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LIQUID METAL-HEATED SPACE RADIATOR-MOUNTED
THERMIONIC GENERATOR

Technical Documentary Report No. APL TDR 64-121

October 1964

Air Force Aero Propulsion Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base

Project No. 8173, Task No. 817305-25

(Prepared under Contract AF33(657)-11320
by the Pratt & Whitney Aircraft Division
of United Aircraft Corporation, East
Hartford, Connecticut; F. C. Harter, author)

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FOREWORD

This report presents a description of work performed from 1 July 1963 through 30 June 1964 by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford, Connecticut, for the AF Aero Propulsion Laboratory of the United States Air Force, under Contract AF33(657)-11320, Project No. 8173, Task No. 817305-25. The work was administered under the direction of Lt. David Raspet of the AF Aero Propulsion Laboratory, Flight Vehicle Power Branch. The Pratt & Whitney Aircraft number assigned to this report is FWA-2369.

ABSTRACT

Pratt & Whitney Aircraft has conducted a program for the Air Force under Contract AF33(657)-11320 to evaluate thermionic generators in a configuration appropriate for liquid metal heating at temperatures up to 1500°C. The thermionic generator evaluated was cylindrical and consisted of a nickel collector surrounding a trilayer emitter structure. The trilayer structure consisted of a tantalum-tungsten alloy tube, which could contain the liquid metal, surrounded by a concentric insulating beryllium-oxide tube and a tungsten-rhenium alloy emitter tube.

The generator met or exceeded the performance goals of the program. At an emitter temperature of 1500°C, the power density measured was 50 per cent greater than the design objective of 4 W/cm², and the measured efficiency matched the goal of 10 per cent. The power density of 1.07 W/cm² at 1195°C exceeded the performance goal of 1 W/cm² at 1200°C.

The generators were tested under conditions which simulated liquid metal heating and radiation cooling of the generators. Strong electronic and thermal interrelations were observed during these tests. Significant discontinuities were found in the current-voltage relationship and a thermal quasi-instability was observed resulting from variations in the electronic heating of the collector. In addition, electronic cooling of the emitter produced a significant axial temperature variation which depended on the method of applying the load. This axial temperature variation produced axial variations in the emitter work function. The average work functions of the emitter and collector also varied with the generator voltage in the regions of high generator current (ion-rich regions).

The trilayer emitter assembly maintained its electrical insulating properties, but the thermal resistivity varied from 2.5 to 10° C/W_{thermal}/cm². To attain adequate heat flux through the trilayer assembly, high central tube and heater temperatures were required. These led to test system difficulties which subjected the generator to major thermal cycling from operating to room temperature. Other thermal cycling (from open circuit to power producing conditions) and the major thermal cycling induced fatigue in the ceramic seals which limited the life of the generators.

Evaluation of generators connected in series indicated that no unusual effects occur.

A generator test station and two generators were delivered under this program.

Publication of this technical documentary report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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I INTRODUCTION

One concept of proposed thermionic powerplants is the use of circulating liquid metal as a heat transfer mechanism from the heat source to the direct-energy conversion system. The heat for such a system could be furnished by a nuclear, isotope, or solar source. The liquid metal must deliver the heat energy to the thermionic converters at a high temperature level to produce significant power. Hence the energy conversion portion of the system lends itself to tubular construction with a number of cylindrical thermionic generator units mounted on one tube. These generators are connected in electrical series to produce a reasonable voltage and avoid excessive lead losses which high current operation would incur. A special design requirement for such a system is that the series-connected generators must be electrically insulated from the common potential of the central liquid metal containment tube and thermally-bonded to this same tube. Provision must also be made to reject heat from the collector. For space applications, a particularly straightforward method is through direct radiation from radiator fins attached to the collector and from the collector surface itself.

The design and fabrication of a generator incorporating electrically insulating layers (a trilayer) capable of being used in a 1500°C liquid metal system required an advance in the state of the art. At the start of the program, little development work was reported for cylindrical thermionic generators or trilayer assemblies designed for 1500°C. An attempt to provide a trilayer electric heater for liquid metal loops was reported, but there was no indication that satisfactory results were obtained¹. Hall, et al² were developing a trilayer assembly for a thermionic generator designed to operate at 1200°C. Prior to the program, Pratt & Whitney Aircraft had done some development of an efficient cylindrical thermionic generator and had conducted experiments on brazed and mechanically bonded trilayer assemblies at temperatures up to 1600°C. The experiments indicated that the efficiency of the brazed trilayer assembly was at least equal to if not better than that of the mechanically bonded assembly.

The subject program was conducted to experimentally evaluate thermionic generators suitable to be heated by a liquid metal at a temperature between 1200 and 1500°C. The specific objectives were to evaluate a particular thermionic generator at temperatures up to 1500°C, to investigate the performance of series-connected converters operating at different temperatures, and to determine the optimum heating techniques for prolonged, controlled operation of tubular thermionic generators.

II SUMMARY OF RESULTS AND CONCLUSIONS

Tubular thermionic generators were experimentally evaluated under conditions which simulated operation with a liquid metal heat source and a radiant heat rejection system. The generators met the efficiency design objective and exceeded the power output design objectives for the temperature range over which testing was conducted. The generators produced 1.07 W/cm^2 with an emitter temperature of 1195°C and 5.9 W/cm^2 with an emitter temperature of 1490°C . The measured thermal efficiency during operation at 1490°C was 9.7 per cent.

The trilayer structure had a thermal resistivity range of 2.5 to $10^\circ \text{C/W}_{\text{thermal}}/\text{cm}^2$ with the higher resistivity being exhibited immediately after a major thermal cycle between the operating temperature and room temperature. Continued operation at steady-state conditions lowered the resistivity to a level approaching that attained before a major thermal cycle. Thermal cycling from open-circuit to power-producing conditions caused an initial increase in thermal resistivity that also decreased to approximately the original value during continued steady-state operation. For useful powerplant operation, a resistivity of about $1^\circ\text{C/W}_{\text{thermal}}/\text{cm}^2$ is necessary, and hence, further development will be necessary. The trilayer structure maintained its electrical insulating properties throughout the test.

Strong interrelations between electronic and thermal characteristics were observed during the testing of the generators at steady-state conditions which would not have been observed if a sweep data-collecting technique had been used. Significant discontinuities were found in the current-voltage relationship and a thermal quasi-instability was observed resulting from variations in the electronic heating of the collector. In addition, electronic cooling of the emitter produced a significant axial temperature variation which depended on the method of applying the load. This axial temperature variation produced axial variations in the emitter work function. The average work functions of the emitter and collector also varied with the generator voltage in the region of high generator current (ion-rich regions).

Empirical analysis of two generators in series with mismatched emitter temperatures showed that a power density equivalent to the average of the maximum power densities for those emitter temperatures would be obtained when the temperatures of the cesium reservoirs and collectors were independently controlled for each generator providing the emitter temperature mismatch was not more than 100°C .

This generator requires further development to achieve long life, particularly to develop an ability to withstand thermal cycling. In this test program, a generator life of 234 hours was demonstrated. Further development is especially required on the seals and the trilayer assembly.

An evaluation of the most suitable methods for heating the emitter during testing was conducted. For this program a radiant electric heater consisting of a bifilar wound 0.090-inch tungsten filament was selected.

Two thermionic generators and a generator test station were acceptance tested and delivered.

III THERMIONIC GENERATOR DESIGN

The thermionic generators produced under the subject contract were required to be cylindrical and to incorporate a trilayer emitter assembly using a central tube with an inner diameter of at least 0.5 inch and made from either tantalum-10 per cent tungsten or tantalum-8 per cent tungsten -2 per cent hafnium. The emitter was required to have a surface area of at least 15 cm^2 and to be insulated from the central tube. In addition, performance goals were established specifying power densities of 1 W/cm^2 with an emitter temperature of 1200°C and 4 W/cm^2 with an emitter temperature of 1500°C . An efficiency goal of 10 per cent for an emitter temperature of 1500°C was established.

The thermionic generator designed to meet these requirements and goals is shown in Figure 1. The emitter is a tungsten - 25 per cent rhenium tube bonded to an insulating beryllia tube which in turn is bonded to the central tantalum alloy tube. Tungsten - 25 per cent rhenium was selected for the emitter because previous testing by Pratt & Whitney Aircraft of cylindrical generators indicated that this alloy could produce the power densities desired, and because its high recrystallization temperature and high strength indicated that it would be mechanically stable at temperatures up to 1500°C . A nickel collector was selected to provide good thermal and electrical conductivity. The relative thermal expansion coefficients of nickel and the tungsten-rhenium alloy used in the emitter were such that a practically constant emitter-collector spacing would be maintained over the anticipated operating temperature range. The emitter-collector spacing was 0.008-inch, which is the optimum spacing for a converter operating with an emitter temperature of approximately 1350°C .³ The relative position of the collector and emitter was maintained by tantalum end flanges and aluminum-oxide seals.

The radial section of the tantalum flanges was 0.010 inch thick to reduce thermal losses from the emitter. A tantalum boss was incorporated on the top flange for the emitter lead. Six copper fins were brazed to the collector to increase radiation cooling. The collector lead was attached directly to one of these fins. The cesium reservoir was made of nickel and was thermally isolated from and connected to the main body of the converter by a nickel tube with a 0.010-inch wall thickness. The cesium entered the generator through the center of the collector electrode.

The emitter assembly presented special design problems since the material separating the emitter from the central tube had to be a good electrical insulator, a good thermal conductor, and also be compatible with the adjacent materials. The problem of thermal compatibility is particularly difficult since a significant radial thermal gradient exists across the emitter assembly. The thermal gradient arises from the heat flux across the assembly, and this heat flux varies by a factor greater than two over the operating conditions experienced at a single emitter temperature. The candidate materials for the insulating material included aluminum oxide and beryllium oxide, and beryllium oxide was selected because of its relatively high thermal conductivity and because its coefficient of thermal expansion is between the coefficients of the tantalum and tungsten alloys used.

Regardless of the insulating material used, however, thermal strains will be introduced. Radial expansions may be accommodated in some designs, but the axial expansions and contractions will strain the bonds between the elements of the emitter assembly. It was therefore desirable to provide a method by which new bonds could be formed in the event that the original bonds were disrupted. Therefore, a 0.0035-inch thick high-temperature braze containing a significant quantity of zirconium was used between each of the emitter assembly elements. At operating temperatures, the diffusion of the zirconium is expected to promote rebonding. The "trilayer" emitter assembly, therefore, actually contains five layers: a 0.545-inch diameter tantalum - 10 per cent tungsten tube with a 0.020-inch thick wall, a 0.0035-inch thick layer of braze material, a 0.016-inch thick beryllium oxide cylinder, a second layer of braze material, and a 0.692-inch diameter tungsten - 25 per cent rhenium emitter tube with a 0.52-inch wall thickness.

IV THERMIONIC GENERATOR FABRICATION

The thermionic generators produced under the subject contract were fabricated from the parts shown in Figure 2. The materials used were as follows:

Tungsten - Rhenium Alloy Emitter

Minimum purity - 99.9 per cent

Rhenium content - 24.5 to 25.5 per cent

Beryllium-Oxide Insulator

Minimum purity - 99.8 per cent

Minimum density - 95.0 per cent

Tantalum - 10 Per Cent Tungsten Alloy Tube

Double electron-beam melted with the following maximum impurities:

Oxygen 100 ppm

Carbon 100 ppm

Nitrogen 100 ppm

Tantalum

Minimum purity - 99.9 per cent

Maximum impurities

Oxygen 150 ppm

Carbon 150 ppm

Nitrogen 200 ppm

Nickel

Minimum purity - 99.9 per cent

(equivalent to electronic Grade A)

Ceramic Seal

Alumina body minimum purity - 97 per cent

Copper - AMS 4500

Minimum purity - 99.9 per cent

Cesium

Minimum purity - 99.93 per cent

The detail parts were initially assembled, as shown in Figure 3, into the emitter trilayer, the collector, the cesium reservoir, and the seal subassemblies. The emitter trilayer subassembly consisted of the tungsten-rhenium emitter, the beryllium-oxide insulator tube, and the tantalum-tungsten central tube. Each of the components was chemically cleaned and then brazed together using Zimo 31, a high temperature molybdenum-zirconium brazing material developed at Pratt & Whitney Aircraft. Brazing was conducted at 1560°C for 30 minutes under a high vacuum to outgas the subassembly. The collector subassembly consisted of the nickel collector and the copper radiator fins. The fins were coated with a chrome spinel coating before being brazed to the collector to increase their thermal emittance. The collector was cleaned by being heated in hydrogen to 1125°C and then heated in a high vacuum at 1100°C. The fins were then brazed to the collector at 1100°C in a hydrogen atmosphere using a gold-nickel brazing material. The cesium reservoir subassembly consisted of a reservoir tube, a heat dam tube, and an end plug. All of these components were nickel. The subassembly was welded together and then cleaned by the hydrogen-vacuum heating cycle used for the collector. The seal subassembly consisted of the tantalum end flanges, the emitter power takeoff boss, and the aluminum-oxide compression seals. The end flanges were outgassed in a high vacuum furnace at 1750°C and the emitter power takeoff boss was subsequently electron-beam welded to the top end flange. The seal was formed by a molybdenum-manganese metallizing process. The two nickel flanges were then brazed with oxygen-free, high conductivity copper to the metallized ceramic at 1060°C in a hydrogen atmosphere. The copper braze area was nickel plated to retard the corrosive action of cesium. The nickel flange of the seal was resistance seam welded to the tantalum end flange under an argon atmosphere. The final dimensions and surface finishes of the electrodes were recorded before final assembly. After the parts were cleaned, special handling techniques were used to preclude contamination of the surfaces before or after assembly.

Final assembly consisted of welding the subassemblies together in an argon atmosphere. Initially, the seal subassembly was heliarc welded to the collector subassembly using a special fixture to ensure the concentricity of the parts. The emitter subassembly was then fusion welded to the collector-seal weldment and the cesium reservoir was welded to a short extension tube already incorporated on the collector.

The generator was outgassed by heating the emitter to 1550°C for five hours under high vacuum. The cesium was then distilled into the generator and the unit was sealed. Finally, the axial alignment of the electrodes was inspected by an X-ray process.

V. HEATER EVALUATION

An evaluation of the various methods of heating the generator emitter was conducted during the first three months of the program. Electrical, liquid metal, solar, and chemical fuel methods were considered. Of these, only certain methods of electrical heating were found to be simple, relatively inexpensive, reliable, and amenable to the accurate measurement of the thermal input. Electrical resistance heating employing a clean, annealed tungsten wire wound as a bifilar coil filament was found to be the most satisfactory. Details of the evaluation including design techniques for electron beam and electrical resistance radiant heaters were included in the first quarterly report (PWA-2275) issued under the subject contract.

VI GENERATOR INSTRUMENTATION

The thermionic generators investigated under the subject contract were instrumented to provide for measurement of the generator output voltage and current, the generator heat input, and the temperatures at various locations within the generator.

Conventional instrumentation was used to measure the electrical parameters. Voltage probes were installed on the nickel flanges of the bottom compression seal and the output current was measured by instruments installed in the test stand described in the following section. The heat input to the generator (supplied electrically by a bifilar wound filament) was calculated from measurements of the voltage obtained from probes installed on the filament and the current through the filament.

Extensive thermocouple instrumentation was used to obtain data for evaluating the thermal performance of the emitter assembly, the converter as a unit, and the heat rejection system. Figure 4 shows the locations of the thermocouples. Three types of thermocouples were used. Tungsten-tungsten 26 per cent rhenium thermocouples were used to measure temperatures on the emitter assembly. These thermocouples were fabricated by inserting the 0.003-inch diameter thermocouple wires into a two-bore 99.9 per cent aluminum-oxide rod and subsequently welding the wires together at the end of the rod. The rods were then inserted into 0.025-inch diameter axial holes in the emitter and resistance welded at the desired locations on the inner surface of the central tube. Microminiature chromel-alumel thermocouples were used to measure the collector temperatures within 0.075-inch of the electrode surface. These units were sheathed in tantalum and measured only 0.014-inch in diameter. Bare 0.005-inch diameter wire chromel-alumel thermocouples were used at other locations. These thermocouples were formed by tack welding the thermocouple wire directly to the surface for which temperature measurements were desired. A partially instrumented generator is shown in Figure 5.

VII TEST APPARATUS AND PROCEDURE

The thermionic generators were tested in the specially designed test station shown in Figure 6. The test station provided the vacuum environment required for testing, the power required by the generator, and means for monitoring the generator operation.

The temperatures of the emitter, collector, and cesium reservoir were maintained by electric resistance heaters. The emitter was heated by a bifilar wound filament of 0.090-inch diameter tungsten wire. The collector was heated by tantalum-wire heaters wound on the bases of the cooling fins, and the cesium reservoir was heated by a coil tantalum wire heater mounted in a stainless steel heatshield cylinder. Heatshields were installed at either end of the emitter and around the collector coil to reduce thermal losses. The locations of the heaters are shown in Figure 7.

Each generator was mounted such that the emitter tube assembly was vertical by inserting three of the collector fins into slots in a mounting stand (see Figure 8). After being installed, the generator instrumentation and heater leads were connected to the permanently installed wiring on the test mount. An installed generator is shown in Figure 9.

Power supplies and instruments for controlling and monitoring the generator operation were located in the control console. Variable AC transformers were used to control the cesium and collector heaters, and high-current DC power supplies were used to control the emitter heater and generator load. Measurements of thermal input, generator output, and thermocouple signals were made with a self-balancing potentiometer capable of measuring voltages from 0.001 to 1000 volts in 13 ranges. The readings were accurate to within 0.2 per cent of the true values. The schematic wiring diagram of the test system is shown in Figure 10.

Data were recorded by using a point-by-point technique so that all data would be obtained at thermally stable conditions. Initially the emitter was heated to a predetermined temperature and data was taken with a fixed load. The load was then changed and the emitter thermal input was adjusted to reproduce the original emitter temperature. Since the cesium reservoir was thermally isolated from the generator, the cesium temperature remained essentially unchanged during these tests, and the collector temperature was allowed to vary as a function of the load. From two to thirty minutes were allowed at each operating condition to permit the generator to stabilize so that, at the time the data was re-

corded, the electrode temperature drifts were less than 5°C in 10 minutes. The temperature of the cesium reservoir was then changed to produce additional series of points. Finally, the collector heater input was changed to change the collector temperature levels.

The data obtained by this method produced current-voltage characteristic curves for constant emitter and cesium reservoir temperature but collector temperatures varied with load. This procedure simulated actual generator operating conditions, and since complete sets of data were taken at each operating condition, thermal patterns and generator efficiency as a function of the load could be studied.

VIII DISCUSSION OF RESULTS

A. Over-All Generator Performance

The generators evaluated during this program produced more power than was required by the design objectives for the temperature range of 1200 to 1500°C. In fact, for an emitter temperature of 1500°C, the minimum desired power of 4 W/cm² was exceeded by 50 per cent. The maximum power densities measured at each emitter temperature are presented in Figure 11. These power densities, obtained using tungsten-25 per cent rhenium emitter material, are comparable to those reported by Kitrilakis et al⁴ for rhenium and iridium electrodes with 0.008-inch electrode spacing. As there is an optimum spacing for each emitter temperature and electrode materials combination, power outputs equal to or higher than those reported here are possible at temperatures other than that for which the spacing was optimized in these generators. In previous tests, generators using tungsten-rhenium emitters have produced 27 per cent more power (1.4 W/cm²) at 1200°C by an increase in spacing of 25 per cent.

Generator thermal efficiencies ranging from 3.8 to 10 per cent were measured over the emitter temperature range of 1200 to 1500°C (see Figure 12). This performance meets the design objective of an efficiency of 10 per cent at an emitter temperature of 1500°C. In powerplant applications, higher efficiencies could be expected since the end losses could be reduced. Removing the heat losses from the filament heat shields would increase the efficiency to 11.5 per cent, and, if several generators were arranged on a tube containing liquid metal, the end losses from the flanges could be reduced and the efficiency could be increased to 13 or 14 per cent.

The generator voltages measured during maximum generator power output are shown in Figure 13. It might be expected that a linear relationship between this voltage and the emitter temperature would be obtained since the maximum power for thermionic devices usually occurs at the transition between ion-rich and electron-rich conditions and the voltage at which this transition occurs varies linearly with emitter temperature. However, as shown in Figure 14, at low emitter temperatures, the transition occurs at low generator voltages and in some cases in the power-consuming region. For low emitter temperatures, therefore, maximum power is obtained at higher voltages and with electron rich conditions.

The test data recorded at 1490°C shown in Figures 11, 12, and 13 were with the collector temperature somewhat lower than the optimum temperature since raising the collector temperature to the optimum value would exceed the temperature limits of the ceramic-to-metal seal. A ratio of collector temperature to cesium reservoir temperature of 1.68 with an emitter temperature of 1200°C and 1.75 with an emitter temperature of 1500°C produced the maximum power.

The trilayer assemblies tested in this program had measured thermal resistivities between 2.5 and 10°C/W_{thermal}/cm². Hall, et al² reported a temperature difference of 20°C across a trilayer assembly of another type which apparently transmitted 4 W/cm². This trilayer assembly, therefore, had a thermal resistivity of about 5°C/W_{thermal}/cm².) The thermal performance of the trilayer assembly deteriorated when the unit was subjected to thermal cycling. Thermal cycling occurred during outgassing of the generator and during testing. This cycling, together with the temperature gradient existing across the assembly, produced shear stresses at the interfaces as a result of the differential axial thermal expansion among the three materials. These stresses disrupted the thermal performance of the unit. However, after the generator was held at a constant temperature for a time, the zirconium in the brazing material diffused and apparently re-established the bond. These trends are shown in

Figure 15. The generator was subjected to thermal cycling as a result of load and emitter temperature variations during the first 100 hours of testing and the temperature drop across the assembly was approximately 250°C. After this time, the emitter temperature was held constant at 1500°C and the generator output was held at nearly the peak value. At these conditions, nearly 60 W/cm² were transferred across the emitter assembly and after approximately 25 hours the temperature drop across the assembly decreased from 250°C to 150°C. After 147 hours of testing, the generator was shut down, producing a major thermal cycle, and during subsequent testing, which included additional thermal cycling, the temperature drop was approximately 350°C. It is evident that additional work is required to develop a trilayer assembly capable of withstanding the many thermal cycles anticipated during normal thermionic generator operation.

During this program, generators were operated for durations up to 234 hours, and the desired objective of 1000 hours of operation, therefore, was not attained. The limited life of the generators results from a combination of factors, most of which are a result of the high central tube and heater temperatures required to compensate for the thermal resistance of the emitter assembly. As a result of these high temperatures, several instrumentation and test system failures were encountered which produced severe thermal cycles. As a result, fatigue failures caused leaks in the ceramic-metal seals and in some cases in the tantalum end flanges. Both of these components require further development to produce a generator capable of consistently meeting the life objective.

B. Series Generator Performance

An axial temperature gradient would be present in a circulating liquid metal loop system; hence each generator emitter would operate at a slightly different temperature. A study was made of the effect of these emitter temperature mismatches on the performance of an overall system based on the generator data obtained on this program. The effect of the temperature mismatch has been calculated for two generators electrically connected in series for independently controlled cesium reservoir and collector temperatures. The power output of a system containing a greater number of generators or having controlled or constant cesium reservoir and collector temperatures can readily be constructed from the information presented.

Basically all single generator data obtained at a given emitter temperature was plotted on a I-V coordinate system and an envelope was established by using the maximum current at each of a series of voltage conditions. This was done at four emitter temperatures as shown in Figure 16. The cesium reservoir and collector temperatures can also be obtained from this figure. Since all generators connected in series carry the same current, a plot was constructed of the power density at each of the four emitter temperatures as a function of current (Figure 17). This information was used to construct Figure 18 which is the power density as a function of current for two series-connected generators at various conditions of matched and mismatched emitter temperature. Each emitter is considered isothermal. It is interesting to note that the current required to achieve maximum power for the mismatched converters is the optimum current for a single converter operating at the isothermal emitter temperature which is the average of the two mismatched conditions. Hence the power output of a 1300 and 1500°C dual generator system should be approximately equivalent to the output of a 1400°C dual generator system. It is concluded that practically no power loss results from electrical series operation in this temperature range if an average emitter temperature is used as the basis for power production, and if separately controlled cesium reservoir and collector temperatures are employed.

C. Generator Current-Voltage Data

Electronic heating of the collector at constant emitter temperature produced a major effect on the current-voltage characteristic curves obtained for these generators during this program. For generators with radiant heat rejection systems, the electrical-thermal interrelationship could lead to a quasi-instability. A typical characteristic curve is shown in Figure 19. Testing began with no load applied. The load was gradually applied and a series of data points were obtained for nonarc mode operation. At a low voltage, a further reduction in load impedance causes ignition of an arc and the generator operates in a high current condition. The increase in current increases the electron heating of the collector and the collector temperature rises as shown. A stabilized point can be recorded at this condition. A further reduction in load resistance with the higher collector

temperature causes the generator to jump to a still higher current condition. As can be seen in the data, the collector temperature increases again at the higher current. The total increase in collector temperature from the point where the arc was initiated to the highest current recorded was 226°C . As the load resistance is reduced further, the temperature of the seals reaches a limit of 815°C so that short-circuit conditions cannot be attained at steady-state conditions. The influence of electron heating and the generator sensitivity to collector temperature were observed for all converters at all emitter temperatures.

The inter-relation between the collector temperature and the electrical performance of the generator can be qualitatively illustrated using Figure 20. The upper sketch in the figure presents typical current-voltage characteristic curves for four collector temperatures with the other parameters held constant. A motive diagram for each of the collector temperatures at a given voltage is shown at the lower left. In deriving the motive diagrams, three basic assumptions were made:

1. The low current condition must have a large space charge barrier adjacent to the emitter (electron-rich);
2. A potential difference of approximately 1.3 volts exists between the most negative and the most positive position in the plasma during arc-mode operation, this being the voltage required to produce significant volume ionization⁵, and
3. The magnitude of the plasma sheath at the collector is relatively constant.

The motive diagrams indicate that a collector work function variation must account for the generator performance variation. The illustration at the lower right shows the type of collector work function variation experienced by the generators as a function of the collector-to-cesium reservoir temperature ratio. At low current levels (Condition 1), the collector temperature is low and the collector work function is relatively high. As the current is increased, the collector temperature rises, and the collector work function decreases (Condition 2). The lower collector work function increases the contact potential difference, which in turn

increases the rate of volume ionization. Greater volume ionization reduces the electron-rich condition which results in an increased current. The high current obtained at Condition 4 is achieved in a series of steps as the collector work function approaches a minimum. If the seal temperature were not limiting the collector temperature in this generator, a still higher power condition might be possible with a lower collector work function.

A load variation at the high current, high collector temperature condition produces a series of stable, high-output power data points. As the voltage increases and the current is reduced, the collector temperature is reduced. Finally, the retarding region of arc-mode operation is reached, where a very small voltage increase results in a large change in current. In this region a small increase in load resistance produces a significant reduction in collector temperature and a corresponding increase in the collector work function. Therefore, the volume ionization is reduced, and the generator operates stably at a lower current and voltage (Figure 21). A further increase in load impedance produces a normal current-voltage characteristic slightly distorted by the varying collector temperature.

These tests indicate that a quasi-thermal instability exists for thermionic generators with fixed geometry, radiant heat rejection systems, if the operating collector temperature is below the optimum. If the operating collector temperature is above the optimum, the system tends to be thermally stable. In this case, a perturbation which increases the current will produce a higher collector work function which will tend to reduce the volume ionization and the system will tend to return to the initial condition. Using a collector temperature higher than the optimum value, of course, would result in a higher back emission from the collector and therefore the power output would be slightly reduced.

The generator performance was extremely sensitive to the collector-to-cesium reservoir temperature ratio. It was possible to achieve high power output over a wide range of cesium pressures and collector temperatures only if the temperature ratio of these two variables was maintained between 1.5 and 1.8.

The I-V data has been presented in Appendix V of this report. Several features of the current-voltage characteristic curves could not be explained in terms of collector temperature variations. The reversal in the direction of isothermal collector lines for the 80-ampere data point with respect to the 90-ampere point shown in Figure 21 is one example of such a feature. Brief studies were made of the electrode work functions and the axial electrode thermal patterns to explain these inconsistencies.

D. Electrode Work Functions

Some data recorded at a set emitter temperature and cesium pressure produced several values of apparent saturation current as shown in Figure 62. This implies that the emitter electron barrier is multi-valued for high-current data points near short-circuit conditions. To determine a cause for the existence of a multi-valued barrier at the emitter, the emitter work function was evaluated at various data points of a given I-V curve. It was found that the emitter work function was apparently reduced as plasma conductivity was increased. A similar variation was noted for the collector work function.

For point-by-point thermally stable data, an apparent work function or emitter electron barrier can be evaluated for each data point using the relationships between electron cooling and the work function. A detailed discussion of the apparent emitter work function evaluations using this technique is presented in Appendix III. The emitter work functions calculated by this method separate into two groups, the normal work functions and "lower than expected" work functions. The majority of data points produced the former category and are shown in Figure 22 as a function of the ratio of emitter temperature to cesium reservoir temperature. The values agree with those calculated in previous work using a tungsten-rhenium emitter⁶. The "lower than expected" values are shown in Figure 23. These data points were obtained after achieving a high current condition near short circuit by appropriate variation of the external load. Thereafter, a series of points could be obtained between the short-circuit condition and a condition approaching the retarding region of arc-mode operation which exhibited "lower than expected" work function values. These values no longer describe an effective work function. Apparently significant thermal energy from the plasma returns to the emitter at these conditions. The heat

flow used to define the work function now represents the difference between the electron cooling and the plasma thermal input to the emitter, rather than the correct thermal energy, electron cooling. A 10 w/cm^2 heat flux from the plasma to the emitter could occur if one percent of the atoms arriving at this electrode were in an excited state rather than a ground state. It is believed that the arrival of excited-state atoms would reduce the effective emitter work function by 0.1 to 0.2 eV. This small variation would tend to explain the appearance of several values of saturation current for a given I-V curve.

The dependence of the emitter work function on the plasma conditions indicated the need for a study of the collector work function. This study indicated that a minimum work function was obtained at 1.2 collector-to-cesium reservoir temperature ratio at open-circuit conditions. At maximum power conditions the ratio is 1.68 at 1200°C emitter temperature and 1.75 at 1500°C . Since this ratio is an inverse function of cesium surface coverage, the required surface coverage to produce a minimum work function decreases if: 1) the emitter temperature is increased, and 2) the generator voltage is decreased. Both of these conditions would produce increased plasma conductivity. The minimum collector work function value was approximately 1.2 eV as evaluated in Appendix III.

Apparently a reduction of electrode work function occurs as the plasma conductivity is increased. The increased conductivity can be produced by a decrease in external load or by an increase in electrode temperatures for the data in this program. The change in work function is probably caused by a change in absorbed particle species at the electrode surfaces. This reduction of work function tends to explain why a constant current saturation cannot be achieved in a thermionic generator as a function of voltage. Furthermore the heat required to generate a given current is a function of electron cooling and plasma heating of the emitter for certain conditions of operation.

E. Generator Thermal Analysis

In order to evaluate the performance of the thermionic generator, a detailed thermal analysis was required. Specifically, the analysis was required to evaluate the efficiency of the generator, the performance of the trilayer assembly, and the factors and

mechanisms contributing to thermal losses. A summary of the analysis is presented in this section. Initially, the over-all heat balance within the generator is considered. Some unique thermal distributions which are interrelated with generator operating conditions are then examined, and, finally, the performance of the trilayer is discussed.

1. Generator Heat Balance

Complete thermal analyses of two sample generator conditions are presented. In the first the generator was operating at open circuit and an emitter temperature of 1500°C. In this analysis, some data obtained during outgassing were also included since test data indicated that these conditions were practically identical thermally. A complete thermal analysis was also conducted for a generator delivering the maximum power at an emitter temperature of 1500°C. This analysis included the effects of electronic thermal changes which were found to be an important parameter in defining the generator performance.

The data for open circuit operation was taken during the initial stage of generator testing, and therefore the effects of changes in the generator characteristics such as electrode emissivity or trilayer performance which occur during continued operation are not included. The recorded temperature data are shown in Figure 24. For these data, the thermal input to the emitter heater was 586 watts.

In determining the various mechanisms and paths for heat transfer, two relations must be satisfied. First, the total heat flux through the generator computed from the emitter temperature must equal the measured heat input. Secondly, the collector temperature computed from the measured emitter temperature must equal the measured collector temperature. When these relations are satisfied, the calculated heat transfer paths should be representative of true conditions. The thermal fluxes computed at various generator locations are presented in the following table.

TABLE 1
Generator Heat Balance

Thermal Input

Measured Thermal Input	586 watts
Thermal Loss From Heater Leads	39 watts
Heat Generated Between the Heat Shield and the Voltage Probes	<u>22 watts</u>

Net Thermal Input	525 watts
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Emitter Shell

Heat Radiated to Central Tube	236 watts
Heat Radiated to Exposed Ends of Emitter Tube	126 watts
Heat Loss From Heat Shields	<u>127 watts</u>

Total	489 watts
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Collector Shell

Heat Radiated to Collector	116 watts
Thermal Input to End Flanges	246 watts
Heat Loss From Heat Shields	<u>127 watts</u>

Total	489 watts
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End Flange Heat Losses

Heat Conducted Into Seal	78 watts
Heat Radiated to Space Within Heatshield	67 watts
Heat Radiated to Space Outside Heatshield	76 watts
Heat Radiated to Collector	17 watts
Heat Radiated to Seal	<u>15 watts</u>

Total	253 watts
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TABLE 1 (Cont'd)

Collector Heat Input

Heat Radiated From Emitter	116 watts
Heat Input From Seals and End Flanges	<u>110 watts</u>
Total	226 watts

Collector Heat Losses

Conduction From Bolted Fin	78 watts
Radiation From Five Free Fins	140 watts
Radiation From Exposed Collector Surface	<u>13 watts</u>
Total	231 watts

The techniques employed in the thermal analysis are described in Appendix II. The calculated temperature for open circuit operation with an emitter temperature of 1500°C appear in Figure 25.

Several conclusions can be drawn on the basis of the thermal analysis for open circuit conditions. First, the emitter heat-shields are extremely efficient in reflecting heat and produce a sizable thermal input to the exposed section of the emitter not covered by the central tube. Second, the thermal contact between the various bonded layers of the trilayer structure is poor. Thermal contact was effectively achieved on only 7 per cent of the mating surfaces. Third, a 90 per cent effective thermal contact was present between the emitter tube and the cylindrical section of the tantalum end flange.

The analysis conducted for operation with maximum power output with an emitter temperature of 1500°C was similar. The measured and calculated temperatures are presented in Figure 26. The measured data were recorded after a considerable period of generator operation. To satisfy the thermal balance conditions and produce the observed temperature pattern, it was necessary to assume that a less efficient thermal bond existed at the ends of the trilayer assembly than at the center. A uniform bond with a 3.1 per cent thermal contact would satisfy the heat flux condition, but to satisfy the flux and thermal requirements

simultaneously, a 7 per cent bond at the center and a 1 per cent bond at the ends of the trilayer assembly was required. Table 2 presents a summary of the thermal conditions at peak power conditions:

TABLE 2

Generator Heat Balance

Thermal Input

Measured Thermal Input	1193 watts
Thermal Loss from Heater Leads	84 watts
Heat Generated between the Heat Shield and the Voltage Probes	<u>48 watts</u>
Net Thermal Input	1061 watts

Emitter Shell

Heat Radiated to Central Tube	614 watts
Heat Radiated to Exposed Ends of Emitter Tube	288 watts
Heat Loss from Heatshields	<u>193 watts</u>
Total	1095 watts

Collector Shell

Heat Radiated to Collector	76 watts
Thermal Input to End Flanges	317 watts
Heat Loss From Heat Shields	193 watts
Heat Conducted by Cesium	26 watts
Electron Heating of Collector	<u>483 watts</u>
Total	1095 watts

For these operating conditions, the generator produced 100 watts of power with a thermal input of 1061 watts. The generator efficiency was therefore 9.45 per cent. If all end losses were removed, an efficiency of 18 per cent would result. In a practical system in which several generators were mounted on a liquid-metal-heated tube, the end losses would be reduced although not altogether eliminated,

and an efficiency between 13 and 14 per cent would be attained.

2. Axial Temperature Distribution

A strong variation was recorded in the axial emitter temperature distribution as a function of generator load. This variation was produced by the changing relationship between thermal conduction and the thermal flux produced by electron flow. Two stable emitter distributions were recorded at any voltage near that at which the maximum power output was obtained. One pattern was obtained when the load was applied from a short circuit condition, and the second was obtained when the load was applied from an open circuit condition. This section will discuss the causes for axial emitter temperature variations as well as the recorded distributions for the emitter, collector, and central tube.

The varying relationship between conduction and electron cooling of the emitter can best be explained by use of Figure 27. This figure shows the emitter temperature distributions obtained for five different operating points on the current-voltage characteristic curve. During open circuit operation (Point 1), the anticipated temperature distribution occurs since the effects of electron cooling are not present. Slightly lower temperatures occur at the ends of the emitter than at the center as a result of thermal conduction through the end flanges. As the load resistance is reduced and the generator supplies current, higher currents are produced in regions of low emitter temperature. In these regions, there is an increased emitter cesium coverage which produces a lower work function and higher electron emission locally. Higher emission imposes more electron cooling which tends to further depress the emitter temperature locally. This effect of local preferential electron cooling is evident even when the generator is operating at fairly low current, as indicated at Point 2 in Figure 27.

The extent of this local cooling phenomenon is limited by thermal conduction from the hot portions of the emitter to the parts being cooled electronically. The ends of the emitter immediately adjacent to the end flanges do not produce significant current and the minimum temperature is located inwards from the ends of the emitter as shown is Point 2, Figure 27. As the generator current is increased

(to Point 3) the electron cooling increases and the low temperature regions become larger and are located closer to the center of the emitter.

If the emitter is heated uniformly and maintained at a constant average temperature, the temperature at the ends of the emitter will rise as the current is increased. Eventually, increasing the current through Point 4 to Point 5 in Figure 27, the minimum emitter temperature occurs at the center of the emitter.

When the generator is operated at a current high enough to establish the minimum emitter temperature at the center of the emitter, the thermal patterns discussed above will not recur as the current is reduced. If the load is subsequently reduced to Point 4, the 'B' curve is obtained. Thermal conduction to the center of the electrode has increased, and preferential electron cooling from the center section produces a strong inverted pattern. Further reduction of the load to Point 3 causes a rapid decrease in current, but the inverted pattern (Curve B) is still maintained. At Points 2 and 1, however, the electron cooling flux is no longer dominant over the thermal conduction flux and the inverted temperature pattern cannot be maintained.

Since the emitter thermal patterns are dependent upon the method of applying load, the current-voltage relation might also be expected to be dependent upon the method of applying the load. The integrity of the bonds in the trilayer structure as a function of axial location may affect the magnitude of the thermal patterns recorded in this program. However, tests conducted by Pratt & Whitney Aircraft on the other cylindrical converters which did not contain a trilayer structure indicated that the temperature distributions reported for the trilayer-emitter cylindrical converters are normal for cylindrical converters with high thermal flux.

Emitter temperatures were recorded at the center and midway between the center and the end of the collector electrode. The rise in temperature at the end of the electrode could not be observed except for inverted-pattern conditions. The axial temperature distributions for the central tube, the emitter, and the collector are shown in Figures 28 through 31 for the selected points from the current-voltage characteristic curves presented in Appendix V. The measured emitter temperature distributions for various loads can be seen in these curves.

The collector temperature distribution is as expected for the generator design. The major path for heat rejection is at the center of the collector, causing a slight drop in temperature at this location. The average collector temperature variation from open-circuit to short-circuit operation with an emitter temperature of 1200°C was over 300°C. Similar variations were recorded at other emitter temperatures.

The axial temperature pattern of the central tube is strongly influenced by the heat conduction properties of the trilayer structure and the direct radiation to the exposed ends of the emitter structure. The central tantalum-tungsten alloy tube of the brazed emitter assembly has the highest coefficient of thermal expansion and the outer tungsten-rhenium alloy tube has the lowest coefficient. Thus, as the parts are heated, radial thermal expansion creates a force which promotes bonding action. The reverse is true during cooling. The radial temperature gradient further increases the differential expansion effects. Both axial thermal expansion and contraction during heating and cooling cause shear forces which tend to break the interlayer bonds. During generator calibration, changes in the load and emitter levels produce thermal cycles which cause shearing of the interfaces. The trilayer assembly appears to expand outwards from the center so that the shearing stresses near the ends of the emitter assembly are greater than those at the center. Hence, better thermal conductivity is found at the center. The emitter tube wall thickness is more than twice that of the central tube, and therefore the axial temperature profile of the emitter tube is more uniform than that of the central tube. Consequently, the increased radial thermal gradient at the ends of the trilayer assembly results in higher temperatures at the ends of the central tube than at its center.

When the emitter temperature pattern becomes inverted during high generator currents and high thermal inputs, a stronger axial temperature gradient is produced along the central tube. Direct radiation to the exposed ends of the emitter tube, however, produces a higher percentage of the thermal input to the emitter than during operation with a lower power output, and the axial temperature variation is not so great as it might be otherwise.

The magnitudes of the axial temperature variations depend strongly on the generator load. For example, for a generator operating with an emitter temperature of 1200°C with one end of the emitter held to within 4°C of a fixed temperature, the temperature at the center changed with loading over a range of 144°C (Figure 28). During open-circuit operation, the profile was constant within $\pm 10^\circ\text{C}$, whereas with a 57.6-ampere current, a gradient of 97°C in 0.3 inch was present. These data are typical, having been taken after the generators had been operated for between 50 and 100 hours, and emphasize the need for thermal analysis of thermionic generators if refined electrical analyses are to be conducted.

Figure 32 shows the axial temperature distributions obtained for various cesium pressures with constant emitter temperature and generator voltage. The effects of the generator current are clearly demonstrated here, although it should be noted that current and thermal input are synonymous for this plot and that it is the increased thermal input required to produce the higher current which causes the temperature pattern inversion.

Figure 33 shows the temperature patterns recorded during maximum power output of a particular generator for four emitter temperature levels. The range of temperatures observed for each temperature level were:

1150°C - 1215°C
1265°C - 1290°C
1350°C - 1430°C
1430°C - 1530°C

Variations in temperature of these magnitudes could cause a significant shift in the emitter work function and a consequent shift in the generator current.

3. Axial Current Distribution

The magnitude of the axial temperature variations indicates that a noticeable variation should also exist in the axial current distribution. An analysis was therefore conducted using the following relationship for the current density at a given location:

$$J = AT_E^2 e^{-(\phi + \delta)/KT_E}$$

where

- J = Current density
- A = Richardson's constant
- T_E = Emitter Temperature
- ϕ = Emitter work function
- δ = Space charge barrier potential
- K = Boltzmann's constant

This equation can be solved for each point on the emitter for which the temperature is known. The work function varies in accordance with the relations discussed in Appendix III. These relations show that, at the temperature level of the emitter, the work function increases with temperature, and consequently lower currents flow from the higher temperature regions of the emitter. The current distribution has the same instability as the axial emitter temperature pattern, with the magnitude of the current density indicating that strong variations in axial heat flux occur as a result of preferential electron cooling. Saturation current density distribution curves are presented for a variety of emitter temperatures in Figures 34 through 38.

Multiplying the average current density by the emitter area, 17 cm², should yield the generator current near maximum power. Inspection of the data, however, reveals that the analytical current densities do not integrate to produce the maximum measured current. An increase of 0.15 ev in the work function used in the analysis would produce excellent agreement. An error of 0.15 ev in the work function calculated by the electron cooling technique would be introduced if a 15- to 30-watt error had been made in the thermal input value used for the calculations, and an error of this magnitude could readily be produced by a change in the radiation from the emitter to the collector as a result of changes in the load and temperature distribution.

4. Generator Performance Variation with Time

A brief study was performed to evaluate the effect of operating time on the generator thermal characteristics and emitter work function. The complicating effects of thermal cycling were avoided by selecting a 50-hour segment of operations that was free of major thermal cycles.

The time-dependent thermal characteristics are presented in Figure 39. The rebonding within the trilayer causes an increase in the emitter temperature for this constant thermal flux data. The effect is more pronounced at the ends of the structure since effects of thermal cycling are greater there.

The temperature gradient across the trilayer structure is shown in Figure 40. Initially, the thermal gradient decreased over the entire length of the structure. However, after 27 hours the gradient in the center section began to increase. This does not necessarily imply a decrease in the conductivity of the center section, however, since the continued decrease in the thermal conductivity of the end sections reduces the thermal flux through the center section and changes the axial heat flow. The change in axial heat flow increases the temperature at the center section to produce the shift in temperature pattern shown in Figure 39.

The shift in the temperature distribution may be understood through an analysis of the effects of electron cooling of the emitter. Since the cesium pressure is constant along the entire length of the electrode, the lowest emitter work function is located at the section of the emitter at the lowest temperature. This section, therefore, has the highest current and the greatest rate of electron cooling. The axial current distribution is shown in Figure 41. As the temperatures of the warmer sections increase as a result of the increased conductivity of the trilayer, the work functions in these areas increase and the electron cooling is reduced while the axial conduction from the warmer areas to the cooler areas increases. Since the net current remained relatively constant and the data for the 1510°C point remained constant, a continuous increase in current must have occurred at that location.

The emitter work function for four data points was calculated and plotted as a function of the emitter temperature-to-cesium reservoir ratio as shown in Figure 42. A line representing the emitter work functions of the calibration data has been included. The plotted data shows an increase in the work function with time.

F: Generator History

In accordance with the subject contract, Pratt & Whitney Aircraft fabricated ten thermionic generators appropriate for liquid metal heating. Six of the generators were used for experimental evaluation; two generators were acceptance tested and delivered to the Air Force; and two generators were damaged during processing. The generators were fabricated and tested in accordance with the designs and procedures discussed in the preceding sections except for certain variations for particular generators as discussed below.

Generator 1 - During the final assembly of this generator, difficulties were encountered during the welding of the tantalum end flanges to the tungsten-rhenium alloy emitter. The emitter was subsequently damaged during attempts to repair the welds, but the generator was completed for use as a model of the design.

Generator 2 - This generator was the first unit subjected to testing. It operated for 195 hours and was subjected to thermal cycling between the operating temperature and room temperature twice during this period. The first thermal cycle occurred after 49.3 hours of operation when it was found necessary to add a cooling fin to lower the cesium reservoir temperature to obtain the optimum cesium pressure. The second was caused by a test system failure. This was attributed to a series of events. The inner tube reached levels around 1900°C as a result of the high thermal resistance of the trilayer structure. At this temperature, the alumina supporting housing sheath around the inner tube thermocouples deteriorated. One of the thermocouple wires subsequently struck and damaged the emitter heater filament, terminating the test.

This generator differed from those built in accordance with the final design in the following respects:

1. A special flange was incorporated at the top end of the generator to preclude the welding difficulties encountered with the first generator. It was later found that the flange was not required, and it was therefore not included on the remaining generators.
2. A copper fin was attached to the cesium reservoir to lower its temperature. For the remaining generators, the reservoir temperature was lowered by extending the heat dam tube by one inch and by using a chrome spinel coating to increase the rate of heat rejection.
3. Both the collector and collector fins were coated with chrome spinel. On generators 6 through 10, only the fins were coated so that the seals were at a lower relative temperature.
4. The collector heater did not incorporate the heat shields shown in Figure 7. The heat shields were included on generators 6 through 10.

Generator 3 - This generator was operated for 101 hours during which it was exposed to one thermal cycle. Thermal cycling occurred after 54 hours of operation when one of the alumina rods insulating the emitter filament voltage probes fell against the leads of the heater filament and terminated the test.

Generator 4 - The emitter of Generator 4 was damaged during the welding of the tantalum end flange to the tungsten-rhenium alloy emitter. The fabrication procedure used to form the end flange was subsequently modified to prevent further difficulties of this nature.

Generator 5 - This generator was operated for 234 hours. After 150 hours of operation, a test system failure occurred identical to that which was encountered during operation of the second generator. To prevent similar failures with subsequent generators, the central tube thermocouples were relocated at the ends of the central tube on the remainder of the generators. During out-gassing, an emitter tube thermocouple was damaged such that it could not be completely removed. Consequently, a new thermocouple was inserted 0.5 inch from the center of the electrode rather than 0.31 inch as specified.

Generators 6 and 7 - Generators 6 and 7 were operated for 231 hours in a dual generator test as shown in Figure 43. The use of a metal vacuum chamber and the operation of two generators on a common mount system resulted in higher structure and feed through temperatures for a given emitter temperature than those encountered during operation of a single generator. Although a series of vacuum leaks hampered the series-generator program, both single generator and electrical-series-connected dual generator data was obtained.

Generator 8 - Generator 8 was operated for 145 hours when a short developed between the generator electrodes.

Generators 9 and 10 - Generators 9 and 10 were acceptance tested and delivered.

General Remarks - The performance of all of the generators was consistent to within five per cent for identical operating conditions. Generators 2, 3, 5, and 8 were calibrated at emitter temperatures of 1200, 1300, 1400, and 1500°C after which Generators 2 and 5 were endurance tested. Generators 6 and 7 were calibrated and then used to obtain data for series-connected operation.

G. Post-Test Inspection

Generators which failed during testing were examined to determine the cause of failure. The failures encountered usually could be traced to the high inner tube temperatures required for generator operation. These temperatures induced a variety of instrumentation and test system failures which resulted in severe thermal shock and, in some cases, in exposure of the generator to air at elevated temperatures. The thermal shocks imposed by test system difficulties coupled with the thermal cycling encountered during normal generator operation ultimately caused thermal fatigue failures, usually in the seals.

Examination of the failed seals revealed intergranular cracks in the copper braze of the metal-to-ceramic joint. Generator operation enlarged the grain size of the copper, and repeated thermal cycling induced strains as a result of the differential thermal expansion of the metal and ceramic parts. The com-

bination of the grain growth and the strain imposed by thermal cycling evidently produced the thermal fatigue failure. Photomicrographs of a ceramic-copper braze at the nickel flange of the seal are shown in Figure 44. Before testing, the grain size of the copper was quite large as a result of the 1100°C brazing process. The white layer on the surface of the braze is the nickel plating. Small crevices were present in the outer surface of the braze and acted as stress concentration points. These crevices are covered by the nickel plate. After testing, larger grains were evident.

Analysis indicated that the stress level in the nickel was above its yield point and that a nickel fatigue failure could be produced by varying the load from open circuit to the maximum power condition at 1500°C for 50 cycles. Failure occurs in the copper braze, which is the weakest member of the structure. Longer seal life could be attained if the generator could be operated with either a constant thermal flux input or a constant collector temperature so that the effects of thermal cycling would be reduced. This type of operation, however, would not be typical of the actual operating conditions anticipated.

Several failures occurred in the tantalum end flanges through intergranular cracks produced by strains induced by thermal cycling. All but one of these flanges were components of Generators 6 and 7 which were tested together for the series tests. This test was hampered by several vacuum leaks which resulted in exposing the generator to air at operating temperatures. It is believed that the oxygen introduced caused embrittlement of the tantalum parts such that subsequent thermal cycling, which produced strains as a result of the differential thermal expansion of the nickel and tantalum flanges, caused failure. Analysis of the problem indicated that a solution might be sought through a change in materials to reduce the strains induced by differential thermal expansion. Use of a refractory metal in place of the nickel in the nickel-to-alumina seal would reduce the differential expansion, but would introduce brazing problems since a vacuum-tight joint must be formed using a material which is compatible with cesium. A change in materials might also alleviate the thermal strains induced in the end flange. Introducing radial flexibility would also reduce the thermal strains although the accuracy with which the electrode axial alignment is maintained would be reduced.

Post-test inspection revealed that the 97 per cent alumina body was gray after testing. A spectroanalysis was therefore conducted and the presence of cesium was detected. Although photomicrographs showed no evidence of surface changes in the ceramic structure, a slight corrosion of the alumina by the cesium may have occurred.

Failures of the tantalum-to-tungsten rhenium alloy weld were observed on Generators 6 and 7. These failures were believed to have resulted from the exposure of the parts to air at operating temperatures as a result of a vacuum chamber leak. Such exposure would cause embrittlement and subsequent thermal fatigue failure.

In several generators the emitter surface directly opposite the cesium entrance was found to be pitted, apparently as a result of cesium-oxygen corrosion. It is believed, however, that the oxygen required to support this type of corrosion was introduced after generator failure, and that the corrosion occurred during the period that the generator was operated to verify the failed condition. In one case, a test was terminated by a short circuit between the filament and a central tube thermocouple. The generator was rapidly cooled to room temperature and the thermal shock cracked the braze in the metal-to-ceramic seal. When the vacuum chamber was subsequently opened to replace the generator filament, air was introduced into the generator through the leak in the braze. The corrosion occurred during subsequent testing before it was realized from the data that operation was not normal. The appearance of the emitter after testing is shown in Figure 45 and a profile of the pitted area is shown in Figure 46. Preferential loss of the tungsten occurred along the entire length of the emitter tube and was particularly severe in the pitted area. The area of the emitter which was not pitted contained alpha (tungsten - 25 per cent rhenium) and sigma phase indicating a composition with approximately 35 per cent rhenium. In the pitted area, sigma and beta phases were present indicating a rhenium content of approximately 75 per cent. X-ray diffraction and spectrographic techniques did not reveal the presence of any carbon, nitrogen or oxygen compounds nor the presence of any unidentifiable materials. Photomicrographs (Figures 47 through 49) indicated that no significant changes in the grain size or structure of the emitter occurred. Photomicrographs of the trilayer structure appear in Figures 50, 51 and 52 for various

axial locations. The quality of these photomicrographs is poor since specimen polishing tended to remove small particles from this extremely brittle, hard, composite surface. It can be observed that the quality of bond appears to be better in the axial center of the structure than at the ends or mid-span area.

A similar cesium-oxide corrosion occurred on the collector (see Figure 53). This type of corrosion had not been encountered during earlier thermionic generator testing and was encountered in this program only when testing was continued after a converter failure.

APPENDIX I

References

APPENDIX I

References

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APPENDIX II
Thermal Analysis

APPENDIX II

Thermal Analysis

1. Heater

For this analysis, the heater was assumed to be a spiral ribbon. The radiant exchange of heat between the inside and outside of the ribbon and the trilayer wall were analyzed. The net heat flux radiated to the trilayer wall is given by:

$$q_t'' = \frac{\sigma (T_h^4 - T_t^4)}{\frac{D_t \left[2 + \frac{\gamma}{1 - \gamma} t_h \right]}{D_h \left[1 + \frac{\gamma}{1 - \gamma} t_h \right]} \frac{1}{e_h} + \frac{1}{e_t} - 1}$$

where

- q_t'' = heat flux on trilayer surface
- T_h, T_t = heater and trilayer temperatures
- D_h, D_t = heater and trilayer diameters
- e_h, e_t = heater and trilayer emissivities
- σ = Stefan-Boltzmann constant
- γ = heater geometric factor

The heater geometric factor, γ , is given by:

$$\gamma = \frac{2d}{p} \sqrt{1 + \left(\frac{p}{\pi D_h} \right)^2}$$

where:

- d = heater wire diameter
- p = single wire pitch

Thus, the geometric factor is unity if adjacent coils of the heater are in contact. For this analysis, the factor was 0.425.

2. Emitter

Local heat fluxes on the trilayer structure can be found by a heat balance on an emitter segment. The equation obtained considers both radiation and axial heat conduction and is presented below.

$$D_t Z q_t = D_e Z \sigma \frac{(T_i^4 - T_c^4)}{\frac{1}{e_e} + \frac{1}{e_c} - 1} + \frac{D_e F_e k_e}{Z} (2T_i - T_{i-1} - T_{i+1})$$

where

- D_e = emitter diameter
- T_i = temperature of i th emitter segment
- T_c = collector temperature
- e_e, e_c = emitter and collector emissivities
- t_e = emitter thickness
- k_e = emitter thermal conductivity

3. Trilayer Structure

The trilayer efficiency is defined by the per cent of thermal contact between the concentric tubes. The per cent of thermal contact was calculated by assuming that:

1. perfect thermal contact would give a trilayer structure thermal resistivity equal to the sum of the resistivities of the materials used in the structure,
2. an axial circumferential crack divided the trilayer structure
3. the circumferential temperature was constant for any radial position at any axial position, and
4. the heat flux was equal to the sum of the heat transferred by conduction and radiation.

Using these assumptions, the following equation was obtained:

$$q_t'' = \left[\sum_j \frac{B_i}{\frac{t_j D_t}{k_j D_j}} + \sum_j \frac{1 - B_i}{\frac{t_j D_t}{k_j D_j} + \frac{(2 - e^*) D_t}{4 \sigma e^* T^{*3} D^*}} \right] (T_t - T_i)$$

where

- B_i = fraction of bonding in the i th segment
- t_j = thickness of the j th layer
- k_j = conductivity of the j th layer
- D_j = mean diameter of the j th layer
- e^* = emissivity of the cracked layer
- T^* = estimate of mean temperature of the cracked layer
- D^* = mean diameter of the cracked layer

APPENDIX III
Work Function Analysis

APPENDIX III

Work Function Analysis

1. Emitter

There are two methods for determining the emitter work function in an operating thermionic converter. If the converter is operated at low cesium pressures such that the ions produced by surface ionization are sufficient to neutralize the electrons emitted by the high work function electrode, the saturation current can be obtained from a current-voltage characteristic curve and the work function evaluated by direct substitution into Richardson's equation. Alternatively, if steady-state data is obtained, the thermal input required to cause thermionic emission can be calculated and the electron cooling equation can then be solved for the emitter work function.⁵

Both techniques yield an apparent work function in that both rely upon the average current from a confined emission area. Neither considers local variations of the electrode emission surface such as crystal face orientations or surface roughness. The electron cooling techniques, however, does enable evaluation of the effect of operating conditions on the average electrode work function. One such effect is the replacement of adatoms by adions on the surface of the electrode. A partial monolayer coverage of cesium atoms on an electrode establishes a dipole moment which lowers the effective work function of the electrode. If some of the atoms are replaced by ions, a further reduction in work function must result.⁶ In a generator operating in the arc mode, the number of ions present in the interelectrode space has been increased, and it is, therefore, probable that a lower work function is present in the electrode. Since the data used for the electron cooling technique are obtained under actual operating conditions, such effects are necessarily included in the analysis.

The second technique was used here for several reasons. Data obtained during this program was not obtained at low cesium pressures, and, therefore, no definite saturation current was obtained. Further, it was desired to determine the work function for conditions near those for maximum power and this would not necessarily be the value obtained using the first technique.

The first step in reducing the data to calculate a work function was the construction of a plot showing the change in the emitter thermal input as a function of the generator current at a given cesium temperature and emitter temperature. An example of such a plot is shown in Figure 54 for the data shown in Figure 55. The plot of generator current vs change in thermal input is constructed to screen the data before thermal corrections are made. The thermal corrections are somewhat cumbersome and therefore only one data point and the open circuit point are corrected. Points below 140 amperes which fall above the line are considered poor points or points which represent shifts in the work function and are not used for the initial data analysis. Data points for low currents are not expected to fall on the line since the magnitude of the space charge barrier adjacent to the emitter is too great. If a space charge barrier is present, the electron cooling equation is as follows:

$$Q_{ec} = I [(\phi_e + \delta) + (2KT_e/e)]$$

where:

Q_{ec} = electron cooling heat flux
 I = generator current
 ϕ_e = emitter work function
 δ = emitter space charge barrier
 K = Boltzmann's constant
 T_e = emitter temperature
 e = electron charge

Since the magnitude of the space charge barrier cannot be defined, only data near the nonretarding region of arc-mode operation is used. The 194-ampere point of this data was used.

The next step in the analysis was the determination of the electron cooling heat flux from the data for the change in thermal input. The equation used was as follows:

$$P = Q_{ec} + Q_{el} + Q_{fl}$$

P represents the change in the emitter thermal input at a given current minus the thermal input at an open circuit condition using raw data. Q_{f1} is the correction for the heat conducted from the heater filament leads and the heat generated in the filament leads between the filament voltage probes and the outer emitter heat-shield. Q_{f1} is also a difference between a value at a given current condition and the open circuit condition. Q_{e1} is the change in the heat losses from the emitter heatshields, the emitter lead, the end flanges, and the seals at a given current condition from that for open circuit conditions.

The analysis is simplified by constructing a plot of $Q_{f1} + Q_{e1}$ vs the measured thermal input to the emitter as shown in Figure 56. Several small heat fluxes such as that produced by the ion current have not been included in this analysis since they have negligible magnitudes.⁵ Also neglected for this analysis was the change in the radiation from the emitter to the collector for a change in operation from open circuit conditions to those for which the analysis is conducted. Previous data has indicated that the change is small but not negligible. However, without the correction, the general trends are still obtained and these were considered sufficient for this analysis.

Current-voltage characteristic curves and plots of the generator current vs the change in thermal input are presented in Figures 57 through 62 for emitter temperatures of 1300°C, 1400°C, and 1500°C. The data presented in Figure 61 indicates a shift in the emitter work function. The change was not a result of a reduction in the space charge barrier since higher currents were recorded for the greater slope. The change can also be seen in Figure 59. Figures 63 and 64 show other variations in the emitter work function. It is noted that these changes always occurred during low voltage-high current generator operation, and that they were not recorded during operation with an emitter temperature of 1200°C. One shifted data point was observed with an emitter temperature of 1300°C, a minority of the data showed changes for an emitter temperature of 1400°C, and the majority of the data for an emitter temperature of 1500°C showed changes.

The analysis indicates that a continuous reduction in the emitter work function would occur as the generator voltage is reduced if a constant collector work function near the minimum value were maintained.

2. Collector

The analysis of the emitter work function indicated that the effects of changes to the electrode work functions should be studied using data obtained during steady-state operation. For the collector analysis, however, several difficulties arose. First, there is no direct method for measuring the collector work function during normal converter operation. Second, the data obtained was insufficient to permit evaluation of the collector work function using the standard techniques. However, by properly combining several evaluation methods, the effect of the variation in the collector performance on the generator performance was established.

Normally, the collector work function can be determined by measuring the saturation current for operation with a positive voltage applied to the emitter or by determining the $1/KT_e$ slope from which the work function can be calculated.⁸ At low cesium pressures, the saturation current can be determined, but, at operating pressures normal for refractory metal emitters (1 to 10 mm Hg), arcing obscures the saturation current. Further, at normal operating pressures and collector temperatures, back emission and plasma scattering eliminates the $1/KT_e$ slope. Hence, neither technique was suitable.

The collector work function was, therefore, evaluated using a method suitable for nonarc-mode conditions. At open circuit conditions, the back emission can be set equal to the forward emission, and the resulting equation can be solved as shown in Figure 65.

Figure 66 is a plot of the collector work functions vs the collector - cesium reservoir temperature ratio for three generators. The data does not include any corrections and is intended only to indicate a level and a trend. It can be seen here that increasing the emitter temperature increases the Y parameter. The X function incorporates the effect of ion current and the effect of a space charge barrier adjacent to the collector surface (δ in Figure 65). Rough calculations indicate that the effect of the ion currents are negligible and would reduce the value of the collector work function if present. At open circuit conditions, only surface ionization is present and with a work function of 2.5 ev and an emitter temperature between 1200 and 1500°C, ion currents would be approximately 10^{-11} amp/cm². Electron currents are approximately 10^{-3} amp/cm². The presence of a space charge barrier would also reduce the calculated collector work function. Since work functions of approximately 1.3 ev are calculated, it is unlikely that the space charge barrier exceeds 0.2 ev, although the term would increase with the emitter temperature and could cause the 0.3 to 0.4 ev change noted between the data taken with emitter temperatures of 1200 and 1500°C.

This work indicated that the collector work function was between 1.2 and 1.6 ev when the collector-cesium reservoir temperature was 1.2. It is known, however, that maximum power is obtained with a collector-cesium temperature ratio between 1.6 and 1.8. Experimental evidence, therefore, indicates a need to raise the collector temperature beyond that which the analysis indicated produced the minimum work function at open circuit conditions, and it is unlikely that maximum generator output is obtained with high collector temperatures and work functions.

It was, therefore, assumed that the plasma conditions which exist during arc-mode operation modify the work function. Apparently work functions on the order of 1.1 to 1.3 ev exist with collector-cesium reservoir temperature ratios between 1.6 and 1.8. Hence, a brief study of the work function was conducted using thermal data in an attempt to verify this conclusion. The corrected heat flux used to calculate the emitter work function was used in the following equation:

$$Q_{ec} = Q_{eh} + IV_d$$

where:

- Q_{ec} = electron cooling thermal flux of emitter
- Q_{eh} = electron heating thermal flux to collector
- I = generator current
- V_d = plasma voltage loss

This equation does not consider the heat flow resulting from the ion current, and it assumes that all of the energy lost from the plasma is delivered to the collector. However, the ion current should be negligible, and the plasma voltage term can be related to pressure and distance parameters.⁸ The plasma voltage term ranged from 0.45 to 0.6 ev for the data plotted. The relation is valid only for data near that for maximum power output, and, therefore, the analysis was restricted to this region. Although the resulting heat loss occurs at both the emitter and the collector, it was assumed for simplicity that all the loss occurred at the collector. The resulting error in Q_{eh} is less than 0.3 ev.

The equation for Q_{eh} was divided by the current and solved for various data points. The values obtained are plotted against the collector - cesium reservoir temperature ratio in Figure 67. Both "shifted" emitter cooling points and normal emitter cooling points were used. Note that:

$$Q_{eh}/I = \phi_c + KT_p$$

where:

- K = Boltzmann's constant
- T_p = plasma temperature
- ϕ_c = collector work function

The plasma energy term, KT_p , should be approximately 0.3 ev, which is the same magnitude as the probable error of the simplifying assumption. Apparently, near short circuit conditions, the collector work function is reduced to approximately 1.0 ev. The minimum work function for operating data does appear at a collector - cesium reservoir temperature ratio of 1.70, contrary to the results of the open circuit analysis, but it varies with the conditions required to achieve maximum power.

APPENDIX IV

Figures

Figure 1 Schematic Diagram of Thermionic Generator

Figure 2

Thermionic Generator Details

Figure 3

Thermionic Generator Subassemblies

Figure 4 Locations of Thermocouples on Thermionic Generator

Figure 5 Thermionic Generator Instrumented for an Outgas Cycle

Figure 6

Test Station

Figure 7 Schematic Diagram of Thermionic Generator Showing Heaters and Electrical Connections

Figure 8 Thermionic Generator Test Mount

Figure 9 Operating Thermionic Generator

Figure 10 Schematic Wiring Diagram of Thermionic Generator Test Stand

Figure 11

Generator Power Output

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Figure 13

Generator Voltage Output

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Figure 18 Two Generator Series Connected Power Densities
at Mismatched Emitter Temperature Conditions

Figure 19 Generator Current-Voltage Characteristic

Figure 20 Variable Collector Temperature I-V Curves

Figure 21 Generator Current-Voltage Characteristic

Figure 22

Emitter Work Function - Normal Points

Figure 23 Emitter Work Function - "Lower than Expected" Points

Figure 24 Measured Temperatures at Open-Circuit Conditions

Figure 25 Calculated Temperatures at Open-Circuit Conditions

Figure 26 Temperature Distribution at Maximum Power with Emitter at 1500 °C

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Figure 28 Temperature Distribution at 1200 °C

Figure 29

Temperature Distribution at 1300°C

Figure 30 Temperature Distribution at 1400°C

Figure 31 Temperature Distribution at 1500°C

GENERATOR VOLTAGE IS CONSTANT

Figure 32

Temperature Distribution at 1500°C for Variable Cesium Pressures

Figure 33 Temperature Distribution at Maximum Power Points for Generator No. 5

Figure 34 Axial Current Distribution at 1200°C

Figure 35 Axial Current Distribution at 1300°C

Figure 36 Axial Current Distribution at 1400°C

Figure 37 Axial Current Distribution at 1500°C

Figure 38 Axial Current Distribution at 1500 °C

Figure 39

Temperature Distributions as
a Function of Time

Figure 40

Temperature Gradient Across Trilayer Structure as a Function of Time

Figure 41 Variation of Axial Current Distribution With Time

Figure 42 Emitter Work Function Variation as a Function of Operating Time

Figure 43 Generators Nos. 6 and 7 Partially Installed in Electrical Series Test Mount

Nickel Flange

Copper Braze

Alumina Ceramic

Before Testing

Nickel Flange

Copper Braze

Alumina Ceramic

After Testing

Figure 44

Ceramic-Copper Braze Nickel Flange Area

Figure 45 Emitter Surface after 103 Hours of Testing

Figure 46 Profile of Pitted Emitter

Figure 47

Mag: 150X
Typical Photomicrograph of Tungsten-25 Per Cent
Rhenium Emitter Prior to Testing

Figure 48 Emitter Nonpitted Area after 103 Hours of Testing
Mag: 100X

Figure 49 Emitter Pitted Area after 103 Hours of Testing
Mag: 100X

Tungsten-25 Per Cent Rhenium

Tantalum - 10 Per Cent Tungsten

Mag: 100X

Figure 50 Photomicrograph of One End of Emitter Assembly

Tungsten-25 Per Cent Rhenium

Tantalum - 10 Per Cent Tungsten

Mag: 100X

Figure 51 Photomicrograph of Center Area of Emitter Assembly

Tungsten-25 Per Cent Rhenium

Tantalum - 10 Per Cent Tungsten

Mag: 100X

Figure 52 Photomicrograph of Area Midway between Center and End of Emitter Assembly

Figure 53 Collector Surface after Test

Figure 54

Emitter Thermal Input as Function of Generator Current

Figure 55 Typical I-V Performance Data

Figure 56 Generator Thermal Losses of Filament and Support Structure as a Function of Thermal Input

Figure 57

Thermal Input vs Generator Current

Figure 58

Typical IV Data at 1300°C

Figure 59

Emitter Thermal Input as Function of Generator Current

Figure 60 Typical I-V Performance Data

Figure 61

Emitter Thermal Input as Function of Generator Current

Figure 62 Typical I-V Performance Data

Figure 63

Emitter Thermal Input as Function of Generator Current

Figure 64

Typical I-V Performance Data

$$J_{E \rightarrow C} = A T_E^2 e^{-(\phi_E + \alpha)/K T_E} = A T_E^2 e^{-(V_{oc} + \phi_C + \delta)/K T_E}$$

$$J_{C \rightarrow E} = A T_C^2 e^{-(\phi_C + \delta)/K T_C}$$

$$J_{C \rightarrow E} = J_{E \rightarrow C}$$

ASSUMING ION CURRENT IS NEGLIGIBLE

$$T_C^2 e^{-(\phi_C + \delta)/K T_C} = T_E^2 e^{-(V_{oc} + \phi_C + \delta)/K T_E}$$

SOLVING THIS EQUATION YIELDS

$$\phi_C + \delta = V_{oc} \left\{ \frac{T_C}{T_E - T_C} \right\} - 2 \frac{K}{e} \left\{ \frac{T_E T_C}{T_E - T_C} \right\} \ln T_E / T_C$$

Figure 65

Motive Diagram

Figure 66

Evaluation of Collector Work Function
Based on Open Circuit Conditions

Figure 67 Collector Electron Heating as a Function of Collector-to-Cesium Reservoir Temperature

APPENDIX V

Current-Voltage Characteristic Curves

Figure 68

Thermionic Generator Performance Data
 Emitter Temperature = $2190^\circ\text{F} \pm 90^\circ\text{F}$

Figure 69

Thermionic Generator Performance Data

Emitter Temperature = $2190 \pm 90^\circ\text{F}$ Cesium Reservoir Temperature = $597 \pm 10^\circ\text{F}$

Figure 70

Thermionic Generator Performance Data
 Emitter Temperature = $2250 \pm 90^\circ\text{F}$

Figure 71 Thermionic Generator Performance Data
 Emitter Temperature = $2370 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $492 \pm 10^\circ\text{F}$

Figure 72

Thermionic Generator Performance Data

Emitter Temperature = $2370 \pm 90^\circ\text{F}$ Cesium Reservoir Temperature = $513 \pm 10^\circ\text{F}$

Figure 73

Thermionic Generator Performance Data

Emitter Temperature = $2370 \pm 90^\circ\text{F}$ Cesium Reservoir Temperature = $534 \pm 10^\circ\text{F}$

Figure 74 Thermionic Generator Performance Data
 Emitter Temperature = $2370 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $555 \pm 10^\circ\text{F}$

Figure 75

Thermionic Generator Performance Data

Emitter Temperature = $2370 \pm 90^\circ\text{F}$ Cesium Reservoir Temperature = $576 \pm 10^\circ\text{F}$

Figure 76

Thermionic Generator Performance Data

Emitter Temperature = $2370 \pm 90^\circ\text{F}$ Cesium Reservoir Temperature = $618 \pm 10^\circ\text{F}$

Figure 77

Thermionic Generator Performance Data
Emitter Temperature = $2370 \pm 90^\circ\text{F}$
Cesium Reservoir Temperature = $660 \pm 10^\circ\text{F}$

Figure 78

Thermionic Generator Performance Data
 Emitter Temperature = $2370 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $660 \pm 10^\circ\text{F}$

Figure 79

Thermionic Generator Performance Data

Emitter Temperature = $2370 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $660 \pm 10^\circ\text{F}$

Figure 80

Thermionic Generator Performance Data
 Emitter Temperature = $2552 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $492 \pm 10^\circ\text{F}$

Figure 81

Thermionic Generator Performance Data
Emitter Temperature = $2552 \pm 90^\circ\text{F}$
Cesium Reservoir Temperature = $534 \pm 10^\circ\text{F}$

Figure 82

Thermionic Generator Performance Data
Emitter Temperature = $2552 \pm 90^\circ\text{F}$
Cesium Reservoir Temperature = $555 \pm 10^\circ\text{F}$

Figure 83

Thermionic Generator Performance Data

Emitter Temperature = $2552 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $576 \pm 10^\circ\text{F}$

Figure 84

Thermionic Generator Performance Data
 Emitter Temperature = $2552 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $597 \pm 10^\circ\text{F}$

Figure 85

Thermionic Generator Performance Data
 Emitter Temperature = $2552 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $618 \pm 10^\circ\text{F}$

Figure 86

Thermionic Generator Performance Data

Emitter Temperature = $2552 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $639 \pm 10^\circ\text{F}$

Emitter Temperature = $2552 \pm 90^\circ\text{F}$
Cesium Reservoir Temperature = $639 \pm 10^\circ\text{F}$

Converter	Current (Amperes)	Voltage (Volts)	Cesium Reservoir Temperature (°F)	Collector Temperature (°F)
III	22.86	0.37	642	953.0
	5.16	0.112	643	792.0
	42.3	0.245	647	967.0
	64.8	0.176	647	976.0
	195.6	0.328	638	1264.0
	198.6	0.345	638	1250.0
	177.0	0.403	633	1205.5
	177.0	0.395	636	1212.0
	126.4	0.440	637	1116.5
	110.0	0.402	632	1101.5
	160.8	0.524	630	1344.0
	232.2	0.388	641	1472.5
	127.8	0.368	643	1231.5
	64.26	0.322	640	1077.5
	24.24	0.131	634	815.0
IV	132.3	0.222	641	1194.5
	110.4	0.181	632	1185.5
	108.6	0.131	632	1191.5
	108.0	0.0845	633	1205.5
	4.32	0.302	634	868.5
	6.48	0.212	634	851.0
	12.54	0.093	634	875.0
	167.7	0.135	638	1275.0
	44.7	0.181	634	1002.0
	216.0	0.252	632	1404.5
	187.2	0.303	636	1354.5
	154.9	0.358	632	1283.5
	127.3	0.376	636	1225.5
	179.7	0.335	634	1370.5
	25.8	0.286	636	1276.0
IX	26.5	0.288	634	1272.0
	24.8	0.276	636	1262.5
	132.0	0.142	645	1424.5
	160.5	0.083	645	1458.0
	105.6	0.218	645	1424.0
	52.6	0.317	641	1329.0
	171.0	0.125	632	1578.0
	141.6	0.22	634	1494.5
	4.92	0.219	634	1119.5
	3.81	0.335	634	1107.5
V	40.8	0.01	634	1226.5

Figure 87

Thermionic Generator Performance Data
 Emitter Temperature = $2552 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $660 \pm 10^\circ\text{F}$

Figure 88

Thermionic Generator Performance Data

Emitter Temperature = $2552 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $681 \pm 10^\circ\text{F}$

Figure 89

Thermionic Generator Performance Data

Emitter Temperature = $2552 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $702 \pm 10^\circ\text{F}$

Figure 90

Thermionic Generator Performance Data

Emitter Temperature = $2552 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $744 \pm 10^\circ\text{F}$

Figure 91

Thermionic Generator Performance Data
 Emitter Temperature = 2732 ± 90°F

Figure 92

Thermionic Generator Performance Data

Emitter Temperature = $2732 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $618 \pm 10^\circ\text{F}$

Figure 93 Thermionic Generator Performance Data
 Emitter Temperature = $2732 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature = $631 \pm 10^\circ\text{F}$

Figure 94 Thermionic Generator Performance Data
 Emitter Temperature $\approx 2732 \pm 90^\circ\text{F}$
 Cesium Reservoir Temperature $= 639 \pm 10^\circ\text{F}$

Figure 95

Thermionic Generator Performance Data

Emitter Temperature = $2732 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $660 \pm 10^\circ\text{F}$

Figure 96

Thermionic Generator Performance Data

Emitter Temperature = $2732 \pm 90^\circ\text{F}$

Cesium Reservoir Temperature = $702 \pm 10^\circ\text{F}$

Figure 97 Thermionic Generator Performance Data
 Emitter Temperature = $2732 \pm 90^{\circ}\text{F}$
 Cesium Reservoir Temperature = $723 \pm 10^{\circ}\text{F}$

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