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Office of Naval Research
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A STUDY PROGRAM ON CESIUM VAPOR-FILLED
THERMIONIC CONVERTERS HAVING HIGH VACUUM WORK
FUNCTION EMITTER MATERIALS

Yearly Summary Report

1 November 1962 - 31 October 1963

MND - 3100

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MND-3100

FOREWORD

This report presents the work accomplished under Contract Nonr-3639(00) for the period 1 November 1962 to 31 October 1963.

The research was carried out in the Energy Conversion R&D Laboratories of the Martin Marietta Corporation, Nuclear Division. The laboratories are under the direction of Dr. M. E. Talaat.

The program was carried out under the auspices of the Power Branch of the Office of Naval Research and was sponsored by Comdr. John J. Connelly.

ABSTRACT

An extensive mapping of the performance of cesium vapor-filled thermionic energy conversion devices was obtained for the high vacuum work function emitter materials iridium and rhenium. Characteristic current versus voltage curves and summaries of the output power density are given for the emitter temperature range of 1600-2100°K, the liquid cesium temperature range of 450-675°K, the collector temperature range of 555-1075° and for interelectrode spacing from 0.004" to 0.052".

The devices used in this program were of flat-plate geometry and were so designed that the interelectrode spacing could be varied accurately and continuously under the conditions that the other test parameters were maintained constant. Consequently, the dependence of performance on interelectrode spacing could be measured to high precision. At low cesium pressure, the best performance is obtained at the widest interelectrode spacing. For the intermediate range of cesium pressures, the best performance is obtained at intermediate (0.012 - 0.032") values of the interelectrode gap. At the highest cesium pressures, the best performance is obtained at the closest spacings. For the rhenium emitter device tested, optimum performance occurred at high cesium pressure, consequently under the condition that significant increase in performance is obtained by using close interelectrode spacings. On the other hand, for the iridium emitter device tested, optimum performance occurred, at intermediate cesium pressures, at interelectrode gaps of 0.012 - 0.032".

In addition to a discussion of the dependence of performance on interelectrode spacing, the report gives discussions of the dependence of performance on liquid cesium temperature, collector temperature, and emitter temperature.

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I. INTRODUCTION

The objective of this program is the study of the performance of cesium vapor-filled thermionic energy conversion devices which utilize, as the emitter material, the high vacuum work function metals iridium and rhenium. These materials were selected on the basis of data obtained in this laboratory prior to the initiation of this contract and on the basis of the data obtained during the first year of the contract (reported in Yearly Summary Report, MND-2934, dated December 1962, Ref. 1). These materials have been judged to be of particular importance in attaining the objective of research in thermionic energy conversion, namely, the realization of output power densities of a few watts/cm² to over 10 watts/cm², and conversion efficiencies of 10% or higher, at emitter temperatures and interelectrode spacings which are compatible with reliable performance and long life.

For the purpose of fulfilling this objective, a program having two parts was carried out. One part consisted of the fabrication and test of four thermionic energy conversion devices having flat-plate geometry and continuously variable interelectrode gaps. The primary function of these tests was to obtain an understanding of the interdependence of interelectrode spacing and liquid cesium temperature.

The second part of the program consisted in the advancement of the theory of plasma phenomena in a thermionic converter, particularly in the volume ionization mode of operation. The theory has been refined and augmented in many aspects and the dependence of performance on the interelectrode spacing and vapor pressure has been particularly brought out.

II. SUMMARY

Four flat-plate devices with continuously variable interelectrode spacing were built and tested under this program. They are identified as CVS 2.1 (rhenium emitter, niobium collector), CVS 2.2 (rhenium emitter, nickel collector) CVS 2.3 (rhenium emitter, nickel collector), and CVS 1.3 (iridium emitter, nickel collector). The devices were tested in the emitter temperature range of 1600-2100°K, liquid cesium temperature range of 450-675°K, collector temperature range of 575-1075°K, and at interelectrode spacings from 0.003" to 0.052".

The device design permitted changes in the interelectrode spacing to be made such that all other parameters affecting device performance could be held very nearly constant. Consequently, the dependence of performance on interelectrode spacing could be examined to high precision. The principal part of this report, Section IV D, reports these experiments showing the trends in the dependence of performance on spacing as a function of liquid cesium temperature and emitter temperature.

A considerable amount of important data, showing systematic trends in the relative dependence of performance on interelectrode spacing, has been obtained. The trends are self-consistent and in agreement with theory (Section V of this report, and also Ref. 1) and, hence, may be expected to represent general thermionic performance, particularly from the viewpoint of plasma phenomena.

The dependence of performance on spacing, an effect which is very much dependent on liquid cesium temperature, is quite similar for both the iridium and the rhenium emitter devices tested. In each case, three conditions are distinguishable, namely 1) the low cesium pressure case, in which the best performance occurs at the largest value of interelectrode spacing, 2) the intermediate cesium pressure case in which the best performance occurs at intermediate spacings (e.g. 0.012" - 0.032") and, 3) the high cesium pressure case in which the best performance is obtained at the closest spacing.

Though the characteristic curves are qualitatively very similar for both the iridium and rhenium emitter devices, significantly different conclusions regarding the optimum value of interelectrode spacing can be drawn for the two materials. For the rhenium emitter device, at emitter temperatures of 1700°K and 1900°K, the optimum performance occurred under conditions of high liquid cesium temperature, consequently, under conditions in which a significant improvement in the output power density is obtained by using the closest interelectrode spacing. On the other hand, for the iridium emitter at temperatures of 2000°K and lower, the optimum output power density was obtained, at intermediate liquid cesium temperatures, at interelectrode spacings of 0.012" and 0.032".

The dependence of performance on interelectrode spacing, as a function of liquid cesium temperature, is given in detail in Section IV D. Summaries of the output power density versus liquid cesium temperature, parametric in spacing, are given for the rhenium emitter at 1600°K, 1700°K and 1900°K and for the iridium emitter at 1700°K, 1800°K, 1900°K, 2000°K and 2100°K. Characteristic current vs voltage curves for the consecutive series of tests on which these figures are based, are given in the Appendix. Selected characteristic curves, which exemplify the trends in the data, are given in the text.

Section IV E gives a discussion of the dependence of performance on liquid cesium temperature. Though most of this information is contained in the section on the dependence of performance on interelectrode spacing, a brief section is included to show explicitly the dependence of performance on liquid cesium temperature. Similarly, the dependence of performance on emitter temperature is treated in Section IV G.

Some significant results were obtained on a series of tests with the iridium emitter device in which the collector temperature was varied, the other temperatures being held constant. Performance was constant over the collector temperature range of 750-800°K. However, at collector temperatures either above or below this temperature range, a significant decrease in output power density was noticed. This data is discussed in Section IV F.

Some data for the surface ionization mode of operation, and its dependence on the interelectrode spacing, is given in Section IV H.

For both the rhenium and iridium emitter devices, the absolute magnitude of the output power density is lower than those obtained during the previous year's program (see Ref. 1). For example, in the case of the iridium emitter the best output power density at 1700°K and 0.032" interelectrode spacing was lower, by a factor of two, than the output power density of 5.6 ± 0.2 w/cm² which was reproduced, in the previous year's program on these different 0.030" spacing devices, two filament devices and one large area (3 cm²) cylindrical device whose geometry approximates that of a flat-plate. As discussed in Section IV J, the absolute magnitude of the output power density for both iridium and rhenium might have been influenced by the crystal structure of the emitter surface, by the presence of impurities or by end-dependent effects peculiar to the devices used.

The work on the theory will be the subject of a topical report and section V of this report outlines the new contributions made to the theory of the volume ionization mode of operation with particular emphasis on the dependence of performance on interelectrode spacing.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions derived from the evaluation of the experimental data obtained in this program may be summarized as follows:

1. The dependence of performance on spacing and on liquid cesium temperature has been measured, with high precision in varying the spacing without changing any of the other parameters affecting device performance, and is in agreement with the trends predicted by theory.
2. There is a tendency for the optimum output power densities from the iridium emitter device to occur at wider interelectrode spacings than those at which the optimum output power densities occur for the rhenium emitter device.
3. An important dependence of performance on collector temperature was observed with the iridium emitter device having a nickel collector.
4. Comparison of the absolute power density levels reported here to those in Ref. 1 and Ref. 2 bring out the need for careful evaluation of the effect of emitter surface crystal structure and of the effect of impurities on the surface adsorption and on performance.
5. The difference in geometry between devices reported on here and in Refs. 1 and 2 point out the need for clear understanding of the dependence of performance on geometrical arrangement of the electrodes, particularly from the view point of ion generation and loss of output voltage due to plasma losses.

The ultimate experimental information on the performance of iridium and rhenium emitter devices has not been attained either in this program or in other programs having parallel objectives. Further testing of iridium and rhenium emitter devices is therefore indicated. The following differences in the experimental procedures are recommended.

1. Large area cylindrical electron bombardment heated devices should be built and tested. Such devices will contribute to the resolution of the problems concerning the effect of device geometry on performance. Steps taken in the present program to evaluate the effect of device geometry on performance include modifications in the geometry of the flat-plate devices to alter the end conditions, and extension of the theory to include diffusion of ions out of the interelectrode gap.
2. In order to evaluate the possibility of contamination within the device, a test procedure should be adapted which enables the re-evacuation and re-test of a device, including the replacement of the cesium supply. Testing according to such a procedure was initiated later in the present program.

IV. TESTS OF FLAT PLATE DEVICES WITH CONTINUOUSLY VARIABLE INTERELECTRODE SPACING

A. Procedure

1. Device Design

The thermionic energy conversion device used in this program is a flat-plate device designed to enable the continuous variation of the interelectrode spacing from 0.003" to approximately 0.070". A schematic of the device is shown in Figure 1 and a photograph is given in Figure 2.

The iridium or rhenium emitter is in the form of a button which is then brazed with vanadium or platinum to a backing of tantalum. The cylindrical tantalum member, having a wall thickness of 0.008", acts as the mechanical support for the emitter and also serves as the electrical lead and as a thermal resistance between the high temperature of the emitter and the lower temperature of the seal. The increased wall thickness of this member in the neighborhood of the emitter (shown in Figure 1) is a design modification, made during the course of this program, which makes the temperature gradient more nearly linear, consequently reducing thermal stress.

The surface area of the emitter is 1 cm². The use of such a small area results in negligible temperature gradients across the face of the emitter. Tests made on some of the emitters show the temperature variation to be less than $\pm 5^{\circ}\text{C}$.

The niobium-to-Al₂O₃ seal, brazed with vanadium, has been developed at Martin and has a demonstrated capability for operation at high temperature in cesium vapor for time periods of at least 2000 hours.

The expansion bellows is made of tantalum or niobium. This member takes up the differential thermal expansion in the device and enables the variation in the interelectrode gap.

The collector structure is made from a relatively large (for better heat rejection) piece of niobium. In device CVS 2.2, 2.3 and 1.3, a nickel face was brazed to the niobium in the region immediately facing the emitter. In the center of the collector, there is a raised button 0.020" in diameter and 0.002" high. By closing the spacing until there is an electrical short circuit between the 0.002" button and the emitter, an exact reference value of the interelectrode spacing is obtained.

Radiation shields are used to reduce heat losses and to maintain the ceramic-to-metal seal at temperatures below 1000°K. In the case of device CVS 2.1, the shields were sprayed with Al₂O₃ so that they would not make electrical contact with either emitter or collector. In devices CVS 2.1, 2.3 and 1.3 the radiation shields were electrically connected to the emitter.

As discussed in section IV-J, modifications in the collector geometry were made in device CVS 2.3.

The device has proved an extremely useful vehicle for research purposes. The spacing variation can be carried out quickly enough that all other parameters remain constant, thus enabling accurate measurements of the dependence of performance on interelectrode spacing. Mechanically, the device is quite rugged. Though two iridium devices, built early in the program, developed leaks in the emitter support structure prior to their test, design modifications were made and the latest device to be tested, CVS 1.3 remained leak free and was removed intact from the test fixture after 700 hours of test with cesium vapor.

2. Test Apparatus

Figure 3 shows a photograph of a device on the test fixture during the process of evacuation.

The input power to the emitter is obtained from a combination of radiation and electron bombardment heating. The emitter temperature is measured by a thermocouple, recorded continuously, and controlled by a saturable reactor system which responds to the emitter thermocouple. The temperature of the cesium reservoir is varied by a resistance heater and controlled by a saturable reactor system. The collector temperature is varied by resistance heating and controlled manually. The cesium temperature, collector temperature and the temperature at various other parts of the device envelope are measured by thermocouples and recorded continuously. The collector temperature is obtained from thermocouples imbedded in holes a distance of 0.060" from the collector face.

The interelectrode gap is varied continuously by using a micrometer screw. The spacing can be decreased until the button (0.002" high, 0.020" in diameter) contacts the emitter, giving an electrical short-circuit. By this means, an accurate measure of the interelectrode spacing is obtained, and since tests are made with the spacing as small as 0.004", the accuracy is important. In order to assure that the small button does not influence the measurements, data was generally not taken at spacings closer than 0.004". (However, on closing of the spacing from 0.004" to short-circuit (0.002"), no radical changes in performance were observed.) The pedestal-like structure below the device in Figure 3 houses the variable spacing mechanism and limits the motion of the collector to the vertical direction, thus maintaining a parallel condition between the emitter and collector surfaces.

3. Test Procedure

Device CVS 2.1 was evacuated using an oil diffusion pump; devices CVS 2.2, 2.3 and 1.3 were evacuated using a vacuum ion pump. During evacuation the metal surfaces of the devices are outgassed, using the criterion that the temperature must be raised sufficiently that further increases in temperature do not result in pressure increases in the device and also that the outgassing temperature is as high as or higher than, operating temperature. In general, the emitter is outgassed at temperatures in the range of 1900-2100°K; the collector and envelope are outgassed at temperatures in the range of 800-1000. (This outgassing is in addition to the outgassing of components in a vacuum furnace prior to assembly).

The cesium for devices CVS 2.1, 2.2, and 1.3 was obtained from Fisher Scientific Laboratories and packed in glass ampules. The cesium ampule is opened by crushing the metal wall surrounding the capsule. The cesium is distilled into a cesium reservoir and then the device is sealed from the vacuum system.

In general, a release of gas from the cesium ampule is noticed by a brief pressure rise at the pump, when the glass ampule is opened.

In the case of device CVS 2.3, the cesium was supplied by Dow Chemical Company in a stainless steel tank equipped with a stainless steel valve. The test setup for this device includes a stainless steel valve inside the bell jar. Outside of the bell-jar, there is a T connection to the cesium supply and to the vac-ion pump, each of which has a separate valve. Cesium is distilled into a reservoir appended to the device and the device is sealed from the pump and cesium supply by closing the valves. The arrangement permits a re-evacuation of the device at any time during testing, as well as a removal of the cesium (by crimping off part of the reservoir) and re-test with new cesium.

The purpose of this test procedure is to examine the possibility of contaminants in the device. At the time of this writing, the initial testing of device CVS 2.3 is being carried out. Opening of the device and replenishment of the cesium will be carried out in the near future.

For testing with cesium vapor, the output circuit of the device includes a D.C. power supply, for convenient variation of the load voltage, and, generally, a variable amplitude 60 cycle A.C. Most of the test data is obtained by imposing the 60 cycles as a means of varying the voltage on the device. This time is sufficiently rapid to permit the full characteristic curve to be observed without changing any of the temperatures in the device. The 60 cycle characteristics are checked regularly against static points to assure that transient effects do not distort the characteristic curves. If such precautions were not taken, transient effects, which are likely to be significant at **very** large sweep amplitudes, would cause these dynamic measurements to be not accurately representative of the steady-state conditions of the thermionic energy converter.

In general, characteristic curves are measured using a Tektronix 536 oscilloscope, with the output voltage giving the horizontal deflection and the current (i.e., the voltage drop over a shunt) giving the vertical deflection. Figure 4 gives an example of characteristic curves measured in this fashion. In this example, characteristic curves over a relatively wide range of interelectrode spacing are shown in a single photograph. When desired, better resolution of differences, between curves, or better resolution of the low-current part of the characteristic (i.e. ignition and de-ignition effects) is conveniently obtained by changing the amplification in the oscilloscope.

4. Temperature Distribution in the Emitter

Prior to the assembly of the devices, some of the emitters were brought to operating temperature, under a bell jar, for the purpose of examining the temperature distribution over the emitter face by means of an optical pyrometer. In each case, no temperature variation across the emitter face was observable. Thus, the emitter temperature is constant to within the sensitivity of the optical pyrometer, about $\pm 5^\circ\text{K}$.

Measurements were taken with a Shawmeter, a two color optical pyrometer, which gives the true temperature under the assumption that the body under test is "grey", i.e. has the same emissivity in the red part of the spectrum as in the blue part of the spectrum. These measurements show the optical temperature

at the emitter surface to be no more than 20°K lower than the thermocouple, which is positioned on the back of the emitter button.

During the test of device CVS 3.1, an experiment was carried out for the purpose of estimating the temperature drop, between the emitter face and the emitter thermocouple, which results from the heat flux through this emitter button. Through the use of a sweep technique for taking data, the characteristic curves can be measured with a low average output current (generally less than 5 amps/cm^2), consequently with low electron cooling of the emitter. For the purpose of estimating the temperature drop across the emitter button, a series of tests (runs 90 through 94) were run at different levels of an average output current. A D.C. ammeter was placed in the output circuit in order to measure the average output current as the characteristic curve was generated during a dynamic test. Run 90 was measured at an average output current of 5 amperes, with $T_E = 1900^{\circ}\text{K}$ as read by the emitter thermocouple. The succeeding runs 91, 92 and 93 were measured at average output currents of 10, 15 and 20 amperes, respectively. Before each of these runs were photographed the input power to the emitter was varied until the characteristic curve matched that taken in run 90. This provides an accurate method of assuming that the emitter face is kept at a constant temperature. The resulting emitter temperatures, as read by the thermocouple, were then 1925°K , 1960°K and 2020°K for runs 91, 92 and 93, respectively. Run 94 was measured at an average output current of 20 amperes and an emitter thermocouple reading of 1900°K . The output power density of run 94 (2.05 w/cm^2) is almost a factor of two smaller than that measured in the other four runs (approximately 3.85 w/cm^2 in each of these runs).

These results show the need for testing using the dynamic method. Although the actual emitter temperature may be slightly lower than that measured with the emitter thermocouple, it is nevertheless known to be constant through the entire characteristic curve. This would not be the case if the run were taken point-by-point, where the load current (and consequently the heat flux through the emitter) changes at each point. Only if the emitter temperature could be measured optically could this point-by-point method be used properly.

In general, the average output current was less than 5 amperes. For this reason, it is estimated that the largest error would be about 30°K . Thus, the emitter temperatures quoted in this report can be expected to have the accuracy of $+ 0^{\circ}\text{K}$, $- 30^{\circ}\text{K}$.

Cross-Sectional View of Parallel Plate Device

Figure 1

**PARALLEL PLATE - LOW TEMP.
THERMIONIC DEVICE**

A DVANCED
M ANUFACTURING
T ECHNOLOGY

MARTIN COMPANY

0 inches 1 2 3 4 5 6

COMPLETED ASSEMBLY OF
INDIRECT HEATING DEVICE

DATE 6-13-63

EMITTER: Ta. WITH Re. BRAZED FACE
REVISED TAPERED WALL THICKNESS

COLLECTOR: Cb. WITH Ni. BRAZED FACE - PURGE HOLES
PERMANENT ATTACHED HEAT SHIELDS

BELLOWS: .005" Ta. - NEW DESIGN CONFIGURATION

WELDING: ELECTRON BEAM, FUSION AND RESISTANCE

DEVICE NO.: 4 - COMPONENTS VACUUM ANNEALED

REFERENCE: ENGR. DIRECTIVE 1572-319 DATED 5-27-63

B-58132

Figure 2

Photograph of Oscilloscope Traces Showing Change
In Performance with Spacing

CVS 2.1

Origin - 0 vertical, -5 horizontal

Vertical - 4.0 amp/cm

Horizontal - 0.1 volt/cm

$T_E = 1900^{\circ}\text{K}$

$T_L = 589^{\circ}\text{K}$

$T_C = 757^{\circ}\text{K}$

Gap = .052", .037", .032", .022", .012", .004" left
to right

Figure 4

B. Tests of Rhenium Emitter Devices

Three flat plate variable spacing devices with rhenium emitters, of the design discussed in section IV-A, were tested during the program. The devices were tested in the emitter temperature range of 1600 -2100°K, the collector temperature range of 575°K to 1075°K, the liquid cesium temperature range of 470°K to 670°K, and at interelectrode spacings from 0.003" to 0.052". The devices are identified as CVS 2.1, CVS 2.2 and CVS 2.3.

The collector material was niobium in device CVS 2.1 and nickel in devices CVS 2.2 and CVS 2.3. Another difference between the devices was in the radiation shields (see Figure 1). In device CVS 2.1, the radiation shields were electrically isolated from the emitter and collector; in devices CVS 2.2 and CVS 2.3, the radiation shields were electrically connected to the emitter.

Significant modifications in design and test procedures were made in device CVS 2.3. These include a modification in collector geometry, to examine the influence of end-effects on device performance, and a modified test apparatus, to permit the removal of cesium from the device and retest with a new cesium supply. Some tests have been carried out with this device and the data is under evaluation at the time of this writing.

Device CVS 2.1 was operated 170 hours with cesium vapor. A total of 42 photographs of characteristics curves were obtained, most of which give data at four values of interelectrode spacing. Device CVS 2.2 was operated a total of 230 hours with cesium vapor and 142 characteristic curves were obtained.

Device CVS 2.3 has thus far been operated for 220 hours with cesium vapor and is still under test at the time of this report. A total of 39 photographs of characteristic curves have been taken to date.

The primary objective of the testing of these devices was the measurement of the dependence of performance on interelectrode spacing. These measurements are presented in section IV-D. The dependence of performance on liquid cesium temperature is discussed in section IV-E, and the dependence on emitter temperature in section IV-G. A comparison of the data from the different devices and a discussion of the reproducibility of the data, is given in section IV-J.

C. Tests of Iridium Emitter Device

Two iridium emitter devices, built in the early parts of the program, developed leaks, prior to test with cesium vapor, in the emitter support member. As mentioned in Section IV A, the design was modified to provide a more nearly linear temperature distribution in this member, thereby reducing thermal stresses. Device CVS 1.3, an iridium emitter device incorporating this design modification, was removed intact from the test fixture after a total of 700 hours of operation with cesium vapor. The device was tested at emitter temperatures of 1700-2100°K, liquid cesium temperatures of 430-622°K, collector temperatures of 600-970°K, and interelectrode spacings of 0.004" to 0.052". The device had a nickel collector, and the radiation shields were electrically connected to the emitter.

A total of 115 photographs of characteristic curves, most of which include data at four different values of the interelectrode gap, were obtained in the testing of this device. The main bulk of the data was obtained for the purpose of mapping the dependence of performance on interelectrode spacing, as a function of emitter temperature and liquid cesium temperature. This data is reported in Section IV D. A series of tests were made in which the collector temperature was varied, the other device temperatures being held fixed. This data is reported in Section IV F. Section IV E and IV G replot some of the data of Section IV D to bring out more explicitly the dependence of performance on liquid cesium temperature and emitter temperature, respectively.

D. Dependence of Performance on Interelectrode Spacing

The series of Figures 10 through 17 show the dependence of output power density on liquid cesium temperature for various values of the interelectrode spacing from 0.004" to 0.052". Figures 10, 11 and 12 show data for the rhenium emitter at temperatures of 1600°K, 1700°K and 1900°K, respectively, obtained with device CVS 2.1; figures 13 through 17 show data for the iridium emitter at temperatures of 1700, 1800, 1900, 2000 and 2100°K, obtained with device CVS 1.3.

The absolute magnitude of the output power density in Figures 10-17 are lower than those reported in Ref. 1. In the case of the Rhenium emitter device CVS 2.1 some data was obtained showing higher output power than the optimum powers of Fig. 12. This data is given and discussed in section IV-J. Each of Figures 10 through 17 is based on a consecutive series of measurements. The systematic trends in the dependence of performance on spacing as a function of liquid cesium temperature are similar in each case and are in good agreement with theory (Ref. 1). Hence, the data given in this section may be expected to represent general thermionic performance, particularly with regard to the plasma phenomena, in spite of the fact that the absolute magnitude of the output power density is probably not representative of clean electrode surfaces (see section IV-J).

Figures 10 through 17 show that the dependence of performance on interelectrode spacing is very much dependent on the liquid cesium temperature. In general, three regions of cesium pressure, each having a characteristic dependence of performance on interelectrode gap, can be identified.

1. Low pressure case. At low liquid cesium temperature, the best output power density is obtained at the wider values of interelectrode spacing.
2. Intermediate pressure case. As the liquid cesium temperature is increased, the output power density increases for each spacing, in such a fashion that the best output power density is obtained at intermediate values of the interelectrode spacing.
3. High pressure case. At high liquid cesium temperature the best performance is obtained at the closest values of interelectrode spacing. As pressure is further increased, the performance drops rapidly. Frequently the optimum output power density occurs in this region (Figures 11, 12 and 17); however, for the iridium emitter at temperatures up to 2000°K (Figures 13-16) and for the rhenium emitter at 1600°K (Figure 10), the optimum output power density was obtained at .032" to .012" spacings at intermediate liquid cesium temperatures.

A more detailed discussion of these conditions, including characteristic current-vs-voltage curves, is given below. Selected characteristic curves are given together with the text (Figures 18 through 28). The remaining characteristic curves which form the basis for Figures 10 through 17 are given in appendix A. (For the purpose of clarity, in the case of double-valued characteristic curves,

the figures given in this report show the upper or higher power branch of the curves.)

1. Low cesium pressure. The fact that the best output power density, at low liquid cesium temperature, is obtained at the wide values of interelectrode spacing is a result of the fact that volume ionization is best maintained at wide spacings. As shown in Figure 18 (rhenium emitter, at $T_E = 1900^\circ\text{K}$ and $T_L = 523^\circ\text{K}$) the extinction voltage at a gap of 0.052" is approximately 0.4 volts higher than the extinction voltage at 0.004". As short circuit is approached, the curves at the different spacings are very nearly parallel. This is in agreement with theoretical considerations (see Ref. 1, Eq. 41) which show that the voltage drop in the plasma, at low cesium pressure, is approximately independent of spacing. Note that, for the low pressure case, the output current density is generally less than 10 amps/cm². This is a consequence of the fact that the cesium pressure is not sufficiently large to lower the emitter work function to its optimum value. As a result, good output power density is generally not obtained at low cesium pressure.
2. Intermediate cesium pressure. As the cesium pressure is increased, two competing effects occur, namely (1) a lowering of the emitter work function with consequent gain of output current density and (2) an increase of power losses in the interelectrode gap, with consequent loss of output voltage. Volume ionization is still maintained at higher output voltages at the wider interelectrode gaps but, since the power losses are spacing dependent, the closer-spacing characteristic curves rise more steeply than do the characteristic curves at wide spacings. As a result, the curves cross and the best output power density is obtained at intermediate values of the spacing.

Examples of characteristic curves in the intermediate pressure region are given in Figures 19-23. Figure 19 shows the rhenium emitter at 1900°K at a liquid cesium temperature of 540°K, a 17°K increase in liquid cesium temperature over that of Figure 18. Performance has increased at each value of interelectrode spacing, but the change is such that the best output power density is obtained at 0.032". Figure 20, the iridium emitter at $T_E = 1900^\circ\text{K}$ and $T_L = 567^\circ\text{K}$, is a similar curve showing best performance at 0.012". Figure 20 also brings out clearly the general trends that, at the smallest spacing (0.004"), there is the lowest extinction voltage and the steepest rise, resulting in a crossing of the other curves by the 0.004" curve.

Figures 21, 22 and 23 are a series of curves taken for iridium at 1700°K which show the performance attaining its optimum value (optimum liquid cesium temperature), and dropping from the optimum value, while remaining in the condition that the best output power density is obtained at intermediate values of interelectrode gap. Thus, for the iridium emitter device CVS 1.3 at the emitter temperature of 1700°K, the best output power density (approximately 2.1 watts/cm²) is obtained at spacings of 0.012" and 0.032", the best power density at 0.004" spacing being considerably lower. Figure 21 ($T_L = 521^\circ\text{K}$) and Figure 22 ($T_L = 547^\circ\text{K}$) each gives the same output power density (approximately 2.1 watts/cm² at both 0.012" and 0.032" spacing). However, the shapes of the characteristic curves show significant differences, the peak power being obtained for $T_L = 521^\circ\text{K}$, at higher voltage and lower current than for $T_L = 547^\circ\text{K}$. At the liquid cesium temperature of 572°K, Figure 23 shows the performance to have dropped significantly from its optimum value.

As shown in Figures 13-16, the iridium emitter device CVS 1.3 shows the best performance at 0.012" and 0.032" to be better than or almost equal to the best performance at 0.004" for temperatures up to 2000°K (Figures 13-17). At 1700°K and 1800°K, the intermediate spacing performance is clearly better than the close-spacing performance (Figure 13, 14) at temperatures of 1900 and 2000°K, the best .004" performance is very nearly equal to that at .012" (Figure 15-16). At 2100°K, the .004" spacing gives the best performance (Figure 17). There is an indication in Figure 10 that, for the rhenium device CVS 2.1 at 1600°K, the best performance occurs at intermediate spacings; at higher temperatures, however, the best rhenium performance clearly occurs at the closest spacing (Figures 11-12).

3. High cesium pressure. At high values of the liquid cesium temperature, power losses due to collisions in the interelectrode gap become important. Since, at high pressures, the voltage drop in the plasma is proportional to the interelectrode gap (See Ref. 1, Equation 42, the output power density at close spacings is considerably greater than that at the wide spacings. In the case of Re at emitter temperatures of 1700 and 1900°K, and in the case of Ir at the emitter temperature of 2100°K, the optimum output power density occurs in this region.

Examples of characteristic curves in the high pressure region are given in Figures 24-28. Figure 24 gives an example for iridium at $T_E = 1900^\circ\text{K}$ and $T_L = 595^\circ\text{K}$. These curves are at a liquid cesium temperature greater than the optimum for this device at 1900°K, the best performance occurs in the intermediate pressure region. Figure 25, the iridium emitter at $T_E = 2100^\circ\text{K}$ and $T_L = 572^\circ\text{K}$, gives an example in which the best performance is obtained under high pressure conditions.

Figures 26, 27 and 28 show characteristics for the rhenium emitter device at liquid cesium temperatures of 575°K (approximate optimum cesium temperature for 0.032"), 589°K (approximate optimum cesium temperature for 0.022" and 0.012") and 605°K (approximate optimum cesium temperature for 0.004"). An interesting factor in the structure of the characteristic curves is brought out in these figures. The devices used in this program enable the interelectrode spacing to be varied quickly enough that all other parameters remain constant. As a result, subtle factors in the dependence of performance on spacing can be observed. Note, for example the families of curves of Figure 27. If one considers a fixed output current density (e.g. 10 amps/cm²), the change in voltage is approximately the same (0.1 volt/10 mil) for each change in interelectrode spacing. There is, however, a conspicuous exception, i.e. a relatively large voltage change occurs between a change of spacing from 0.022" to 0.032". There is a slight curvature in each characteristic curve, and the curvature of the characteristics at spacings of 0.022" and less is oppositely directed to the curvature at spacings of 0.032" and greater. By reference to Figure 12, it can be seen that the value of liquid cesium temperature of Figure 27, 589°K, is probably greater than the optimum for the spacing of .032" and greater, and lower than the optimum for 0.022" and less.

Similar effects are noticeable in the characteristic curves of Figures 26 and 28. In Figure 26, $T_L = 575^\circ\text{K}$, the large change in performance occurs between .052" spacing and 0.032" spacing, in Figure 28, $T_L = 605^\circ\text{K}$, the

large change occurs between 0.004" and 0.012". In each case, reference to figure 12 shows that the large change in performance tends to separate those values of spacing which are below their optimum liquid cesium temperature from those which are above their optimum liquid cesium temperature.

Such trends are not seen as clearly for the iridium emitter device CVS 1.3, probably because of the fact that the optimum cesium pressure tends to be in the intermediate range rather than in the high pressure range. However, Figure 25 tends to indicate a large change in performance occurs between 0.032" and 0.012" for $T_E = 2100^\circ\text{K}$ and $T_L = 572^\circ\text{K}$.

Figures 29 and 30 show the dependence of performance on spacing for the iridium and rhenium emitters. This manner of plotting the data brings out the fact that the dependence of output power density on interelectrode spacing is not particularly sharp. It should be emphasized that engineering considerations, both cost of fabrication and also reliability of the device for long-term operation, weigh very heavily against the use of interelectrode spacings of less than 0.015". In view of the relative flatness of the output power versus spacing curves, it seems clearly indicated that, for virtually any thermionic application, the wider value of spacing will be preferable even if it does not represent the best possible performance. In the case of iridium, for temperatures of 2000°K and lower, the optimum performance was not, in fact, obtained at the closest spacing but was obtained in the spacing range of 0.012" to 0.032". As the emitter temperature is increased, the advantage of close-spacing becomes more pronounced. However, at 2100°K , a temperature at which strength-of-material considerations would make long-life operation at close spacings virtually impossible, the best output power density at 0.004" is only 15% better than the best performance at 0.012" and less than a factor of two better than that at 0.032". As shown in figure 30, spacing dependence is more important for the rhenium device CVS 2.1 than for the iridium device CVS 1.3. However, for the rhenium emitter at 1900°K , the factor-of-two increase in output power density, which results on decreases in spacing from 0.022" to 0.004", will probably not be sufficiently important in an application of thermionics, to outweigh the reliability advantage of wide spacing.

Output Power (watts/cm²)

OVS 1.3

Iridium Emitter - Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_C = 726 \pm 6^\circ\text{K}$

Spacing

Volume Ionization Mode

- - .052"
- - .032"
- - .012"
- + - .004"

Output Power Density
Versus
Liquid Cesium Temperature

Figure 13

10⁻²

450

470

490

510

530

550

570

Liquid Cesium Temperature (°K)

Output Power (watts/cm²)

CVS 2.1.

Rhenium Emitter
Niobium Collector

$T_F = 1900^\circ\text{K}$

$T_L = 523^\circ\text{K}$

$T_C = 710^\circ\text{K}$

Run 24

Figure 18

Spacing
 $\circ - .052''$
 $\square - .032''$
 $\triangle - .012''$
 $\diamond - .004''$

Current Density (amps/cm²)

4

3

2

1

0

.2

.4

.6

.8

1.0

1.2

1.4

1.6

1.8

Voltage (volts)

Current Density (amps/cm²)

Current Density (amps/cm²)

24
22
20
18
16
14
12
10
8
6
4
2
0

Spacing

- - .052"
- - .032"
- △ - .012"
- ◇ - .004"

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1900^\circ\text{K}$

$T_L = 567^\circ\text{K}$

$T_C = 803^\circ\text{K}$

Run 29

Figure 20

Voltage (volts)

.1 .2 .3 .4 .5 .6 .7 .8

Current density (amps/cm²)

16
14
12
10
8
6
4
2
0

1. .2 .3 .4 .5 .6 .7 .8

Voltage (volts)

Spacing
○ - .052"
□ - .032"
△ - .012"
◇ - .004"

CVS 1.3
Iridium Emitter
Nickel Collector
 $T_E = 1700^\circ K$
 $T_L = 521^\circ K$
 $T_C = 727^\circ K$
Run 61
Figure 21

CVS 2.1

Rhenium Emitter
Niobium Collector

$T_E = 1900^\circ\text{K}$

$T_L = 605^\circ\text{K}$

$T_C = 789^\circ\text{K}$

Run 29

Figure 28

Spacing

○ - .052"

□ - .032"

◇ - .022"

△ - .012"

⊙ - .004"

Current Density (amps/cm²)

Optimum Output Power (watts/cm²)

E. Dependence of Performance on Liquid Cesium Temperature

For the purpose of showing explicitly the dependence of performance on liquid cesium temperature, Fig. 31 replots some of the data of Appendix A3, showing characteristic curves for the iridium emitter device CVS 1.3, at 1900°K and 0.012" gap, for various liquid cesium temperatures. The trends of this figure are typical of those seen in each of the devices tested, at various values of emitter temperature and interelectrode gap.

At the lower values of liquid cesium temperature, the output current density tends to be relatively low, suggesting that at these low liquid cesium temperatures the emitter work function has not been sufficiently lowered by adsorbed cesium for copious electron emission. However, with the exception of the very low liquid cesium temperatures (e.g. 488°K) volume ionization can be maintained at higher output voltages for the lower liquid cesium temperatures.

As the liquid cesium temperature is increased, there is a large increase in the output current density together with a slight decrease in the extinction voltage. For the optimum liquid cesium temperature, the characteristic curve (e.g. the curve at $T_L = 567^\circ\text{K}$ in Fig. 31) approximates a straight line, with no sign of approach to a saturation value in the power-output quadrant. At liquid cesium pressures greater than the optimum, the characteristic curve (e.g. the curve for $T_L = 595^\circ\text{K}$ in Fig. 31) is approximately parallel to the curve at optimum, shifted to lower output voltages.*

The dependence of the performance on the liquid cesium temperature is very much a function of interelectrode spacing. For this reason, the principal discussion of the effect of liquid cesium temperature is given in section IV, D.

* An interesting plasma phenomena is noted in the high pressure case. The increased voltage loss in the plasma, though quite large (e.g. about 0.3 v in Fig. 31 for the change of T_L from 567°K to 595°K) is approximately the same throughout the wide variation in output current. Thus, the curves are approximately parallel and do not diverge at higher currents, as would be the case for a simple difference in resistivity at the different cesium pressures. See in this connection Ref. 1, Eq. 42. The voltage loss depends on the electron temperature, hence on the ratio of the output current to the emitter saturation current, but not on the absolute magnitude of the output current.

F. Dependence of Performance on Collector Temperature

A significant dependence of device performance on collector temperature was observed during the testing of device CVS 1.3. A consecutive series of tests, at the interelectrode spacings of 0.004", 0.012", 0.032" and 0.052" was made with the emitter temperature held fixed at 1700°K, the liquid cesium temperature held within $\pm 2^\circ\text{K}$ of 516°K, and the collector temperature varied from 608°K to 884°K.

The output power density for these tests is plotted in Fig. 32 as a function of collector temperature for the various values of interelectrode spacing. Performance is essentially constant for the collector temperature range of 750-800°K. However, at collector temperatures either higher or lower than this temperature range, a significant decrease in performance is noticed. The trends are generally the same for each value of interelectrode spacing.

Characteristic current-vs-voltage curves which form the basis for Fig. 32 are given in Appendix A7. Curves for the typical spacing of 0.032" are given in Fig. 33. For the collector temperatures of 747°K and 799°K the characteristic curves are virtually coincident. For the other collector temperatures, 608°K and 884°K, a significant degeneration of performance is noted.

If the effect of collector temperature on device performance arises only as a result of changes in collector work function, the characteristic curves, though shifted in voltage, would be essentially parallel to one another. Figure 33 suggests that this is not the case. It should be pointed out, however, that the small differences in liquid cesium temperature could affect the shape of the curve and obscure the exact dependence on collector temperature.

To demonstrate that the data of Figs. 32 and 33 is truly the effect of collector temperature, characteristic curves at slightly different liquid cesium temperatures are given in Fig. 33. These curves bring out the fact that the effect of small changes in liquid cesium temperature is a crossing of the characteristic curves, and is clearly different from the "translation" of the curves which is brought about by changes in collector temperature.

Current Density (amps/cm²)

G. Dependence of Performance on Emitter Temperature

The dependence of performance on emitter temperature is contained in the previous sections. In particular, Fig. 29 for iridium, and Fig. 30 for rhenium, show explicitly the optimum performance at the various values of emitter temperature.

As pointed out in Section IV D the emitter temperature plays an important role in the dependence of device performance on interelectrode spacing. Thus, for the iridium emitter device CVS 1.3, at emitter temperatures of 2000°K and less (Figs. 13-16) the optimum performance is obtained at an intermediate value of spacing (0.012-0.032"). A similar effect is apparent for the rhenium emitter device CVS 2.1 at 1600°K (Fig. 10). At the higher temperatures, however, (Figs. 11, 12, 17), the performance at 0.004" spacing is clearly superior to that at the intermediate spacings. However, as pointed out in Section IV D, it is not clear that consideration of lifetime and reliability will permit the use of very close spacings, particularly in the higher temperature range.

The interdependence of emitter temperature and interelectrode spacings can be simply understood in terms of the cesium adsorption on the emitter surface. The higher the emitter temperature, the higher is the cesium pressure required for a given output current density. Consequently, higher emitter temperatures entail high cesium pressure which because of power losses in the interelectrode gap require close spacings for good performance. As such effects are dependent on the nature of the adsorption process on the emitter surfaces, conclusions concerning the interelectrode spacing for optimum performance depend on the specific nature of the emitter surface.

A series of tests were made on the iridium emitter device CVS 1.3 in which the characteristic curves for the surface ionization mode of operation were accurately measured. Summaries of the dependence of output power density on liquid cesium temperature, at the various values of interelectrode spacing are given in Fig. 36, for $T_E = 1700^\circ\text{K}$ and in Fig. 37, for $T_E = 1900^\circ\text{K}$. The best performance occurs at intermediate values of liquid cesium temperature, about 500°K .

Typical characteristic curves, for liquid cesium temperature near optimum, are given in Fig. 38, for $T_E = 1700^\circ\text{K}$, and Fig. 39, for $T_E = 1900^\circ\text{K}$. The other characteristic curves which form the basis for Figs. 36 and 37 are given in Appendix A7.

In each case, the output current density shows significant increase as the interelectrode spacing is decreased. Such performance is typical of the diffusion effects which characterize the transport of charge through the plasma in the surface ionization mode of operation (Refs. 3, 4). The dependence of performance on spacing becomes less pronounced as the liquid cesium temperature is decreased so that for very low liquid cesium temperatures (450°K and less), the characteristic curves at the different spacings become almost coincident.

Comparison of the data of the surface ionization mode of operation from these flat-plate devices to that obtained in last year's program (Ref. 1) with filament-type devices, and also with a cylindrical electron bombardment heated device whose geometry approximates that of a flat-plate, shows an extremely large disagreement. The disagreement is typified in Fig. 9 which shows the surface ionization current for the flat-plate device to be approximately a factor of ten lower, for nearly identical values of the test parameters, than that of the filament and cylindrical electron bombardment heated devices. Graphs in Ref. 1 (similar to Figs. 36 and 37) also show a disagreement of approximately a factor of ten.

It is of interest that the tests on device CVS 2.1 which showed very good performance, Figs. 5, 6 and 7 showed output current densities of the order of 1-2 amps/cm² in the surface ionization mode of operation. Thus, the only data of the flat-plate devices which gave power levels comparable to that of Ref. 1 gave also comparable behavior in the surface ionization mode of operation.

The low output current densities in the surface ionization mode of operation may be symptomatic of a significant deficiency of the positive ion density in the interelectrode gap. As discussed in Section IV J, the small area flat plate devices used in this program may be prone to a depletion of ions by diffusion out of the interelectrode gap. The microscopic nature of the emitter surface, or the patchy nature of the surface, could provide an alternative explanation for the difference in ion generation from devices approximately having the same emitter surface.

This correlation of performance of the surface ionization mode of operation with the high-power performance in the volume ionization mode of operation has only recently been noticed. The effect will be analyzed further in future programs undertaken in this laboratory in the expectation that surface mode performance may become an important diagnostic tool in the evaluation of thermionic data.

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1900^\circ\text{K}$

$T_L = 529^\circ\text{K}$

$T_C = 729^\circ\text{K}$

Run 34

Figure 39

Spacing
○ - .052"
□ - .032"
△ - .012"
◇ - .004"

J. Reproducibility of Data

The best performance obtained using the emitter material rhenium is shown in Figs. 5, 6 and 7. The curves, obtained from a consecutive series of tests which were made during the early part of the testing of device CVS 2.1, show, for the emitter temperature of 1900°K , an output power density of 8.25 w/cm^2 at $0.032''$ spacing (Fig. 5), 9.8 w/cm^2 at $0.012''$ spacing (Fig. 6) and 10 w/cm^2 at $0.003''$ spacing (Fig. 7). The data given by these runs was not reproduced in subsequent runs made with the same device.

The data of Figs. 5, 6, and 7 was taken using the following procedure for varying the cesium pressure for scanning purposes. Starting at a low liquid cesium temperature, the cesium temperature was increased and the performance was observed to rise, reach a maximum value, and then drop off at the higher cesium temperature. The cesium was then cooled, and the characteristic curve was photographed when it returned to this maximum value. Thus, the characteristic curves of Figs. 5 through 7 represent the optimum liquid cesium temperature. However, since the measurements were made under the condition of a varying cesium temperature, the cesium in the interelectrode gap might not have been in equilibrium with the cesium reservoir. Hence, the absolute value of the cesium pressure in the interelectrode gap probably does not correspond to the liquid cesium temperature measured at the reservoir.

The data of Fig. 5, showing 8.25 w/cm^2 at the interelectrode gap of $0.032''$ is in fair agreement with the filament data of Ref. 1 in so far as the magnitude of the power density is concerned. The filament gave a higher output power density, based on the nominal area of the filament device and neglecting its end effects.

The consecutive series of tests on device CVS 2.1 which formed the basis for the data of Section IV D were not in agreement with the data of Figs. 5, 6 and 7. Figure 40 replots the curve of Fig. 5 together with the optimum run at $T_E = 1900^{\circ}\text{K}$ and $0.032''$ for the series of tests discussed in Section IV D. The higher curve shows an output power density of 8.25 w/cm^2 while the lower curve shows an output power density of 2.7 w/cm^2 .

The lack of reproducibility of performance in the same device (CVS 2.1) suggests the possibility of contamination within that device. The data comparison shown in Fig. 40 may give an insight into the nature of such effects. The higher output current density curve measured at 1900°K and at a spacing of $0.032''$ was obtained at a liquid cesium reservoir temperature of 657°K immediately after it had been at higher temperatures. This temperature is significantly higher than that expected to give good performance at the $0.032''$ interelectrode spacing. This may indicate that the high cesium pressure (together with the relatively high collector temperature of 947°K) resulted in a temporary cleaning of one or both of the electrode surfaces, thus enabling relatively good performance of Figs. 5-7.

The hypothesis that contaminants are present in the device may explain the lack of reproducibility of the data and the relatively low power levels shown in Figs. 10 through 17. On this hypothesis, the data of Fig. 10 through 17, in spite of the fact that they show considerable self-consistency of a large number of tests and give a plausible dependence of performance on liquid cesium temperature and interelectrode spacing, should not be expected to represent the true performance of clean electrode surfaces.

Changes of performance during the testing period were also noticed with device CVS 2.2. Figure 41 shows a case of good agreement between data of CVS 2.1 and CVS 2.2. Figure 42 shows two tests made with device CVS 2.2. One of these runs is in moderate agreement with a test made on device CVS 2.1; the other run, at closely similar values of the test parameters, shows considerable disagreement.

The iridium emitter device CVS 1.3 gave consistent performance throughout its long period of testing with cesium vapor (see below). However, the best output power density obtained at 0.032" (Fig. 8, see also Figs. 13-17) is lower than that obtained in the previous year's program (Ref. 1) for 0.030" filament devices having iridium emitters. Reference 1 also shows a verification of some of the filament results which were obtained using a large area (3 cm²) cylindrical device whose geometry approaches that of a flat-plate. An example of the data from the various devices is given in Fig. 9 which shows:

Device	$T_E(^{\circ}\text{K})$	$T_L(^{\circ}\text{K})$	$T_C(^{\circ}\text{K})$	Gap (in)	$P_{\text{out}}(\text{w}/\text{cm}^2)$
MCl	1686	521	603	0.030	5.5
Cl	1700	518	783	0.030	5.6
GL4	1718	530	781	0.030	5.8
CVS 1.3	1700	521	727	0.032	2.1

MCl, metal enveloped filament device (Ref. 1)

Cl, cylindrical electron bombardment heated device (Ref. 1)

GL4, glass enveloped, guard ring, filament device (Ref. 1)

CVS 1.3, flat-plate, variable spacing device (Section IV A)

The close agreement of the three devices provides a clear indication that the performance of $5.6 \pm 0.2 \text{ w}/\text{cm}^2$ can be obtained, with an iridium emitter device, at the emitter temperature of 1700°K and at the interelectrode spacing of 0.030". Nevertheless, the trends shown by the data of device CVS 1.3, particularly with regard to the interdependence of interelectrode spacing and liquid cesium temperature, show clear self-consistency and are qualitatively very similar to the trends shown by the rhenium emitter devices of identical geometry. Consequently, the trends shown by the data may be expected to represent general thermionic performance, particularly with regard to the plasma phenomena.

Figure 8A gives the best measured characteristic curves measured with the device at the emitter temperature of 1700°K. At a spacing of 0.012", the output power density was 2.12 w/cm²; at a spacing of 0.032", the output power density was 2.83 w/cm². (The output power density of Fig. 8A at 0.032" is slightly better than that shown in Fig. 13 for the consecutive series of tests which measured the dependence of performance on liquid cesium temperature and interelectrode spacing. The difference may be due to a difference in collector temperature, 822°K for the data of Fig. 8A, as compared to 726°K for the data of Fig. 13.) Figure 8B shows the best performance obtained at the emitter temperature of 1900°K, 5.31 w/cm² at 0.012" and 4.53 w/cm² at 0.032".

The performance of the iridium emitter device (CVS 1.3) was essentially constant over the 700 hour testing period, with only minor discrepancies which can be explained on the basis of the dependence of performance on collector temperature and on liquid cesium temperature. Figs. 43 and 44 each give two tests, at similar values of the test parameters, which were made at different times during the testing of the iridium emitter device CVS 1.3. In each figure, the characteristic curves are very similar and the differences between them are attributable to the small differences in liquid cesium temperatures (3°K in Fig. 43 and 5°K in Fig. 44). As discussed in section IV-E, the crossing of the characteristic curves is characteristic of a change in liquid cesium. Figure 45 gives three characteristic curves, taken 200 hours apart, which show only minor differences in performance.

An alternate explanation of the different performance of the different devices, under the assumption that differences in surface properties are not the cause of the gross difference in performance, should be considered. It may be that the maintenance of a plasma in the interelectrode gap has an important dependence on end conditions. The devices used in the present program have a relatively small emitter area (1 cm^2). Thus, a large fraction of the active emitter area adjoins the edge of the device. If positive cesium ions are able to diffuse out of the plasma at the edge of the interelectrode gap, the plasma may be depleted, with a resulting loss of output current in the device.

A conspicuous difference between the different data lies in the fact that the output voltage at which the volume ionization mode of operation can be maintained at is, in general, considerably lower for the present devices than it is for the devices of Refs. 1, and also for data taken in a different laboratory and given in Ref. 2. See, for example, Fig. 9 for iridium at the emitter temperature of 1700°K and a spacing of $0.030''$. For the flat-plate device, the volume ionization mode is maintained at output voltages of less than 0.6 v ; under similar conditions the other devices, as well as other data of Refs. 1 and 2, show volume ionization at output voltages of up to approximately 1.2 v . This is consistent with the view that a loss of positive ions tends to deplete the plasma of the present flat-plate devices, thus consuming more of the generated voltage in internal losses to generate more ions.

Conspicuous differences are also noticed in the surface ionization mode of operation. In Fig. 9, the surface ionization current is lower, approximately by a factor of 10, for the flat-plate devices. As pointed out in Section IV H, extremely large differences in the surface ionization mode of operation were noted on comparison of the data of the present flat-plate devices to the data obtained, in last year's program, for filament devices and for a cylindrical electron bombardment heated device. This effect may be symptomatic of a gross deficiency of positive ions in the flat-plate devices.

If end conditions play an important role in device performance, the significant differences between flat-plate devices of different design must be considered. Sketches of flat-plate devices with three different end configurations are given in Fig. 46. In Fig. 46a, the design used for devices CVS 2.1, 2.2 and 1.3, the interelectrode gap is bounded by a relatively large void volume. There is no mechanism for preventing positive ions from diffusing out of the interelectrode gap and eventually recombining at the wall. Depletion of the plasma by diffusion of ions would seriously inhibit device performance. This explanation is consistent with the fact that the voltage at which the volume ionization mode of operation can be maintained is considerably lower for these devices than that of devices reported elsewhere.

Figure 18b shows a modification of the collector structure which has been made on the rhenium emitter device CVS 2.3, in order to evaluate the possibility that end effects play an important role in device performance. The sides of the collector will be raised, so that the collector forms a concave cup whose sides are 0.030" from the emitter. This will result in an increase in the effective emitter area since the sides of the rhenium button can now supply thermionic current to the collector. Part of the tantalum cylinder which supports the emitter also faces the collector; however, the thermionic performance of tantalum is expected to be sufficiently inferior to that of iridium or rhenium that only a small fraction of the output power will be supplied by the tantalum.

Thus, the cup collector will provide conditions at the boundary of the plasma which are significantly different from the conditions of the usual parallel-plate geometry. Hence, the experiment can provide an insight into the effect of device geometry on performance. Some tests have been carried out using this device and the data is under evaluation at the time of this writing.

In the configuration of Fig. 18c (the configuration used in Ref. 2) the interelectrode gap is bounded by the cylindrical member which supports the emitter and which serves as the emitter lead. In this geometry, the side of the hot emitter faces a portion of the emitter lead. Since the lead is at a lower temperature than the emitter, the lead and the emitter will act as a thermionic diode under the condition of electrical short-circuit. Thus, a plasma is generated in the region surrounding the interelectrode gap. Not only may such a situation provide a mechanism for preventing ions from escaping the interelectrode gap, but it could provide an auxiliary ion source, thereby enhancing device performance.

Output Current (amps/cm²)

CVS 2.1
Rhenium Emitter
Niobium Collector

$T_E = 1900^\circ\text{K}$

$T_L = 638^\circ\text{K}$

$T_C = 949^\circ\text{K}$

$G = .012''$

Run 16

Figure 6

40

36

32

28

24

20

16

12

8

4

0

.1

.2

.3

.4

.5

.6

.7

.8

Output Voltage (volts)

Output Current (amps/cm²)

CVS 2.1
Rhenium Emitter
Niobium Collector

$T_E = 1900^\circ\text{K}$

$T_L = 608^\circ\text{K}$

$T_C = 844^\circ\text{K}$

$G = .003''$

Run 17

Figure 7

40

36

32

28

24

20

16

12

8

4

0

.1

.2

.3

.4

.5

.6

.7

.8

Output Voltage (volts)

Output Current (amps/cm²)

CVS 2.1

Rhenium Emitter
Niobium Collector

Figure 40

$T_E = 1900^\circ\text{K}$

$T_L = 642^\circ\text{K}$

$T_C = 947^\circ\text{K}$

$G = .032''$

Run 15

$T_E = 1900^\circ\text{K}$

$T_L = 575^\circ\text{K}$

$T_C = 743^\circ\text{K}$

$G = .032''$

Run 27

Output Voltage (volts)

0 .1 .2 .3 .4 .5 .6 .7 .8

Comparison of Results
from CVS 2.1 and CVS 2.2

$$T_L = 1900^{\circ}\text{K}$$

$$T_L = 589^{\circ}\text{K}$$

$$G = .032''$$

Figure 41

Output Current (amps/cm²)

14

12

10

8

6

4

2

0

Run 28 CVS 2.1

$$T_C = 757^{\circ}\text{K}$$

Run 118 CVS 2.2

$$T_C = 885^{\circ}\text{K}$$

Output Voltage (volts)

0

.1

.2

.3

.4

.5

.6

.7

Comparison of Results
From CVS 2.1 and CVS 2.2

$$T_E = 1900^{\circ}\text{K}$$

$$T_L = 591 \pm 2^{\circ}\text{K}$$

$$G = .004''$$

Figure 42

Output Current (amps/cm²)

20

18

16

14

12

10

8

6

4

2

0

.1

.2

.3

.4

.5

.6

.7

Output Voltage (volts)

Run 28 CVS 2.1

$$T_L = 589^{\circ}\text{K}$$

$$T_C = 757^{\circ}\text{K}$$

Run 123 CVS 2.2

$$T_L = 589^{\circ}\text{K}$$

$$T_C = 986^{\circ}\text{K}$$

Run 84 CVS 2.2

$$T_L = 593^{\circ}\text{K}$$

$$T_C = 929^{\circ}\text{K}$$

CVS 1.3

Iridium Emitter - Nickel Collector

$T_F = 1700^\circ\text{K}$

Figure 8A

Output current (amps/cm²)

Run 67C

$T_L = 541^\circ\text{K}$

$T_C = 822^\circ\text{K}$

$G = .032''$

Run 61C

$T_L = 521^\circ\text{K}$

$T_C = 727^\circ\text{K}$

$G = .012''$

20

18

16

14

12

10

8

6

4

2

0

.1

.2

.3

.4

.5

.6

.7

Output Voltage (volts)

CVS 1.3

Iridium Emitter - Nickel Collector

$T_E = 1900^\circ\text{K}$

Figure 8B

Run 29C

$T_L = 567^\circ\text{K}$

$T_C = 803^\circ\text{K}$

$G = .012''$

Run 28B

$T_L = 540^\circ\text{K}$

$T_C = 785^\circ\text{K}$

$G = .032''$

Output current (amps/cm²)

Output voltage (volts)

Comparison of Four Thermionic Converters with Iridium Emitters

Iridium emitter - nickel collector

Figure 9

	$T_L (^{\circ}K)$	$T_C (^{\circ}K)$	$T_E (^{\circ}K)$	Gap
MNEC-MCl	526	603	1686	.030"
MNEC-G14	530	780	1718	.030"
MNEC-Cl	518	783	1700	.030"
CVS 1.3	521	727	1700	.032"

Output Current (amps/cm²)

Voltage (volts)

CVS 1.3
Iridium Emitter - Nickel Collector

$$T_E = 1700^\circ\text{K}$$

$$T_L = 520 \pm 2^\circ\text{K}$$

$$T_C = 737 \pm 10^\circ\text{K}$$

$$G = .032''$$

Figure 43

Output Current (amps/cm²)

Run 61 B

$$T_L = 521^\circ\text{K}$$

Run 53 B

$$T_L = 518^\circ\text{K}$$

Output Voltage (volts)

CVS 1.3
Iridium Emitter - Nickel Collector

$T_E = 1700^\circ\text{K}$
 $T_L = 539 \pm 3^\circ\text{K}$
 $T_C = 824 \pm 2^\circ\text{K}$
 $G = .032''$

Figure 44

CVS 1.3

Iridium Emitter - Nickel Collector

$T_E = 1900^\circ\text{K}$

$T_L = 568 \pm 1^\circ\text{K}$

$T_C = 813 \pm 10^\circ\text{K}$

$G = .052''$

Figure 45

Output Current (amps/cm²)

Run 29A

$T_L = 567^\circ\text{K}$

Run 96A

$T_L = 568^\circ\text{K}$

Run 75A

$T_L = 568^\circ\text{K}$

Output Voltage (volts)

359T-14

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FIG. 46 SKETCH OF THREE DIFFERENT
FLAT-PLATE DIODE CONFIGURATIONS

FIG. 46a

FIG. 46b

FIG. 46c

V. Theory of Cesium Vapor Filled Thermionic Converters

In references 3 and 4 the general equations governing the behavior of the thermionic plasma energy converter were presented and discussed. These equations were first formulated in Ref. 3 around a model in which the space between the emitter and collector was divided into three regions, two space charge sheath regions at the emitter and collector surfaces and a quasi-neutral plasma region occupying the space between electrodes from the emitter sheath to the collector sheath. The equations given in Ref. 3 included the voltage balance equation, two current balance equations, one for the emitter sheath and one for the collector sheath, two charge balance equations, one at the emitter sheath-plasma edge and one at the collector sheath - plasma edge, one ion balance equation and the generalized energy balance equation. The lack of data on excitation collision cross sections of cesium and its influence on calculation of ion balance and energy balance was pointed out in Ref. 3. It was also pointed out that for electron mean free paths several times smaller than the interelectrode spacing the current transport will be governed mainly by the electron and ion current diffusion equations. In Ref. 4 the surface ionization and volume ionization modes of operation of the thermionic plasma converter were pointed out and the mode diagrams and equations governing their behavior were presented and discussed. A solution of the diffusion equations for the surface ionization mode of operation was presented and it was pointed out that the equations presented in Ref. 3 applied primarily to the volume ionization mode of operation which is generally the higher output power density mode of operation. Also, the generalized energy balance equation was reorganized to contain essentially two equations; one dealing with energy balance evolving from the transport of charges across the emitter and collector sheaths, and the other dealing with energy balance evolving from the elastic and inelastic collision losses across the interelectrode plasma region. An expression for the charge distribution in the emitter sheath and the solution of Poisson's equation for the electric field distribution in the emitter sheath were also presented in Ref. 4.

Advancement of the theory during the past year emphasized particularly the dependence of performance on interelectrode spacing in the volume ionization mode of operation. The theory was refined and augmented, particularly with regard to the following aspects:

1. The diffusion equations are solved for the case when volume recombination is negligible and the rate of ionization is proportional to the electron density. An expression for the electron density distribution across the plasma region is derived and used to obtain more accurate expressions for the ion balance and the emitter sheath-plasma edge to collector sheath-plasma edge voltage loss.
2. The expression for the electric field distribution derived in Ref. 4 is used to obtain an additional equation relating the virtual saturation current emitted by the virtual emitter, (for the case of a double sheath i.e. a potential minimum existing near the emitter surface.) to the ion current reaching the emitter surface from the plasma. This equation thus gives the dependence of the virtual emitter saturation current on the ions generated inside the plasma region and which reach the emitter surface by diffusion.

3. The expression for the ions generated per second per electron and the expression for excitation losses, given in Ref. 3, are extended, in the light of recent measurements of excitation collision cross sections and the likelihood of extended life of the excited states of cesium due to photon trapping, to include the ionization from these trapped excited states.
4. The effect of loss of ions to the walls is also included in this presentation.

The theory will be presented in the near future as a topical report. Numerical calculations are given for a typical set of test conditions of a thermionic plasma energy converter having planar electrodes, means for varying the interelectrode spacing, and operating in the volume ionization mode of operation. The results of the theoretical calculation are compared with the test results obtained in this program and the extent of the agreement between theory and experiment is discussed.

BIBLIOGRAPHY

1. Martin Marietta Corporation, "A Study Program on Cesium Vapor-Filled Thermionic Converters Having Iridium Emitters," Yearly Summary Report, MND-2934, (1 November 1961 - 31 October 1962).
2. Thermo Electron Engineering Corporation, Annual Technical Summary Report for the Thermionic Emitter Materials Research Program, TEE 4015-3, (1 July 1961 - 30 June 1962).
3. Talaat, M. E., "Generalized Theory of the Thermionic Plasma Energy Converter," AIEE Transaction Paper 62-291.
4. Talaat, M. E., "The Surface Ionization and Volume Ionization Mode of Operation in the Thermionic Plasma Energy Converter," Advanced Energy Conversion, Vol. 2, pp. 447-458, Pergamon Press, 1963.

APPENDIX - SOME CHARACTERISTIC CURRENT VS VOLTAGE CURVES

In this appendix, all of the characteristic curves are given which have been used as a basis for the various summaries of output power density given in the text. Each sub-section of the appendix gives the data obtained from a consecutive series of tests. These curves are replotted from characteristics curves obtained as photographs of oscilloscope traces (see section IV-A). The data is taken in the form of continuous curves, hence data points are not shown. As in the case for the characteristic curves given in the text, only the upper level of current is shown in the case of double-valued characteristic curves, an exception is the curves of appendix A7 which show only the surface ionization mode of operation.

Each figure in the appendix gives a set of curves at different values of the interelectrode spacing. The measurements were made according to the procedure of namely the interelectrode spacing while the various device temperatures were maintained very nearly constant.

The appendix is indexed as follows:

	Emitter Materials	Emitter Temperature	Variable
A1	Iridium	1700°K	T_L
A2	Iridium	1800°K	T_L
A3	Iridium	1900°K	T_L
A4	Iridium	2000°K	T_L
A5	Iridium	2100°K	T_L
A6	Iridium	1700, 1900°K	T_L (surface ioni- zation mode)
A7	Iridium	1700°K	T_C
A8	Rhenium	1600°K	T_L
A9	Rhenium	1700°K	T_L
A10	Rhenium	1900°K	T_L

A-1 Iridium Characteristics at 1700°K (Device CVS 1.3)

T_L (°K)	T_C (°K)
458	720
471	723
498	725
521	727 (text, figure 21)
547	734 (text, figure 22)
572	372 (text, figure 23)

Current Density (amps/cm²)

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_L = 471^\circ\text{K}$

$T_C = 723^\circ\text{K}$

Run 57

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

QVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_L = 498^\circ\text{K}$

$T_C = 725^\circ\text{K}$

Run 59

Spacing

○ - .052"

□ - .032"

△ - .012"

⊙ - .004"

Current Density (amps/cm²)

A-2 Iridium Characteristics at 1800°K (Device CVS 1.3)

T_L (°K)	T_G (°K)
473	715
495	720
516	725
546	735
573	753
622	743

CVS 1.3
Iridium Emitter
Nickel Collector

$T_L = 1800^\circ\text{K}$

$T_L = 473^\circ\text{K}$

$T_C = 715^\circ\text{K}$

Run 39

Spacing

○ - .052"

□ - .032"

△ - .012"

○ - .004"

Current Density (amps/cm²)

10 X 10 TO THE CM.
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2.0

1.5

1.0

.5

0

0 .1 .2 .3 .4 .5 .6 .7 .8 .9

Voltage (volts)

Current Density (amps/cm²)

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

DVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1800^\circ\text{K}$

$T_L = 495^\circ\text{K}$

$T_C = 720^\circ\text{K}$

Run 40

.4

.3

.2

.1

0

.1

.2

.3

.4

.5

.6

.7

.8

.9

Voltage (volts)

Current Density (amps/cm²)

Spacing

○ - .052"

□ - .032"

△ - .012"

○ - .004"

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1800^\circ\text{K}$

$T_L = 516^\circ\text{K}$

$T_C = 725^\circ\text{K}$

Run 41

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1800^\circ\text{K}$

$T_L = 546^\circ\text{K}$

$T_C = 735^\circ\text{K}$

Run 42

Spacing

○ - .052"

□ - .032"

△ - .012"

○ - .004"

Current density (amps/cm²)

16

14

12

10

8

6

4

2

0

.1

.2

.3

.4

.5

.6

.7

.8

Voltage (volts)

Current Density (amps/cm²)

QVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1800^\circ\text{K}$

$T_L = 573^\circ\text{K}$

$T_C = 753^\circ\text{K}$

Run 43

Spacing

○ - .052"

△ - .032"

□ - .012"

◇ - .004"

Voltage (volts)

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1800^\circ\text{K}$

$T_L = 622^\circ\text{K}$

$T_C = 743^\circ\text{K}$

Run 44

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current Density (amps/cm²)

5

4

3

2

1

0

.1

.2

.3

.4

.5

.6

.7

.8

Voltage (volts)

A-3 Iridium Characteristics at 1900°K (Device CVS 1.3)

T_L (°K)	T_G (°K)
488	727
517	746
540	785
567	803 (text, figure 20)
595	782 (text, figure 24)

Current Density (amps/cm²)

Spacing

○ - .052"

□ - .032"

△ - .012"

○ - .004"

CVS 1.3

Iridium Emitter
Nickel Collector

T_E = 1900°K

T_L = 488°K

T_C = 727°K

Run 26

A-4 Iridium Characteristics at 2000°K (Device JVS 1.3)

T_L (°K)	T_G (°K)
493	780
513	790
554	793
573	803
609	808

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CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 2000^\circ K$

$T_L = 493^\circ K$

$T_C = 780^\circ K$

Run 98

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CVS 1.3

Iridium Emitter
Nickel Collector

$T_F = 2000^\circ\text{K}$

$T_L = 513^\circ\text{K}$

$T_C = 790^\circ\text{K}$

Run 99

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current Density (amps/cm²)

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 2000^{\circ}\text{K}$

$T_L = 554^{\circ}\text{K}$

$T_C = 793^{\circ}\text{K}$

Run 100

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

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Current Density (amps/cm²)

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CVS 1.3

Iridium Emitter
Nickel Collector

$T_L = 2000^\circ\text{K}$

$T_L = 573^\circ\text{K}$

$T_C = 803^\circ\text{K}$

Run 101

A-5 Iridium Characteristics at 2100°K (Device CVS 1.3)

T_L (°K)	T_C (°K)
500	773
529	783
558	813
572	828 (see text, figure 25)
599	823

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 2100^\circ\text{K}$

$T_L = 500^\circ\text{K}$

$T_C = 773^\circ\text{K}$

Run 106

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current Density (amps/cm²)

Current Density (amps/cm²)

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CVS 1.3

Iridium Emitter
Nickel Collector

$T_F = 2100^{\circ}\text{K}$

$T_L = 558^{\circ}\text{K}$

$T_C = 813^{\circ}\text{K}$

Run 108

Spacing

○ - .052"

□ - .032"

△ - .012"

○ - .004"

Current Density (amps/cm²)

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

CVS 1.3

Iridium Emitter
Nickel Collector $T_E = 2100^\circ\text{K}$ $T_L = 599^\circ\text{K}$ $T_C = 823^\circ\text{K}$

Run 110

40

36

32

28

24

20

16

12

8

4

0

.1

.2

.3

.4

.5

.6

.7

.8

Voltage (volts)

A-6 Surface Ionization Mode of Operation for Iridium (Device CVS 1.3)

T_E ($^{\circ}\text{K}$)	T_L ($^{\circ}\text{K}$)	T_C ($^{\circ}\text{K}$)
1700	458	720
	470	723
	500	725
	521	727 (see text, figure 38)
	548	734
	572	732
1900	460	720
	477	723
	499	725
	529	729 (see text, figure 39)
	552	736
	575	743
	592	743

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_L = 458^\circ\text{K}$

$T_C = 720^\circ\text{K}$

Run 54

Spacing

○ - .052"

□ - .032"

△ - .012"

⊙ - .004"

Current Density (amps/cm²)

.24

.20

.16

.12

.08

.04

.0

-.04

.2

.4

.6

.8

1.0

1.2

1.4

1.6

1.8

Voltage (volts)

Current density (amps/cm²)

Spacing

○ - .052"

□ - .032"

△ - .012"

⊕ - .004"

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_L = 499^\circ\text{K}$

$T_c = 725^\circ\text{K}$

Run 58

Current Density (amps/cm²)

Current Density (amps/cm²)

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1700^{\circ}\text{K}$

$T_L = 572^{\circ}\text{K}$

$T_C = 732^{\circ}\text{K}$

Run 64

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CVS 1.3

Iridium Emitter
Nickel Collector

$T_C = 1900^\circ\text{K}$

$T_L = 460^\circ\text{K}$

$T_j = 720^\circ\text{K}$

Run 37

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current Density (amps/cm²)

CVS 1.3

Iridium Emitter
Nickel Collector

$T_F = 1900^\circ K$

$T_L = 477^\circ K$

$T_C = 723^\circ K$

Run 36

Spacing

○ - .052"

□ - .032"

△ - .012"

○ - .004"

Current Density (amps/cm²)

CVS 1.3

Iridium Emitter
Nickel Collector

$T_F = 1900^\circ\text{K}$

$T_L = 499^\circ\text{K}$

$T_C = 725^\circ\text{K}$

Run 35

Spacing

○ - .052"

□ - .032"

△ - .012"

○ - .004"

Current Density (amps/cm²)

1.2

1.0

.8

.6

.4

.2

0

0

.2

.4

.6

.8

1.0

1.2

1.4

1.6

1.8

Voltage (volts)

CVS 1.3

Iridium Emitter
Nickel Collector

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

$T_E = 1900^\circ\text{K}$

$T_L = 552^\circ\text{K}$

$T_C = 736^\circ\text{K}$

Run 33

Current Density (amps/cm²)

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1900^\circ\text{K}$

$T_L = 575^\circ\text{K}$

$T_C = 743^\circ\text{K}$

Run 32

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current (amps/cm²)

1.2

1.0

.8

.6

.4

.2

0

-.2

.2

.4

.6

.8

1.0

1.2

1.4

1.6

Voltage (volts)

Current Density (amps/cm²)

A-7 Iridium Characteristics at 1700°K Under Conditions of Variable
Collector Temperatures (Device CVS 1.3)

T_L (°K)	T_C (°K)
515	608
515	706
518	747
516	799
516	884

CVS 1.3
Iridium Emitter
Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_L = 515^\circ\text{K}$

$T_C = 608^\circ\text{K}$

Run 46

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current Density (amps/cm²)

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5

4

3

2

1

0

.1

.2

.3

.4

.5

.6

.7

.8

Voltage (volts)

CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_L = 515^\circ\text{K}$

$T_C = 706^\circ\text{K}$

Run 47

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current Density (amps/cm²)

Voltage (volts)

Current Density (amps/cm²)

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CVS 1.3

Iridium Emitter
Nickel Collector

$T_E = 1700^\circ\text{K}$

$T_L = 516^\circ\text{K}$

$T_C = 884^\circ\text{K}$

Run 51

A-8 Rhenium Characteristics at 1600°K (Device JVS 2.1)

T_L (°K)	T_G (°K)
508	637
526	639
547	651

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CVS 2.1

Rhenium Emitter
Niobium Collector

$T_E = 1600^\circ\text{K}$

$T_L = 508^\circ\text{K}$

$T_C = 637^\circ\text{K}$

Run 31

Spacing

$\circ$ - .052"

$\square$ - .032"

$+$ - .014"

$\triangle$ - .012"

$\square$ - .004"

Current Density (amps/cm²)

CVS 2.1
Rhenium Emitter
Niobium Collector

$T_E = 1600^\circ\text{K}$

$T_L = 526^\circ\text{K}$

$T_C = 639^\circ\text{K}$

Run 32

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

Current Density (amps/cm²)

Current Density (amps/cm²)

A-9 Rhenium Characteristics at 1700°K (Device CVS 2.1)

T_L (°K)	T_C (°K)
508	661
535	679
559	686
589	804

CVS 2.1
Rhenium Emitter
Niobium Collector

$T_E = 1700^\circ\text{K}$

$T_L = 508^\circ\text{K}$

$T_C = 661^\circ\text{K}$

Run 22

Current Density (amps/cm²)

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

2.5

2.0

1.5

1.0

.5

0

.1

.2

.3

.4

.5

.6

.7

.8

.9

Voltage (volts)

Current Density (amps/cm²)

Current Density (amps/cm²)

11

10

9

8

7

6

5

4

3

2

1

0

Spacing

○ - .052"

□ - .032"

◇ - .022"

△ - .012"

⊗ - .004"

CVS 2.1

Rhenium Emitter
Niobium Collector

$T_E = 1700^\circ\text{K}$

$T_L = 559^\circ\text{K}$

$T_C = 686^\circ\text{K}$

Run 20

Voltage (volts)

.1

.2

.3

.4

.5

.6

.7

.8

CVS 2.1
Rhenium Emitter
Niobium Collector

$T_E = 1700^\circ\text{K}$

$T_L = 589^\circ\text{K}$

$T_C = 804^\circ\text{K}$

Run 18

Spacing

- - .032"
- ◇ - .022"
- △ - .012"
- - .004"

Current Density (amps/cm²)

40

36

32

28

24

20

16

12

8

4

0

.1

.2

.3

.4

.5

.6

.7

.8

.9

Voltage (volts)

A-10 Rhenium Characteristics at 1900°K (Device CVS 2.1)

T_L (°K)	T_G (°K)
505	699
523	710 (see text, figure 18)
540	719 (see text, figure 19)
575	743 (see text, figure 26)
589	757 (see text, figure 27)
605	789 (see text, figure 28)
618	798

Current Density (amps/cm²)

2.0

1.5

1.0

.5

0

Spacing

○ - .052"

□ - .032"

△ - .012"

◇ - .004"

CVS 2.1

Rhenium Emitter
Niobium Collector

$T_E = 1900^\circ\text{K}$

$T_L = 505^\circ\text{K}$

$T_C = 699^\circ\text{K}$

Run 23

Voltage (volts)

.2

.4

.6

.8

1.0

1.2

1.4

1.6

1.8

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Current Density (Amps/cm²)

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