applied to a Zener diode. Under overload conditions, the Zener diode breaks down and a voltage is applied to a flip flop. Output of the flip flop drives an amplifier which is returned to 30 volts below ground. When this amplifier is turned on, it develops a negative voltage which turns off the two-core drive oscillator removing the drive signals, and the output falls to zero.

Ionizer High Voltage Section. The ripple requirements for the positive high voltage are only 5 percent. Since the ripple frequency is 12 kc, a small filter would meet these requirements. However, during overloads and engine arcs there will be some time lag before the supply can be turned off. During this time, the overload currents could rise to very high values before shutdown, causing a catastrophic failure of switching transistors. A larger choke is used to limit the current rise before shutdown. When higher-current high-speed transistors become available, a smaller choke can be used, since larger peak currents could be tolerated.

It is difficult to estimate peak currents under overload. The impedance of the supply has a direct relationship to these peak currents. Assuming solar panels are used to power the supply, the peak currents would be limited due to the output impedance of the panels (i.e., as overload current is increased, solar panel output voltage decreases).

To calculate overloads, impedances will be referred to the secondary side of the transformer.

\[
\begin{align*}
E_p & = \frac{E}{s} = \frac{N_p}{N_s} \times (1.1) \times (2000) = 40 \times \frac{I_p}{I_s} = \frac{R_p}{R_s} \\
a^2 & = \left( \frac{N_s}{N_p} \right)^2 \frac{R_s}{R_p} = (40)^2 \\
R_s & = A^2 R_p = (40)^2 R_p = 1600 R_p
\end{align*}
\]
The equivalent secondary circuit with load shorted circuited:

\[ E_s \overset{\sim}{R_{p1}} \overset{A^2 R_{p2}}{\sim} R_{SEC} \overset{\text{SHORT + 0}}{\sim} Z \]

It is assumed that no circuit inductance is present. This will be a severe condition, since any circuit inductance would tend to limit current flow at the instant of short circuit.

Assume:
\[ A^2 R_{p1} = \text{resistance reflected to secondary by power supply impedance,} \]
\[ A^2 R_{p2} = \text{resistance reflected to secondary from primary of bridge power amplifier circuitry,} \]
\[ R_s = \text{resistance of secondary circuitry.} \]

The terms of \( A^2 R_{p2} \) and \( R_s \) will be lumped together and calculated, as circuit losses at full load (\( \eta = 90 \text{ percent} \)).

\[ A^2 R_{p2} + R_s = \frac{E}{I} = \frac{170}{(0.65)^2} = \frac{170}{0.423} = 400 \Omega \]

Actually, this is a conservative estimate, as the circuit losses would be higher under overload, consequently representing a high impedance.

It is assumed that under overload the power supply will present approximately 0.1 ohm at the primary. The reflected impedance into the secondary is approximately:

\[ A^2 R_{p1} = (40)^2 (0.1) = 160 \Omega \]

Then the approximate total equivalent secondary resistance under short circuit conditions is:

\[ R_t = A^2 R_{p1} + \left( A^2 R_{p2} + R_{sec} \right) = 160 + 400 = 560 \Omega \]

Neglecting circuit inductance and assuming that a filter choke is not used, the total secondary fault current that would flow when the engine arced would be:

\[ I_{\text{fault}} = \frac{E}{R} = \frac{2000 \text{V}}{560 \Omega} = 3.6 \text{ amps} \]

Peak Power at \( T = 0 \)
\[ P = 3.6 \times 2000 = 7200 \text{W} \]

Peak Transistor Current:
\[ I_p = A I_{\text{fault}} = 40 \times (3.6) = 144 \text{ amps} \]

Therefore, if no filter choke were used, and assuming no circuit inductance, the instant the engine arced a peak current of approximately 150 amperes would flow through the transistors causing catastrophic failures.

The filter choke limits the current rise to tolerable limits until the supply can be turned off. Turn-off time is fast, as small-signal, fast-switching transistors are used in the overload circuitry.

It would be desirable to use as large a choke as possible to limit current rise before turn-off. However, weight and volume were a key factor in the design; therefore, a compromise was made.

When inductance is added to the circuit, the transistor fault currents that flow will be:

\[ i = \frac{E}{R} \left( 1 - e^{-\frac{tR}{L}} \right) \]

where:
\[ i = \text{transistor fault currents} \]
\[ a = \text{turns ratio of output transformer} \]
\[ (\text{approximately 40}) \]
\[ E = \text{ionizer output voltage +2000 volts} \]
\[ R = \text{equivalent secondary resistance} \]
\[ L = \text{equivalent secondary inductance} \]
\[ t = \text{switching time to turn-off supply after sensing} \]

The equation shows it would be desirable to keep the switching speed as fast as possible and the circuit inductance as large as possible to keep the fault currents to a minimum.

Figure 8 illustrates a waveform of fault currents as a function of time. At \( t_0 \), normal load current is flowing when a short is applied. The current rises exponentially to a value where the overload is sensed, \( I_{\text{g}} \). At this time a signal is applied to the overload circuitry. It then takes a time, \( \Delta t \), for the supply to be turned off, during which time \( \Delta i \) amperes flows. It is desirable to keep this \( \Delta i \) as small as possible to minimize the peak currents through the transistor, \( I_p \).

Assuming a 50 millihenry choke is used, the time constant is:
\[ T = \frac{L}{R} = \frac{50}{560} \times 10^{-3} = 0.09 \times 10^{-3} \approx 90 \mu\text{sec} \]

If 90 microseconds for turn-off is allowed, the fault current will rise to approximately:
Figure 9 illustrates the power transistor fault currents $A_i$ that would flow as a function of the switching speed of the turn off circuitry.

The curve assumes that the total secondary resistance is 56 ohms and consists of the secondary resistance, plus the reflected resistance from the primary including the dc supply impedance. It also implies that the total inductance appearing in the secondary is 50 millihenries. In the actual design, a 50 millihenry choke was used, therefore, the actual secondary inductance will be greater than 50 millihenries.

As stated previously, it is difficult to determine the true fault currents that will flow under overloads; the curve in Fig. 9 gives a rough estimate of the fault currents that might be expected using a 50 millihenry filter choke. The time for turn-off is between 10 and 20 microseconds; therefore, the fault currents are between 10 and 30 amperes (above the overload trip point).

Due to the inherent internal circuit inductance of the supply, the fault currents will be lower than the calculated values.

Ionizer High Voltage Losses. Semtech 1248 diodes are used as rectifiers. These are specially built stacks, rated at one amp at 55°C with a PIV rating of 6000 volts. The stacks connected in a bridge configuration give a current rating of 2 amps. The current safety factor at full load is $2/0.65 = 3.1$; the voltage safety factor is 6000/2000 = 3. Diode drops at one ampere are 9 volts. Using this same figure at 650 milliamperes, the diode losses will be approximately $2 	imes 0.65 = 1.3$ watts or approximately 2 watts per stack.

The copper resistance of the 50 millihenry choke is approximately 20 ohms. The copper loss of the filter choke at full load is $P = I^2R = (0.65)^2 (20) = 8.5$ watts. The core loss is approximately 4.5 watts; therefore, the total choke loss is approximately 13 watts. Total high voltage secondary losses, diodes plus choke: $12 + 15 = 27$ watts.

Accelerator High Voltage Section. The accelerator high voltage output is adjustable from 4500 to 8500 volts and is regulated. Output from the main bridge output transformer is applied to a control magamp, and then to a step-up transformer which gives the required negative output voltage after rectifying and filtering.

Fault currents are calculated similar to those of the ionizer high-voltage supply shown in previous paragraphs.

Diodes used are Semtech SCH 20000. They are rated at 0.5 amps (55°C), with a PIV rating of 20,000 volts. Used in a bridge configuration they give a dc output current capability of one amp at 55°C. The current safety factor is $1/0.02 = 50$ and the voltage safety factor is $20,000/8500 = 2.36$.

The voltage drop of each stack (4 in bridge) is 27 volts at 0.5 amperes. The voltage drops would be much less at 20 mA. Assume the voltage drop to be half this value, or 13.5 volts. The diode losses are approximately:

$$P = 2 \times (20 \, \text{mA}) \times 13.5 \, \text{V} \times 0.54 \, \text{watts}$$

Choke resistance is approximately 1,500 ohms.

Copper loss:

$$P = I^2R = (4 \times 10^{-4}) (1500) = 0.6 \, \text{w}$$

Core loss is approximately the same.

Total choke loss is approximately 1.2 watts. The total accelerator high voltage secondary loss (diodes, plus choke) is approximately 1.74 watts.

The accelerator high-voltage transformer is designed to have a minimum conversion efficiency of 95 percent at full load (8500V at 20 mA). The power required at the primary of the accelerator high voltage transformer is:

$$P = \frac{P_0}{\eta} = \frac{170 + 1.74}{0.95} = 181 \, \text{watts}$$

where:

$$P_0 = P - P_s = 181 - 170 = 11 \, \text{watts}$$

A Semtech type SF10 diode was chosen for the accelerator high-voltage control magamp. This is a fast-recovery controlled-avalanche silicon diode. It is rated at 1 amp at 55°C with a PIV rating of 1000 volts. The efficiency of this magamp operating at 6 kc with 400 volts is approximately 95 percent. Power applied to the magamp will be approximately:

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Therefore, the total magamp loss is approximately 10 watts. At full load to the accelerator, each diode of the magamp will carry approximately:

\[
I = \left(\frac{1}{2}\right) \frac{P}{E} = \frac{1}{2} \frac{191 \text{ W}}{400 \text{ V}} = 0.24 \text{ amps}
\]

The current safety factor is approximately: 
\[
\frac{1}{0.24} \approx 4
\]

The voltage safety factor is approximately: 2.5

As stated previously, the main output transformer drives the accelerator control magamp. Its minimum efficiency is 95 percent at full load. Therefore, its primary current or the current that must be switched by the bridge inverter transistors is:

\[
I = \frac{191/0.95}{56 \text{ V}} = \frac{201 \text{ W}}{56 \text{ V}} = 3.6 \text{ amps}
\]

Vaporizer Output. The main inverter output transformer also supplies power to the vaporizer supply. Output from the transformer is 150 volts rms. This 150 volts is applied to a self-saturated magamp (to be described in detail later).

The maximum output of the vaporizer supply is 90 watts. Overall efficiency of the vaporizer supply is approximately 90 percent. Therefore, the main inverter transformer must supply 90/0.9 = 100 watts. The bridge inverter transistors must supply:

\[
I = \frac{P}{\eta} = \frac{100/0.95}{56 \text{ V}} = \frac{105}{56} = 1.87 \text{ amps}
\]

The losses for the high voltage inverter are summarized below:

<table>
<thead>
<tr>
<th>Losses</th>
<th>(watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionizer Filter Choke</td>
<td>13.00</td>
</tr>
<tr>
<td>Ionizer Rectifier Diodes</td>
<td>12.00</td>
</tr>
<tr>
<td>Main Output Transformer</td>
<td>82.00</td>
</tr>
<tr>
<td>Accelerator Filter Choke</td>
<td>1.20</td>
</tr>
<tr>
<td>Accelerator Diode</td>
<td>0.54</td>
</tr>
<tr>
<td>Accelerator Transformer</td>
<td>11.00</td>
</tr>
<tr>
<td>Accelerator Magamp</td>
<td>10.00</td>
</tr>
<tr>
<td>Bridge Transistors</td>
<td>60.00</td>
</tr>
<tr>
<td>Drive Losses</td>
<td>2.00</td>
</tr>
<tr>
<td>Overload Losses</td>
<td>1.00</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2.00</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>194.74</td>
</tr>
</tbody>
</table>

The conversion efficiency for the entire high-voltage inverter is as follows:

\[
\eta = \frac{P_0}{P_{in}} = \frac{P_0}{P_0 + P_{loss}} = \frac{1580}{1580 + 194.74} = 89.5\%
\]

Vaporizer Heater Circuit. The primary functions of the vaporizer heater circuit are to provide controlled power to the engine cesium vaporizer and to control and regulate the engine thrust by controlling the cesium mass-flow rate. To perform this control function a voltage analog of the positive high voltage current \(I^+\), which is a function of thrust, is used to control the vaporizer heater power. This control is actually accomplished by controlling the heater output voltage. The control is in such a manner that it constitutes a feedback control and regulating system.

Along with these regulation requirements, manual adjustment of the \(I^+\) regulating level is required as well as an adjustable threshold level of \(I^−\) below which control of the vaporizer voltage does not occur. An approximate analysis of the feedback system reveals that the level at which the beam current, \(I^+\), regulates is inversely proportional to the loop gain. It is also obvious that the adjustments of the threshold and loop gain will be interacting. Once the threshold level is reset, the loop gain must be adjusted to obtain the same regulation level.

In addition to the above control of the vaporizer power by \(I^+\), it is required that the negative high voltage drain current, \(I^−\), be used to control the vaporizer power in such a manner that limiting of \(I^−\) is obtained. In this control scheme adjustable threshold and limit (or regulation) levels are also required. An open loop \(I^−/V^−\) characteristic similar to that of the \(I^+/V^+\) characteristic is necessary. This control must override the \(I^+\) control which requires some type of OR logic in the control system.

The final requirement of the vaporizer heater control circuit is that it provide limiting of the vaporizer heater current. This is necessary to prevent overloading of the heater circuit during turn-on when the cold resistance of the heater coils is 1/4 to 1/3 of the operating (hot) value.

A rather wide range of vaporizer heater power is necessary to meet the requirements of individual engines, since the ionizer perveance can vary from engine to engine. Full-on voltages of 4 to 7 volts rms are provided by transformer output taps.

Since the heater must be capable of supplying more than 100 watts (at initial turn-on and during warm-up) and its normal operating power is approximately 20 watts, an efficiency figure is somewhat meaningless. For this reason efficiency must be considered over the entire operating range. As shown in Fig. 10, efficiency is a function of conduction angle or duty cycle of the controlling magnetic amplifier. This graph is a plot of the vaporizer ac circuit and dc control circuits total efficiency as a function of the ac duty cycle under the worst conditions of control settings.
In the full-on condition (duty cycle of 100 percent), the efficiency is maximum at 90 percent, while at normal beam current regulation at a duty cycle of approximately 20 percent the efficiency is down to 77 percent. The duty cycle in the regulation mode, of course, is dependent upon individual engine characteristics.

Low Voltage Inverter Design

The low-voltage inverter was designed to provide power for the ionizer and neutralizer heaters. The total output power is 450 watts. The following design goals were determined to be of primary importance: (1) minimum weight, and (2) reliability through not only proper design, but also through the use of redundant power stages.

An inverter operating frequency of 10 kc was chosen as a compromise between efficiency and minimum transformer weight. Presently available silicon power-transistors preclude operation above 10 kc, if reliability and reasonable efficiencies are to be maintained.

The basic inverter consists of two redundant switching amplifiers operated in parallel. Each switching amplifier is composed of four transistors, operating in series connected pairs. Series operation is used to provide the voltage capability required to operate from a solar panel source in the range of 56 to 84 Vdc. Transistor voltage division is insured by dividing the primary windings such that only one-half of the total voltage will appear across each transistor. The conventional techniques of operating switching transistors in parallel are to either use emitter resistors to insure current division or to provide identical parallel windings on the output transformer, such that the current divides equally. Neither of these techniques was deemed feasible in this case, as redundancy could not be reliably insured. Should one transistor fail (collector to emitter short) it would immediately be reflected through the output transformer as a shorted load and cause failure of the remaining transistors.

Consequently, a new technique was developed. The output transformer was wound on two toroidal cores with the primary of each inverter wound on one core. Both cores, with primary windings, are then stacked one above the other and a common secondary is wound over both cores. This transformer configuration may be analyzed as two transformers with series connected secondaries. It can readily be seen that should one of the two inverter transistors short, the remaining amplifier will continue to operate in a normal manner. The shorted transistor may cause the remaining transistors in this amplifier to fail, but this failure will not be reflected as an overload to the second amplifier. This action will cause the output voltage to drop to one-half its normal value. The voltage is restored to normal by disconnecting the transistors that have failed from the transformer primary and reconnecting that primary to the other amplifier. This is accomplished with relay switching. It will be noted that the relays are connected in such a manner that, during normal inverter operation, they are inactive. They are required to switch only in the event of a failure. This method of operation was chosen so as not to degrade the reliability of the basic inverter. If a transistor should fail by exhibiting an open circuit between collector and emitter, the transformer primary in that amplifier will cause the core to saturate on the next few cycles of operation. This action will cause one or more transistors to fail by shorting and then cause the relay to switch by action of blowing the fuse.

Ionizer Heater Power Supply. The power required to maintain the porous tungsten ionizer at the desired ionization temperature is provided by the ionizer heater power supply. The primary power is derived from the low voltage inverter in the form of a 10 kc signal that will have a 100 volt rms minimum value at mission start and a maximum of 170 V rms at mission completion. The output of the power supply is current regulated for changes in heater resistance and provides for constant output as the input voltage increases from the minimum 100 V rms to the maximum of 170 V rms.

The 10 kc 100 V rms square wave output from the low-voltage inverter is applied through a self-saturating magnetic control amplifier to a high-voltage isolation transformer. The transformer matches the impedance of the ionizer heater element to the output of the power supply and provides high-voltage isolation between the +2 kV on the engine and the power supply circuitry. The supply is current regulated to maintain current-input to the ionizer heater within ±1%. This is accomplished by a current feedback signal that is obtained by applying the rectified output of a current-sense transformer to the control winding of the magnetic amplifier. The feedback signal is also processed and used for telemetry data on the ionizer heater current.

Neutralizer Heater Power Supply. The requirements of the neutralizer system are to provide 10 watts of power with a four volt output. This is accomplished by a separate tapped winding on the low-voltage inverter power transformer. The taps give slight variations in the output voltage to take care of differences between neutralizers. A neutralizer electron emission current sensor is connected between this output winding and the engine return. This sensor gives an indication of the electron being provided to the beam.

Mechanical Design

General

In the mechanical design of the power conditioning system no attempt was made at a flight package design. The system was packaged in
broadboard fashion to check the system's compatibility with operation in vacuum and its ability to power the 10 mlb cesium contact ion engine.

Packaging

The power conditioning system was packaged on three aluminum plates 1/2-inch thick and 12-inches square (Fig. 11). One of these shelves or plates contains the low-voltage inverter, the ionizer heater supply and the neutralizer heater supply. The second shelf contains the high-voltage inverter and the positive high-voltage output section, and the third contains the negative high-voltage output section and the vaporizer heater power supply.

These three shelves are mounted on slide rails which allow easy removal for servicing. The shelves are installed on a rack which is attached to the front flange of the vacuum chamber. Between each of the three component shelves are liquid-nitrogen-cooled heat exchange shelves. These LN2 shelves are placed as close to the component shelves as possible to allow for the greatest radiation heat transfer possible. Since all cooling in a flight system will be by radiation to outer space, this was the cooling mechanism chosen for the breadboard system. In fact, in vacuum the majority of the heat transfer in any case is by radiation so the attempt is made to make the heat transfer as efficient as possible.

All the electrical connections to the power conditioning are made through sealed connectors on the vacuum chamber front flange. The low-voltage control and telemetry signals go through vacuum-sealed Deutsch connectors. The input dc power is connected to the system through heavy single-pin feedthroughs and all high-voltage connections leave the tank through single high-voltage feedthrough pins.

Vacuum Chamber

The vacuum chamber used to test the power conditioning system is a small chamber measuring 2 ft x 2 ft x 3 ft on the inside (Fig. 12). The chamber has a medium-size Welch pump used for rough pumping on the chamber and for maintaining the diffusion pump foreline pressure. The diffusion pump is a CVC 3-inch vapor pump. With this pumping system, pressures in the 10^-5-torr region can be maintained. With the cryogenic pumping action of the LN2-cooled heat exchange shelves, pressures in the low 10^-6-torr range are possible.

The vacuum chamber is completely instrumented with vacuum thermocouple gauges on both the chamber and the foreline and a cold-cathode vacuum gauge and a Varian ionization gauge on the chamber. A pressure alarm circuit on the Varian gauge is interlocked with the prime power source so that any failure of the vacuum system will shut off the power conditioning before the system is damaged by high pressure.

The entire vacuum system is mounted on casters so it can be rolled up next to the vacuum chamber containing the ion engine. This will keep the connections from the power conditioning to the engine as short as possible.

Test Phase

The testing phase of the complete power conditioning system was divided into four sections:

1. Power conditioning system, at atmospheric pressure, powering ion engine simulator
2. Power conditioning system, at atmospheric pressure, powering 10 mlb ion engine
3. Power conditioning system, in vacuum, powering ion engine simulator
4. Power conditioning system, in vacuum, powering 10 mlb ion engine

A description of these test phases is given below:

1. Testing the entire system, at atmospheric pressure, with an ion engine simulator was the first test phase. The phase went smoothly and no basic weaknesses in the design philosophy were evident.

2. Testing the power conditioning system with a 10 mlb ion engine but with the power conditioning system operating at atmospheric pressure. This phase would show the compatibility of the power conditioning with the engine, without having the system subjected to the added restraint of vacuum operation.

One problem area revealed by this testing was in the area of heater return leads to the engine. The ionizer heater and the vaporizer heater are both sheathed type heater elements that are brazed to the engine. One end of the heater element is electrically connected to the engine body. A single connection to the engine serves as a common return line for both the ionizer and vaporizer heaters. The currents that flow to the ionizer heater element are in the range of 20 to 30 amperes, enough current to induce a significant voltage drop along the body of the engine. This induced voltage reflects, by autotransformer action, back into the vaporizer control circuit and gives improper indications to both the control element and also the telemetry readout. This problem was completely solved by running separate return leads for each of the heater elements.

3. Testing the power conditioning system, in vacuum, with the ion engine simulator. The transition from atmospheric to vacuum operation is probably the most difficult step in the design of an ion propulsion system. In most previous cases the possibility of high-voltage breakdown in vacuum has been avoided by sealing the electronics in a canister at atmospheric pressure. On two successful EOS/Air Force ballistic flight tests, in 1964, the entire power conditioning system was sealed at atmospheric pressure. On the first orbital flight...
test of an ion engine, in April 1965, only the high-voltage circuitry was sealed at atmospheric pressure. However, for a mission to Mars, the possibility of maintaining an adequate seal on the system is questionable. Consequently, the Air Force decided that the high-voltage problem had to be solved without resorting to componented sealing at atmospheric pressure.

The technique used was to have the high-voltage circuitry exposed as much as possible and to use no potting compounds. In this way no gases could be trapped and the outgassing under vacuum would be complete. Prior to vacuum operation the power conditioning component shelves were baked in a high-temperature vacuum chamber to remove any volatile substances; this minimizes outgassing under actual operation.

During the initial phases of vacuum operation no failures occurred as a result of high-voltage breakdown. This significant accomplishment was directly attributable to the design techniques employed.

Several component failures were experienced after several hours of operation, but these were the result of defects in the components themselves. In the design of the power conditioning system every effort was made to use qualified parts approved and recommended by the Jet Propulsion Laboratory and the Marshall Space Flight Center as shown in their Preferred Parts Lists. However, no such list exists for state-of-the-art transistors and diodes or high-voltage components. The best approach to this problem, and one that is highly recommended, is to set up a screening process and test all such components under vacuum operation prior to installation into the system.

4. Testing the power conditioning system, in vacuum, with the 10 lb ion engine. All the design effort on this program has been directed toward the operation of the ion engine with the power conditioning system to test the performance of the entire system under conditions as closely simulating outer space as possible. One difference is evident in that the engine is operated in one vacuum chamber and the power conditioning in another. This would allow continuation of the power conditioning test if anything should happen to the engine's performance.

The design goal of this power conditioning system is to show a 500 hour operating lifetime with the engine and an additional 1500 hours of operation of the power conditioning with an ion engine simulator. At the present time the power conditioning system has been operating the 10 lb engine for greater than 300 hours with no problems anticipated in meeting the 500 hour lifetime goal. The test will not be terminated after 500 hours but will continue as long as the engine is operating. Should the engine fail prior to 2000 hours, the power conditioning system will be operated with an engine simulator to achieve the objective of 2000 hours.

Conclusion

The ion engine power conditioning system described in this paper has demonstrated that a long-lived ion propulsion system is not only possible but also practical. While there must be more improvement in reducing size and weight, and in increasing reliability, before ion propulsion systems will be considered as the primary propulsion systems for deep space missions, the system described here has brought us one step closer to that objective.

With the continual development of high-frequency, high-power switching devices and the improvements in circuit techniques, along with the experience gained in the development of ion propulsion power conditioning systems, such as the one described in this paper, the goal of achieving a practical, highly advanced, ion propulsion system will be achieved.
Fig. 1. 10 mlb Ion Engine and 20-Pound Feed System
Fig. 2. Schematic of a Typical Cesium Contact Ion Engine
Fig. 4. Block Diagram, Power Conditioning System
Fig. 5. Power Conditioning Control Console
Fig. 6. Transistor Losses for 1300 Watt Load

Fig. 7. Redundant Bridge Inverter Amplifiers
\( I_L \) = NORMAL LOAD CURRENT
\( I_{LS} \) = CURRENT LEVEL AT WHICH OVERLOAD IS SENSED
\( I_P \) = PEAK CURRENT THROUGH TRANSISTORS
\( \Delta i \) = CURRENT THROUGH TRANSISTORS BETWEEN SENSE TIME AND OFF TIME
\( \Delta T \) = SWITCHING TIME OF OVERLOAD CIRCUITRY BETWEEN TIME OVERLOAD IS SENSED AND TIME TO TURN POWER TRANSISTORS OFF

Fig. 8. Waveform of Typical Fault Current as a Function of Time
Fig. 9. Measured Transistor Fault Currents as a Function of Time

FAULT CURRENT, $\Delta I$, AS A FUNCTION OF TURN OFF TIME, $\Delta T$

$R_{\text{sec}} = 560 \, \Omega$ (EQUIVALENT)

$L_{\text{sec}} = 50 \, \text{mh}$ (EQUIVALENT)
Fig. 10. Vaporizer Circuit Efficiency as a Function of Duty Cycle
Fig. 11. Complete Breadboard Power Conditioning System
Fig. 12. Power Conditioning System Vacuum Test Chamber