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Performance Evaluations of a Nonfueled and a UO_2-Fueled Cylindrical Thermionic Converter

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Preface

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Abstract

Two cylindrical thermionic energy converters similar to those in a "flashlight" thermionic fuel element were tested electrically at the Jet Propulsion Laboratory. One converter was not fueled, but the other was fueled with UO_2 imbedded in six pencil-lead-size holes in the emitter, which was made of rhenium. The nonfueled converter was tested primarily for endurance under open-circuit conditions that might occur as a result of a loss of cesium or a broken power lead. The UO_2-fueled converter was tested for fuel-converter compatibility under normal operating conditions with an electric load.

The nonfueled converter showed no change in its performance during 4,000 h of testing, whereas the output current of the UO_2-fueled converter degraded 15% during 2,400 h of testing at 2,000°K. Measurements on the UO_2-fueled converter showed an increase in the collector work function and an increase in the bare emitter work function, which indicate that the degradation was caused primarily by foreign deposits on the collector, probably uranium that effused from the UO_2 fuel through the emitter.

Performance Evaluations of a Nonfueled and a UO_2-Fueled Cylindrical Thermionic Converter

I. Introduction

Two nuclear-type thermionic converters for reactor thermionic power systems, which are to generate the tens of kilowatts of electrical power required for electric ion engines, were performance and life-tested out-of-core. The converters tested had a cylindrical electrode geometry similar to that of a converter in the "flashlight" thermionic fuel elements. One converter was not fueled and was tested (and is being tested) mainly to investigate the long-term performance of a converter operating under the open-circuit conditions that might occur during the life of a power system utilizing thermionic converters. Such conditions would occur if the cesium were depleted or an output lead were broken. The other converter was UO_2-fueled and tested to correlate its long-term power output with basic converter parameters including work functions, so that the fuel-converter compatibility could be evaluated. This was the first investigation of a converter with a UO_2-fueled rhenium emitter.

II. Converter and Test Setup

Both converters tested were the RD 502 series converters fabricated by the Thermo Electron Corporation, Waltham, Massachusetts, and their construction was identical to that described in Ref. 1. The emitter of each converter was an electroetched rhenium cylinder with a diameter of 1.27 cm and a length of 3.81 cm; hence the emitter area was 15.2 cm^2. The collector of each converter was niobium with a thin film of vacuum-deposited molybdenum to achieve a low collector work function. The interelectrode gap of both converters was 0.203 mm.

During the laboratory tests, the emitter was electrically heated by electrons bombarding it from a gun filament inserted into the cylindrical cavity of the emitter (Fig. 1). The bombarding current was electronically maintained constant at a preset value to avoid undesirable drift of the emitter temperature. The emitter temperature was measured with tungsten-5%-rhenium vs tungsten-26%-rhenium thermocouples during the parametric tests. The emitter temperature was also measured as a function of the total heating power (heating power = filament power + bombarding power), so that the temperature could be estimated after the emitter thermocouples became inoperative. The collector was cooled with a water jacket that was attached to the collector through copper fingers, and the collector temperature was varied by the use of a collector heater. A separate heater was attached to the

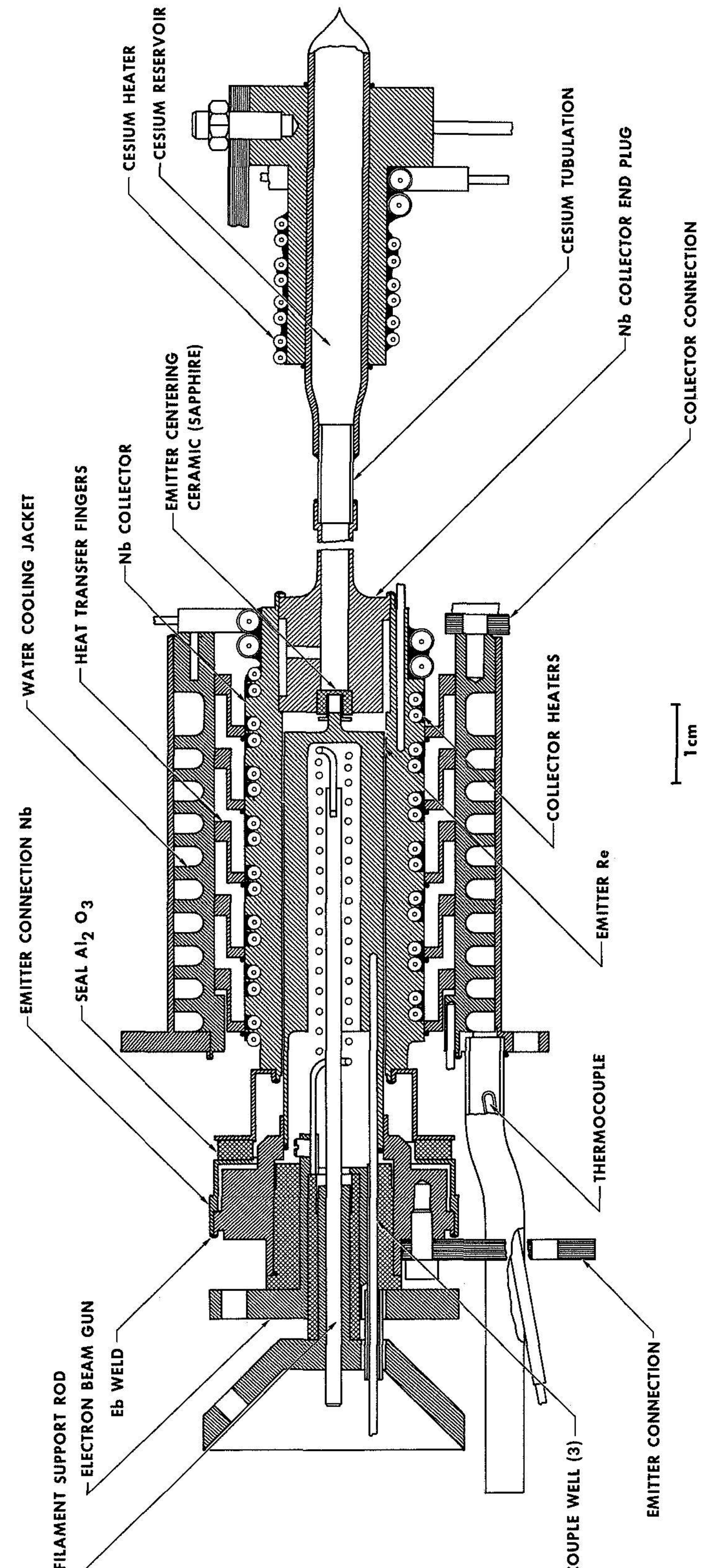

Fig. 1. Schematic drawing, RD 502 series converter

cesium reservoir, and both heaters were current-controlled to maintain the desired temperatures as measured by chromel-alumel thermocouples.

The converter was placed in a metal vacuum bell jar (Ref. 2); a 600 l/s Vac-Ion pump was used to keep the background pressure below 1×10^{-4} N/m² with the converter at operating temperatures.

All data, including thermocouple readings, output voltages and currents, and the input voltages and currents were recorded by a 6-digit digital voltmeter. During the life tests, the output quantities, collector temperatures, cesium temperatures and the emitter temperatures were recorded on a 12-channel strip-chart recorder. Also, for the measurement of work functions, the dynamic data acquisition system (Ref. 3), which was developed at the laboratory, was used in lieu of the electronic load used during life test.

III. Test Results

A. Nonfueled Converter, RD 502-12

1. Temperature calibration. Calibration of the emitter temperature was first performed by measuring emitter temperatures with three immersion thermocouples located at three different points along the length of the cylindrical emitter with the electric load disconnected. Temperatures T_E measured at the center (equal distance from the bottom and top of the emitter body), are plotted in Fig. 2 as a function of the total input power. For comparisons, the total emissive power from a tungsten filament (Ref. 4) is also shown in a chain line. The total area used in this calculation was 17.7 cm² since the cylindrical emitter area

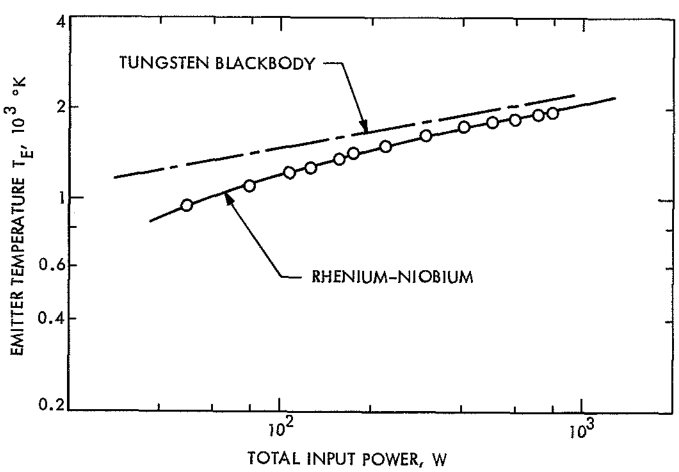

Fig. 2. Temperature calibration curve, open-circuit RD 502-12

(15.2 cm²) and both ends of the emitter (2.5 cm²) contributed equally to the thermal radiation. Larger deviations from the radiation law at lower temperatures were caused by conduction losses through the emitter support, the cesium vapor, and the gun filament structure. The conduction losses were estimated to be 36 W and 124 W at 1,000°K and 2,000°K, respectively. Since the total input power less the conduction losses must be lost by radiation, an effective emissivity of the combination of the rhenium electrode and the molybdenum-coated niobium collector were then determined. It was 0.395 at T_E = 2,000°K; this value, which is larger than the emissivity of tungsten by approximately 50%, may have resulted from an increase in emissivity by the electroetching of the rhenium emitter and a vapor deposition of molybdenum on the niobium collector during fabrication.

The measurements also showed that the temperatures varied between +150°K at the bottom and −150°K at the top of the emitter, with respect to the middle temperature of approximately 2,000°K. However, these temperatures tended to equalize when the converter was connected to an electronic load, and also the temperature at the bottom of the emitter became lower than that at the top of the emitter in some instances. It appears that an additional electron cooling contributes to the temperature equalization.

2. Static V-A characteristics. The static volt-ampere characteristics of the converter were obtained by connecting it to a transistorized electronic load designed to maintain the preset output voltage under varied output current conditions. During the acquisition of any one volt-ampere curve (Fig. 3), the total input power was maintained constant to simulate operation in a nuclear reactor that also had a constant power. To correlate the output power with the emitter temperature T_E for each input power, the temperature was estimated from the temperature calibration curve (Fig. 2) that was obtained for the open-circuit converter. The method for obtaining this estimate follows:

(1) The best estimate of T_E was picked for a given current at a given total input power P_{in}; for example, T_E = 1,820°K, I = 51.5 A at P_{in} = 700 W.

(2) Losses due to the converter current were estimated by calculating electron cooling losses P_e from $P_e = I(\phi_E + 2kT_E)$, in which the effective emitter work function ϕ_E was calculated from the Richardson equation; for example, when I = 51.5 A and T_E = 1,820°K, ϕ_E = 2.93 eV, the electron cooling P_e was 168 W.

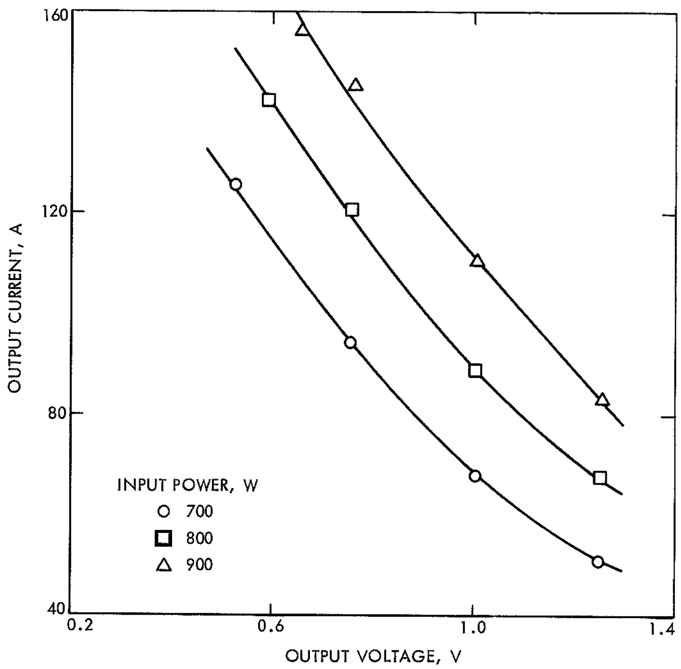

Fig. 3. Static volt-ampere curves, RD 502-12

(3) T_E on Fig. 2 was read for the reduced total input power at $P_{in} - P_e$; for example, $T_E = 1{,}820°K$ at $P_{in} - P_e = 532$ W. In this calculation, $P_{in} - P_e$ was considered equal to the input power required to raise the temperature of the emitter in an open-circuit converter. Since the cesium conduction losses and other stray losses, approximately 5% of $P_{in} - P_e$, were neglected, a maximum of 30°K error exists in the estimated T_E.

(4) The process from (1) to (3) was iterated where the original estimate did not agree with the value in (3); the emitter temperature calibration curve shown in Fig. 4, for the converter having an electronic load, was obtained by repeating the calculations for three different input powers.

It is seen that the emitter temperature decreased linearly with output current at a different rate depending upon the input power. These curves will be used for determining the emitter temperature of a converter under load. The output volt-ampere curves shown in Fig. 3 were redrawn for Fig. 5 as output power curves for three different input powers. The maximum output power of 112 W occurred at 0.9 V with an input power of 900 W. An emitter temperature estimated from the temperature calibration curve was 1,815°K at this point, where the output power density was 7.37 W/cm² (= 112 W/15.2 cm²), and the measured efficiency was 12.4% (= 112 W/900 W × 100). In Fig. 5, it is also shown that the output

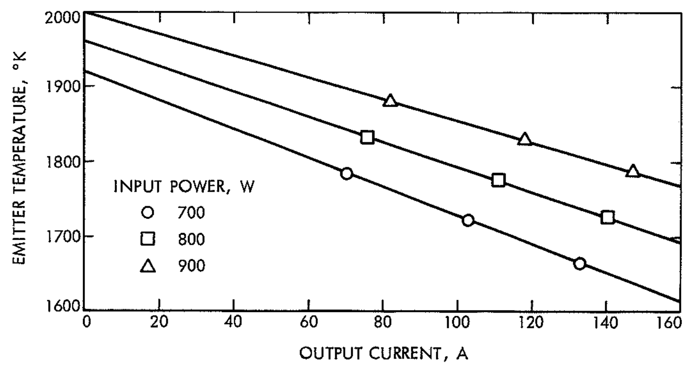

Fig. 4. Temperature calibration curve, loaded RD 502-12

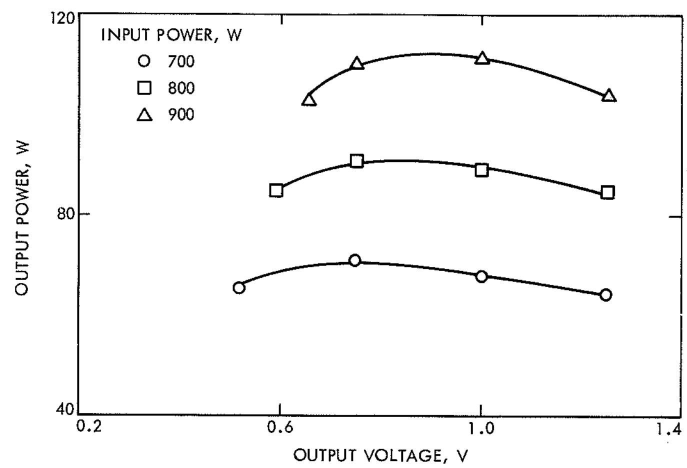

Fig. 5. Output power vs output voltage, RD 502-12

power did not vary appreciably as the output terminal voltage was varied as long as the input power, not the emitter temperature, was maintained constant. This was a result of the self-adjustment of the emitter temperature. At larger output voltages where the output current was small, the emitter temperature increased if the input power remained constant, and hence the current did not diminish rapidly as it would if the temperature remained constant. For example, the emitter temperature varied between 1,700°K and 1,880°K as the output voltage varied between 0.65 V and 1.25 V at $P_{in} = 900$ W. This self-adjustment is desirable from a viewpoint of converter operation in a nuclear reactor where the input power, and not the emitter temperature, is maintained constant.

3. *Work function measurements.* To correlate any change in the converter performance with converter parameters during the life test, the emitter work functions were determined from volt-ampere curves by the pulsed dynamic data system (Ref. 3); typical curves are

shown in Fig. 6. The emitter work functions are shown in Fig. 7 as a function of the temperature ratio, T_E/T_R, between 3.2 and 4.3. This result shows that the emitter had a bare work function of 4.8 eV, indicated by a dashed line in the figure, which is in good agreement with that of a polycrystalline rhenium. The collector work functions were determined from volt-ampere curves in an electron-retarded voltage region as a difference between the emitter work function and the voltage at the knee of the curve. The collector work function was approximately 2.0 eV, which was higher than expected, at the temperature ratio T_C/T_R of 1.7. A possible reason for this is that the molybdenum coating of the collector was insufficient in this converter, or that foreign deposits existed on the collector.

During the life test of the converter, the electrode work functions were periodically examined for any change. Results are discussed under the following subheading.

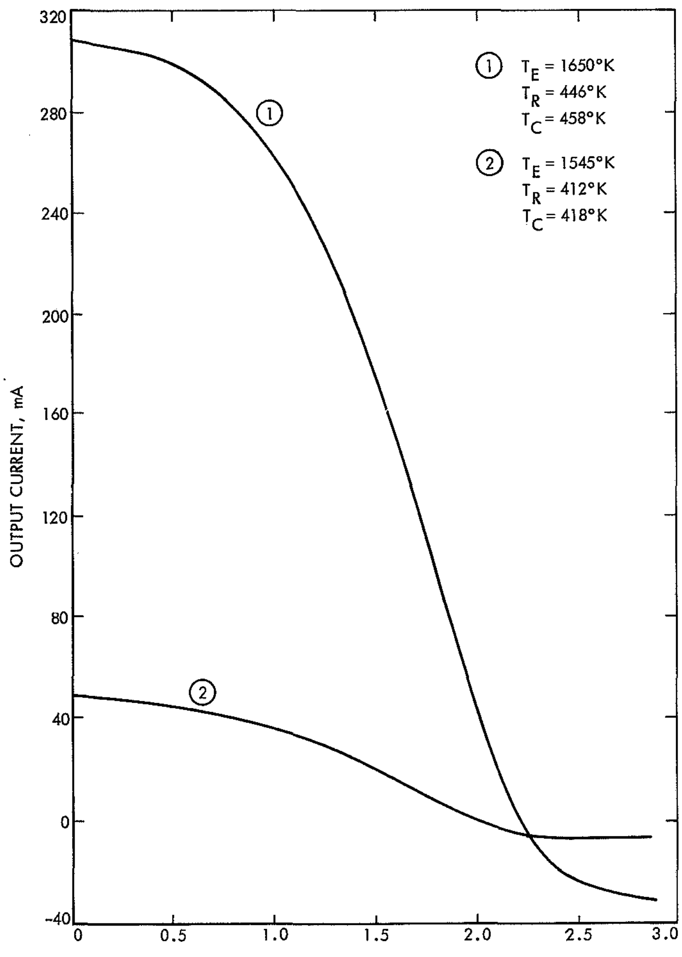

Fig. 6. Dynamic volt-ampere curves, RD 502-12

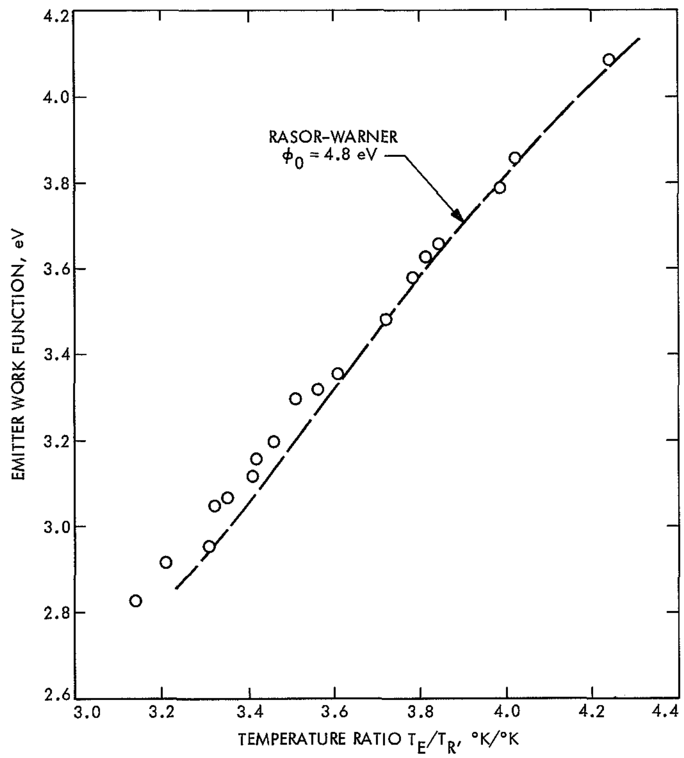

Fig. 7. Nonfueled rhenium emitter work function, RD 502-12

4. Life tests. The life test of this converter was unique in that the test was performed under open-circuit conditions. The purpose of this test was to investigate any peculiarities that might occur under open-circuit conditions that simulate a loss of cesium or a broken output lead. The test, which began on August 28, 1970, follows:

(1) The converter was connected to an electronic load and both the cesium and the collector temperatures were optimized at an output voltage of 0.8 V and an estimated emitter temperature of 1,800°K.

(2) Static data were recorded.

(3) The cesium reservoir temperature was reduced to a minimum.

(4) The converter was open circuited to raise the emitter temperature and the input power was trimmed to 870 W, at which the temperature was 2,000°K.

(5) Data including the open circuit voltage were recorded.

(6) The converter was continuously operated without the load under constant input power conditions of 870 W.

(7) The converter was periodically connected to the load, and (1) and (2) were repeated to check any change in performance.

(8) Work functions were checked whenever any change was noticed; otherwise, they were checked at a 4-mo interval.

The open-circuit voltage of the converter, approximately 2.0 V, remained unchanged although there were occasional anomalies due to instabilities or oscillations in the converter. It was concluded that the open-circuit voltage was not a satisfactory indicator of degradation in the converter's performance since it was sensitive also to changes in cesium pressures and collector temperatures. Therefore, the converter performance was periodically verified by measuring the output current upon connecting the converter to the load. The results are shown in Fig. 8 where the current is seen unchanged during the 9 mo of tests (4,000 h) at an estimated emitter temperature of 2,000°K. The stability of this converter was also substantiated by the work function measurements, which indicated no change.

To accelerate changes in performance of the converter during open-circuit operation, the input power was raised to 1,200 W, at which point the estimated T_E increased from 2,000°K to 2,150°K.

At a power input of 1,200 W, the optimized power output was 142 W at 0.8 V; hence, the power density was 9.34 W/cm^2 with the conversion efficiency at 12%. The emitter temperature at this load was estimated to be 1,950°K from the temperature calibration curve with an electron cooling of approximately 450 W; without the load it was 2,150°K. After this measurement, the converter was again open circuited and the life test with an input power of 1,200 W was resumed.

B. UO_2-Fueled Converter, RD 502-13

The construction of this converter was identical to that of RD 502-12, except that No. 13 had six pencil-lead-size (0.127 cm diameter by 3.18 cm length) UO_2 fuel rods imbedded in six coaxial holes drilled in the emitter cylinder; the closest distance between the fuel and the emitter was 0.09 cm. The interelectrode gap of this converter was 0.0203 cm.

1. *Emitter temperature curve.* The emitter temperature was measured at the middle of the emitter as a function of the total input power. The results shown in Fig. 9 indicate that the temperature was higher in this converter than in No. 12. The difference may be attributed to a difference in the emissivity of electrodes. This curve will be used during subsequent life tests if the emitter thermocouple becomes inoperative.

2. *Life tests.* On October 1, 1970, the converter was put in a life-test mode with T_E = 1,900°K to investigate the compatibility between the UO_2-fuel and the rhenium emitter in which the fuel was imbedded.

The converter was connected to an electronic load, and the input power was maintained constant during the life test such that T_E was at 1,900°K. The initial value

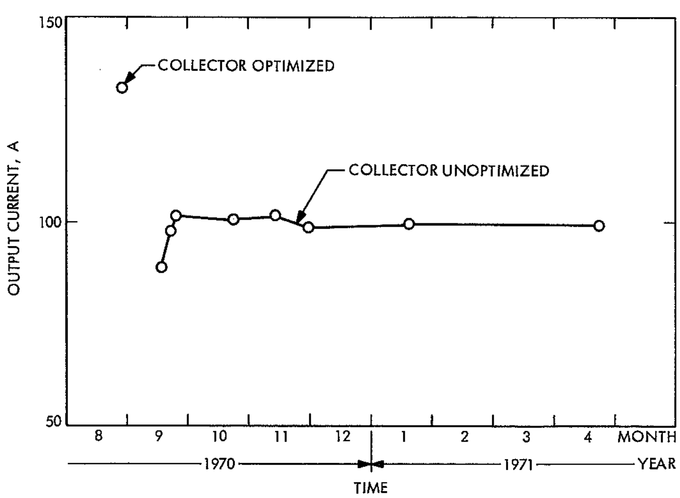

Fig. 8. Output current vs time, RD 502-12

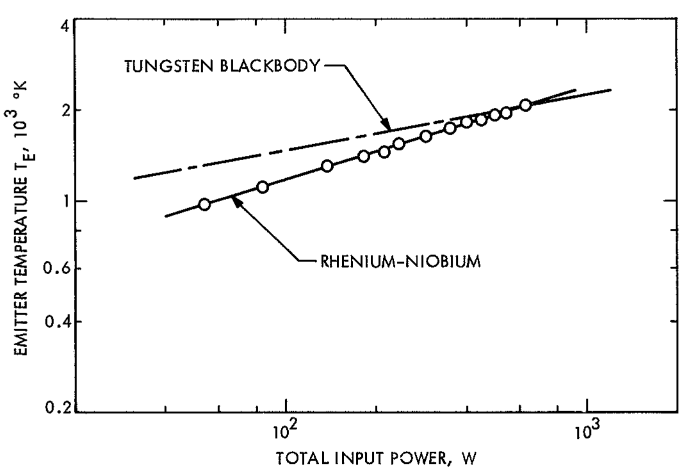

Fig. 9. Temperature calibration curve, open-circuit RD 502-13

for the output power was 51 W at an output voltage of 0.9 V. The output increased slowly to 62 W in the first 480 h at which time the input power was increased to 870 W to increase the emitter temperature to 2,000°K. The initial work functions for the emitter and the collector were 5.1 eV with the emitter uncesiated and 1.4 eV with the collector at T_C/T_R = 1.3. The converter was re-optimized at T_E = 2,000°K, at which the output power was 98 W (6.5 W/cm²) at an output voltage of 0.9 V. Since the input power was 870 W, the measured efficiency was 11% at T_E = 2,000°K; this performance was inferior to that of the nonfueled converter, No. 12. The life test continued at this emitter temperature with a periodic reoptimization and continued data acquisition. The collector temperature was not optimized since the collector heater had become inoperative during the life test.

As shown in Fig. 10, the output current decreased slowly from 110 A at 480 h to 94 A at the end of 2,400 h of operation. Fluctuations about the average line shown by a dotted line were correlated with the variations in the input power; therefore, a smoother dotted curve could have resulted if there were no variations in the operating parameters of the converter. To further correlate the observed degradation with fundamental parameters of the converter, the electrode work functions were measured at the beginning of the life tests and 1,200 h and 2,400 h thereafter. The work functions of the emitter and the collector are plotted as functions of the temperature ratio in Figs. 11 and 12 at three different dates. The bare emitter work function is seen to have increased by 0.3 eV from 5.1 eV to 5.4 eV during the first 1,200 h of operation. As also seen, the cesiated emitter work function decreased by approximately 0.3 eV during the same period. Conversely, the cesiated collector work function continuously increased by approximately 0.4 eV during the total of 2,400 h. To compare the output performance with the work functions, the cesiated work functions of electrodes at the operating temperature ratio are also plotted as a function of time in Fig. 13. Comparison of Figs. 10 and 13 shows that the initial degradation appears to be correlated with the decrease in the cesiated emitter work function, or the increase in the uncesiated emitter work function, whereas the slow degradation during the last half of the life test is correlated with the increase in the cesiated collector work function.

The unusually large increase in the uncesiated work function appears to be a result of an electronegative gas such as oxygen from the emitter. This fact is substantiated by correlating the work function with the optimum cesium reservoir temperature, which decreased as much as 20°K from 536°K during this life test (Fig. 14); a lower reservoir temperature is required for the optimization of a converter having an emitter with

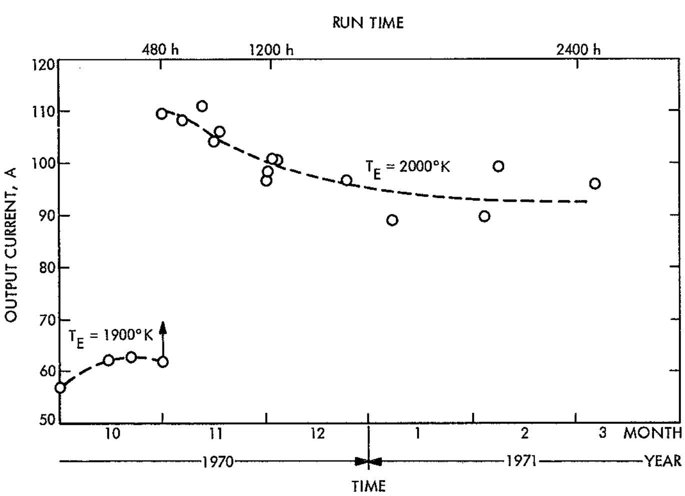

Fig. 10. Output current vs time, RD 502-13

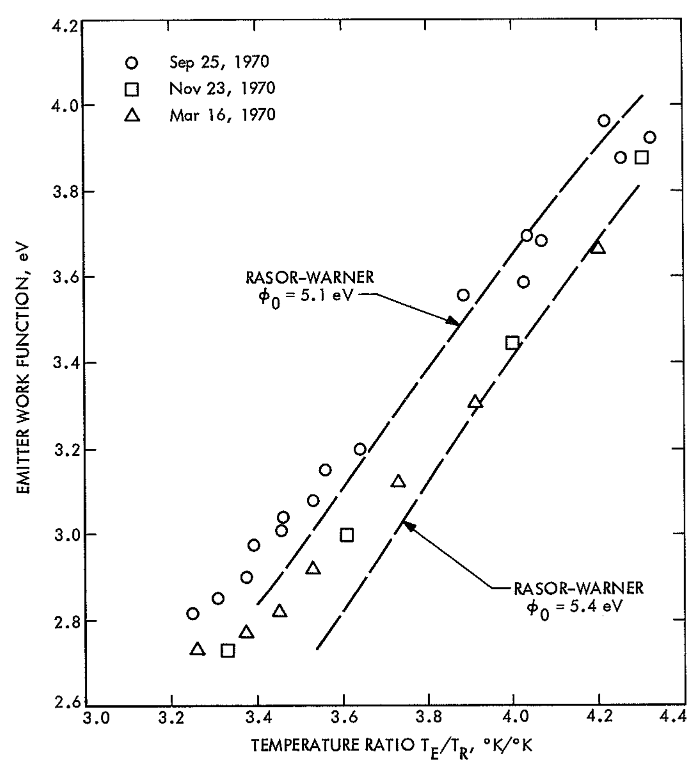

Fig. 11. Fueled rhenium emitter work function, RD 502-13

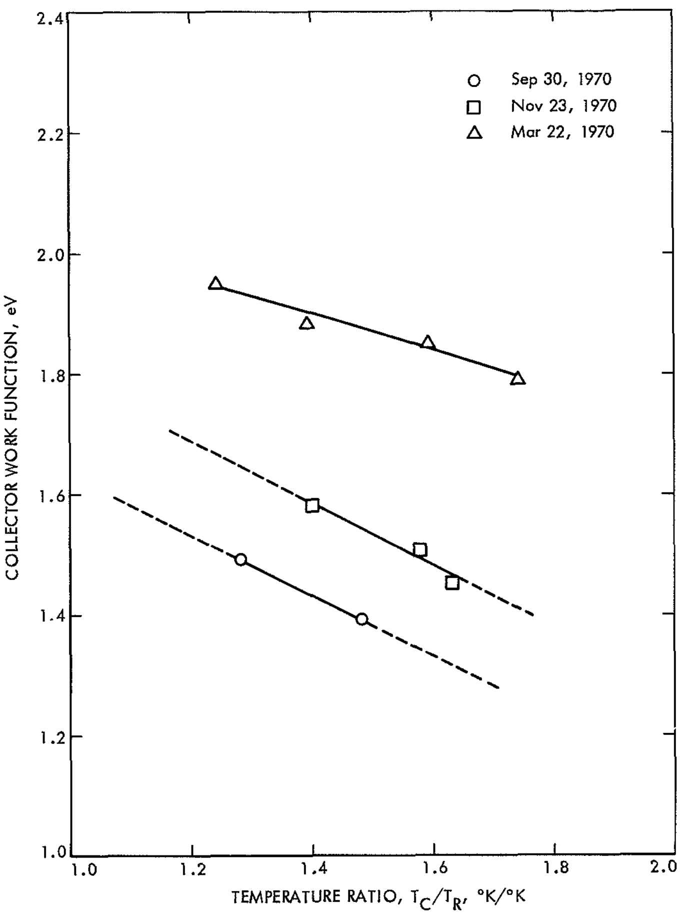

Fig. 12. Molybdenum-coated niobium collector work function, RD 502-13

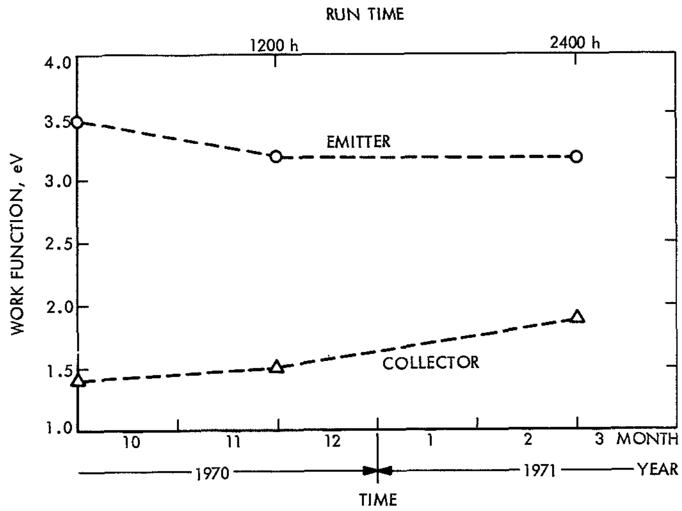

Fig. 13. Cesiated work functions vs time, RD 502-13

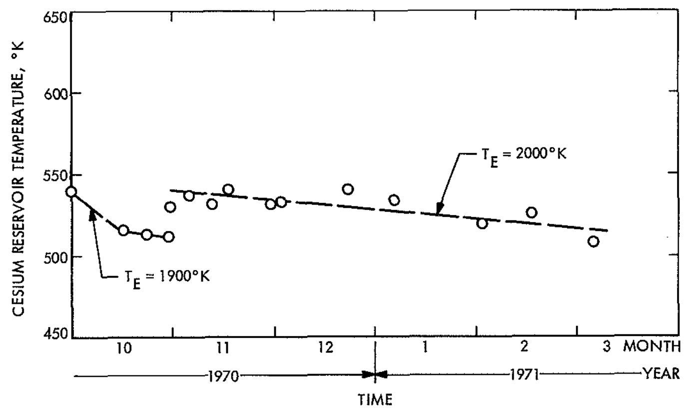

Fig. 14. Optimum cesium reservoir temperature, RD 502-13

higher uncesiated work functions. Note, however, that the cesiated emitter work function remained unchanged after 1,200 h of test as shown in Fig. 13.

Conversely, the effect attributable to oxygen on the collector work function was not evident. The increase in the cesiated collector work function was caused apparently by some sort of an electrode poisoning, probably by uranium from the emitter.

IV. Conclusion

Two nuclear-type thermionic energy converters having a cylindrical geometry were performance and life-tested out-of-core. A converter without a nuclear fuel has been and is being life tested in an open circuit condition to simulate the loss of cesium or a broken output lead. These conditions would increase the emitter temperature by approximately 200°K when the power input is kept unchanged as it would be in a reactor. During the life test at an estimated emitter temperature of 2,000°K, no changes in the performance of the converter, open circuit or otherwise, were observed.

Another converter with UO_2 fuel has been tested to determine the effect of the fuel on the performance of a converter that is operating under an electronic load in a normal manner. The output current of this converter degraded 15% during the 2,400 h of life test at an emitter temperature of 2,000°K. To provide further information of the fuel-converter compatibility, the electrode work functions were carefully measured at the beginning of, and during the life tests. The results showed that the uncesiated emitter work function increased by

0.3 eV to 5.4 eV during the 2,400 h of test. At the same time, the cesiated collector work function increased by 0.4 eV to 1.8 eV. These changes in the work function indicate that the UO_2 fuel diffused from the emitter and modified the electrode work functions.

The tentative conclusions are:

(1) The oxygen and the uranium both diffused through the rhenium emitter at temperatures ranging between 1,900 and 2,000°K.

(2) The oxygen increased the uncesiated emitter work function according to Rasor-Warner.

(3) The uranium continuously evaporated at the emitter and deposited on the collector.

(4) Oxygen was gettered by the cesium.

The effect of the fuel on the converter performance could have been overlooked unless the work functions were measured in situ because the change in work functions occurred in such a way that the loss of power output was compensated. Therefore, it is important to incorporate the work function measurements with the life tests so that any change in the converter performance can be identified promptly and accurately.

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