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TOPICAL REPORT

PERFORMANCE REPRODUCIBILITY OF CYLINDRICAL
DIODES WITH CVD FLUORIDE TUNGSTEN-
NIOBIUM ELECTRODES

B. Gunther and P. Teagan

June 1970

Thermo Electron Corporation
85 First Avenue
Waltham, Massachusetts 02154

Prepared for
U. S. Atomic Energy Commission
Space Nuclear Systems Division
Lester K. Price, AEC Project Manager
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I. INTRODUCTION

During the past decade, the electrical performance characteristics of numerous thermionic converters utilizing a variety of electrode material combinations and converter designs have been measured. Usually only a very limited number of diodes of a given type were built and tested. Often the performance of an electrode pair had to be evaluated on the basis of a single diode test. In many cases, there is significant disagreement between the reported performance of identical electrode pairs. Because of variations in processing techniques, testing methods, diode design, etc., it is very difficult to ascertain the sources of these discrepancies in the data. It was therefore considered very desirable to fabricate and test a number of identical diodes to determine the performance reproducibility that could be expected among diodes of a given type. This information is important for several reasons:

1. For the design of thermionic reactors and their associated control systems, it is necessary to know the average performance of the thermionic diodes and to have a quantitative measure of the expected variation in performance between diodes.
2. In order to meaningfully compare diode performance and, in particular, to determine if reported differences in performance are significant, a knowledge of the expected reproducibility of the various converter types is required.
3. Reproducibility data provide a means of evaluating the fabrication and processing techniques presently used in diode fabrication.

This reproducibility study consisted of fabricating and testing 12 identical cylindrical diodes with CVD fluoride tungsten emitters and niobium collectors. This electrode pair is typical of those considered for fission-heated thermionic converters. The converters were tested and are compared at common output current densities and cesium reservoir temperatures, such as may be present in a string of series-connected modules with a common cesium reservoir.

The average performance of the converters was established and variations in performance of the individual converters from this average were quantified by a standard deviation. This standard deviation is a measure of the reproducibility of this type of converter. After the performance of each of the converters was established, they were operated under steady state conditions for 200 hours. The converters were then retested to determine the extent of possible short-term changes in performance of individual converters and to what extent such changes in individual diode performance affected the average performance and the standard deviation.

II. CONVERTER DESIGN

The converter design was similar to previous cylindrical converters built and tested at Thermo Electron.⁽¹⁾ Figure 1 shows the converter and the separate test stand onto which the converters were mounted for testing. Collector and reservoir heaters were part of the test stand, simplifying converter construction and testing. The electrode area ($20 \text{ cm}^2 \pm .1\%$) was defined by a step on the collector surface and by the tip of the emitter at the closed end of the converter. Converter spacing was $.010 \text{ inch} \pm .0005$ at operating temperature. A nickel-brazed aluminum oxide bushing centered the closed end of the emitter. The open end of the emitter was attached to the niobium collector via a tungsten heat choke, a niobium emitter flange and a copper-brazed Al_2O_3 seal insulator. The emitter and collector both had heavy walls to reduce temperature gradients in the electrodes. The cesium reservoir, made of niobium, was welded to the end of the collector. A separate niobium tube welded to the niobium emitter flange was used for outgassing and pinchoff.

The test stands were designed to provide a common test environment for the converters and to facilitate switching diodes between stands for performance testing and steady state operation. The diode collector temperature was controlled by a segmented copper cylinder spring-loaded against the collector. The cesium reservoir was immersed in a temperature-controlled indium bath to ensure uniform reservoir temperatures. Power input to the emitters was provided by electron bombardment from a helical tungsten filament. Emitter temperatures were measured with three sheathed W 5% Re/W 25% Re thermocouples located at three axial positions and collector temperatures were measured by three similarly located sheathed chromel-alumel thermocouples.

Figure 1. Cylindrical Converter and Test Stand.

III. EMITTER SURFACE CHARACTERIZATION

The emitter material was CVD fluoride tungsten obtained from San Fernando Laboratories. The emitter surfaces were ground to final dimensions and then heat-treated for one hour at 1980°C. The emitters were analyzed by x-ray diffraction and the work function measured by thermionic emission in vacuum.

Partial pole figures were obtained using the apparatus and procedure described by van Someren and Sprengle.⁽²⁾ Figure 2 shows PPF's for the (100) orientation versus tilt angle. The tungsten is slightly oriented, (100) plane, with small differences between emitters. The emitter surfaces are more characteristic of ground or mechanically worked surfaces than the highly oriented substrate material which is observed in CVD fluoride tungsten.

The work function of each emitter was measured in a special test stand just prior to assembly into the converter. The emitter was surrounded by a cylindrical niobium collector assembly (with the collector in the center and a guard collector at each end). Emitter temperature was measured by optical pyrometer on the actual emitting surface through holes in the collector. Saturated emission was measured at four emitter temperatures over a 400°C range, and an effective work function was calculated for each measurement. Figure 3 shows the data from 12 emitters. The average measured work function at 2000°K was 4.59 eV, with a range of $\pm .03$ eV. As seen in Figure 3, a temperature dependence of 1.2×10^{-4} eV/°C was observed; this could be due to a systematic uncertainty in the temperature measurements.

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Figure 2. Partial Pole Figures of 12 Emitters.

Figure 3. Work Function versus Temperature of 12 Emitters.

IV. CONVERTER PERFORMANCE

A. EXPERIMENTAL PROCEDURE

The diodes were tested with a constant power input to the emitter provided by an electron bombardment filament (the sum of electron bombardment and filament heating). The collector temperature was 740°C for all operating conditions, which was an average optimum for the testing range. The data were taken by fixing the emitter input power, the diode output current and the collector temperature, and then measuring the diode output voltage (or power density) as the cesium reservoir temperature was slowly varied. The variation in cesium reservoir temperature was sufficiently slow (3.5°C/min) that the converter performance was measured under essentially static conditions.

Data were recorded at one-minute intervals by a 15-channel data system. These data were later transferred to magnetic tape and reduced by computer. The resolution of the measured data is as follows:

<u>Measurement</u>	<u>Resolution</u>
Electron Bombardment Current -	.001 amp
Electron Bombardment Voltage -	.25 volt
Output Current -	.04 amp
Output Voltage -	.0002 volt
Emitter Temperature -	.7°C
Cesium Temperature -	.24°C
Collector Temperature -	.24°C

For each diode, 17 output power density versus reservoir temperature curves were generated. Data were obtained at three input power levels (40, 50, and 60 watts/cm²) and at six output current levels (2.5, 4.25, 6.0, 7.75, 9.5, and 11.25 amps/cm²). For the highest input power case (60 watts), no data were taken at the lowest current conditions, to prevent overheating of the diode emitter.

B. RESULTS

Figure 4 shows a typical output voltage versus reservoir temperature curve. The circles represent points taken during increasing cesium reservoir temperature and the squares points taken during decreasing reservoir temperature. The scatter in the data is seen to be very small, indicating good reproducibility for the experimental techniques and the absence of transient effects due to the slowly changing cesium reservoir temperature.

Figure 5 illustrates the data obtained from 12 converters at an input power density of 60 watts/cm² and a current density of 7.75 amps/cm². Similar curves for the other 16 operating points are presented in the appendix. The greatest variations in output power density among the converters occur at the low cesium reservoir temperatures, where the effects of small differences in work function or temperatures would be accentuated. Different emitter work functions, for example, shift the individual converter curves along a diagonal direction from the upper left-hand side of the figure to the lower right-hand side. Changes in collector work function shift the curves in a vertical direction. Emitter temperature or temperature gradient differences shift curves along a diagonal direction from the upper right-hand side of

the figure to the lower left-hand side. All of these effects are apparent in the figure to a limited extent.

Data from the 12 converters were used to calculate the average output power density as a function of cesium reservoir temperature. The average power density multiplied by the number of converters is equal to the total power density which would be realized by connecting the 12 converters electrically in series and operating each converter at the same cesium reservoir temperature. The standard deviation from the average performance was calculated as follows:

$$S(T_R) = \left\{ \frac{1}{12-1} \sum_{i=1}^{12} [p_i(T_R) - p(T_R)]^2 \right\}^{1/2}$$

where:

$p_i(T_R)$ - power density of diode i at cesium reservoir temperature T_R

$p(T_R)$ - average power density of 12 diodes at cesium reservoir temperature T_R

$S(T_R)$ - standard deviation at cesium reservoir temperature T_R .

Figures 6, 7, and 8 illustrate the average performance curves at three test conditions. The indicated bandwidth represents a total of two standard deviations ($\pm$ one standard deviation from the average value). Comparison of Figures 5 and 7, which present data at the same test condition, reveals that most of the experimental data fall within a bandwidth of $\pm$ two standard deviations. Figure 9 shows the cesium optimized average power output as a function of current density at the three input power levels considered. The horizontal bars show

the standard deviations corresponding to these optimized average power points. This figure indicates that:

1. The magnitude of the standard deviation tends to increase as the output current is adjusted to higher levels.
2. For a given current level, the magnitude of the standard deviation is not a strong function of the input power which, along with the output current level, determines the emitter temperature. The fractional standard deviation is, therefore, largest at the lowest input power levels (or lowest emitter temperature) and, at optimum current conditions, ranges from 3.7% at 60 watts/cm² input ($J = 7.75$ amps/cm²) to about 5.8% at 40 watts/cm² input ($J = 6$ amps/cm²).

After the as-built performance data were taken, the diodes were operated for 200 hours under steady state conditions at a power input of 50 watts/cm², a cesium reservoir temperature 15°C above optimum, and a diode output current density of 8.5 amps/cm². After 200 hours of operation, each diode was retested to determine its performance. These post-200 hour test data consisted of generating power density versus cesium reservoir curves at a power input of 50 watts/cm² and at current densities of 11.25, 7.75, and 4.25 amps/cm². These new performance data were then compared to the as-built data taken under the same operating conditions.

Figure 10 shows typical output power versus cesium reservoir curves, comparing as-built and post-200 hour performance. As Figure 10 indicates, the shape of these curves remained essentially unchanged. The magnitude of the curves varied, however, both in output power density and optimum cesium reservoir temperature.

The shift in the cesium optimized operating point for each converter is shown in Figures 11, 12, and 13. The as-built optimum value is located at the tail of the arrow and the post-200 hour optimum is located at the head of the arrow.

These figures indicate that there were changes in diode performance and that the magnitude of the change appears to be larger at the highest current density (11.25 amps/cm²). Figures 14, 15, and 16 show curves for the "average" power density as a function of reservoir temperature for both the as-built and post-200 hour cases. These curves indicate that for the two lower current densities (4.25 and 7.75 amps/cm²) the change in the "average" power density was quite small, particularly near optimum conditions. At optimum conditions, the change was +1.7% for the 4.25 amps/cm² case and +0.5% for the 7.75 amps/cm² case. The shift in average optimum cesium reservoir temperature was 2°C or less. For the highest current case, 11.25 amps/cm², the post-200 hour curve is about 9% higher than the as-built curve but, again, the shift in optimum reservoir temperature is less than 2°C.

These figures, which also indicate the pre- and post-200 hour values of the standard deviation, show that the change in standard deviation was very small for the lower current cases. For the 11.25 amps/cm² case, the change in standard deviation is seen to be about the same magnitude as the changes in average value.

It is interesting to note that, for the two lower current cases, the "average" performance of the diodes was nearly identical (within experimental error) before and after the 200 hour testing. Also, the magnitude of the standard deviations remained essentially unchanged.

This agreement between the pre- and post-200 hour average power output values, despite the observed variation in the performance of the individual diodes, might be explained by a combination of the following:

1. The changes in diode performance during steady state operation were random.
2. Much of the observed change in individual diode performance was due to random experimental errors (such as variations in emitter temperature gradients).

The relatively large change between the pre- and post-200 hour power densities for the highest current conditions (11.25 amps/cm^2) may be due to changes in the diode characteristics (i. e. work functions, spacing, etc.). These effects would be most observable as the current density increases, since their major effect is on the steepness of the optimum I-V envelopes.

The possibility that some of the observed differences in diode performance are a result of emitter temperature gradients is given some justification by the measurements from the emitter thermocouples. Analysis of the readings from the three tungsten-rhenium thermocouples used to measure emitter temperatures indicated that:

1. The average emitter temperatures varied somewhat between diodes operating at the same power point (i. e. same input power and output current). Figure 17 shows the as-built data for 12 converters, relating input power density, output power density, and average emitter temperature. These data indicate a variation in measured average emitter temperatures of about $\pm 20^\circ \text{C}$ at similar operating points. It should be noted, however, that the accuracy of thermocouple

temperature readings is often very questionable at these high temperatures; therefore, only limited significance can be attached to $\pm 20^{\circ}\text{C}$ variations in thermocouple readings.

2. The shallow thermocouple nearest the sleeve consistently read lower than the two deeper thermocouples (which usually agreed to within $\pm 20^{\circ}\text{C}$). This is probably due to both the poor thermal contact between this thermocouple and the emitter and the fact that the thermal loss up the sleeve does lower the temperature in this region. The measured thermal gradient between the deepest and shallowest thermocouples averaged about 60°C .

Even accepting the fact that individual thermocouple readings are somewhat unreliable in this temperature range, the thermocouple readings suggest that emitter temperature gradients did exist, which might have accounted for some of the variation in diode performance. These temperature gradients are probably a result of uneven emitter power input, which is very difficult to avoid using electron bombardment as the heating method.

Figure 4. Output Voltage versus Reservoir Temperature.

Figure 5. Output Power Density versus Reservoir Temperature for 12 Converters.

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Figure 6. Average Output Power versus Reservoir Temperature at low Current Density.

Figure 7. Average Output Power versus Reservoir Temperature Near Maximum Efficiency.

Figure 8. Average Output Power versus Reservoir Temperature at High Current Density.

Figure 9. Optimum Average Power Output as a Function of Current Density.

Figure 10. Power Output as a Function of Cesium Reservoir Temperature, Comparing as-built with Post-200 Hour Data.

Figure 11. Comparison of Optimum Converter Performance Before and After the 200 Hour Testing ($J = 4.25 \text{ amps/cm}^2$).

Figure 12. Comparison of Optimum Converter Performance Before and After the 200 Hour Testing ($J = 7.75 \text{ amps/cm}^2$).

Figure 13. Comparison of Optimum Converter Performance Before and After the 200 Hour Testing ($J = 11.25 \text{ amps/cm}^2$).

Figure 14. Comparison of Average Converter Performance Before and After the 200 Hour Testing ($J = 4.25 \text{ amps/cm}^2$).

Figure 15. Comparison of Average Converter Performance
 Before and After the 200 Hour Testing
 ($J = 7.75 \text{ amps/cm}^2$).

Figure 16. Comparison of Average Converter Performance Before and After the 200 Hour Testing ($J = 11.25 \text{ amps/cm}^2$).

Figure 17. Power Density as a Function of Average Emitter Temperature.

V. SUMMARY AND CONCLUSIONS

Test results from 12 converters of identical construction with CVD fluoride tungsten emitters and niobium collectors indicate significant variations in performance. The fractional variation in performance is generally larger at low cesium reservoir temperatures and high output current densities and decreases at higher cesium temperatures and lower current densities.

The data tended to fall most heavily near the average value, so that a bandwidth of $\pm$ one standard deviation about the average performance contained a majority of the test data. At a given current output, the magnitude of the standard deviation was not a strong function of the input power level (and, therefore, the emitter temperature) and, at optimum current conditions, averaged about 0.23 watt/cm^2 . The fractional standard deviation as a percent of the average output power tended, therefore, to decrease as the input power (and emitter temperature) increased and ranged from 3.7% at 60 watts/cm^2 input to about 5.8% at 40 watts/cm^2 (at optimum output current conditions).

Steady state operation of the diodes for 200 hours resulted in measured changes in individual diode performance. The average performance and the standard deviation about this performance were not, however, affected by the changes in individual diode performance except at the highest current densities (11.25 amps/cm^2), where the change in average power density was about $\pm 9\%$. The fact that the "average" performance of the diodes did not change significantly indicates that if these diodes had been connected in a series array with a common cesium reservoir, little change would have been observed in the performance of the array during the 200-hour testing period.

It is difficult to determine if all the measured changes in individual diode performance were due to actual changes in diode characteristics or whether some of these changes were due to random experimental variations, such as changes in the emitter temperature gradients. Because of the high heat fluxes involved, it appears that elimination of the emitter temperature gradient effects requires emitter heating methods other than electron bombardment. One such heating method which shows promise of minimizing temperature gradients is the use of emitter heat pipes.

The observed variations in diode performance indicate that care should be taken when evaluating diode performance on the basis of data from a very limited number of diodes. For example, the total spread in the optimum power densities for the case of 60 watts/cm^2 power input and 7.75 amps/cm^2 current output was approximately $\pm 6\%$ about the average. If the data from a different diode (tested in a similar way) were found to lie within this spread, it would be difficult to evaluate its performance relative to the fluoride tungsten-niobium diodes described here. If the spread measured in the present data is typical of other electrode pair experimental arrangement combinations, the performance of two different diodes (if only one of each type was tested) would have to differ by at least 12% at this current level-power input point before a definite conclusion on the relative superiority of an electrode pair could be reached.

In general, therefore, the results of these experiments indicated that a relatively large number of diodes of a given type must be tested before the average performance of that class of diodes can be accurately evaluated, and that meaningful comparisons of the performance of different diode types should be between "average" curves.

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APPENDIX A

POWER DENSITY AS A FUNCTION OF
CESIUM RESERVOIR TEMPERATURE:
SUMMARY FOR ALL SEVENTEEN TEST CONDITIONS

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