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Liquid Metal-Heated Space Radiator-Mounted
Thermionic Generator
Report PWA-2275

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Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION
EAST HARTFORD CONNECTICUT

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FOREWORD

This report presents a description of work performed from July 1 to September 30, 1963 by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford, Connecticut for the Flight Vehicle Power Division of the United States Air Force under Contract AF 33(657)-11320, Project No. 8173, Task No. 817305-25. The work is administered under the direction of Lt. David Raspet of the Flight Vehicle Power Division.

The work covered by this report was accomplished under Air Force Contract AF33(657)-11320, but this report is being published and distributed prior to Air Force review. The publication of this report, therefore, does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.
ABSTRACT

Pratt & Whitney Aircraft has initiated work to evaluate thermionic converters suitable for liquid metal heating in space radiator configurations. During this report period (July 1 to September 30, 1963) the design of the converter to be evaluated in this program has been completed. The converter incorporates a tantalum-10 per cent tungsten alloy liquid metal containment tube insulated by BeO from a tungsten-25 per cent rhenium emitter. A nickel collector with an inter-electrode space of 8 mils has been selected. The predicted performance of this converter indicates a power output of 4.7 watts per square centimeter with an efficiency of 12 per cent when the emitter temperature is 1500°C. A bifilar tungsten filament was selected for use as a heater in this program based on a study contained in this report.
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I. INTRODUCTION

Cylindrical generators capable of operating in series from a 1500 °C liquid metal system potentially have use in several space power configurations. Several problem areas or unknowns remain to be explored before the practical feasibility of these generators is assured. Among these are, 1) high temperature (1500 °C) insulation and ceramic-to-metal bonding technology, 2) high temperature (1500 °C) liquid metal containment, 3) the endurance characteristics of practical converters, and 4) power degradation due to electrical mismatch.

The work described in this report is directed towards demonstration of the use of thermionic generators heated by liquid metal in the temperature range of 1200 to 1500 °C. The specific objectives of the current program are:

1) Experimentally evaluate advanced thermionic converters in a configuration appropriate for liquid metal heating up to 1500 °C.

2) Investigate performance when converters at different temperatures are connected in series.

3) Determine the optimum heating technique for prolonged accurately controlled evaluation of thermionic converters operating at these temperatures.

To satisfy these objectives the following goals will be sought during this program:

1) A converter will be designed to produce at least 4.0 watts/cm² at 1500 °C emitter temperature at an overall thermal efficiency in excess of 10 per cent. This same converter will be designed to produce at least 1.0 watt/cm² at 1200 °C emitter temperature.

2) One thousand hours of power-producing operation per converter at emitter temperatures not less than 1450 °C and not more than 1500 °C on at least two converters. Time at power density levels below 2 watts/cm² will not be counted.
3) Four thousand hours of total power-producing operation at emitter temperatures between 1200°C and 1500°C. Time at power density levels below 0.5 watt/cm² will not be counted.

This report covers the work conducted from July 1 to September 30, 1963. It includes a description of the generator designed to meet the program requirements, and a report of heating methods appropriate to testing cylindrical thermionic generators.
II. TECHNICAL DISCUSSION

The engineering program to experimentally evaluate advanced thermionic generators in a configuration appropriate for liquid-metal heating at temperatures of 1500 °C has been separated into three parts, 1) to determine optimum heating techniques for prolonged, accurately controlled evaluation of these generators, 2) to investigate performance when converters at different emitter temperatures are connected in series, and 3) to conduct life tests of such converters.

To meet the stated objectives, a technical program has been established which can be summarized as follows:

1) Compile a heater report that will include a discussion of various methods of heating, 1) direct and indirect electrical resistance, 2) electron bombardment, 3) induction, 4) liquid metal, and 5) fossil fuel methods.

2) Design and fabricate 10 generators of a configuration appropriate for liquid-metal heating with the goal of at least 4 watts/cm² at a 1500 °C emitter temperature and at a thermal efficiency of at least 10 per cent. The design power output at 1200 °C will be in excess of 1 watt/cm² at optimum operating conditions.

3) Conduct an engineering test program in three parts to evaluate these generators:
   a) Calibration Tests - Determination of optimum collector temperature, cesium pressure and output voltage for maximum power conditions at emitter temperatures of 1200, 1300, 1400, and 1500 °C.
   b) Electrical Series Test - Investigate the performance of two converters connected in series electrically, with varying emitter temperature mismatched and matched conditions.
   c) Endurance Test - Conduct life tests at the original maximum power operating condition for an emitter temperature of 1500 °C.

4) Deliver a complete test system and two generators identical to those used in this program to Wright-Patterson AFB.
The design phase of this program has been completed and is discussed in the next section. The heater report has been completed and is included in this report. Procurement of all converter and test station parts was initiated in this period.
III. THERMIONIC GENERATOR DESIGN

The guiding consideration in the generator design was to combine the electrode materials and interelectrode spacing to obtain the desired performance with the most reliable converter components and fabrication techniques to insure generator long life. The resulting generator design is shown in Figure 1. As can be seen from this drawing the converter consists of a tungsten-25 per cent rhenium emitter tube insulated by beryllium oxide from the tantalum-10 per cent tungsten alloy liquid metal containment tube; an 8-mil interelectrode spacing, a heavy nickel collector collector with iron-titanium oxide coated copper cooling fins; and an aluminum oxide compression seal. The cesium reservoir is thermally isolated from the main body of the converter and controlled separately. The electrical resistance radiant emitter heater is a tungsten bifilar coil filament. The entire assembly is mounted within a vacuum bell jar which utilizes a vacion pumping system to eliminate contamination from diffusion pump oils.

The work performed during cell design can be divided into the following areas:

1) Selection of components
2) Description of generator fabrication method
3) Heat transfer analysis
4) Predicted cell performance

A. Selection of Components

Liquid Metal Containment Tube - The prime requirements for the inner tube of the generator design are compatibility with lithium and structural strength at 1500°C. The tube material must also be easily formed and have good weldability since several joints must be made for use in a system. The tube material must also have a coefficient of thermal expansion similar to that of the material selected to electrically insulate this tube from the emitter tube. Two materials appear to offer promise of meeting these requirements: a tantalum-10 per cent tungsten alloy and a tantalum-8 per cent tungsten-2 per cent hafnium alloy. No data has been reported on the direct liquid-metal compatibility with tantalum, columbium, tungsten, or molybdenum at 1500°C. It may be expected, however, that all of these metals will be satisfactory under these conditions. This is based principally on extrapolation of corrosion and solubility data established by prior
work at lower temperatures in the CANEL laboratories. No mass transfer was observed in Cb-1-Zr alloy-lithium forced circulation loops over the full range of temperatures and times studied.

One extremely important aspect of alkali metal compatibility is associated with the effect of impurities on corrosion. Corrosion chemistry studies at CANEL, showed clearly that lithium attack was associated with previous oxygen contamination of the columbium: the oxygen-rich solid solution or oxide phases are attacked rapidly by lithium. This problem was successfully solved by the addition of zirconium which served to immobilize oxygen as stable zirconium oxides. This approach was consistent with free energy data and was proven over a broad range of test conditions. Heat treatment cycles were developed to ensure zirconium effectiveness, and basic studies, using internal friction techniques, were conducted to ascertain the underlying mechanisms.

This experience must be taken into account in considering a new alloy at 1500°C. The alloy should contain one element which will form a very stable oxide to prevent attack of tantalum-oxygen phases or oxygen-rich solid solutions. This is especially important since preliminary corrosion evaluation of tantalum in lithium has shown an attack very similar to that shown by unalloyed columbium. Alloying elements whose oxides are highly stable include beryllium, yttrium, zirconium, titanium, and hafnium. Thermodynamic data suggests that the oxides of these metals should form in preference to either the tantalum oxides or Li₂O. The Ta-W-Hf alloy series would appear to be particularly attractive in this regard. Although the hafnium-containing alloy is preferred for liquid metal testing, a 0.500-inch diameter, 0.020-inch wall tantalum-10 per cent tungsten alloy tube was tentatively chosen because of better availability and because it should not differ significantly from the hafnium-containing alloy for the purposes of this investigation.

Insulation - The prime requirements for this material are high thermal conductivity, high electrical resistivity and dielectric strength, compatibility with the tantalum and tungsten alloys, suitable thermal expansion coefficient, and structural integrity at high temperatures. A 0.015-inch wall BeO tube was chosen as the insulator.
BeO was selected over other insulation candidates because of its apparently higher thermal conductivity, thermal stability, assumed compatibility with structural materials, and good electrical resistivity. Its thermal expansion characteristics closely match those of tantalum. To insure that good thermal conductivity was obtained, a high-density body was used rather than a plasma-sprayed body. The inner tube and emitter tube will be bonded to the insulation tube with Zimo 31, a high temperature brazing material developed by Pratt & Whitney Aircraft.

Emitter - The emitter material for this design should have low evaporation rate at 1500 °C, superior thermionic emission qualities, a high work function to satisfactorily ionize the cesium vapor, high electrical and thermal conductivity, low thermal emissivity, compatibility with cesium vapor and the brazing materials, adequate strength at emitter temperatures, resistance to grain growth at operating temperatures, and acceptable fabrication and welding properties. A tungsten-25 percent rhenium alloy was chosen to best meet all of the requirements. Rhenium is also an excellent candidate for this application; however, it has not been tested sufficiently in cylindrical configurations to warrant its selection at this time. The table below shows a comparison of various refractory metal candidates. A later section gives a description of the performance expected from using this emitter material.

<table>
<thead>
<tr>
<th>Material</th>
<th>W-Re</th>
<th>W</th>
<th>Ta</th>
<th>Mo</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recrystallization Temperature</td>
<td>Very</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Very</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fabricability</td>
<td>Fair</td>
<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Strength</td>
<td>Very</td>
<td>Very</td>
<td>Good</td>
<td>Good</td>
<td>Very</td>
</tr>
<tr>
<td>Strength</td>
<td>Good</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vaporization</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Performance</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

An emitter wall thickness of 0.050 inch, chosen to minimize axial temperature gradients, produces an emitter diameter of 0.700 inch. An emitter length of 1.2 inch was chosen to meet single-cell operating efficiency requirements, resulting in an emitter area of 17 square centimeters. The emitter surface finish is controlled to 20 rms during fabrication and its outside diameter is machined to within 0.0005-inch to assure a controlled spacing.
Collector - The collector material must meet the same requirements as the emitter except that it will operate near 750 °C and must have a low cesiated work function for optimum thermionic performance. The high conductivity and low cesiated work function of nickel make this metal the logical choice. A number of copper fins are attached to the nickel collector. The copper is nickel plated to reduce the effect of evaporation and this plate in turn is coated with an iron-titanium oxide to improve the emissivity.

Collector temperature control for experimental purposes is supplied by a heater at the base of each fin. The use of heater control permits the temperature of the collector to be adjusted to obtain the 60 to 80 per cent cesium coverage necessary to provide the desired minimum collector work function. In actual use, this temperature would be preset by adjusting fin area. The finish of the inside surface of the collector is controlled to 20 rms during manufacture.

Interelectrode Spacing - A spacing of 0.008 inch was chosen as a compromise between a small spacing for peak cell performance and a practical spacing based on extended life and fabricability criteria. Spacing and concentricity measurements are confirmed by means of x-ray radiography after fabrication of the generator.

Collector-to-Emitter Support - This support acts as a structural member and should have a low thermal conductivity, high electrical conductivity, compatibility with cesium, low vapor pressure at operating temperature, and reasonable fabrication and welding properties. Since this connection conducts heat as well as generator current, the length-to-area ratio was optimized for this program.

Ceramic Seal - This member provides a nonconducting support between the emitter and collector and must contain the cesium vapor. The requirements of the seal are low electrical and thermal conductivity, low evaporation rate in vacuum, compatibility with cesium vapor, and structural integrity. A low silica content alumina compression seal was chosen. Figure 2 shows a typical compression seal used with cylindrical generators. This seal of low silica alumina, has been run in a thermionic converter at an emitter temperature of 1650 °C for more than 1000 hours at seal temperatures in excess of 800 °C.
Cesium Reservoir and Heater - The function of this subassembly is to maintain the desired cesium pressure within the body of the converter. Two prime factors for the reservoir material choice are compatibility with cesium and ability to cold pinch the metal. Nickel has been chosen for this purpose on the basis of several hundred successful pinch and cesium compatibility tests. The cesium reservoir is attached to the main body of the converter by a short small-diameter thin-walled nickel tube. This tube acts as a heat dam and thermally isolates the reservoir from the main body of the converter. The reservoir is made of 0.050-inch wall 3/8-inch diameter high thermal conductivity nickel.

The temperature of the liquid cesium is measured by thermocouples inserted within the end probe cap of a reservoir containing titanium sponge. This design has been analyzed to insure that the coldest spot of the system is known, measured, and controlled. A definite controlled cold spot is assured by extending the end cap slightly below the heater assembly.

The reservoir will normally operate at less than 200°C when the cesium heater is not used. The heater consists of an electrical resistance coil filament which is insulated from a support and heat shield enclosure. The thermal mass of this system is also low; hence the cesium pressure can be adjusted quite rapidly.

The cesium is distilled into this reservoir and the reservoir tube is then pinched off to remove the glass vial from the active system. The titanium acts as a getter and can be activated at any time during converter operation.

Emitter Heater - The emitter heater is a 0.375-inch diameter, eight coil, bifilar wound, electrical resistance radiant filament made of clean and annealed 0.070-inch diameter tungsten wire. The filament will operate at about 2430°C to supply the required heat flux to produce 4 watts/cm² at 1500°C emitter temperature. The heater is discussed further in Section IV.

Emitter Heatshields - A triple set of tantalum heatshields will be used to reduce end heat losses, enhance generator efficiency, and reduce the emitter temperature gradient in the axial direction.

Temperature Instrumentation - Temperatures will be measured using sheath (Figure 3), bare wire (Figure 4), and aluminum oxide plasma-sprayed C-A and W-W/Re thermocouples:
Emitter - three 0.014-inch diameter W-W/26 per cent Re sheath thermocouples
Collector reservoir - two 0.014-inch diameter C-A sheath thermocouples
Inner Tube - three W-W/26 per cent Re plasma-sprayed thermocouples

Other critical areas (seals, weld joints, etc.) will be instrumented using bare wire thermocouples.

B. Generator Fabrication

The design of the thermionic generator includes a variety of fabrication considerations. The critical fabrication and assembly procedures are specified on the working drawings. These procedures are specified in the thermionic generator design or are standard procedures at Pratt & Whitney Aircraft:

1) All materials used in converter fabrication are ordered according to rigid specifications.

2) All parts are vacuum-outgassed at temperatures necessary to provide optimum cleaning of each particular material without incurring deleterious effects such as excessive grain growth. These operations are so scheduled during subassembly that interferences caused by dissimilar materials are avoided.

3) After any part or subassembly has been vacuum-outgassed, it is kept in an inert atmosphere container to avoid atmospheric contamination.

4) All welds as well as brazes are processed in controlled atmospheres or in vacuum.
5) The completed converter is outgassed in a vacion pumping system to avoid contamination by pumping system oils at temperatures higher than those achieved during operation.

6) The cesium is distilled into the cesium reservoir and the cell is pinched off.

7) The cell is x-rayed to determine the concentricity of the emitter and collector.

C. Heat Transfer Analysis

A heat transfer analysis was performed as part of the design study to define the following:

1) Temperature map of converter body
2) Collector heat rejection system
3) Cesium temperature control system

A temperature map is needed to determine the operating temperature conditions of critical materials and joints and to define the emitter temperature gradient.

The results of this study show that the seals will operate at a reasonable temperature and that simple heating technique can be used to control the temperature of both the collector and cesium reservoirs.

The temperature map produced by a heat transfer computer program is shown in Figure 5. The basic input used for this computer-programmed temperature map is outlined below.

1) The thermionic performance calculation was based on the data presented in Section D, Performance.
2) The coil section of the emitter heater filament was considered to be a constant temperature cylinder. The power leads attached to this cylinder were considered in this analysis.

3) The emitter heat efflux included radiation, conduction, and electron cooling. The conduction through the cesium gas is small (about 1 w/cm²) and was neglected for the temperature map calculation.

4) Joule heating was considered in all current-carrying members. Current values were based on optimum power output at the optimum output voltage.

5) The heater filament temperature was precalculated as that required to produce a 1500°C emitter temperature with its corresponding heat efflux, and then used as a boundary condition.

6) The electrical lead temperature was selected from observations under similar operating conditions to determine a boundary condition for this conductive heat loss term.

7) The heat shield temperature was precalculated by a heat balance with estimated tube end conditions.

8) The collector cylinder temperature was used as a boundary condition. Gradients in an axial and radial direction were precalculated based on optimum heat flux conditions.

The collector heater and cooling fin design was also analyzed to determine the size of radiation area and heater input required to produce the desired range of collector temperatures for various emitter temperatures. The four boundary conditions chosen to size the fin and heater were:

<table>
<thead>
<tr>
<th>Emitter Temperature</th>
<th>Collector Temperature</th>
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<tbody>
<tr>
<td>1500°C</td>
<td>760°C</td>
</tr>
<tr>
<td>1500°C</td>
<td>670°C</td>
</tr>
<tr>
<td>1200°C</td>
<td>650°C</td>
</tr>
<tr>
<td>1200°C</td>
<td>540°C</td>
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</table>

It was found that a 2.6-inch length fin of copper coated with a high emissivity (0.8) material was required for a six-fin arrangement. The 1500°C emitter temperature - 670°C collector temperature boundary condition established these maximum requirements.
With this configuration it was found that a heater input to the collector of 115 watts was required to maintain the 1200 °C emitter temperature - 650 °C collector temperature condition. All other conditions of interest required less heat input.

The factors considered in the calculation of the required heat dissipative capacity of the fin array included:

1) Assumed sink temperature of 20 °C.
2) A view factor correction for the fin radiation term.
3) Heat rejection from the exposed parts of the collector cylinder.
4) Heat input to fin from collector which was based on:
   a) Heat radiated from emitter to collector.
   b) The net electron heating effect as a result of electron cooling of the emitter minus the electron cooling of the collector.

The collector heater design shown in Figure 1 can produce 180 watts of heat input to the collector.

The cesium reservoir heater was sized in a similar fashion. This heater was designed to produce a temperature in excess of 760 °C on the cesium reservoir tube. This high temperature is required to activate the titanium sponge getter. Without auxiliary heat input the reservoir would operate at 200 °C.

D. Performance

Analysis of the thermionic performance of the generator indicates that a power density in excess of 4.4 watts/cm² is expected at 1500 °C emitter temperature. The efficiency at this operating condition was 11.2 per cent based on the power delivered to the electrical leads divided by the heat flux delivered to the emitter. The heat flux calculations included electron cooling, radiation, conduction through the structure and cesium vapor, and joule heating of the emitter and collector.

The predicted power density value was derived from test data (Figure 6) from several cylindrical converters utilizing tungsten-25 per cent rhenium emitters. The predicted output of the generator should be slightly higher than the 4.4 watts/cm² shown by this graph for the following reasons:

1) Careful design of the generator has reduced the axial temperature gradient in the emitter.
2) The collector temperature for the test data was 40°C lower than the optimum collector temperature.

Optimization of these two effects should increase the power density at 1500°C emitter temperature to 4.7 watts/cm$^2$ with a resulting overall thermal efficiency of 12 per cent.

Optimum cesium reservoir temperature as a function of emitter temperature for the generator design is shown in Figure 7. Optimum collector temperature versus cesium reservoir temperature is shown in Figure 8 for a nickel collector. The expected voltages at the optimized power condition will range from 0.15 volt at 1200°C to 0.45 volt at 1500°C.

A summary of the predicted performance and thermal losses for the optimized power output condition at 1500°C emitter temperature is:

<table>
<thead>
<tr>
<th>thermal losses</th>
<th>value</th>
</tr>
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<tbody>
<tr>
<td>electron cooling</td>
<td>475 watts</td>
</tr>
<tr>
<td>radiation</td>
<td>84</td>
</tr>
<tr>
<td>cesium conduction</td>
<td>25</td>
</tr>
<tr>
<td>structural conduction</td>
<td>84</td>
</tr>
<tr>
<td>Joule heating</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>669.5 watts</td>
</tr>
<tr>
<td>power delivered to leads</td>
<td>78.5 watts</td>
</tr>
<tr>
<td>voltage at leads</td>
<td>0.435 volts</td>
</tr>
<tr>
<td>efficiency</td>
<td>12.0 per cent</td>
</tr>
</tbody>
</table>
IV. HEATING TECHNIQUES

The proper evaluation of thermionic generators designed for use in a high-temperature liquid-metal circuit requires that a heating method be used which simulates the effects of liquid-metal heating on a thermionic generator. The excellent heat transfer properties of the liquid alkali metals necessitates a careful selection and design of a heating method to achieve an adequate simulation.

Of course, direct heating of thermionic generators on a pumped liquid-metal loop would most closely approximate the actual conditions expected on a practical system. However, since the temperatures involved (1500°C) are beyond the state-of-the-art capabilities of present liquid-metal loops, a study was conducted to determine whether a proper generator evaluation could be conducted using state-of-the-art methods.

The high heat transfer rates, small temperature gradient, and thermal stability expected in liquid metal-heated systems were those characteristics which were desired to be properly simulated in this study. Several techniques were examined for heating the cylindrical diodes used in this program in which consideration was given to long life, simulation of the proposed use, and controllability. Electrical, liquid metal, solar and chemical fuel methods were considered for use. Of these, only electrical heating was found to be simple, relatively inexpensive, reliable, and amenable to accurate measurement of power input.

Liquid-Metal Heating

An evaluation of the feasibility of heating converters by a liquid-metal system can probably be conducted in the most straightforward manner by heating the converters on a liquid-metal loop. To meet the goals of this program, liquid-metal loops capable of operating at temperatures to 1500°C would be required. Although these systems are within the realm of feasibility, much development work is required before this heating method can be considered as a state-of-the-art working tool. It is, however, not particularly convenient to measure the heat flux to a thermionic generator on a liquid-metal loop and, unless many generators were arranged in a practical configuration on a pumped loop, the overall performance and efficiency of these generators would be difficult to determine. In addition, the cost of providing, operating and maintaining a number of systems for evaluation of several separate diodes is less than attractive if other convenient methods can be found to simulate liquid-metal heating.
Chemical Fuel Heating

Combustion devices have been shown to have the capability of providing the required temperatures and heat fluxes needed to meet the requirements of this program. At present, however, these devices have relatively short life and poor controllability.

Solar Heating

Solar heating of cylindrical diodes would require the use of some indirect heat transport mechanism such as a liquid-metal circuit. Although this system should provide an excellent simulation of the problems, the same type of development and measurement problems discussed above would require solution. This method is not applicable for continuous, extended life testing.

Electrical Heating

Electrical heating has been classically used for numerous devices such as furnaces and test equipment where controllability and clean atmosphere were prime requisites. There are several methods of electrical heating deserving of consideration. These are, 1) induction heating, 2) arc radiation and arc image heating, 3) electron bombardment, 4) direct resistance heating, and 5) radiant resistance heating.

There are several factors which must be considered in the selection of electrical heating methods:

A) Design
   1) Simplicity
   2) Ruggedness
   3) Adaptability
   4) Ease of fabrication
   5) Ease of replacement
   6) Power density limitation
   7) Size
   8) Cost
   9) Re-useability
  10) Safety

B) Operational Use
   1) Long life
   2) Reliability
   3) Controllability
4) Heat flux distribution to diode
5) Accuracy of power input measurements
6) Magnitude of current and voltage requirements

C) Effects on Test
1) Influence on converter performance
   a) Magnitude and character of electromagnetic fields
   b) Magnitude of thermal end losses
2) Influence on converter instrumentation readings

D) Heater Accessory Equipment Requirement
1) Power supply
   a) Reliability
   b) Cost
   c) Availability
2) Heater instrumentation and controls
   a) Reliability
   b) Accuracy
   c) Cost
   d) Availability

Induction Heating
This method is not particularly suitable for heating thermionic generators. Induction supplies are difficult to control and are not particularly amenable to use over extended periods. The design of a converter to use induction heating would require compromises that would seriously impair the performance that could be expected in a practical application. The stray fields associated with this type of heating would cloud the ability to determine the magnitude and location of the heating in the converter, particularly the collector. These fields may also affect the performance through interaction with the plasma.

Arc Image and Arc Radiation Heating
Arc image heating of cylindrical converters would, like solar heating, require an indirect heat transfer method. In addition to this problem, stable, long lasting arcs are difficult to achieve and considerable thermal cycling could be expected using this method. The latter is true of radiation heating with high current arcs. Electrode erosion is difficult to control and the arc stability necessary to provide continuous, constant heat flux is difficult to achieve.
Electron Beam Heating

This type of heating provides a method of delivering large quantities of thermal energy to an emitter and is recommended for the heating of cylindrical converters producing high currents at temperatures in excess of 1800°C. Equipment has been developed which can provide suitable temperature control of the same quality that can be achieved with electrical resistance heating. Although this method of heating is acceptable, some precautions in design and operation must be recognized to insure that stray leakages do not perturb accurate recording of generator output, and that adverse "runaway" or unstable heating conditions do not develop. A treatment of these problems is contained in Appendix A. Several other precautions are listed below:

1) Safety precautions
   a) Vacuum - high voltage interlock
   b) Power supply door interlock
   c) Shielded cables
   d) Well grounded system

2) Electron leakage - If the heater section is not properly shielded from the generator section, heater filament leakage can cause erroneous generator output results.

3) Power supplies - An additional power supply is required to impress an accelerating voltage between the filament and emitter.

4) The aging effect on the work function of the filament will cause a change in heat input conditions with time. The advantage of a constant heat flux at open-circuit condition is that it provides a method of checking emitter temperature instrumentation fluctuations with time.

5) Measurement of heat flux to emitter becomes more complex.

6) A distortion of the electrical field due to thermocouples or heat shields can cause localized concentration or diffusion of the electron beam.

It can be seen that the advantage of the increase in available heat flux is offset by safety factors, cost, complexity, and reliability when this system is compared with the radiation filament methods discussed later. However, since this method of heating does fill the heating requirements for the present program, a design guide for cylindrical electron beam heaters, has been included in Appendix A.
Direct Resistance Heating

Direct resistance heating of the liquid-metal containment tube of a cylindrical converter requires that either very thin wall tubing or very high currents be used. For a converter designed in a configuration appropriate for liquid metal heating, Figure 1, with a liquid metal tube wall thickness of about 0.020 inch, the current required would be approximately 800 amperes. The large current associated with this type of heating dictates the use of a coaxial return of the current through the tube to cancel the magnetic field external to the tube. In addition, a large current capacity, low voltage power supply is required. Direct current supplies of this size pose problems in control, regulation and long term stability.

Alternating current supplies at these low voltages and high currents present instrumentation pickup problems and have, to a lesser degree, the same control and regulation problems as DC supplies. Large, heavy, vacuum-tight current feed-throughs are required to penetrate the converter vacuum test facility. To minimize axial temperature variation in the directly heated tube, the end-connection configuration must be optimized to reduce axial heat flow from that portion of the heater adjacent to the emitter. The resultant relatively large heater end connection, the I^2R conduction and lead-in losses, cause a sizable heat dissipation problem within the test stand. Differential expansion between the tube and inner conductor requires that one of the input-lead connections be flexible. In the event of a heater failure resulting from an open circuit, repair would be difficult.

Radiant Resistance Heating

Radiant resistance heating can be accomplished by three methods:

1) Straight wire filament
2) Tubular filament
3) Coiled filament

A typical hairpin type filament used for converters is shown in Figure 9. The disadvantages of this type of heater are:
1) The radiation area of the filament is small. The use of abnormally high filament currents and temperature is necessary to provide the required heat flux.

2) The radial temperature distribution is poor.

3) This design has experimentally been shown to be not structurally stable.

4) The high filament temperatures required lead to material evaporation and short filament life.

A tubular heater has been used at Pratt & Whitney Aircraft for a variety of purposes. Two major features of this design are:

1) Severe longitudinal temperature variation. Heat losses to the massive end-connections are difficult to correct.

2) Extremely high currents produce sizable electromagnetic fields which could interfere with converter performance.

The problems associated with this method are similar to those discussed previously with direct resistance heating of the liquid-metal tube.

The coiled filament combines several of the best features of the hairpin and tubular filament in that it has flexibility with respect to thermal expansion and a large radiating area. It meets the requirements, as previously indicated, of a heat source for a thermionic generator emitter. The following filament designs have been tested.

1) Evenly spaced coil (Figure 10)

2) Unevenly spaced coil (Figure 11)

3) Axial return coil (Figure 12)

4) Bifilar coil (Figure 12)

These filaments have been tested on converters having emitter areas between 9 and 14 square centimeters and have been used to produce emitter temperatures in excess of 4000°F. The present filament coils are made from clean, annealed tungsten wire of 0.070 to 0.090-inch diameter to assure rigidity, long life, low voltage and controllable characteristics.

The open-circuit temperature distribution using an evenly spaced coil in a 5/8 inch diameter 0.020-inch wall tantalum emitter is shown in Figure 13. Heat shields were not employed in this test. Later tests showed that a three-fold improvement in the temperature pattern was produced after the installation of heat shields.
A similar graph, Figure 14, illustrates the improvement in open-circuit temperature distribution through use of an unevenly spaced coil filament. This graph also shows the changes in temperature pattern for non-open circuit conditions. The change shown is caused by significant electron cooling at the center of the emitter as the average emitter temperature is held constant.

The magnetic field effect as a result of filament currents in excess of 100 amperes can affect generator performance for these single pass coil filament designs.

This magnetic field effect was studied by examining heaters of three types:

1) Evenly spaced coil
2) Axial return coil
3) Bifilar coil

Measurements were made of the axial and circumferential magnetic field for all three heaters. The field strength was measured by placing the probe of a sensitive gauss meter at selected radial distances from the centerline of the heater. The results shown in the table below indicate that axial return and bifilar filaments have very low disturbing electromagnetic fields and have the additional advantage of single end coupling.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Evenly Spaced Coil</td>
<td>10.3</td>
<td>16.6*</td>
<td>21.5</td>
<td>24.7*</td>
</tr>
<tr>
<td>Axial Return Coil</td>
<td>5.5</td>
<td>9.6**</td>
<td>1.7</td>
<td>1.8**</td>
</tr>
<tr>
<td>Bifilar Coil</td>
<td>1.7</td>
<td>8.0*</td>
<td>1.0</td>
<td>1.8*</td>
</tr>
</tbody>
</table>

*Lead end
**Opposite lead end
***For heater current of 100 amperes
The characteristics of the bifilar filament type of heater represent an optimum combination of the previously listed heater criteria. It is simple, rugged, compact, easy to manufacture and inexpensive. It is easily installed or replaced without disturbing the converter, circuitry or instrumentation. The inner converter tube can be readily instrumented with thermocouples and the accuracy of converter performance is not affected by direct current heater operation. The input heater power can be accurately measured and controlled. The end losses can be made small through the use of simple heat shields, and the magnetic fields developed have little effect on diode performance. Converters can be heated uniformly at high power densities up to inner tube temperatures of 2200°C. These heaters have proven to be reliable and give long lasting, trouble free operation at emitter temperatures up to 1800°C.

Radiant resistance electric heaters have been used extensively for powering cylindrical thermionic converters. These heaters have been reused as many as eight times, cycled twenty-five times from room temperature to 3000°F (emitter temperature), subjected to severe thermal shock (as great as 3000°F/minute) and have been used under cyclic temperature conditions for periods in excess of 1000 hours. Of all the filament heaters used, none has failed during operation after the first twenty hours of life.

A complete description of a heater design method using the bifilar filament is given in Appendix B.
APPENDIX A

Design of a Cylindrical Electron Beam Heater
APPENDIX A

Design of a Cylindrical Electron Beam Heater

An electron beam heater can provide the very high heat fluxes required to operate a high temperature cylindrical thermionic generator. When emitter operating temperatures of 1800 °C or higher are used, excessively high filament temperatures are required at the radiant resistance heater for prolonged use. Since an electron bombardment heater requires a heater surface for electron emission, advantage can be taken of the development of heaters for use with lower temperature converters. The bifilar tungsten filament is recommended for this application for the identical reasons offered for its use as a prime heat source. In fact, much of the heat flux is provided by radiant heating with the additional needs supplied through electron bombardment.

Some additional design and operation criteria are recommended and listed below:

1) The heater should always be operated in the space charge limited mode. This precaution is needed to insure that a runaway condition stemming from thermal feedback from the target does not develop.
2) Pure filament materials (non-thoriated tungsten) should be used to insure against current surges and thermal cycling of the target.
3) All high vapor pressure materials must be removed from the system to prevent high voltage arcing and plating on the cold high voltage connections.

For purposes of simplicity, the bifilar filament will be assumed to be a solid cylinder. It has been shown that the space charge limited current of a configuration with long concentric cylindrical electrodes is

\[ i = 14.7 \times 10^{-6} \frac{\ell V^{3/2}}{r_a \beta^2} \text{ amps} \quad (1) \]

where
- \( \ell \) is the length of the cylinders
- \( r_a \) is the outer cylinder radius
- \( r_K \) is the inner cylinder radius
- \( V \) is the accelerating voltage
- \( \beta^2 \) is a function of \( \frac{r_a}{r_K} \) as shown in Figure 15
The power input per unit length to the outside cylinder is then

\[ P = \frac{i}{\lambda} \quad V = 14.7 \times 10^{-6} \quad \frac{V^{5/2}}{r_a \beta^2} \quad \text{watts/unit length} \quad (2) \]

A plot of the above equation for various values of \( V \) is shown in Figure 16 with \( \beta^2 \) assumed to be 0.767 and \( r_a = 1/2 \) inch. For significant changes in the configuration, a new curve should be made using Equation (2).

From Figure 16 the user simply estimates the necessary accelerating voltage for a desired power input. The total current requirements are then obtained from the familiar relation

\[ I = \frac{P}{V} \]

It now becomes important to determine what conditions are necessary to obtain space charge limited conditions. Figure 17 can be used to determine the necessary minimum electron emitter operating temperature for effective emitting areas corresponding to a wire diameter of 0.100 inch.

This curve was obtained by combining Equation (1) with Dushman's equation

\[ J = A_o T^2 e^{-b_0} \quad \text{amps/meter}^2 \quad (4) \]

where for tungsten, \(^1\)

\[ A_o = 60.2 \times 10^4 \]

\[ b_o = 52,400 - 11,600E_W, \quad E_W = 4.52 \]

\[ T = \text{emitter temperature, } ^\circ \text{K} \]

The horizontal lines correspond to temperature-limited emission as obtained by multiplying Equation (4) by the effective emitting area. The space charge limited line corresponds to Equation (1) with the appropriate \( \beta^2 \) and \( r_a \) of 1/2 inch.

The following is an example illustrating the use of these curves.

From the accompanying diode power input vs emitter temperature curve we know that we need a power input of 550 watts/inch to reach an operating temperature of 3000°F for a diode with an internal diameter of 1 inch and 2 inches in length.

\(^1\)Review of Modern Physics, J. A. Becker, 1935
What are the power supply requirements and minimum emitter operating temperature?

1) From Figure 17 for a $P/\ell$ of 550 watts/inch it is seen that we need an accelerating voltage of approximately 825 volts.

2) Figure 16 indicates an operating temperature in excess of 4200°F for a tungsten emitting area is required corresponding to a wire 0.100 inch in diameter.

3) Figure 16 also indicates that at an accelerating voltage of 825 volts, $i/\ell = .9$ amp/inch is required. The power input to the diode is then

$$P/\ell = V \cdot i/\ell = 825 \times 0.9 = 742 \text{ watts/inch}$$

The original assumption included, however, a design power of 550 watts/inch. The discrepancy between Figure 16 and Figure 17 is due to the difference in $\beta^2$ and therefore operation will be conducted at lower accelerating voltages and currents than initially indicated.

4) The total required current becomes, at most,

$$I = \frac{i}{\ell} \times \ell = .9 \times 2 = 1.8 \text{ amps}$$
5) To specify the regulation of the power supply the diode power input vs emitter temperature curve must be considered. The point within the operating temperature range where the slope is a minimum should be used to determine the approximate regulation requirements. For example, consider the minimum slope point to be between 2500 and 3000°F. If the power requirements at these points are 460 and 550 watts/inch respectively, Figure 17 indicates operating voltages of 750 and 820 volts. So

\[
\frac{\Delta V}{\Delta T} = \frac{820 - 750}{3000 - 2500} = 0.14 \text{ volts/}^\circ\text{F}
\]

Now if we are interested in holding the emitter temperature to within ±10 per cent or ±30°F we must be able to hold the voltage to within

\[(0.14 \text{ volts/}^\circ\text{F}) \times (±30^\circ\text{F}) = ±4.2 \text{ volts}\]

The regulation, \(R\), is then

\[R = \frac{±4.2 \times 100}{185} = ±.54 \text{ per cent}\]

6) For a constant load situation, the above example would specify the line regulation. However, the recovery time of the power supply might be an important factor in specifying load regulation, since the recovery time should always be much less than the thermal response time of the test specimen.

If the thermal response time of the test specimen is known, the attached table may be used to find the necessary type of regulation equipment

<table>
<thead>
<tr>
<th>Control Type</th>
<th>Approx. Recovery Time</th>
<th>Approx. Load Regulation, %</th>
<th>Cost Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Reg.</td>
<td>2 seconds</td>
<td>1.0</td>
<td>Base cost</td>
</tr>
<tr>
<td>Control Rectifier</td>
<td>50-100 mili sec.</td>
<td>0.01</td>
<td>B.C. + 20%</td>
</tr>
<tr>
<td>Magnetic Amplifier</td>
<td>100-150 mili sec.</td>
<td>0.5</td>
<td>B.C. + 20%</td>
</tr>
<tr>
<td>Series Regulation</td>
<td>100 micro sec.</td>
<td>0.1</td>
<td>B.C. + 40%</td>
</tr>
</tbody>
</table>
7) In the case where current-voltage maps are to be made, the supply sees a variable load, so that the recovery time must be much less than the scan time of any loading equipment used to map the diode output. Again the above table can be used to specify the type of control and estimate the corresponding regulation.
APPENDIX B

Design of a Cylindrical Electrical Resistance Radiant Heater
APPENDIX B

Design of a Cylindrical Electrical Resistance Radiant Heater

The method selected by Pratt & Whitney Aircraft to heat cylindrical thermionic generators operating at emitter temperatures of less than 1800°C is an electrical resistance radiant heater. A tungsten bifilar coil filament was chosen as a result of the following considerations:

1) A coil filament is characterized by a large radiating area and retains the necessary flexibility for thermal expansion.
2) The filament should be constructed of a high temperature material which is easily fabricated into the desired coil configuration.
3) A low voltage heat source is desirable to minimize the possibility of leakage currents to the generator and generator instrumentation. This suggests the need of large heater current.
4) A bifilar coil was chosen to minimize magnetic effects.
5) Adequate heat shields must be employed to reduce radiation end losses and insure uniform emitter temperatures.

After the design configuration is established, the maximum required heat flux must be determined for the particular generator design. This heat flux will then be used to determine the filament temperature and an estimate of heater life.

The maximum required heat flux $Q_1$ must be evaluated at the maximum emitter temperature and consists of the following terms.

1) Radiation from the emitter to the collector.
2) Cesium conduction from emitter to collector. This heat loss is usually less than 1 watt/cm² of emitter area.
3) Conduction losses through the end of emitter tube.
4) Radiation losses through the filament heat shields.
5) Maximum electron cooling heat loss.

Knowing $Q_1$, the heat rejected by the filament can be written as:

$$Q_1 \propto \sigma \left[ \frac{1}{1} \right] \frac{1}{1 + \left( \frac{e_2}{e_1} - 1 \right)} A_1 \left( T_F^4 - T_E^4 \right)$$

(1)
\( \sigma \) = Stefan - Boltzmann constant  
\( \varepsilon_1 \) = filament emissivity  
\( \varepsilon_2 \) = emissivity of emitter inside surface  
\( A_1 \) = effective surface area of filament  
\( T_F \) = filament temperature  
\( T_E \) = emitter temperature

This equation can be used for a reasonable approximation of the filament temperature if \( A_1 \) is known and if the radiation end losses through the filament heat shields are small compared to the total heat flux.

For the purpose of this calculation the area of a cylinder of 1/8-inch smaller diameter than the inside diameter of the emitter tube and 1/4-inch longer than the emitter length can be used to approximate \( A_1 \). As can be seen from Equation (1) a fairly large error in the selection of the area will not have a great effect on the value of the filament temperature.

After solving Equation (1) for the filament temperature, the life of the filament can be determined for any given filament wire diameter, using tungsten evaporation data.

A more detailed examination of the heater configuration is necessary to simplify the determination of the wire length, wire diameter, coil length and coil diameter. The basic limitations imposed on the coil design are:

1) The minimum wire diameter should be greater than 0.040-inch diameter to provide structural rigidity for high temperature operation.  
2) The minimum coil spacing should be 0.050-inch to avoid shorting problems. The coil spacing can be made equal to the wire diameter for ease in fabrication.  
3) The coil diameter should be made as large as possible for maximum radiation area to bring about long life at lower filament temperatures. A minimum spacing of 0.050 inch between coil outside diameter and emitter inside diameter is recommended for converters having L/D ratios of less than three, to reduce the possibility of shorting the heater and the emitter.  
4) The coil axial length should be slightly larger (0.1 inch) than the emitter axial length to provide for uniform emitter temperatures.
Since the coil length, coil diameter, and coil spacing are confined for a particular converter design, the wire diameter will be the most effective variable in matching the filament to the power supply.

For the generator design shown in Figure 1 a wire diameter \((d)\) of 0.080 inch was chosen. The coil length \(L\) was selected as indicated in Item 4 above and the coil diameter \(D\) was designed to be \(1/8\) inch less than the inside diameter of the filament. The wire length \(S\) can be determined by the following equation:

\[
S = \sqrt{L^2 + n^2 \pi^2 D^2}
\]  

(2)

Where \(n\) = number of coils

Figure 18 is a graph of the resistivity \(\rho\) of tungsten versus temperature. Using this figure and the wire length the resistance \(R\) can now be calculated:

\[
R = 4\rho S / \pi d^2
\]  

(3)

This resistance can now be used to determine the current-voltage characteristics of the filament power supply by the following relations

\[
Q_1 = I^2 R = IV
\]

As indicated previously the voltage should be kept low to avoid leakage problems and the current should not be excessively high to eliminate the need for bulky input leads. In addition to these criteria the availability of a power supply possessing particular current-voltage characteristics may influence the choice of filament operating conditions.

Summary of Calculations for Heater Shown in Figure 1

Heat Flux

Radiation from emitter to collector

\[
q_r = \frac{1}{\varepsilon_E} + \frac{AE}{A_c} \left( \frac{1}{\varepsilon_c} - 1 \right) \left( T_E^4 - T_c^4 \right) = 83.6 \text{ watts}
\]

Cesium conduction from emitter to collector

\[
q_c = H(P, S) (T_E - T_c) = 25 \text{ watts}
\]
Conduction end losses along emitter tube

\[ q_c = \frac{KA}{L} (T_E - T_{E,E}) = 83.9 \text{ watts} \]

Radiation to filament heat shields

\[ q_r = \frac{\sigma A_1 (T_{S1}^4 - T_{S2}^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} = 30.1 \text{ watts} \]

Maximum electron cooling

\[ q = I \left( \Phi_E + \frac{2KT_E}{q_e} \right) = 870 \text{ watts} \]

\[ \Omega_1 = 1093 \text{ watts} \]
\[ T_F = 2770^\circ \text{K} \]
\[ S = \sqrt{L^2 + n^2 \pi^2 D^2} = 9.52 \text{ inches} \]
\[ R = \frac{4\Omega S}{\pi d^2} = .0678 \Omega \]
\[ I = \sqrt{\frac{\Omega}{R}} = 126.4 \text{ amps} \]
\[ V = 8.57 \text{ volts} \]
APPENDIX C

Figures
THERMIONIC GENERATOR

- Emitter Lead
- Compression Seal
- Collector Heater
- Collector
- Cesium Reservoir
- Trilayer
  W - 25% Re Emitter
  BeO Insulation
  Ta - 10% W Inner Tube
- Cesium Heater
- Collector Lead
Figure 2

Compression Seal
MINIATURE W-W/RE SHEATH THERMOCOUPLES INSTALLED IN TRILAYER ASSEMBLY

XP-31678
BARE WIRE W-W/RE THERMOCOUPLES USED ON TRILAYER ASSEMBLY

XP-27346

Figure 4
POWER DENSITY VS EMITTER TEMPERATURE FOR 8-MIL SPACING TUNGSTEN - 25 PER CENT RHENIUM ALLOY EMITTER

Figure 6
OPTIMUM CESIUM RESERVOIR TEMPERATURE VS Emitter TEMPERATURE

Figure 7
OPTIMUM COLLECTOR TEMPERATURE VS CESIUM RESERVOIR TEMPERATURE

Figure 8
Figure 9

STRAIGHT WIRE FILAMENT
EVENLY SPACED COIL FILAMENT
REDUCED MAGNETIC FIELD COIL FILAMENTS
A-BIFILAR HEATER FILAMENT
B-AXIAL RETURN HEATER FILAMENT
AXIAL TEMPERATURE DISTRIBUTION
FOR EVENLY SPACED COIL

Figure 13
AXIAL TEMPERATURE DISTRIBUTION
FOR UNEVENLY SPACED COIL

To EMITTER
Ni COLLECTOR
15 - MIL SPACING
DATA AT
OPEN-CIRCUIT
CONDITION

Figure 14
CONFIGURATION FACTOR FOR RELATIVE ELECTRODE RATIOS

Figure 15
EMISSION vs ACCELERATING VOLTAGE

$\bar{W} =$ WIRE
$\gamma_0 =$ 0.5 INCH
$\gamma_r =$ 0.10 INCH
$\beta^2 =$ 0.767

Figure 16
SPACE CHARGE LIMITED OPERATION

POWER VS ACCELERATING VOLTAGE

\[ \gamma_a = 0.5 \]
\[ \beta^2 = 1.0 \]

Figure 17
RESISTIVITY OF TUNGSTEN VS TEMPERATURE

Figure 18