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TOPICAL REPORT

PERFORMANCE OF A THERMIONIC CONVERTER
WITH A NOMINAL SINGLE-CRYSTAL
<110> TUNGSTEN EMITTER
AND A NIOBIUM COLLECTOR

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I. INTRODUCTION

The performance of single-crystal $\langle 110 \rangle$ tungsten emitter surfaces is important to thermionics, since such a surface can be expected to define an upper limit for the performance obtainable from a tungsten emitter surface. However, exact $\langle 110 \rangle$ oriented material is unavailable in a size suitable for thermionic measurements, and nominally $\langle 110 \rangle$ oriented material must be substituted. This type of data is of interest for theoretical studies, because of the uniformity of the surface, and for practical purposes, for evaluating the performance of surfaces produced by techniques such as chloride vapor-deposition and etching. Since collector material influences converter performance, and since many hardware converters have been constructed of niobium, the characteristics of the $\langle 110 \rangle$ emitter opposite a niobium collector are of considerable practical interest.

II. CONVERTER CONSTRUCTION

The emitter was prepared from a slice of a nominal $\langle 110 \rangle$ oriented single-crystal tungsten bar, made by the Linde Division of Union Carbide. The orientation of the $\langle 110 \rangle$ planes of the various grains was within 4° of the surface. The surfaces of the disc were ground on a surface grinder, and then on SiC abrasive paper to No. 600 mesh; they were next abraded on a glass plate with an aqueous slurry of five-micron Al_2O_3 to produce a damaged, randomly-oriented matte surface. The disc was then vacuum-fired for 3 hours at 2400°C .¹ Figure 1 shows a representative photomicrograph of the surface. Appendix B describes the test converter.

The surface treatment results in a large number of exact $\langle 110 \rangle$ plateaus with the intervening areas having a slightly undulating appearance. Between 70 to 80 percent of the surface has exactly $\langle 110 \rangle$ orientation, as compared to an electropolished surface which has deviations of 4 to 5 degrees from the $\langle 110 \rangle$ direction. The heat-treated surface was chosen because of the high degree of exact $\langle 110 \rangle$ orientation.

The active area of the collector and guard was formed by brazing slices from a niobium rod to the molybdenum substructures. This arrangement takes advantage of the high thermal conductivity of molybdenum while allowing a variety of collector materials to be incorporated into test converters. As the final machining operation, the surface was faced to a 32 microinch finish. A schematic of the converter is shown in Figure 2. Note that the niobium emitter shield also acts as a getter; this feature is particularly important when the collector body is not niobium.

The electrode surface areas are 2 cm^2 for the collector and 3 cm^2 for the emitter. The guard ring extends approximately 60 mils beyond the edges of the projected emitter area. Spacing is adjusted and measured by three micrometer screws fastened to the emitter and guard support structures. These micrometers are shown in Figure 2. Spacing can be read to a precision of about 0.5 mil, with a minimum value of between 0.25 and 0.5 mil. Emitter temperature is determined by optical pyrometry on a hohlraum in the back surface of the emitter. Temperature readings are corrected to surface values using the bombardment power input to give the heat flux. The accuracy of the measurement is $\pm 10^\circ \text{K}$. Thermocouples close to the respective surface are provided for collector and guard temperature measurement.

Reference 6 describes the temperature measurement and the required corrections.

The collector and guard structures were vacuum-fired before final assembly. Particular care was taken throughout outgassing to maintain the pump pressure below 5×10^{-7} torr. (The converter pressure is actually higher than this, because of the conductivity of the exhaust systems.) If the pressure exceeds this value considerably during some stage of the outgassing, oxides might be formed on the internal surfaces and release oxygen during the subsequent thermionic operation of the converter.

To avoid introducing impurities with cesium, a metal capsule containing predistilled cesium was used; this capsule was prepared by refluxing the cesium while pumping through a cold trap. Figure 3 shows the arrangement for the preparation of the capsule. With this system, the converter was not exposed to any additional contaminants during cesiation.

III. VACUUM WORK FUNCTION

The bare work function of the emitter was measured in a vacuum emission apparatus before the emitter was installed in the converter. The value obtained¹ was 5.14 eV, as compared to the expected² values of 5.4 for $\langle 110 \rangle$ tungsten and 4.7 for polycrystalline material. After outgassing, the work function was again measured, and similar results were obtained. In neither measurement was a strong decrease in work function observed as the emitter temperature was increased, indicating that oxygen effects were minimal. Further testing in the converter over the collector temperature range of 580°K to 1000°K showed that the work

function was independent of collector temperature; this indicated the absence of oxides that could influence subsequent cesiated emission.

IV. PERFORMANCE MEASUREMENTS

Before proceeding with the performance measurements, the cesiated converter was again examined for oxygen effects. Figure 4 shows a typical curve from such a test. The saturation current of the J-V curve is observed while the collector temperature is varied. The curves shifted on the voltage axis as the collector work changed, but no significant variations in saturation current were observed. At low cesium pressure and emitter temperature, this is a very sensitive test, since as little as 10^{-8} torr of oxygen can be expected to change the cesiated work function considerably.

Families of volt-ampere characteristics were obtained by changing the cesium pressure while the other converter parameters were held constant. The data cover the emitter temperature range of 1600 to 2000 °K and the interelectrode spacing range of 0.5 to 40 mils. Typical cesium families for the interelectrode spacing of 10 mils are shown in Figures 5 through 9 and the data for other interelectrode spacings are shown in Appendix A. The emitter temperature indicated represents the temperature at the emitting surface, and the collector temperatures were chosen to be in the vicinity of the optimum values. The output voltage is measured from a voltage tap at the cold end of the emitter sleeve and requires a correction of 1.5 mV per amp/cm² for conversion to electrode voltage. In order to facilitate the use of these data for analysis and correlations of converter parameters, the cesium pressures (P)

and the interelectrode spacings (d) in these data are chosen to provide the Pd products of . . . , 5, 10, 20, 40, . . . mil-torr. A table for conversion from cesium reservoir temperature to cesium pressure is shown in Table I, and the envelopes of the cesium families are summarized in Figures 10 through 14. Each curve in these figures represents the optimized performance with respect to cesium pressure and collector temperature. The fully optimized performance is shown in Figure 15.

In reference 3, data are reported on the thermionic performance of a group of chloride tungsten-niobium converters. The converter with the highest performance (C_1 -5 in reference 3) is chosen for comparison with the data in the present paper. The cesium optimized performances of the two converters at an interelectrode spacing of 8 mils and emitter temperatures of 1700 and 1900°K are shown in Figure 16. The "single-crystal" emitter shows a higher performance at both emitter temperatures. Therefore, it appears that further increases in performance can be achieved by improving the vapor deposition techniques.

V. COLLECTOR WORK FUNCTION

The work function of the niobium collector in the present converter was measured by back emission technique. Acceptable data, which could only be obtained for a narrow range of operating conditions, are compared with work function values from a molybdenum collector⁴ in Figure 17. Two sets of data were obtained in the same type of converter with similar procedures for construction, outgassing, and cesiating. Both converters were equipped with

TABLE I
CESIUM VAPOR PRESSURE

CESIUM TEMPERATURE		CESIUM PRESSURE
°C	°K	Torr
163	436	0.016
171	444	0.022
179	452	0.031
187	460	0.044
196	469	0.063
204	477	0.088
214	487	0.13
223	496	0.178
234	507	0.25
244	517	0.35
255	528	0.50
266	539	0.71
278	551	1.0
291	564	1.4
304	577	2.0
318	591	2.8
332	605	4.0
347	620	5.7
363	636	8.0
380	653	11.
398	671	16.
416	689	23.

niobium getters surrounding the interelectrode space. It is interesting to notice that the work function of the niobium collector is approximately the same as the work function of this particular molybdenum collector. Molybdenum work function data from a third converter⁵ which was not equipped with niobium getters are lower by 0.1 eV. It is possible that the lower collector work function values are caused by oxygen contamination.

Some typical raw data (I-V curves) for the niobium collector converter have been included in Appendix C. These curves are presented to show the character of the data in the various regions of the collector work function measurements.

VI. CONCLUSIONS

The performance of a variable-spacing converter with a specially-prepared $\langle 110 \rangle$ tungsten emitter and a niobium collector was recorded for the emitter temperature range of 1600 to 2000°K and an interelectrode spacing range of 0.5 to 40 mils. These data, though not from an exact $\langle 110 \rangle$ emitter, still show a higher output power than data from a chloride tungsten emitter. It appears that further increases in performance can be obtained by improving vapor deposition techniques. The work function of this niobium collector is in agreement with data from a molybdenum collector surrounded by niobium getters, and is higher by 0.1 eV than similar data from a molybdenum collector without niobium getters.

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Figure 1. Photomicrograph of Representative Area of Emitter W25
Before Operation in Converter.

Figure 2 Schematic Diagram of a Research Thermionic Converter.

Figure 3. Apparatus for Refluxing Cesium and Preparing Metal Capsules.

Figure 4. Typical Collector Family of I-V Characteristics.

Figure 5. Variable Cesium Temperature Family at $T_e = 1600^\circ\text{K}$.

Figure 6. Variable Cesium Temperature Family at $T_e = 1700^\circ\text{K}$.

Figure 7. Variable Cesium Temperature Family at $T_e = 1800^\circ\text{K}$.

Figure 8. Variable Cesium Temperature Family at $T_f = 1900^\circ\text{K}$.

Figure 9. Variable Cesium Temperature Family at $T_g = 2000^\circ\text{K}$.

Figure 10. Cesium Optimized Performance for Several Interelectrode Spacings at $T_E = 1600^\circ K$.

Figure 11. Cesium Optimized Performance for Several Interelectrode Spacings at $T_E = 1700^\circ K$.

Figure 12. Cesium Optimized Performance for Several Interelectrode Spacings at $T_E = 1800^\circ K$.

Figure 13. Cesium Optimized Performance for Several Interelectrode Spacings at $T_E = 1900^\circ K$.

Figure 14. Cesium Optimized Performance for Several Interelectrode Spacings at $T_E = 2000^\circ K$.

Figure 15. Fully Optimized Performance at Several Emitter Temperatures.

Figure 16. Comparison of Cesium Optimized Envelopes of the Present Emitter with a Chloride Tungsten Emitter at the Interelectrode Spacing of 8 mils.

Figure 17. Work Function of the Niobium Collector.

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APPENDIX A

CESIUM TEMPERATURE FAMILIES
FOR VARIOUS EMITTER TEMPERATURES
AND INTERELECTRODE SPACINGS

Figure A-1.

A-1

Figure A-2.

Figure A-3.

Figure A-4.

Figure A-5.

Figure A-6.

Figure A-7.

Figure A-8.

Figure A-9.

Figure A-10

Figure A-11.

Figure A-12.

Figure A-13.

Figure A-14.

Figure A-15.

Figure A-16.

Figure A-17.

Figure A-18.

Figure A-19.

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APPENDIX B
TEST CONVERTER

The test converter is a variable-parameter research-type device. It utilizes an active collector guard ring and a planar geometry. The parameters whose values can be varied and accurately controlled include the emitter temperature, the interelectrode spacing, and the collector and reservoir temperatures. The active collector guard ring renders the conversion process free from any radial geometric dependence, and precisely defines the active area of the device. The converter together with its supporting spacing mechanism and heaters is shown in a schematic drawing in Figure B-1 and in a photograph in Figure B-2. The converter itself is shown in Figure B-3.

The emitter is mounted above the collector assembly and has a sleeve extending away from the collector. This arrangement greatly reduces stray effects due to sleeve emission. A niobium shield surrounding the sleeve further reduces the stray emission currents, while at the same time it serves as a getter and provides thermal protection for the spacing bellows. The emitter is heated by electron bombardment from a filament mounted inside the emitter sleeve, while a tantalum shield on the electron gun keeps the sleeve from being bombarded. A hohlraum in the rear face of the emitter is used for temperature measurement. Several additional holes are provided for thermocouple or photocell temperature measurement and control.

The collector-guard assembly is fabricated from molybdenum but provides for different electrode materials through the use of brazed-in plates in the active converter region. A sapphire spacing ring determines the vertical distance between the guard and collector electrode surfaces. A value of 1 - 1.5 mil is established during machining. The radial alignment is maintained by a series of sapphire balls retained in a groove

just below the collector face. The radial spacing is about 4 mils. A pair of thermocouple holes in the guard is used for temperature control. In the collector, there are three sets of holes which provide additional heat flux measurement capabilities. The active area of the collector is 2 cm^2 , while that of the emitter is 3 cm^2 . A collector guard assembly is shown in Figure B-4.

The flexible nickel bellows is partially welded together before being brazed to the emitter and collector subassemblies. The final diode closure is made by electron beam welding the emitter section bellows flange to that of the collector section. There is sufficient flexibility to allow spacing excursions from 0 to 100 mil. The collector and guard heater-coolers are maintained in good thermal contact with the collector and guard structures by spring-loading on the tapered mating surfaces. The design allows the electrode temperatures to be controlled with both high and low current static loading.

Cesium pressure in the converter is controlled from a liquid reservoir connected to the active region by a tube on the mounting plate for the emitter sleeve. The reservoir is electrically heated and water cooled to give a fast response when the temperature must be changed. The heater-cooler is arranged to maintain the temperature gradients in the liquid to less than 1°C .

Interelectrode spacing is adjusted by varying the distance between the emitter ring and the guard support plate. The spring loading on the heater-coolers also serves to maintain solid contact between the rigidly mounted guard locating plate and the guard surface. Three micrometers, mounted on the water-cooled emitter support plate, are extended to the guard locating plate through three ceramic

rods. The micrometer control shafts are brought through the top plate of the vacuum bell jar to allow spacing adjustment during converter operation. A gear box on the outside of the bell jar provides either separate or combined control of the micrometers. Spacing changes may be read directly from the micrometers and a zero reference is established by momentarily shorting the converter. The electrodes can be set and maintained parallel within 0.3 mils at the emitter edge, and the spacing mechanism has a precision of 0.2 mils. Minimum spacing is typically 0.2 - 0.5 mil but tends to increase each time the device is shorted and material is pulled from the collector. Usually a minimum is determined for each emitter temperature during initial testing and this value is used for all further experiments.

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Figure B-1. Research Variable Parameter Converter.

70-TR-5-1 (I-972)

Figure B-2. Variable Parameter Converter, Ready for Outgassing.

70-TR-5-2 (I-973)

Figure B-3. Variable Parameter Converter Without Tubulation.

70-TR-5-3 (I-974)

Figure B-4. Collector Guard Subassembly.

APPENDIX C

TYPICAL RAW DATA FROM COLLECTOR
WORK FUNCTION MEASUREMENTS

Run 42385

$T_E = 1500^\circ\text{K}$

$T_C = 400^\circ\text{C}$

$T_R = 161^\circ\text{C}$

70-TR-1-17

C-4

I-980

C-6

I-975

8-C

I-985

6-C

1-977

C-10

C-11

C-12

70-TR-1-12

70-TR-1-10

Run 42301

$T_E \approx 1500^\circ\text{K}$

$T_C = 900^\circ\text{K}$

$T_R = 545^\circ\text{K}$

$d = 1\frac{1}{2}$ mils

C-15