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A REVIEW OF THE OUTPUT PERFORMANCE OF SIX PLANAR THERMIONIC CONVERTERS WITH VARIOUS ELECTRODE MATERIALS

by V. C. Wilson

Prepared by
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16. Abstract

The converters tested had electrode surfaces as follows: (a) emitter polycrystalline W, collector Nb; (b) emitter (100) oriented W etched to expose the (110) planes, collector Nb; (c) emitter (100) W, collector Ni; (d) emitter (110) W, collector Nb; (e) emitter (112) to (114) W, collector W + WO_2 on Nb; and (f) emitter (110) W, collector 50%Mo-50%Nb. All of these electrode surfaces were carefully prepared and characterized before and after testing. Of the various emitters tested, emitter (b) with (100) W etched to expose (110) planes performed best. The performance of the Ni collector was superior to that of the Nb. The most output power was obtained from converter (c) - (110) W emitter with Ni collector.

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FOREWORD

The research described in this report was conducted by the General Electric Company under NASA contract NAS 3-8511 with Dominic C. DiIanni of the Lewis Research Center Nuclear Systems Division as the NASA Project Manager. The report was originally issued as General Electric report GESP-9012.

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SUMMARY

Six parallel plane thermionic converters were built and tested to identify the most promising electrode surfaces. Table 1 indicates the electrode materials used and the spacings tested.

The emitters were carefully prepared and selected for their uniformity and high degree of special crystal orientation. The report describes each converter and summarizes each converter performance. Several figures compare their output performances.

As predicted by the experiments of H. F. Webster, the (110) planes of tungsten (W) are the best planes to be exposed for the surfaces of W emitters. The (110) planes of W are the most stable and offer excellent prospects for long life, stable, high performance emitters.

The emitter that exhibited the best initial performance was a faceted emitter created by etching a (100) surface to expose the (110) planes. This emitter lost part of its performance as a result of operation for 22 hours at $2133^{o}K$.

The inadvertent inclusion of oxygen in one converter demonstrated the high performance at low T_E (emitter temperature) reported by other observers. At high T_E values, the presence of oxygen reduces the output power and greatly shortens the life of the converter by transporting emitter material to the collector.

When compared to the performance of the niobium (Nb) collector, the nickel (Ni) collector was found to be superior. The converter with a W(110) emitter and a Ni collector had the best output performance. This is attributed to the (110) crystal orientation of the W emitter and to the performance of Ni as a collector material. An attempt to compare Nb with Mo for collectors was

Table 1.

	Emitter	Collector	Spacing (Inches)
(A)	Polycrystalline Tungsten	Nb	0.001 to 0.020*
(B)	Vapor Deposited (100) W, (110) Etch	Nb	0.001 to 0.020
(C)	Vapor Deposited (110) W	Ni	0.005
(D)	Vapor Deposited (110) W	Nb	0.002 to 0.020
(E)	Vapor Deposited (112) to (114) W	W + WO_2 on Nb	0.002 to 0.020
(F)	Vapor Deposited (110) W	Mo and Nb	0.005 to 0.020

*This converter did not have a guard ring.

unsuccessful, but did point out the difficulty of putting a thin coating of Mo on a Nb collector to improve a converter's performance.

An appendix compares the output performance of these converters with the performance of other converters reported in the literature.

INTRODUCTION

This work was part of a program to build and operate thermionic converters with various electrode materials in order to characterize, evaluate and identify the most promising electrode surfaces for converter operation. The design of the test converter was conceived and standardized in 1963. It permitted an accurate determination of the electrode spacing and used a guard ring to accurately define the collector area. The guard ring could be kept at the same temperature and potential as the collector. The first 6 lines of Table 2 list the electrode materials and the spacings for 6 converters built according to the 1963 design. The output power from these converters was consistently high and variations in output power could be explained by variations in electrode surfaces.

In 1966, under NASA sponsorship, the program was altered in two respects: (1) a more elaborate converter was built so that the electrode spacing of the converter could be varied, and (2) a much more intensive program to characterize the emitters was inaugurated. The NASA program, covered by Task III of Contract NAS 3-8511, began with the first variable spaced diode tested--namely, item A of Table 2. Six converters, items A through F, were built and tested on this program. The test results are documented in the references listed in the table.

This Summary Report briefly describes the test apparatus, the character of the electrodes before and after testing, the observed performance and provides a discussion of the results. In an appendix, a comparison is made with other published converter tests.

Table 2.

	Emitter	Collector	Spacing (Inches)
(1)	Polycrystalline Tungsten[1]	Ni	0.005
(2)	Polycrystalline Rhenium[1]	Ni	0.005
(3)	Polycrystalline Rhenium[2, 3, 4]	Ni	0.002
(4)	Polycrystalline Tungsten[4, 5]	Ni	0.002
(5)	Polycrystalline Tungsten[5]	W	0.002
(6)	W-25 w/o Re[6]	Ni	0.005
(A)	Polycrystalline Tungsten[7, 8]	Nb	0.001 to 0.020*
(B)	Vapor Deposited (100) W, (110) Etch[9]	Nb	0.001 to 0.020
(C)	Vapor Deposited (110) W[10]	Ni	0.005
(D)	Vapor Deposited (110) W[11]	Nb	0.002 to 0.020
(E)	Vapor Deposited (112) to (114) W[12]	W + WO_2 on Nb	0.002 to 0.020
(F)	Vapor Deposited (110) W[13]	Mo and Nb	0.005 to 0.020

*This converter did not have a guard ring.

DESCRIPTION OF TEST APPARATUS

Figure 1 is a cross section of the test facility with converter A mounted for test. The collector, 6 Z-shaped legs, and a water-cooled ring were machined from a solid piece of vacuum cast Nb. The legs acted as a heat choke. Two electric heaters were used to adjust the collector temperature. The emitter was supported on a thin tantalum (Ta) cylinder mounted on a large emitter radiator. The ceramic-to-metal seal assembly had a flexible diaphram to permit variation of the electrode spacing. The emitter radiator was clamped, with ruby spheres for insulation, to three adjustable legs. These legs were coupled to a planetary gear system so that the three legs could be moved up or down simultaneously. Each leg had a micrometer screw for leveling the emitter. The entire assembly was covered with a vacuum bell jar. However, the base plate had a reentry chamber to house the gear train; therefore, the train could be operated in air and could be lubricated with oil. A Sylphon bellows was provided as a movable vacuum seal on each leg. The emitter was heated from above by electron bombardment.

Except for converter A (polycrystalline W), each of the other five converters had a guard ring surrounding the collector. The collector and guard in these devices could be kept at the same temperature and electrical potential; equal temperatures are necessary to keep the cesium (Cs) coverage and, thus, the work function of the collector and guard the same. In order to improve the Cs envelope integrity, the Mo and Ni parts for converter F were changed to Nb.

Each emitter was examined before and after operation in the converter. Usually the emitter used was one of four or five prepared and examined for uniformity. After a mechanical polish and an electropolish, each emitter was heated in vacuum to 2500 $^{\circ}$C for a half hour. Vacuum work function measurements were made before and after this treatment. An x-ray determination was made of the average crystal orientation of the material near the surface. The emitter was then given a light etch to form etch pits.

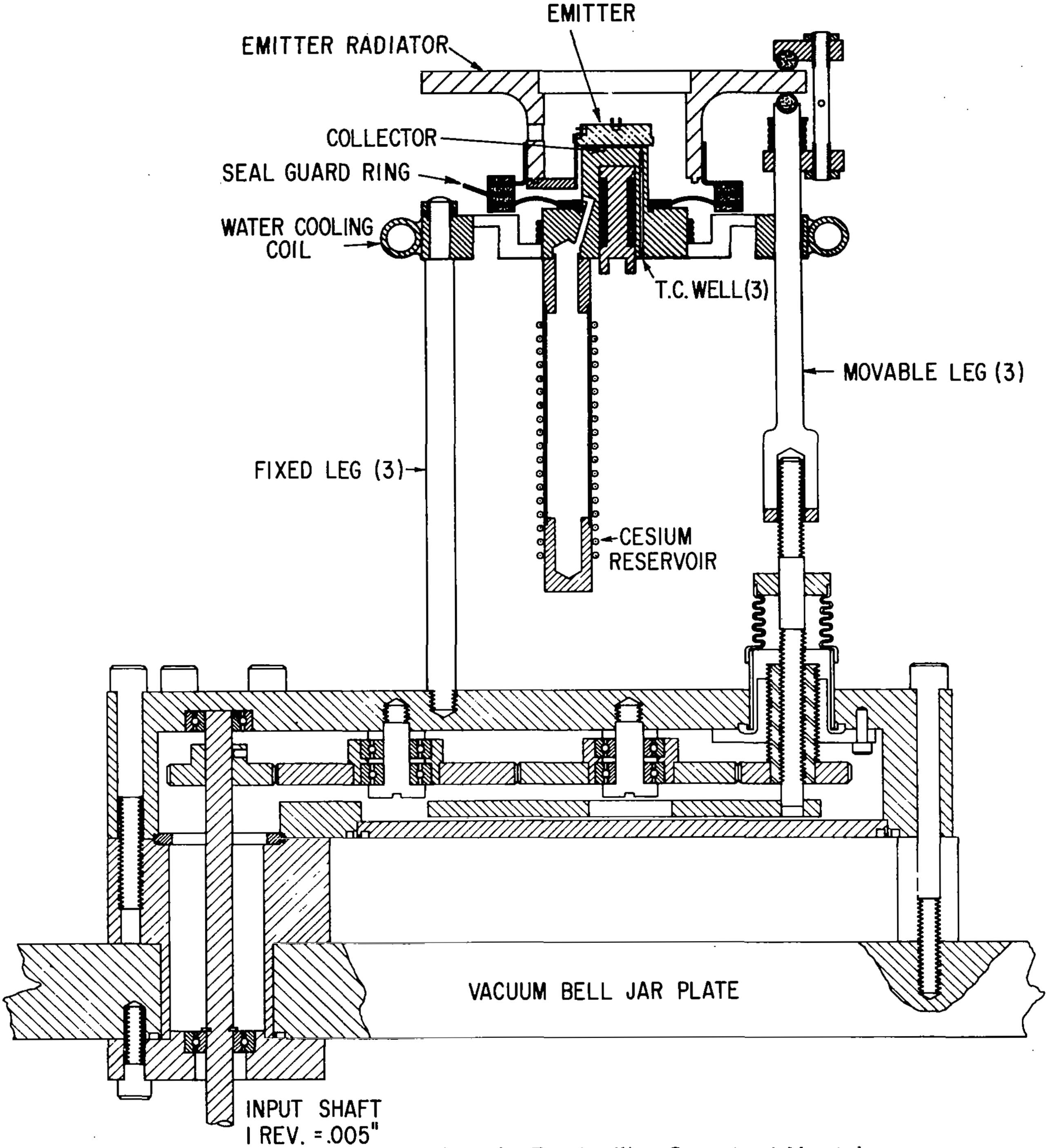

Figure 1. Test Facility, Converter A Mounted.

This technique, developed by H. F. Webster, proved valuable in estimating what fraction of the surface had a particular desired orientation. The pits were removed by a second electropolish. Finally, the average vacuum work function of the emitter was determined by saturation emission versus temperature. The electrode examination after operation in a converter consisted of a visual observation followed by an x-ray analysis for orientation and analysis of any observed deposit and in one case an Auger analysis of the surface composition.

TEST PROCEDURES

The electron bombardment for the emitters was controlled by a circuit that monitored the bombardment current and adjusted the filament temperature to hold the bombardment current at a selected level. The emitter temperature was determined by an optical pyrometer observation of a black-body cavity. Each guard and each collector had three thermocouples inserted in deep holes to monitor temperatures close to the electrode surfaces. One thermocouple was used to actuate a temperature controller, the other two were monitors. The cesium reservoir was controlled by a specially constructed controller operating from thermistor sensors. In addition, there were two thermocouple monitors.

Converter J-V curves were taken by driving the converters at 60 cycles. A special circuit, designed and built at General Electric's Research and Development Center, converted the 60-cycle signals to about 0.1 cycle per second and the current density (J) and electrode potential (V) were recorded on an x, y recorder. Similar circuits were used for special tests such as electrode emission measurements for work function determination. Usually these observations were recorded directly on the x, y recorder. More detailed descriptions of the measuring techniques are given in the appendix of NASA report NASA CR-1033.

When drawing heavy currents, there is an appreciable temperature drop in the 1/4-inch-thick W emitter. A description of the method for calculating and correcting for this effect is given in the topical report for converter F (NASA CR-1699).

In calibrating the optical pyrometer while testing converter F, it was discovered that a consistent error of 22°K had been made in all previous measurements. All the T_E values previously reported were 22°K too high. The T_E values given in this Summary Report have been corrected.

TEST RESULTS

A brief review will be given of the characteristics of the electrode surfaces of the six converters, the test results and the NASA report number that contains the specific detailed converter information.

A. POLYCRYSTALLINE W EMITTER AND Nb COLLECTOR (NASA CR-1033)

This thermionic converter was the only one of the series that did not have a guard ring. A cross section of the converter is shown in Figure 1. Before assembly, the polycrystalline emitter was heated to 2500°C for a half hour in vacuum. The work function in vacuum of the emitter was 4.58 eV at 2200°K. In the presence of Cs the minimum work function of the collector was 1.55 eV. The curves of Figure 2 are envelopes of J-V curves for a 7-mil spacing at various emitter temperatures. Figure 3 illustrates that this converter produced about 0.1 volt lower output than previously tested W and W-25 w/o Re emitter converters with Ni collectors. Figure 4 shows the ouptut power versus T_E for J = 5 and 10 Amp/cm^2 and for 5-, 10-, and 20-mil spacings. Notice that at high T_E the closer the spacing the higher the output power whereas at low T_E the reverse is true. At 1800°K, one obtains equal output at 5- and 10-mil spacings.

B. FLUORIDE VAPOR DEPOSITED W(100) EMITTER ETCHED TO EXPOSE (110) PLANES AND Nb COLLECTOR (NASA CR-1381)

The second converter had a fluoride vapor deposited emitter with the (100) planes oriented parallel to the emitter plane. This emitter was etched to produce a multiplicity of facets with the (110) planes exposed. These planes were inclined 45° relative to the (100) planes. Therefore, the surface was a mass of intersecting planes inclined 45° from the bulk surface. The collector was Nb. This converter had a Nb guard ring. The collector and guard could be kept at the same electrical potential and temperatures. In spite of the lower performance of the Nb collector, this converter produced exceptionally high output power as illustrated by Figure 5. Notice 30 Amp/cm^2 at 1 volt.

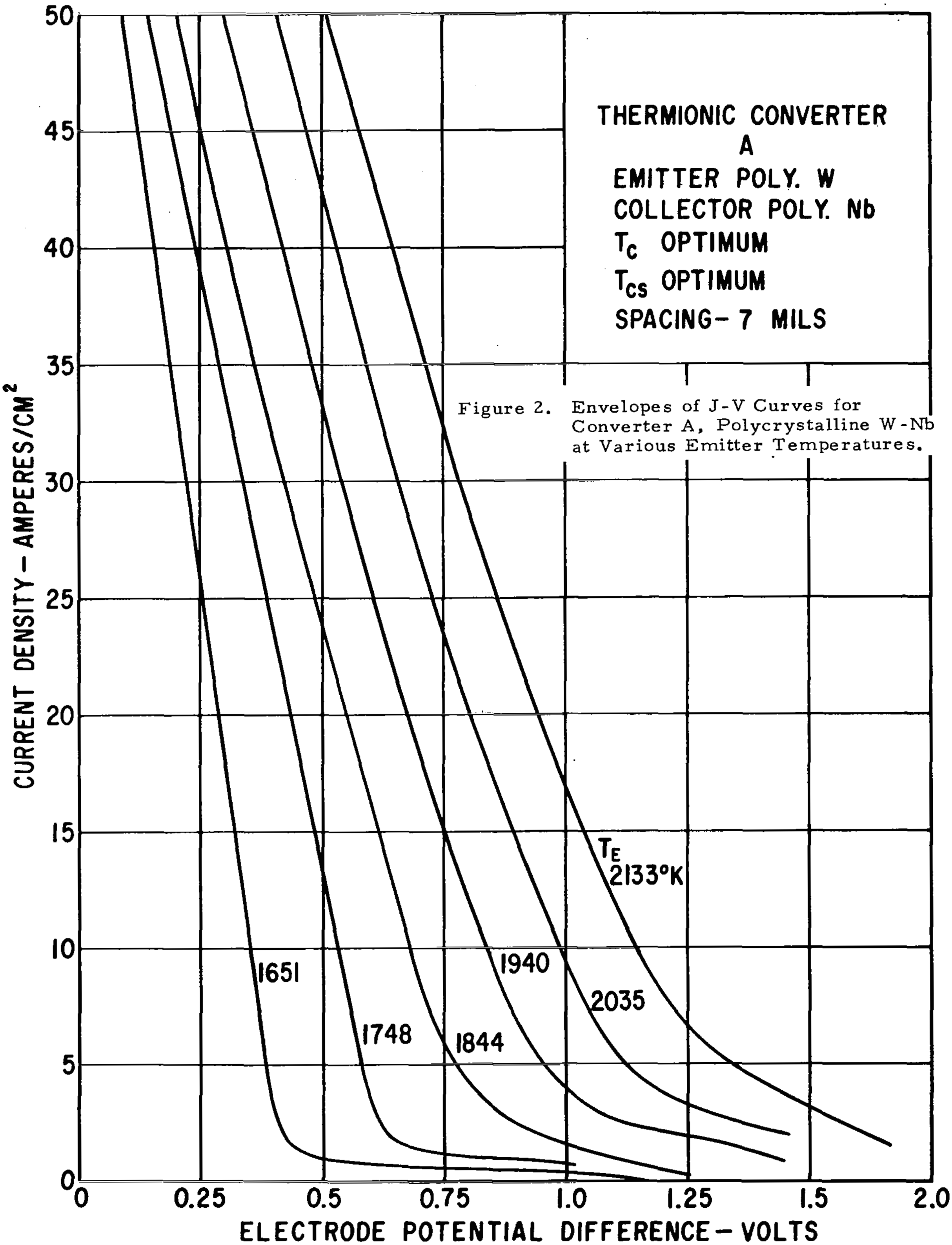

Figure 2. Envelopes of J-V Curves for Converter A, Polycrystalline W-Nb at Various Emitter Temperatures.

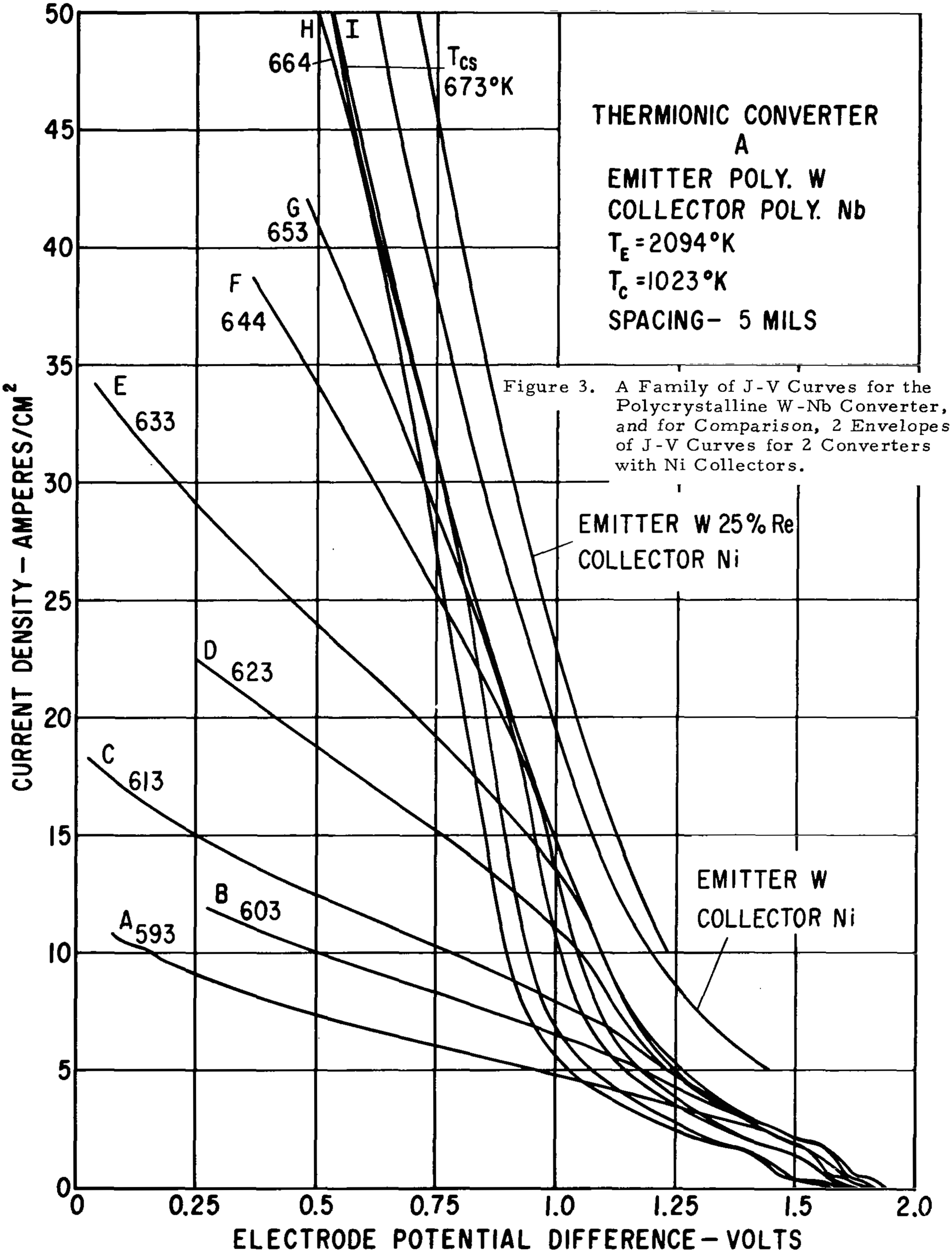

Figure 3. A Family of J-V Curves for the Polycrystalline W-Nb Converter, and for Comparison, 2 Envelopes of J-V Curves for 2 Converters with Ni Collectors.

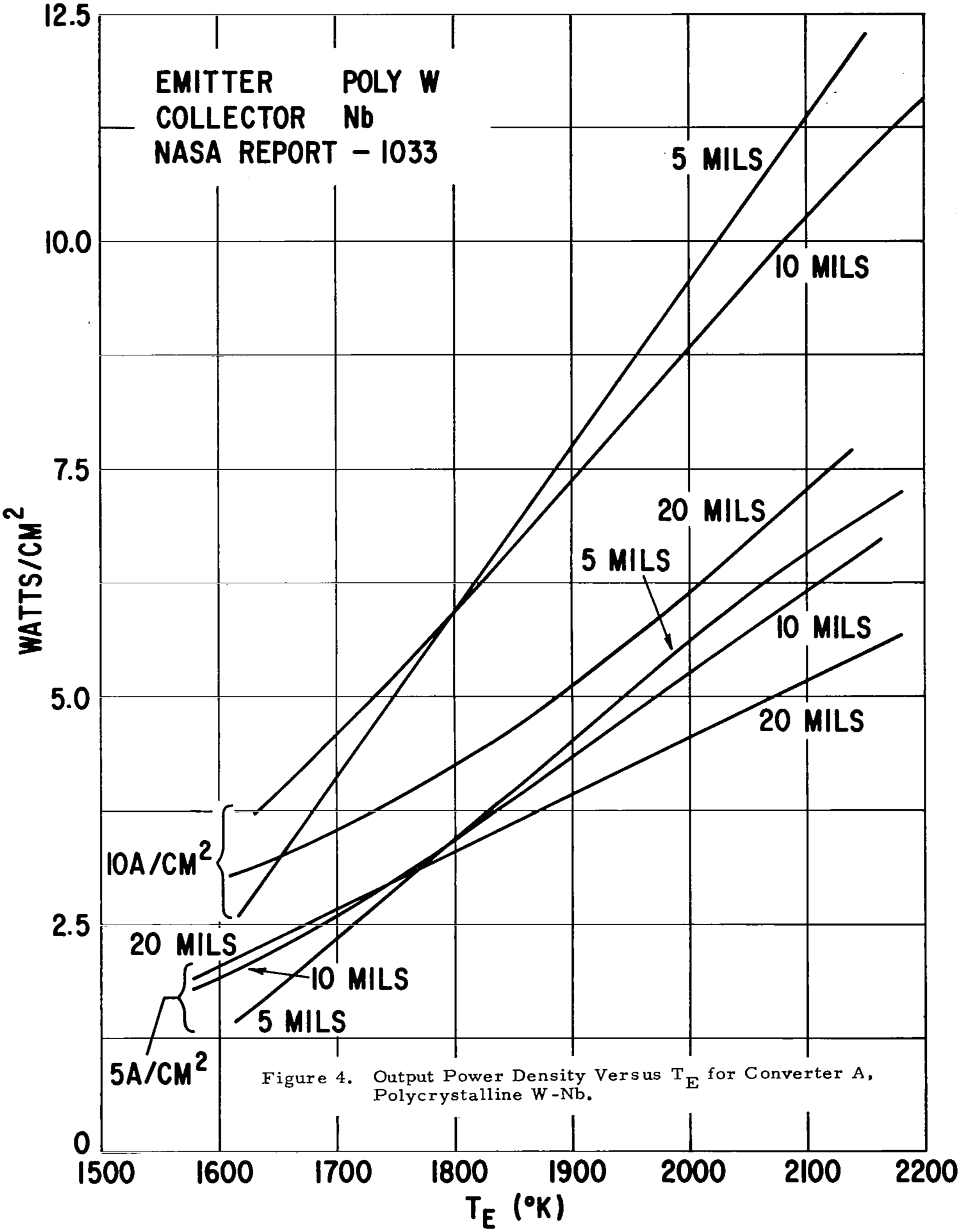

Figure 4. Output Power Density Versus T_E for Converter A, Polycrystalline W-Nb.

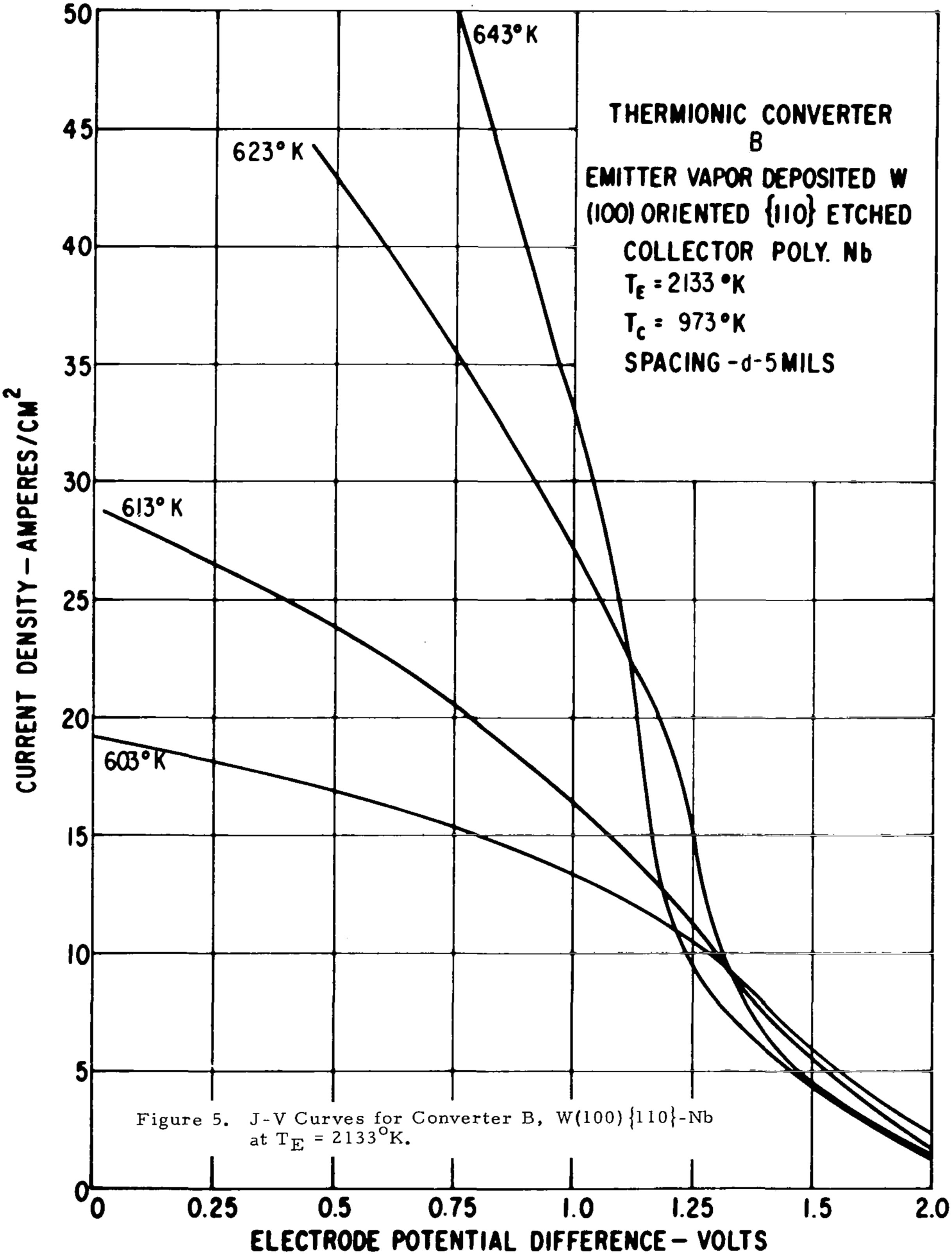

Figure 5. J-V Curves for Converter B, W(100) {110}-Nb at T_E = 2133°K.

Figure 6 shows typical J-V curves for converter B at T_E = 1650, 1844, and 2133°K and 10-mil spacing. A J-V curve at 2-mil spacing was added to show the increase in output that can be obtained at close spacing at high emitter temperatures.

Figure 7 shows the output power density versus T_E for converter B for 5 Amp/cm^2 and 10 Amp/cm^2 for 5-, 10-, and 20-mil spacings. This shows the output power for 5 Amps/cm^2 and 5-mil spacing to be lower when compared to the 10- and 20-mil spacing for T_E<1800°K. Such a condition could be due to the reduced number of encounters between electrons and atoms so that insufficient volume ionization occurs to overcome space charge. This probably explains the figure "S" shape of the curve for 5 Amp/cm^2 and 5-mil spacing. Notice that again at 5 Amp/cm^2 and below T_E = 1800°K, the best output is obtained at 20-mil spacing.

An outstanding characteristic of the etched emitter was that it produced the maximum output powers at comparatively low Cs vapor pressures. This is probably the result of a strong adsorption of Cs on the (110) planes which lowers the necessary Cs pressure to obtain the optimum Cs coverage on the emitter. The lower Cs pressure reduces the electron scattering in the plasma and a particular plasma voltage loss is obtained at a much wider spacing. Also, a better Cs coverage on the collector at the lower Cs pressure slightly increases the output voltage. The increased surface area of the etched emitter appears to increase the effective current density.

After 21.8 hours of operation at 2133°K, the output of this converter degraded somewhat; however, it still produced more power than the similar converter with the polycrystalline W emitter. The degradation was caused by thermal etching of the surface which rounded the sharp edges and valleys of the (110) facets. This reduced the surface area slightly; but more importantly, it exposed W crystal planes that had less desirable orientations. In terms of the work function, the final surface was patchy. Patchy work

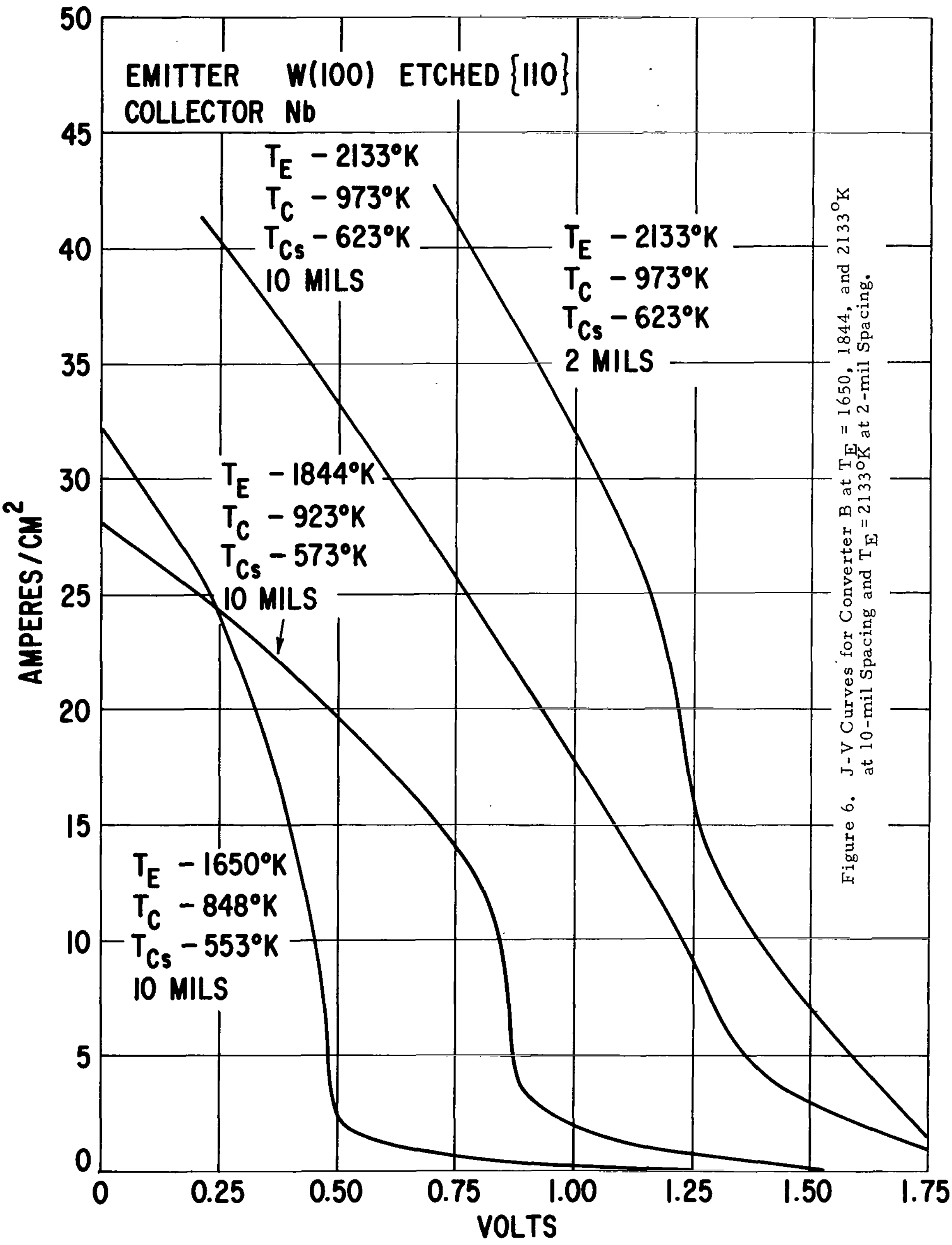

Figure 6. J-V Curves for Converter B at T_E = 1650, 1844, and 2133°K at 10-mil Spacing and T_E = 2133°K at 2-mil Spacing.

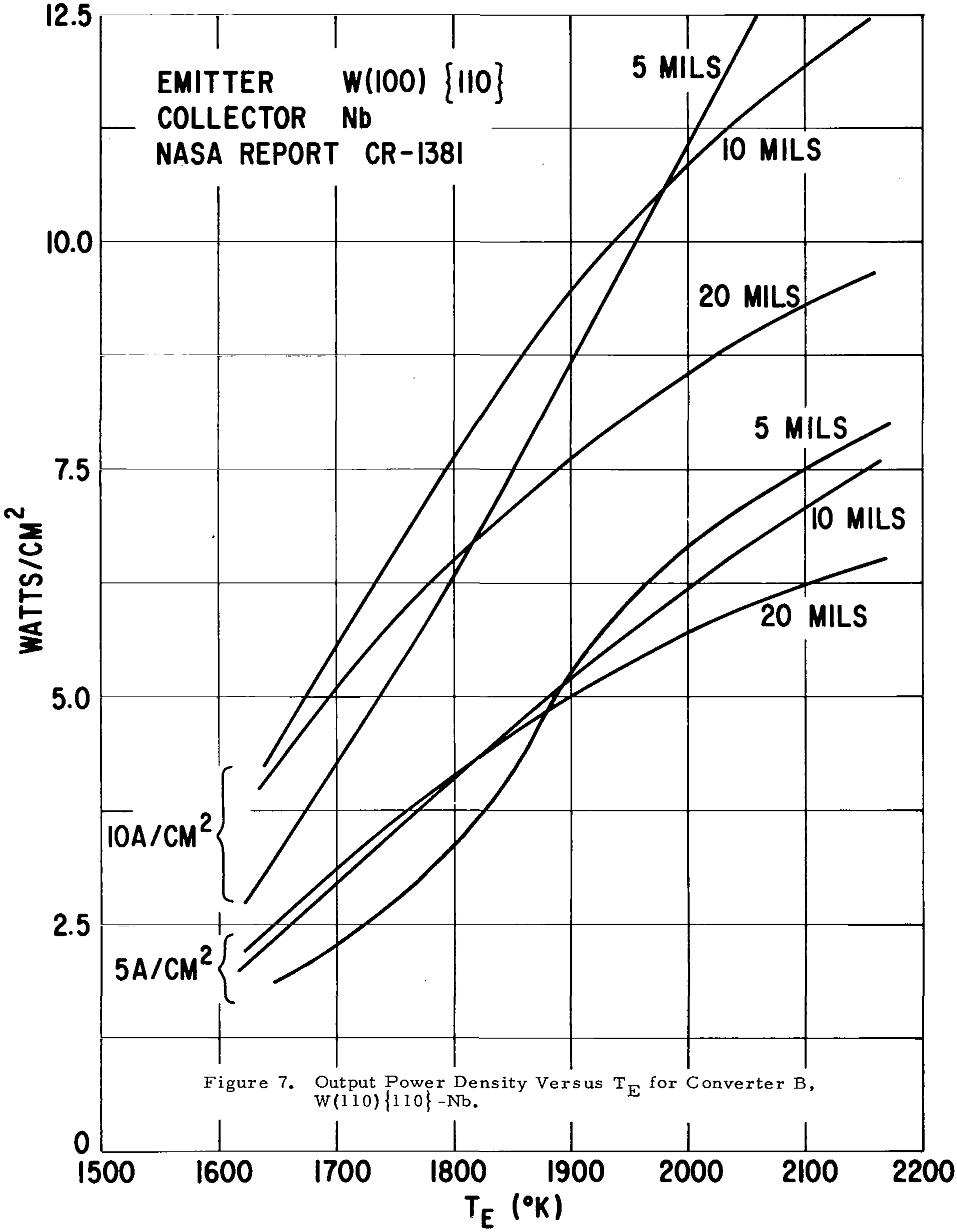

Figure 7. Output Power Density Versus T_E for Converter B, W(110){110}-Nb.

function surfaces are not ideal for thermionic converter emitters because it is impossible to optimize the Cs pressure for optimum Cs coverage of all patches.

C. CHLORIDE VAPOR DEPOSITED W(110) EMITTER AND A Ni COLLECTOR (NASA CR-1416).

The third converter[3] had a fixed spacing of 0.005 inch. The emitter was chloride vapor-deposited W with the (110) crystal planes parallel to the surface. The collector and guard ring were Ni. An important feature of this converter design was that the spacing was established by W spacer pins set in Al_2O_3 cups in the guard ring. Because of the meticulous work of Mr. Henry Guthan, the machinist, it is believed that the spacing of this converter was uniform and accurate to $\pm$ 0.0002 inch. This converter was the best tested.

Figure 8 shows the power density versus T_E at 5 Amp/cm^2 and 10 Amp/cm^2 at the fixed 5-mil spacing. The Ni collector was, in part, responsible for the high output. The (110) crystal orientation of the emitter also contributed to the high output by producing a uniform work function that enabled the Cs pressure to be optimized for the entire surface. Since this surface orientation is the most stable, one expects the emitter to maintain its good properties. Although the converter was operated for only about 40 hours, there was no indication of a reduction in output power with operation. Photomicrographs of the central area of the emitter taken before and after operation showed the exact grain structure and no change in surface appearance.

D. CHLORIDE VAPOR DEPOSITED W(110) EMITTER AND Nb COATED WITH W AND NbC COLLECTOR (NASA CR-1702)

The fourth converter was a variable spaced converter of the same design as the second except for a modification of the emitter structure. A 5-mil-thick W-Re foil was used to support the emitter. The emitter of the fourth converter was similar to the emitter of the third converter--namely,

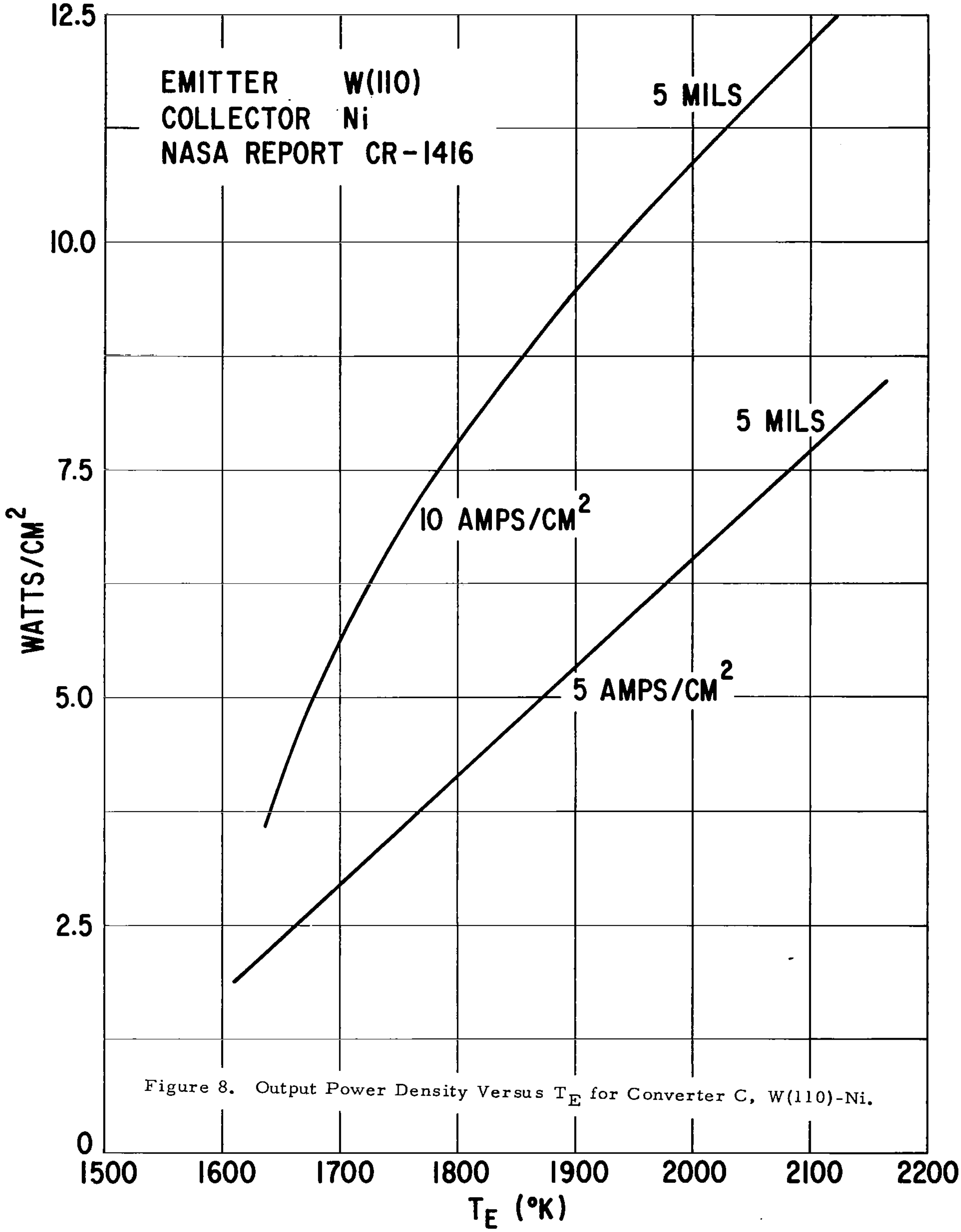

Figure 8. Output Power Density Versus T_E for Converter C, W(110)-Ni.

W(110). In fact, from crystal orientation, etch pitting and work function measurements, the two emitters appeared identical. The collector was Nb. Figure 9 gives the output power of converter D versus T_E for 5 Amp/cm^2 and 10 Amp/cm^2 and various spacings. By comparing Figures 8 and 9, one may observe that at $T_E = 1673^{o}K$, the output power of this converter was comparable to the converter C--W(110)-Ni. However, with increasing emitter temperatures, the output of the W(110)-Nb converter progressively became lower than the output of the W(110)-Ni converter. For example, at 10 Amp/cm^2, 5-mil spacing, and $T_E = 2133^{o}K$, the W(110)-Nb converter developed 1.175 Volts at the electrodes as compared with 1.425 Volts for the W(110)-Ni converter.

The output of the converter appeared to be stable with time. That is, the fall-off of performance relative to the W(110)-Ni converter did not appear to be a function of time rather than T_E. However, as has been observed with other converters, ϕ_C appeared to change if the converter was left for several days at room temperature. Under operating conditions, the converter would return to its initial J-V curves after an hour or two of operation. This observation suggests that ϕ_C returned to some equilibrium condition after a few hours of operation. A post-test examination revealed that the collector had a coating of elemental W and a small amount of NbC. The emitter remained clean and retained its (110) orientation.

E. A W(112) TO (114) EMITTER AND W + WO_2 ON Nb COLLECTOR (NASA CR-1661)

The structure of this converter was the same as for converter D. The emitter surface for the fifth converter was a 0.020-inch-thick layer of fluoride vapor deposited W on a 1/4-inch disk of General Electric weldable grade W. Before assembling the converter, x-ray diffraction tests verified that the emitter surface was (100) oriented W. The vacuum work function of the emitter was measured to be 4.57 eV at $2200^{o}K$ before assembly. Mounted

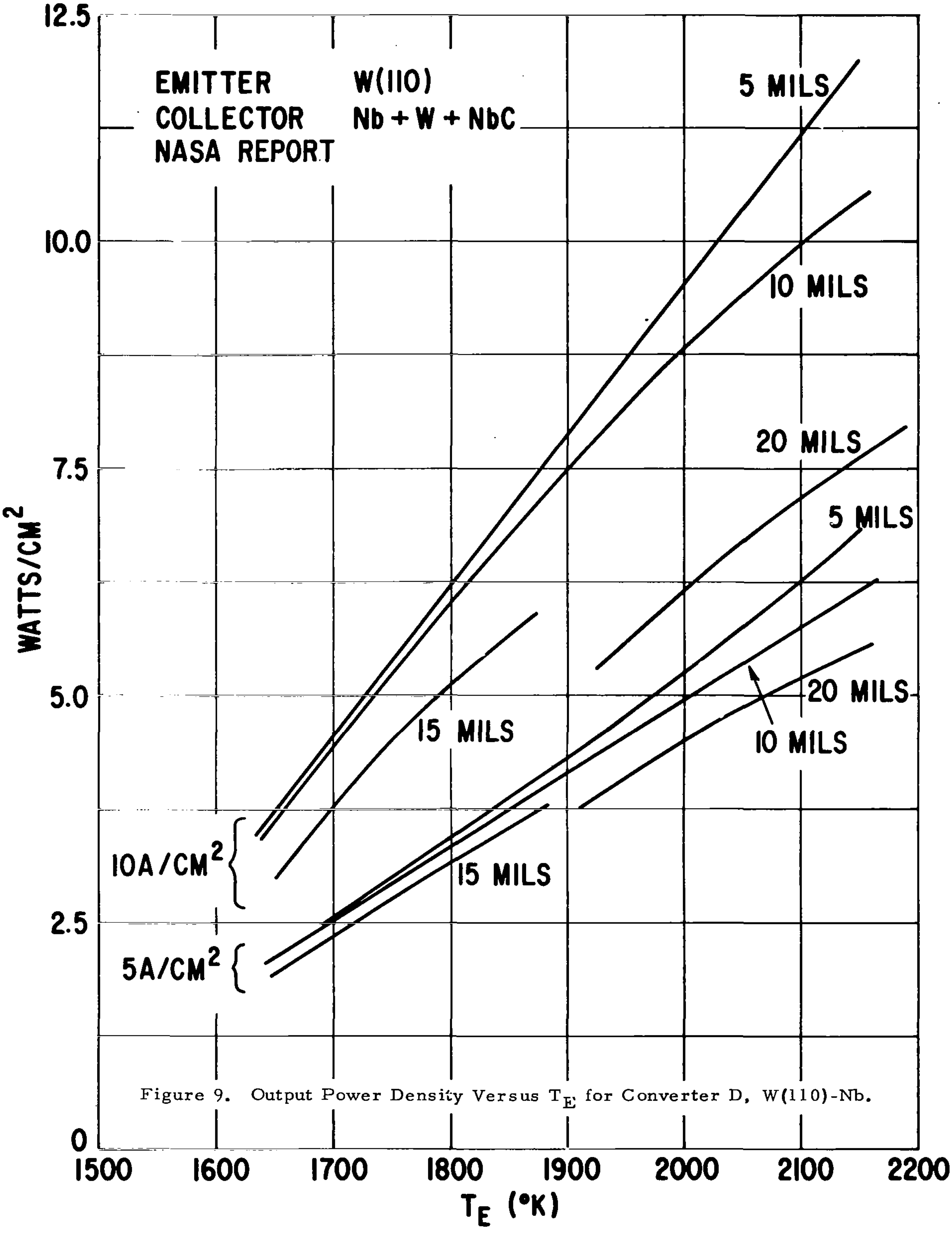

Figure 9. Output Power Density Versus T_E for Converter D, W(110)-Nb.

in theconverter, the emitter vacuum work function at $2200^{\circ}K$ was 4.52 eV and at $2300^{\circ}K$ was 4.56 eV. After introducing the Cs, the collector had a minimum work function of 1.54 eV.

Difficulties were encountered during the outgassing; however, it was thought that the converter was vacuum tight while the Cs was distilled into the converter. During operation, the output characteristics improved, particularly in the first few hours. Upon taking the converter apart, a coating of W and WO_2 was found on the collector and guard. Also, the emitter had recrystallized so that the exposed emitter surface changed from (100) crystal planes to (112), (113), and (114) crystal planes.

The current density versus voltage curves were taken after more than 100 hours of operation and after the converter appeared to have moderately stable output performance. These J-V curves, therefore, were for a W(112) to (114) emitter and a collector of W + WO_2 on Nb.

Figure 10 shows the remarkable performance at low emitter temperature, $1650^{\circ}K$, and wide spacing, 20 mils. This performance was primarily related to the converter operating at exceptionally low Cs pressures.

Figure 11 shows that at this low emitter temperature and up to 15 Amp/cm^2 the best output was obtained at the 20-mil spacing. At $T_E = 1843^{\circ}K$ and at 10 Amp/cm^2 the most output was obtained at 10-mil spacing (Figure 12).

At high emitter temperatures, the output performance of this converter was less spectacular. Figure 13 compares a J-V curve with a plane (110)W (converters D and E) emitter and converter B with a faceted (110) on (100) W emitter. At $T_{Cs} = 603^{\circ}K$, the W(112)(114) emitter with oxygen present produced a higher current at short circuit, but the output voltage at lower current densities (<5 $Amps/cm^2$) was about 0.3 Volts less than the other converters. This change of characteristics with increasing emitter temperature is also illustrated in curves E of Figures 18, 19, and 20. They show the

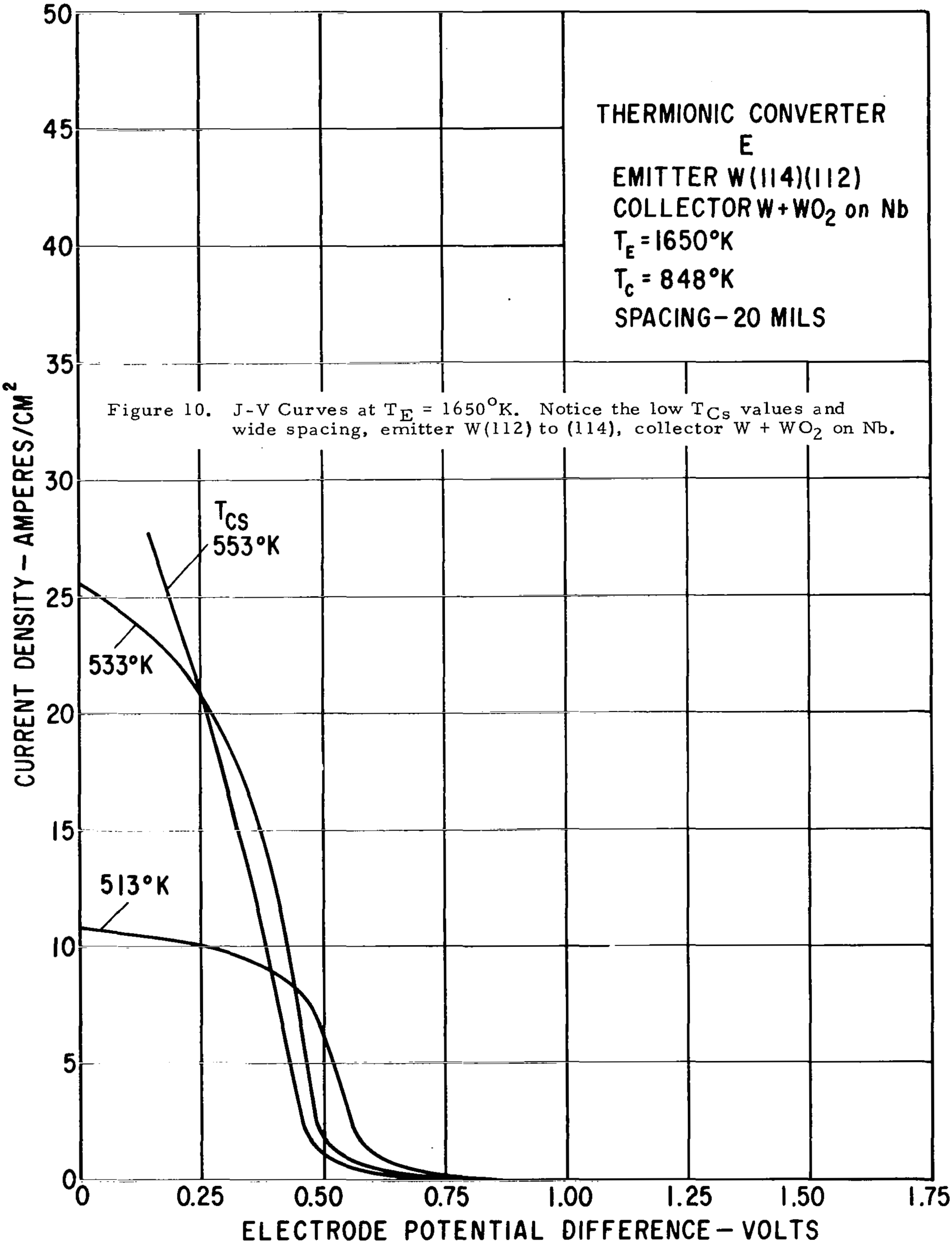

Figure 10. J-V Curves at T_E = 1650°K. Notice the low T_{Cs} values and wide spacing, emitter W(112) to (114), collector W + WO_2 on Nb.

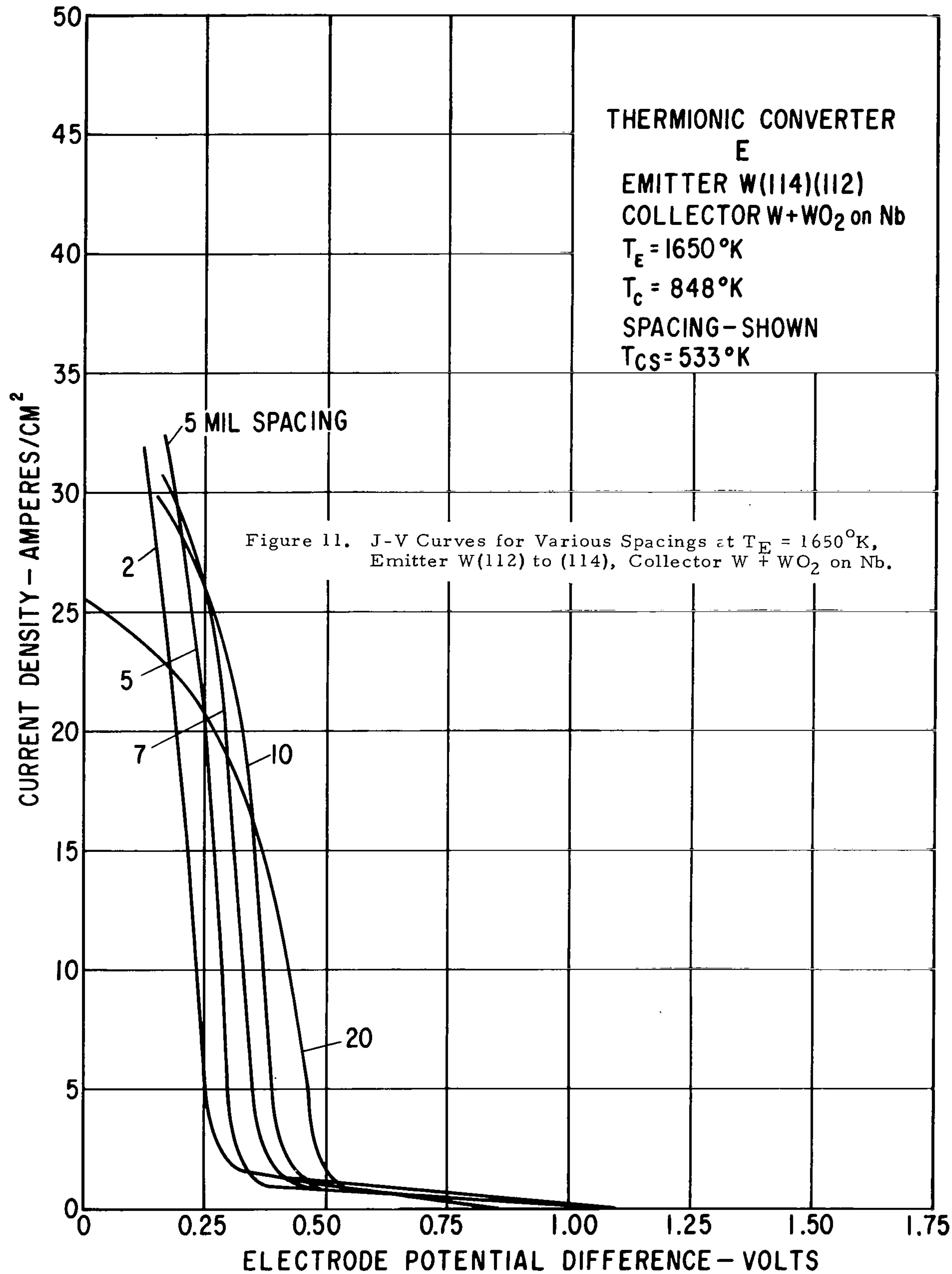

Figure 11. J-V Curves for Various Spacings at T_E = 1650°K, Emitter W(112) to (114), Collector W + WO_2 on Nb.

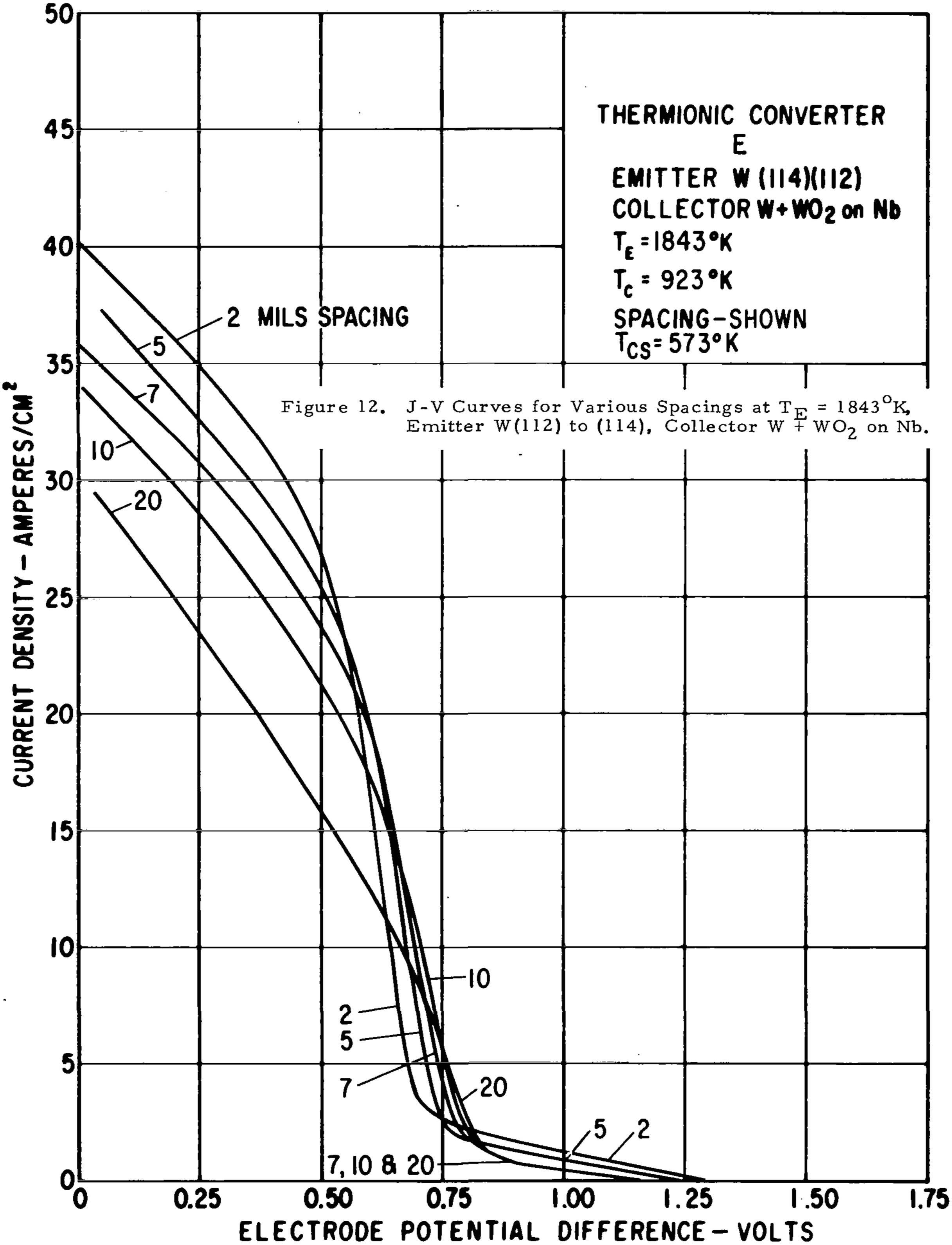

Figure 12. J-V Curves for Various Spacings at T_E = 1843°K, Emitter W(112) to (114), Collector W + WO_2 on Nb.

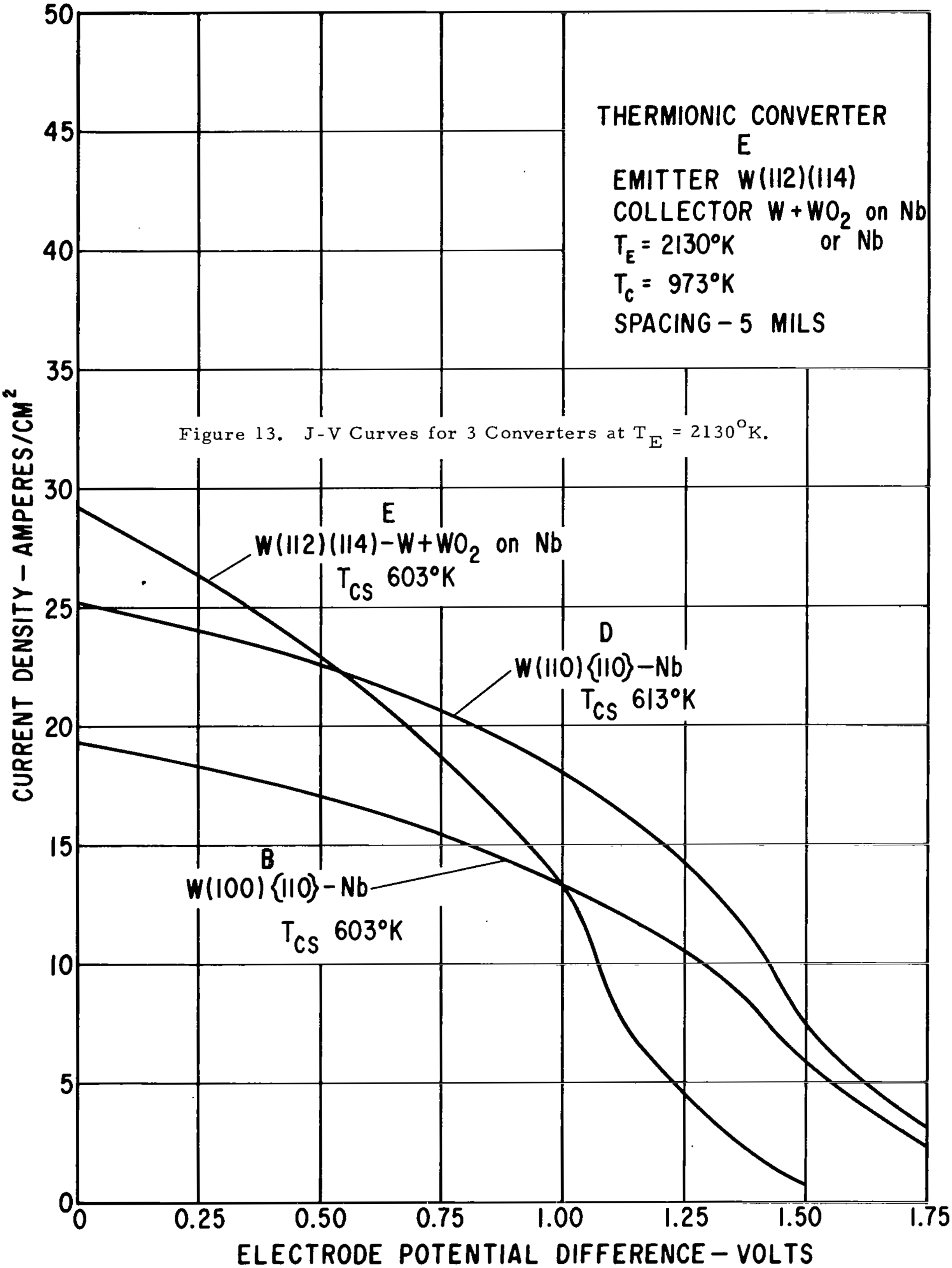

Figure 13. J-V Curves for 3 Converters at $T_E = 2130^{\circ}K$.

output voltages as a function of T_E at 5, 10, and 15 Amp/cm^2 and 10-mil spacing and with T_C and T_{Cs} optimized. After the initial change in characteristics, most of which occurred in the first 10 hours of operation, the converter operation remained stable and the figure "S" curves, E, could be repeated. These output power densities versus T_E for 5 Amp/cm^2, 10 Amp/cm^2, 5-, 10-, and 20-mil spacing are shown in Figure 14.

At low emitter temperatures the high output power at wide spacing and low Cs pressures is similar to the results reported by Levine, Harbaugh, and Shoemaker[14] for converters with oxygen deliberately introduced. At high emitter temperatures, apparently the oxygen cannot remain on the emitter and the beneficial effects of the oxygen are not realized. After only about 100 hours of operation, this converter had a heavy layer of W and WO_2 on the collector. This observation suggests that there is little hope of improving the output performance at higher emitter temperatures by dispensing more oxygen into the interelectrode spacing. More oxygen will probably enhance the W mass transfer such as to shorten the life of the converter.

F. A W(110) EMITTER AND A Mo ON Nb COLLECTOR (NASA CR-1699)

Difficulty with envelope integrity in several preceding converters prompted a design modification. Since Nb is a good getter material, this converter was expected to have a lower partial pressure of oxygen than those previously tested.

Based on observations by TECO,[24] Mo appears to be a better collector material than Nb. Molybdenum also has a thermal expansion coefficient close to Nb and forms a complete isomorphous constitution system--i.e., no intermediate phases. Therefore, a decision was made to fabricate this planar converter using a 1500 Å layer of Mo on a Nb collector base. Initially this collector surface had a minimum work function in Cs of 1.54 eV at $T_C = 800^\circ K$ and $T_C/T_{Cs} = 1.9$ The emitter was a chloride vapor deposited W(110) surface with a vacuum work function of 5.03 eV from $2075^\circ K$ to $2300^\circ K$.

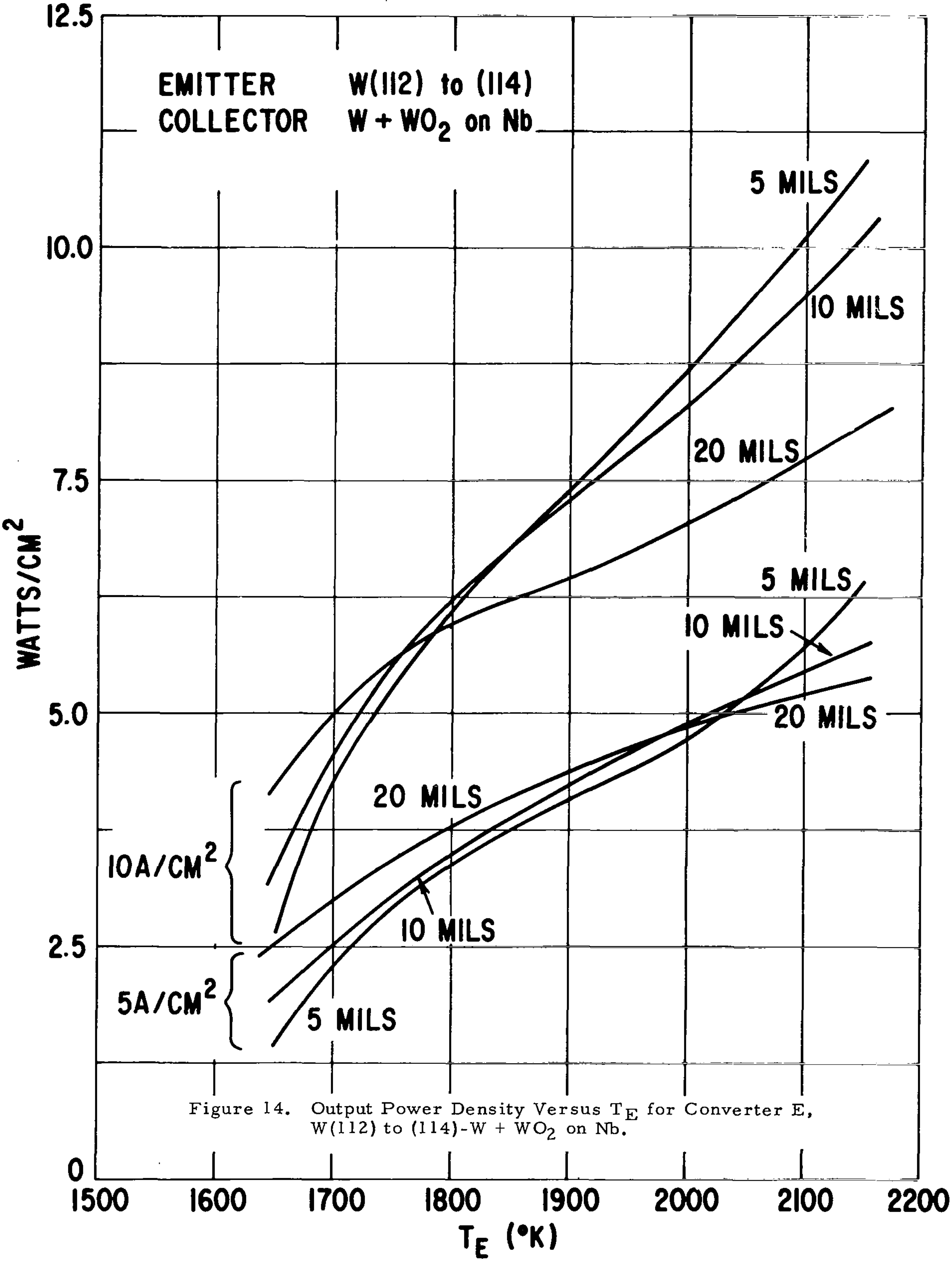

Figure 14. Output Power Density Versus T_E for Converter E, W(112) to (114)-W + WO_2 on Nb.

In operation, this converter was very similar to a W(110)-Nb converter. This performance is illustrated by Figure 15 in which the solid lines are for a W(110)-Nb converter and the dashed lines are for this W(110)-Mo on Nb. The similarity in the output of the two converters is also illustrated by Figure 16. Figure 17 gives the power density versus T_E for converter F at 5 Amp/cm^2 and 10 Amp/cm^2 and for 5-, 10-, and 20-mil spacings. The extremely low value of output at low T_E, 10 Amp/cm^2 and 20-mil spacing appears to be for the opposite reason given for the low values at 5-mil spacing for Figure 7. Converter F operated about 20°C higher in Cs vapor pressure than converters B, C, and D with W(110) surfaces. The correspondingly high Cs pressure and the wide spacing results in a high pd so that there was excessive electron scattering in the plasma.

After operation, the converter was taken apart and an Auger analysis was made of the collector surface. As one might suspect from the converter characteristics, the surface was not all Mo; it consisted of equal amounts of Nb and Mo. After taking the J-V curves, the minimum ϕ_C was still 1.54 eV, which suggests that the Nb diffused to the surface during several hours of outgassing the collector at 900°C before admitting the Cs. This first attempt shows that it may be difficult to produce and keep a thin Mo layer on a Nb collector base without encountering serious diffusion of Nb to the surface.

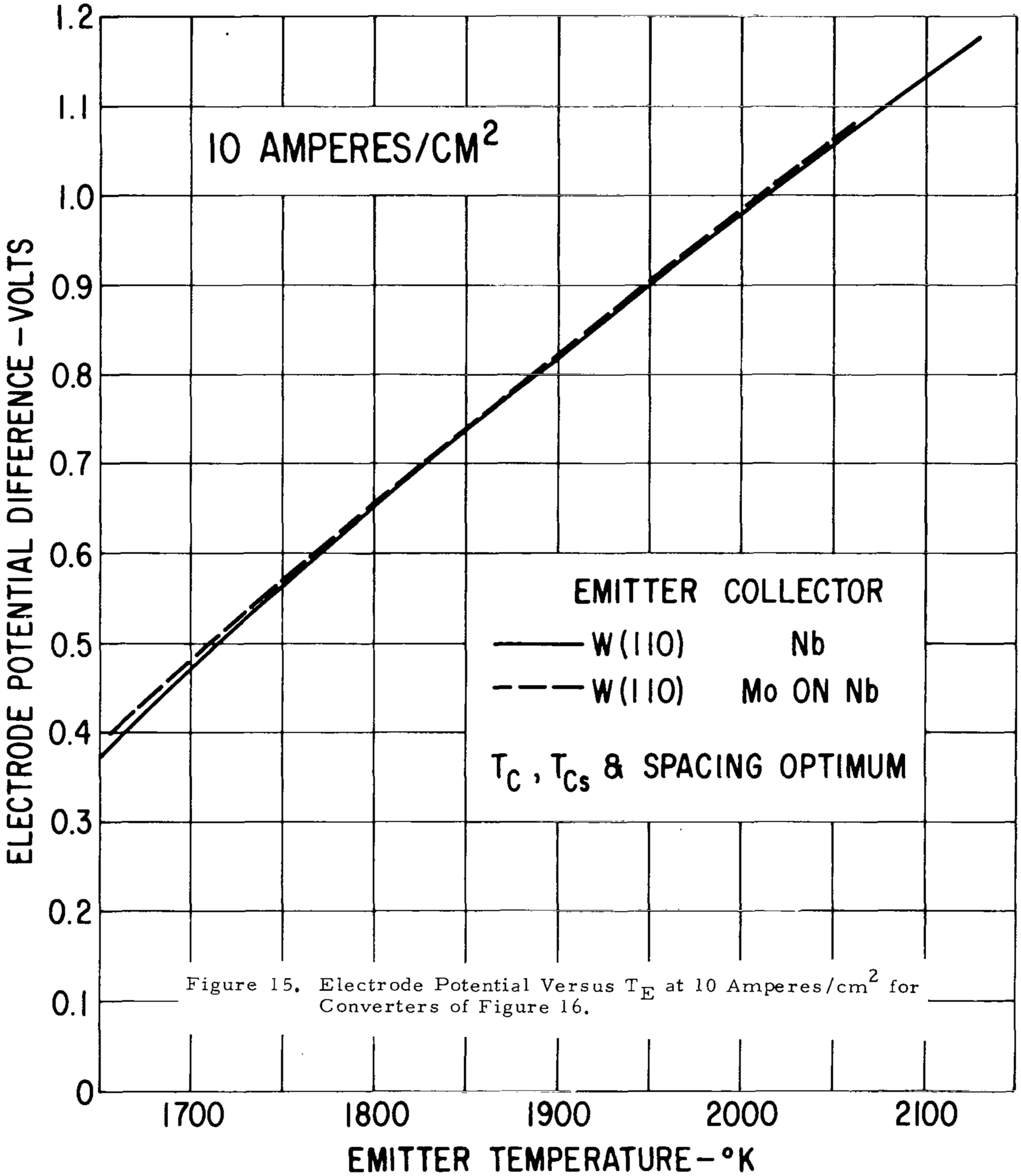

Figure 15. Electrode Potential Versus T_E at 10 Amperes/cm^2 for Converters of Figure 16.

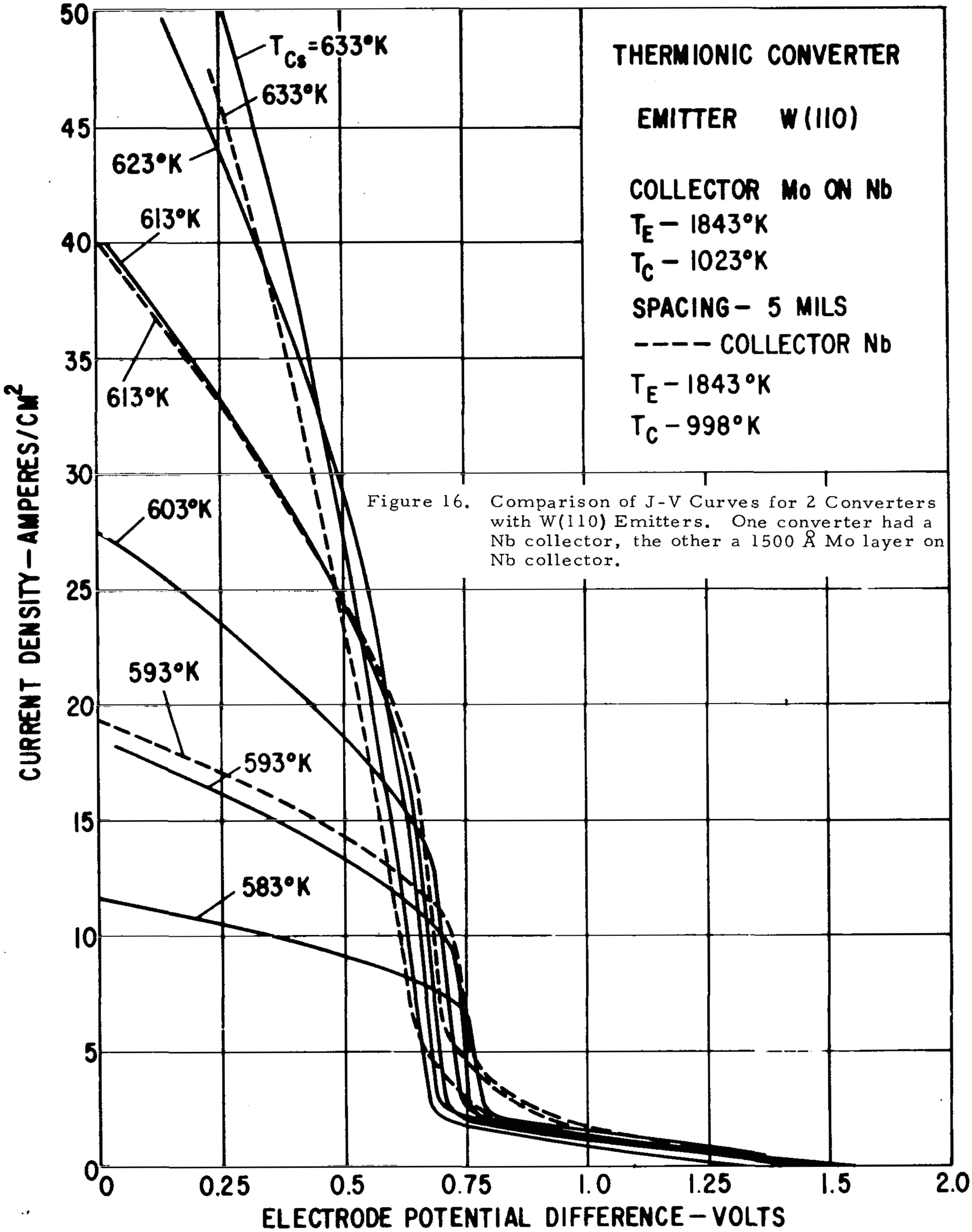

Figure 16. Comparison of J-V Curves for 2 Converters with W(110) Emitters. One converter had a Nb collector, the other a 1500 Å Mo layer on Nb collector.

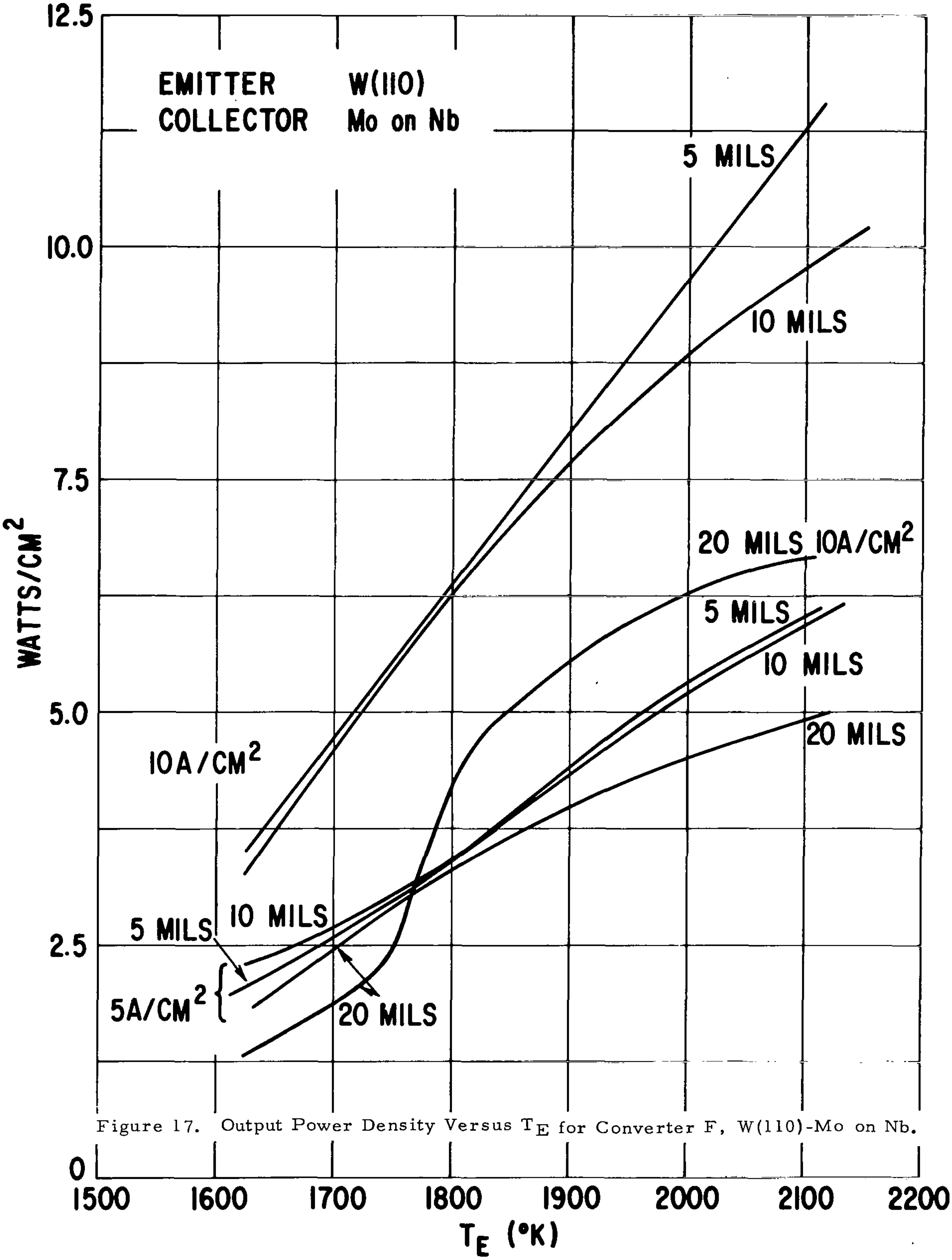

Figure 17. Output Power Density Versus T_E for Converter F, W(110)-Mo on Nb.

COMPARISON OF OUTPUT PERFORMANCES AND DISCUSSION

Figures 18, 19 and 20 give the voltage at the electrodes versus T_E for five of the converters at 10-mil spacing for 5, 10, and 15 Amp/cm^2 with T_C and T_{Cs} optimized. Converter B with the etched faceted emitter produced the most output power. Converter E which had oxygen present is next best at low T_E values. Converters A, D, and F produced comparable outputs. This comparison would suggest that polycrystalline W is about the same as oriented W(110) as an emitter surface. The polycrystalline W was given a high temperature treatment. This converter has not been taken apart, but other samples of the same kind of W subjected to the same polish and heat treatment show a high percentage of (110) crystallite surfaces as revealed by etch pit examinations. It is believed that this predominant (110) surface orientation accounts for the high performance of the polycrystalline emitter.

Since converter C had a fixed spacing of 5 mils, to compare it with the other converters, Figures 21, 22, and 23 were made which give the electrode potentials versus T_E for the six converters at 5-mil spacing and 5, 10, and 15 Amp/cm^2. At this close spacing, as mentioned before, the pd product for the faceted emitter is too low at low T_E values. From these three figures it is apparent that converter C was the outstanding converter. Most probably this is because of the Ni collector.

Some of the special features of these converters may be discussed with the help of Figures 24, 25, and 26 (showing performance at optimum spacing) and with the help of Tables 3, 4, and 5. Figure 24 and Table 3 are for 5 Amp/cm^2. At each emitter temperature, the table gives the spacing and T_{Cs} for the output voltage plotted in Figure 24. For example, for converter E at $T_E = 1843^oK$, the voltage was for a 20-mil spacing and at $T_{Cs} = 553^oK$ (shown 20/553 in the table).

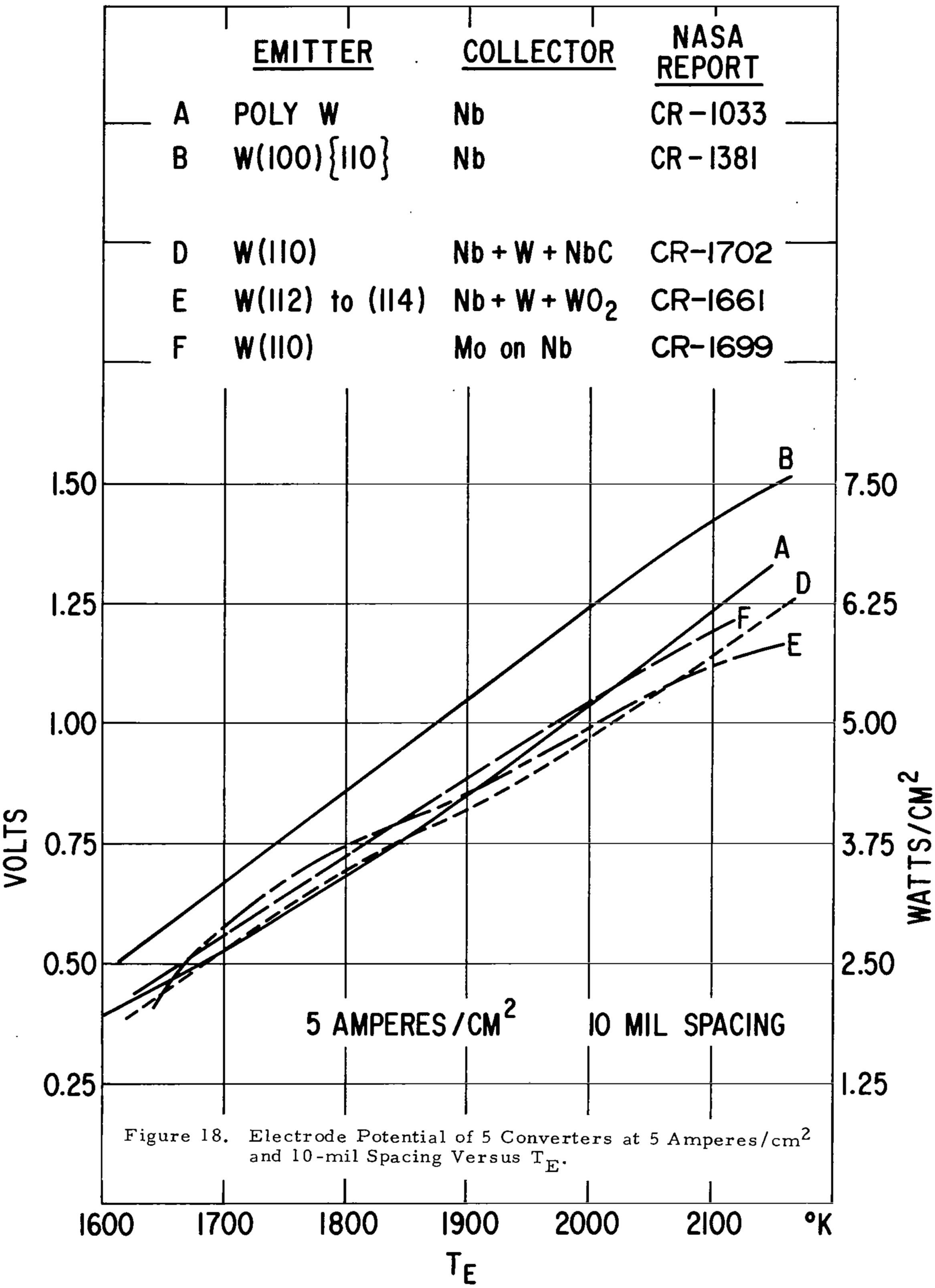

Figure 18. Electrode Potential of 5 Converters at 5 Amperes/cm^2 and 10-mil Spacing Versus T_E.

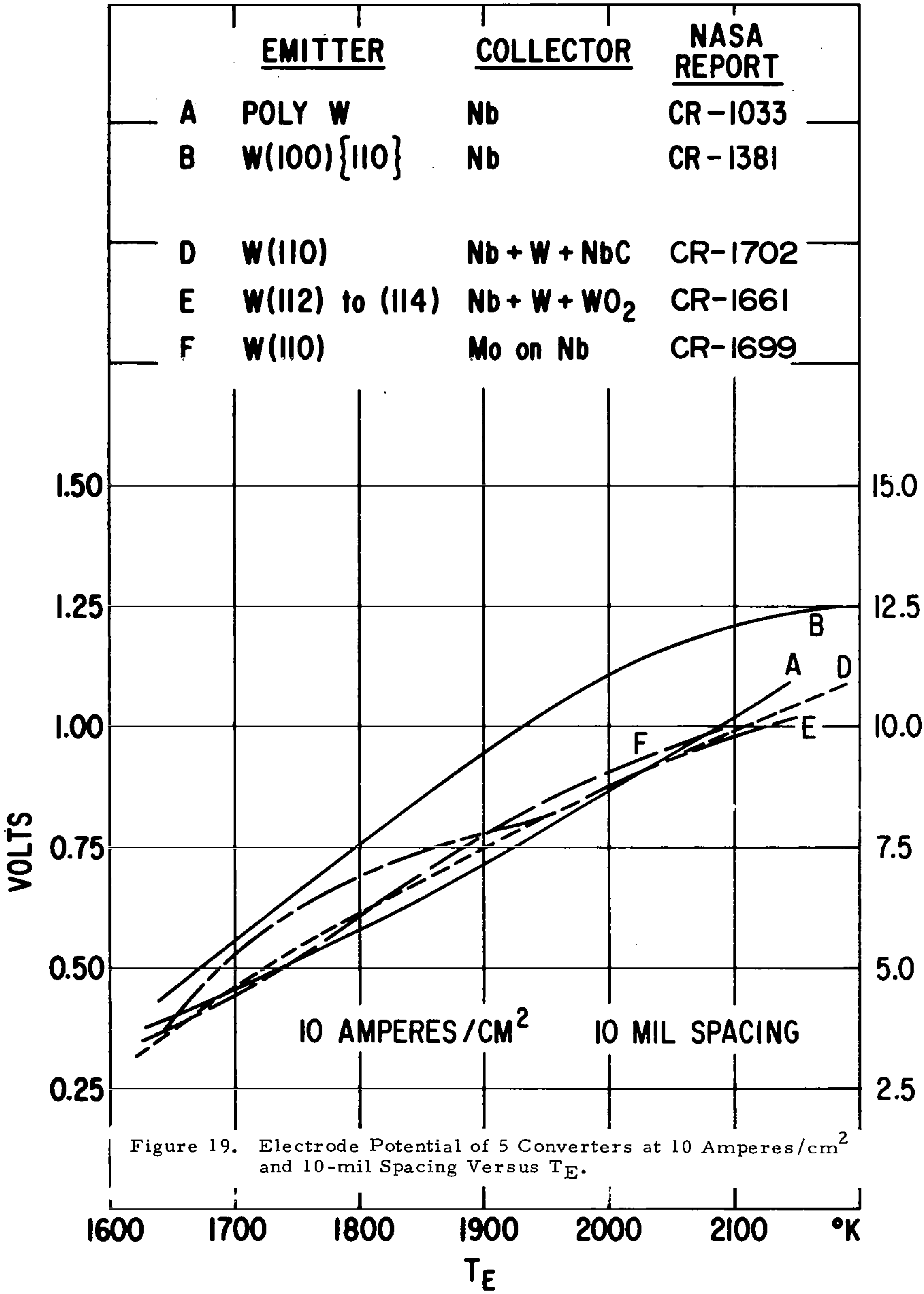

Figure 19. Electrode Potential of 5 Converters at 10 Amperes/cm^2 and 10-mil Spacing Versus T_E.

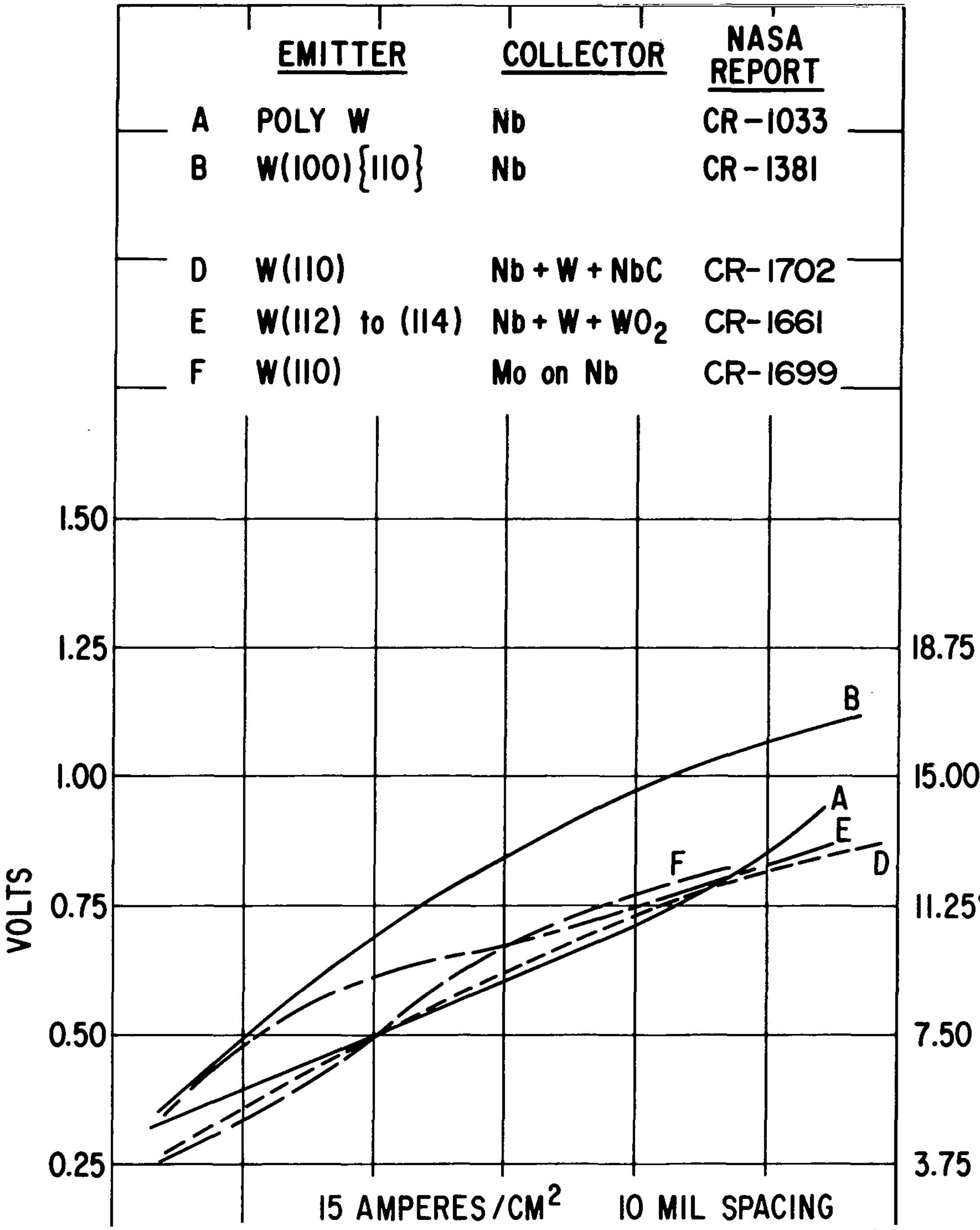

Figure 20. Electrode Potential of 5 Converters at 15 Amperes/cm^2 and 10-mil Spacing Versus T_E.

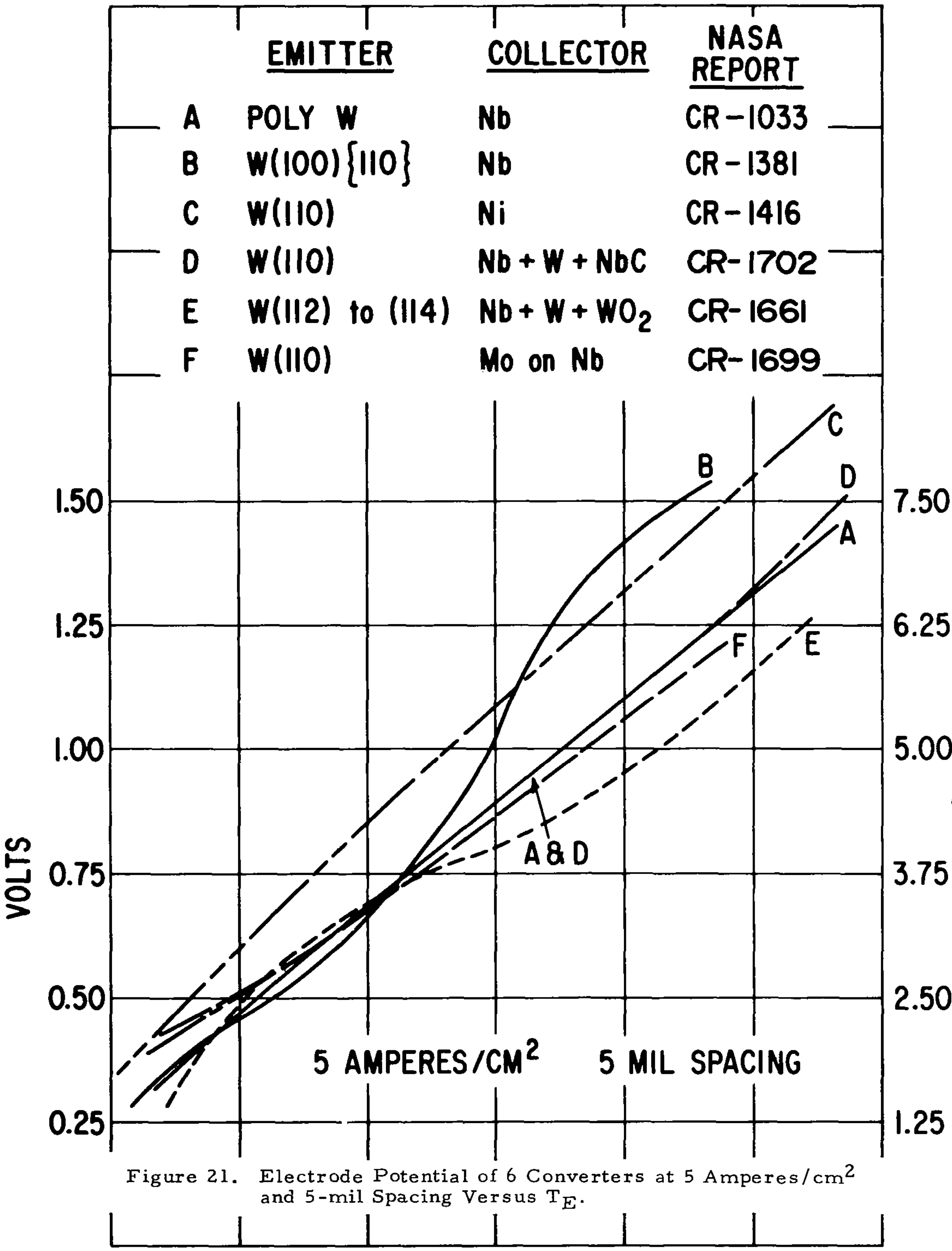

Figure 21. Electrode Potential of 6 Converters at 5 Amperes/cm^2 and 5-mil Spacing Versus T_E.

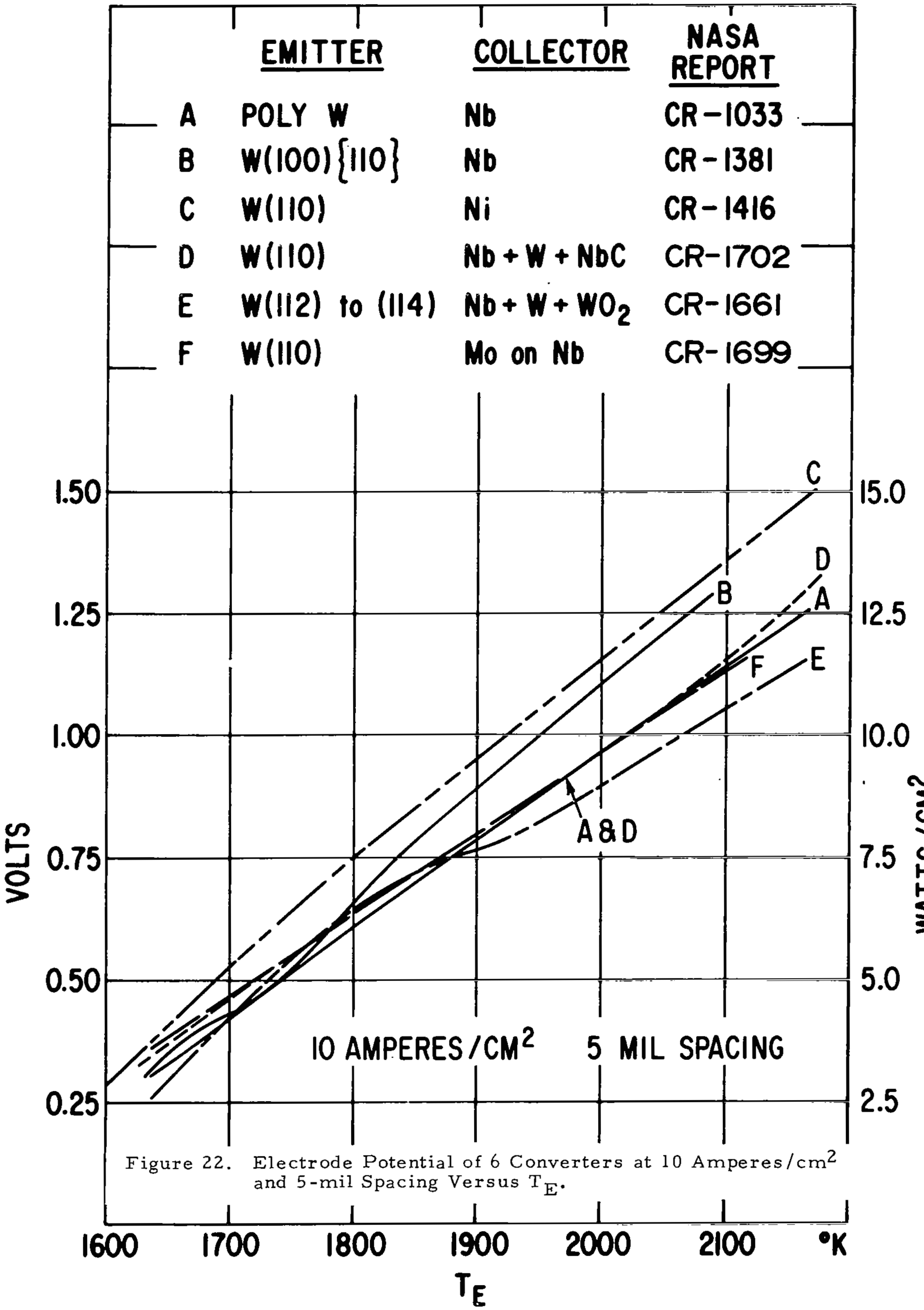

Figure 22. Electrode Potential of 6 Converters at 10 Amperes/cm^2 and 5-mil Spacing Versus T_E.

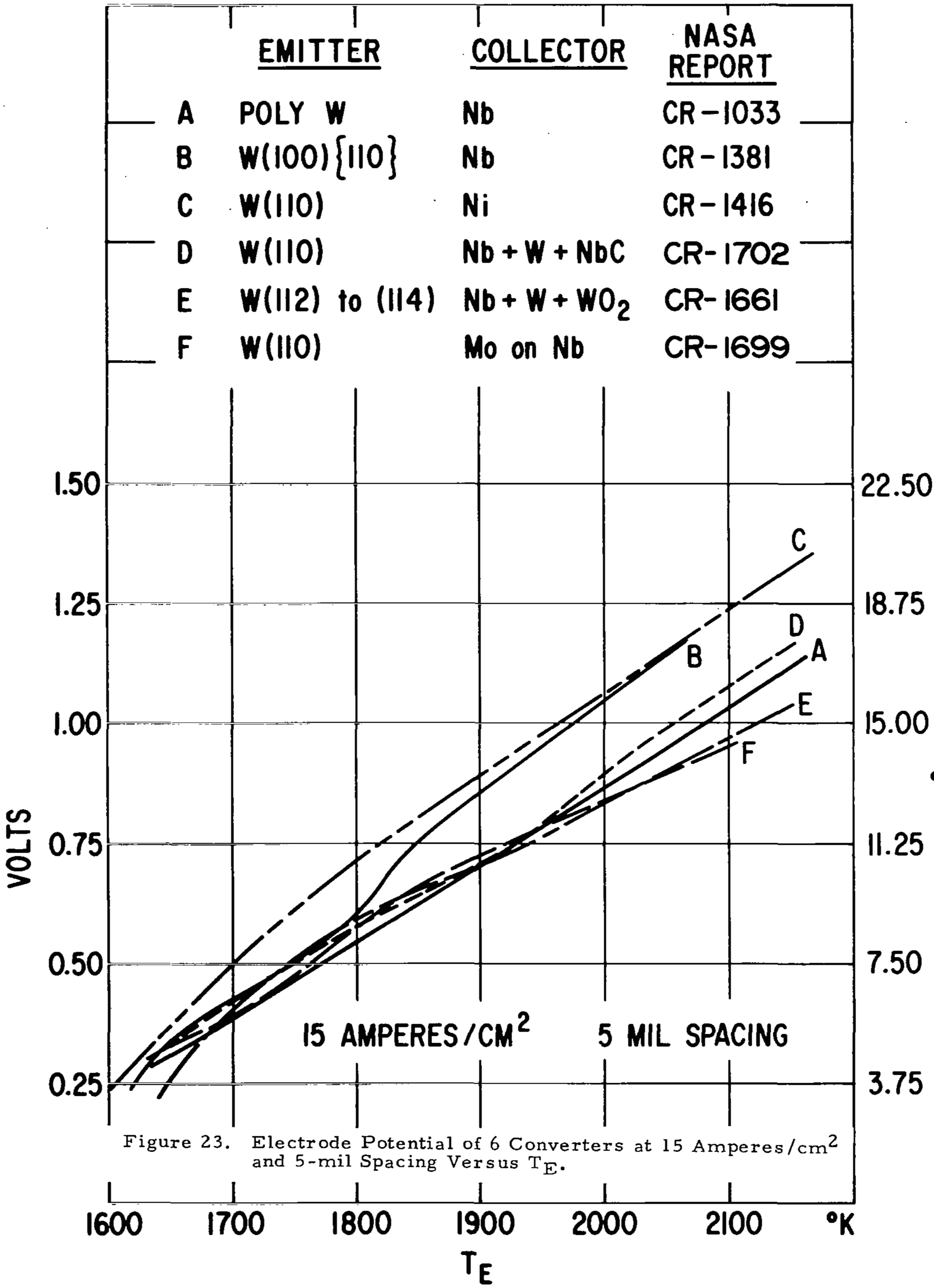

Figure 23. Electrode Potential of 6 Converters at 15 Amperes/cm^2 and 5-mil Spacing Versus T_E.

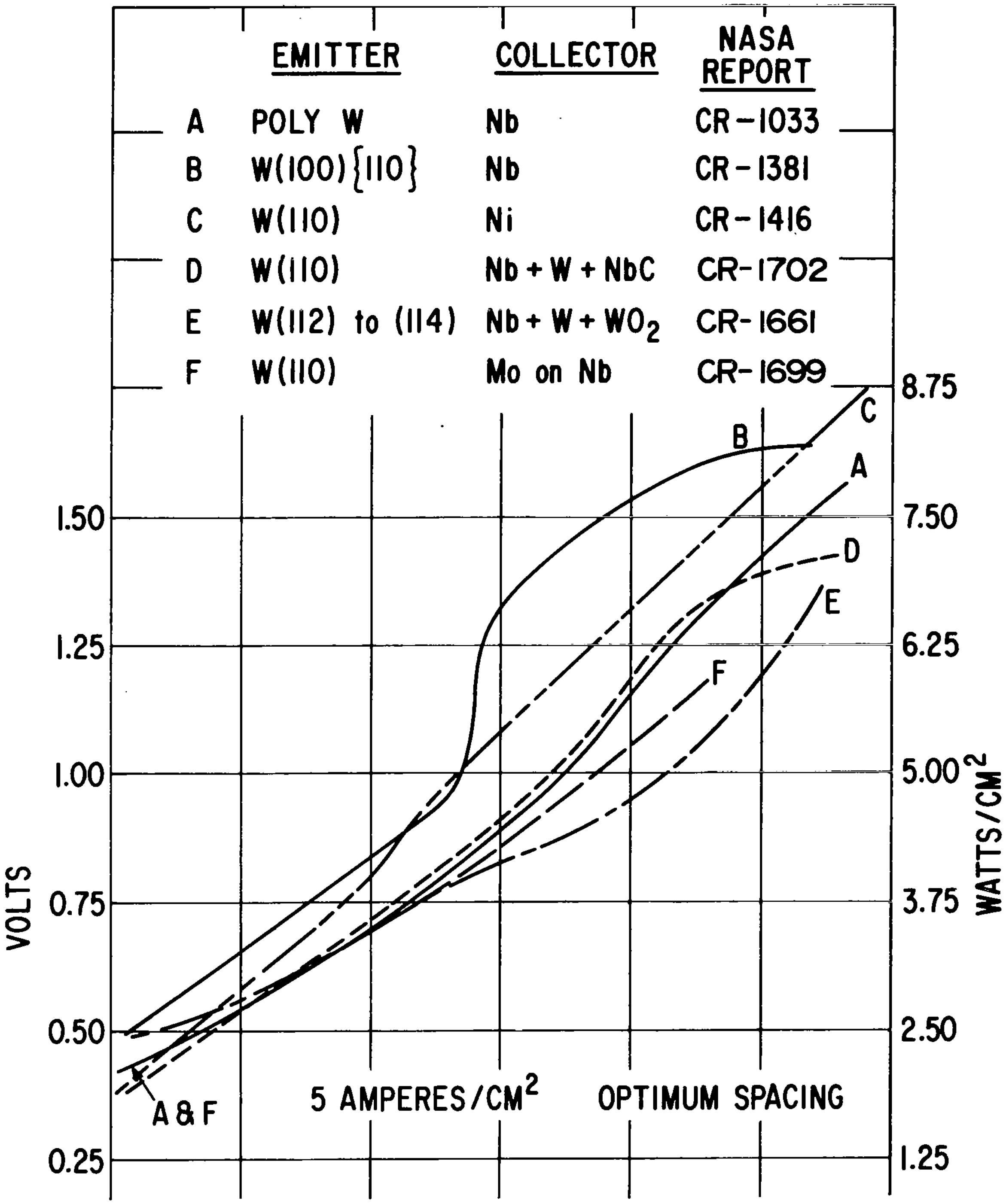

Figure 24. Electrode Potential of 6 Converters at 5 Amperes/cm^2 and Optimum Spacing Versus T_E.

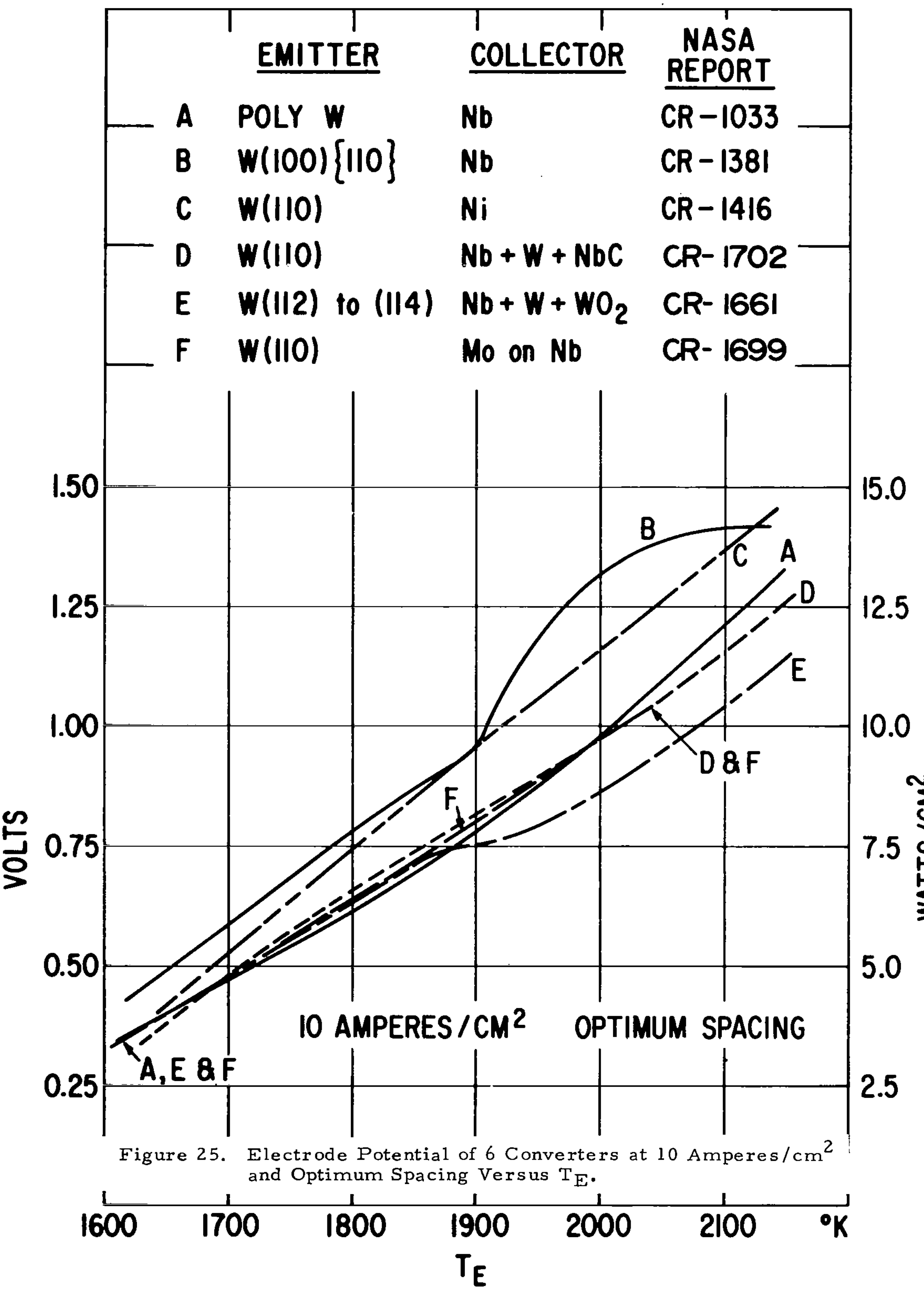

Figure 25. Electrode Potential of 6 Converters at 10 Amperes/cm^2 and Optimum Spacing Versus T_E.

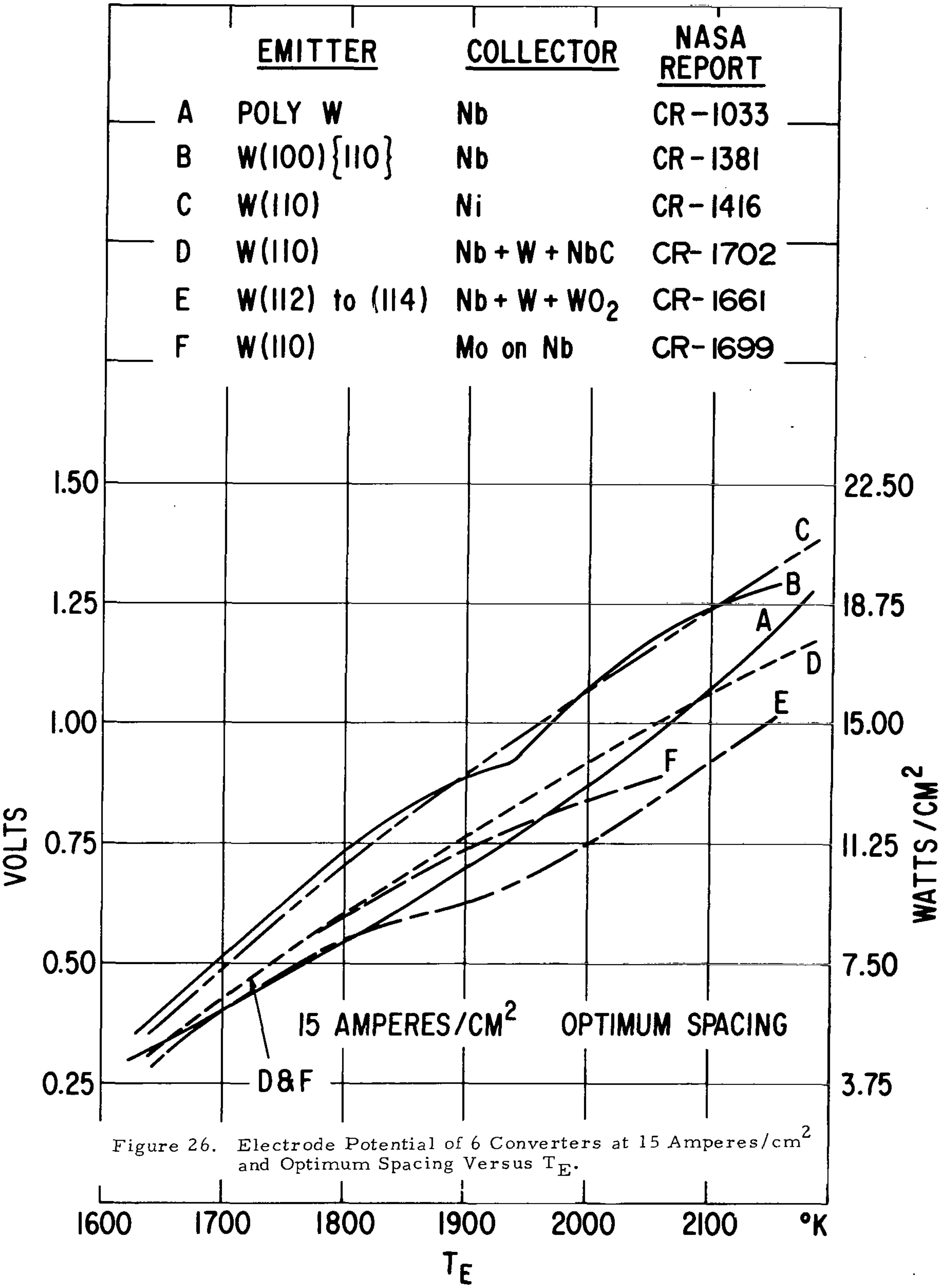

Figure 26. Electrode Potential of 6 Converters at 15 Amperes/cm^2 and Optimum Spacing Versus T_E.

Table 3. SPACING AND T_{Cs} FOR 5 Amp/cm^2

	T_E (^oK)					
Converter	1650	1748	1843	1940	2035	2133
A	$\frac{20^*}{553}$	$\frac{20}{583}$	$\frac{-}{-}$	$\frac{2}{603}$	$\frac{1}{623}$	$\frac{1}{623}$
B	$\frac{20}{553}$	$\frac{20^{**}}{553}$	$\frac{1}{573}$	$\frac{1}{563}$	$\frac{1}{573}$	$\frac{1}{603}$
C	$\frac{5}{553}$	$\frac{5}{553}$	$\frac{5}{573}$	$\frac{5}{573}$	$\frac{5}{593}$	$\frac{5}{613}$
D	$\frac{15}{573}$	$\frac{10}{593}$	$\frac{7}{593}$	$\frac{2}{613}$	$\frac{2}{613}$	$\frac{2}{633}$
E	$\frac{20}{513}$	$\frac{20}{533}$	$\frac{20}{553}$	$\frac{20}{573}$	$\frac{10}{583}$	$\frac{2}{623}$
F	$\frac{10}{573}$	$\frac{10}{603}$	$\frac{10}{583}$	$\frac{7}{603}$	$\frac{7}{613}$	$\frac{-}{-}$

* $\frac{\text{Spacing (mils)}}{T_{Cs}\ (^oK)}$

** 1722^{o}K

Table 4. SPACING AND T_{Cs} FOR 10 Amp/cm^2

Converter	T_E (°K) 1650	1748	1843	1940	2035	2133
A	10*/573	10/593	-/-	2/623	1/623	1/643
B	10/553	10**/553	5/588	1/573	1/593	1/613
C	5/573	5/573	5/593	5/593	5/603	5/613
D	10/573	7/593	5/593	5/613	5/623	2/633
E	20/523	10/543	10/553	7/573	5/583	2/623
F	7/593	5/603	7/603	7/613	5/623	-/-

* $\frac{\text{Spacing (mils)}}{T_{Cs}\ (^{\circ}K)}$

** 1722°K

Table 5. SPACING AND T_{Cs} FOR 15 Amp/cm^2

Converter	T_E (°K) 1650	1748	1843	1940	2035	2133
A	$\frac{10*}{573}$	$\frac{5}{593}$	$\frac{-}{-}$	$\frac{2}{623}$	$\frac{1}{643}$	$\frac{1}{643}$
B	$\frac{10}{553}$	$\frac{10**}{553}$	$\frac{5}{588}$	$\frac{1}{593}$	$\frac{1}{593}$	$\frac{1}{613}$
C	$\frac{5}{573}$	$\frac{5}{573}$	$\frac{5}{593}$	$\frac{5}{603}$	$\frac{5}{613}$	$\frac{5}{633}$
D	$\frac{7}{573}$	$\frac{5}{593}$	$\frac{5}{613}$	$\frac{5}{623}$	$\frac{5}{633}$	$\frac{2}{663}$
E	$\frac{20}{533}$	$\frac{10}{553}$	$\frac{10}{573}$	$\frac{5}{593}$	$\frac{5}{613}$	$\frac{2}{623}$
F	$\frac{5}{603}$	$\frac{5}{613}$	$\frac{5}{613}$	$\frac{5}{623}$	$\frac{5}{633}$	$\frac{-}{-}$

* $\frac{\text{Spacing (mils)}}{T_{Cs}\ (^{\circ}K)}$

** 1722°K

The high output voltages of the B converter at T_E 1900^oK or greater were for 2- and 1-mil spacings. One may postulate that at high T_E and close spacing this emitter was generating sufficient ions by surface ionization and at close spacing, the 5 Amp/cm^2 could be drawn without the help of a discharge mode of operation which generate positive ions in the interelectrode space.

The J-V curve for 2-mil spacing in Figure 6 shows this high output voltage and the unusual shape of the J-V curve as compared with the one at T_E = 1844^oK and 10-mil spacing which is a more usual J-V curve. Curves A, C, and D of Figure 24 appear to show this effect but to a much smaller extent. At 10 Amp/cm^2 (Figure 25 and Table 4) only converter B shows the unusually high output at high T_E and close spacing.

A study of the tables reveals that converter E operated best at the widest spacing and lowest Cs pressure (lowest T_{Cs}). This was attributed to the presence of oxygen in the converter. The opposite effect may be observed for converter F. It operated at high Cs pressures. This converter was the all-Nb structure. Nb is an excellent oxygen getter; so possibly this converter had the lowest oxygen partial pressure. These observations suggest that the outgassing procedure is very important. This dependence is to be expected since the operation of a thermionic converter depends upon monolayers and partial monolayers of atoms on the electrode surfaces. If one could control the oxygen partial pressure, probably one would want a small amount of oxygen in each converter. As illustrated by converter E, oxygen could improve the output at low values of T_E. However, as mentioned in the review of converter E, rapid material transport to the collector will probably shorten the converter life and limit the use of oxygen in converters.

CONCLUSIONS

As predicted by the experiments of H. F. Webster,[15] the (110) planes of W are the best planes to be exposed for the surfaces of W emitters. The (110) planes of W are the most stable and offer excellent prospects for long life, stable, high performance emitters.

The emitter that exhibited the best initial performance was a faceted emitter created by etching a (100) surface to expose the (110) planes. This emitter lost part of its performance as a result of operation for 22 hours at $2133^{\circ}K$.

The inadvertent inclusion of oxygen in one converter corroborated the high performance at low T_E reported by other observers.[14] At high T_E values the presence of oxygen reduces the output power and greatly shortens the converter life by transporting emitter material to the collector.

The converter with a W(110) emitter and a Ni collector had the best output performance. This is probably related to the Ni, which has been previously report,[7] to be an outstanding collector material. An attempt to compare Nb with Mo for collectors was unsuccessful, but did point out the difficulty of putting a thin coating of Mo on a Nb collector to improve a converter performance.

APPENDIX A

A COMPARISON WITH OTHER PUBLISHED RESULTS

A review was made of several converter performance tests of laboratory type thermionic converters with various electrode materials that have been reported in the past few years. This review does not contain an exhaustive literature search; and if some important test results have been omitted, the writer wishes to apologize to the authors.

Some authors report terminal voltages and some electrode voltages. Where possible, terminal voltages were corrected to electrode potential differences. In one or two cases where it was known that the emitter surface was cooler than the back side of the emitter, a correction was made so that the temperature of the emitter surface was used for the plot.

It has been recently discovered that in previous tests, while calibrating our bell jar, mirror and pyrometer system, we made a consistent error. Previously, the temperature of our emitters were reported 22 $^{\circ}$K higher than the true temperature. The families of curves in this report were corrected for this 22 $^{\circ}$K adjustment.

Figure A-1 shows some of the results using Re emitters. Some converters had fixed spacings; but, wherever possible, data were used for T_C, T_{Cs}, and spacing optimum.

Rufeh, Lieb and van Someren(17) found that electroetched Re produced more output than electropolished Re (see curves B and B'). It is rather amazing how nearly uniform the results are for such a variety of collectors. The band of curves and separate points through the central region is for collectors of Mo, Nb, and Re. The two upper curves are for two fixed spaced converters with Ni collectors. These emitters were given a high temperature treatment which probably produced a thermal etch. This

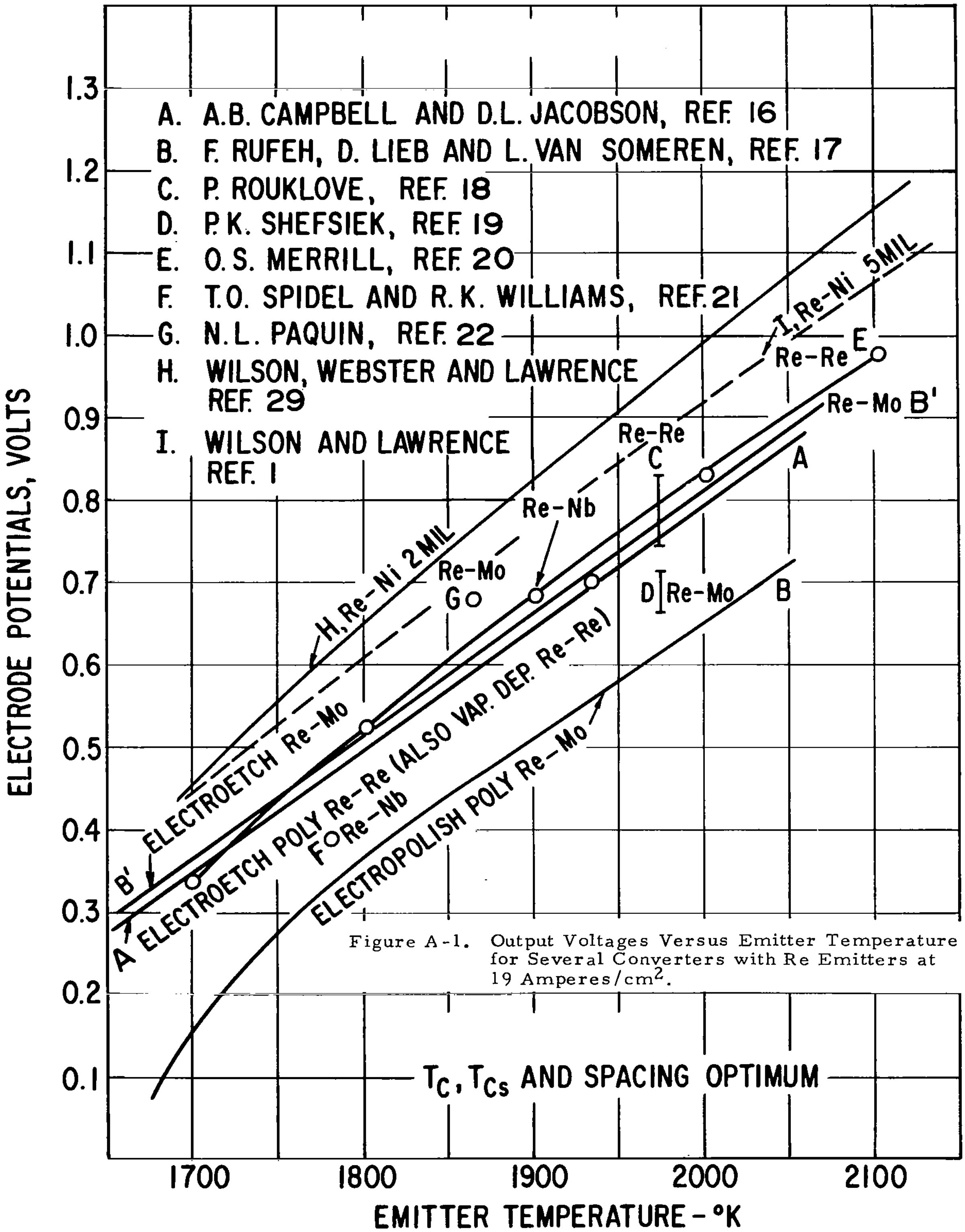

Figure A-1. Output Voltages Versus Emitter Temperature for Several Converters with Re Emitters at 19 Amperes/cm^2.

treatment may have accounted for the high output, but the writer believes that Ni is an outstanding collector material and the use of Ni collectors more probably explains the high output performance of these two converters.

Because Re has a high vacuum work function, it has been assumed by thermionic converter specialists that Re would be an outstanding emitter material. This explains why several converters have been made and tested using Re emitters.

For comparison, curve A of Figure A-1 was repeated in Figure A-2 (curve A). Curve H, the highest curve of Figure A-1, would fall essentially on top of curve B of Figure A-2. Notice that curve D--W(110)-Ni converter (converter C of this report)--throughout the emitter temperature range produced the most output voltage at 19 Amp/cm^2 of any thermionic converter reported to date. At the Stresa conference, it was reported that the vapor deposited W(110)-Ni converter[10, 25] and the single crystal W(110)-Mo[24] converter produced almost identical results; however, with the 22°K adjustment of T_E mentioned above for the vapor deposited W(110) emitter, it appears that the converter with the Ni collector produced more power than the converter with a single crystal W(110) emitter and a Mo collector. The Ni collector was 5 mils from the emitter as compared with 2 mils for the Mo collector. This spacing difference is in the opposite direction to explain the difference in output.

It is surprising that a polycrystalline W-Ni converter, curve E (Figure A-2), produced more output than the Re-Re converter, curve A. The polycrystalline W emitter was given a high temperature heat treatment which in processing W emitters has been shown[31] to have beneficial effects. It is believed that this heat treatment causes preferential growth of the (110) oriented crystallites and also thermally etches the surface to expose the (110) surface planes. This produces a large percentage of high and nearly

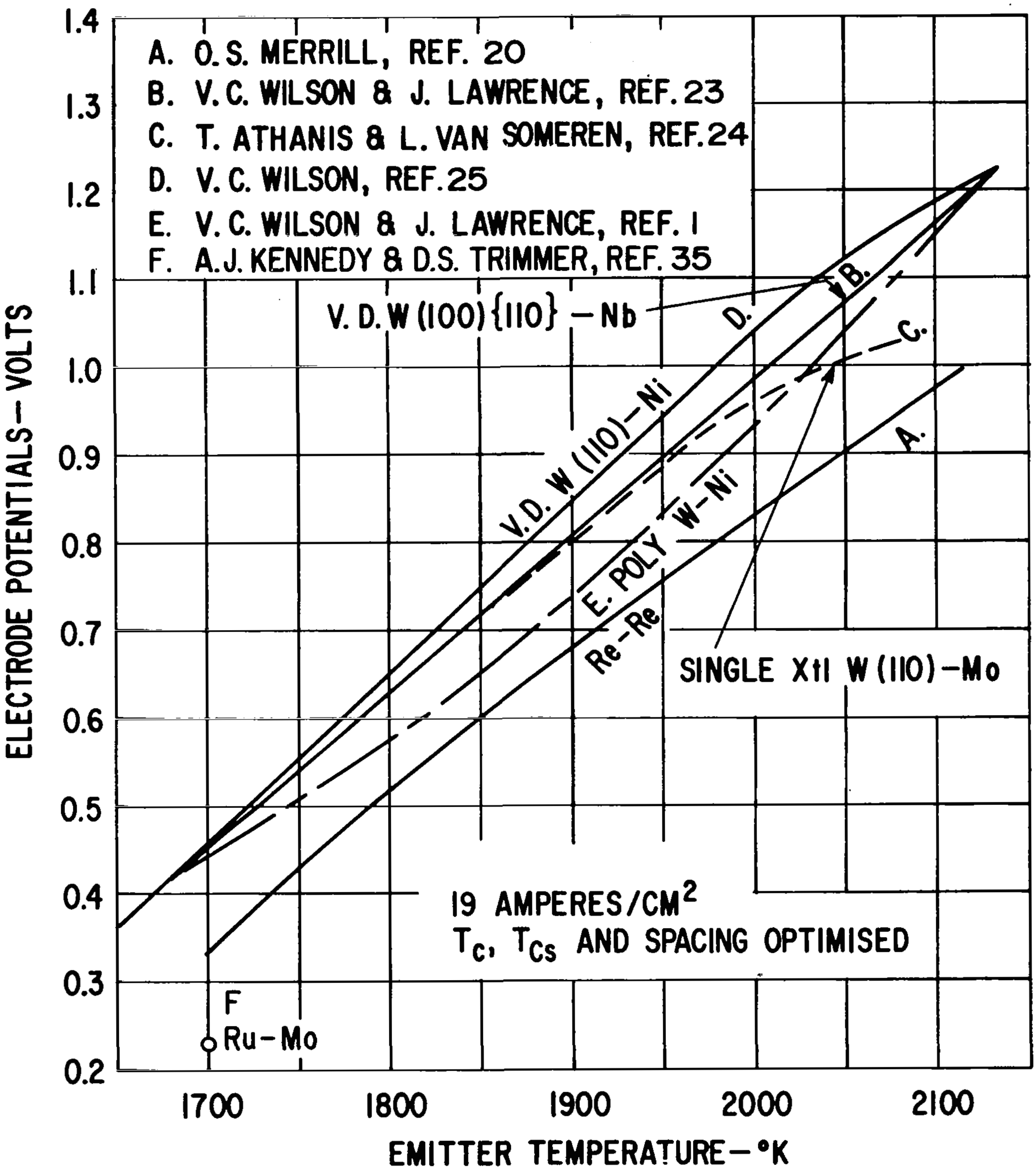

Figure A-2. A Comparison of Converters with W and Re Emitters.

uniform work function surfaces. If the surface has a uniform work function free of "patches", then one Cs pressure can be found to give maximum converter output for the entire emitter surface. If the uniform bare work function is high, then the optimum Cs pressure and the electron scattering is low, which permits good operation at wide spacings.

Figure A-3 shows the performance of several converters with Nb collectors and various emitters at 10 Amp/cm^2. The upper curve, B, gives the output of converter B of this report with a faceted emitter. It may be recalled that this emitter was not stable with time.[23]

As mentioned above, the high output at low emitter temperatures of curve E (Figure A-3) is probably due to the presence of oxygen in this converter. The second best emitter surface up to $T_E = 2050^oK$ is the vapor deposited W(110) emitter. Polycrystalline Re should have a higher work function than polycrystalline W, but the comparable output of the W (compare curves A and F) may be because of the heat treatment given the W. Curve I is low, particularly at the higher T_E values, because of the fixed 8-mil spacing. The difference between curve I and curves H and J probably is caused by the difference in the bare work function of these two crystal planes.

Figure A-4 compares four planar converters with fixed 5-mil spacings and Ni collectors. Here again the W(110) emitter is best above 1850^{o}K. The measured work functions of these surfaces determined before introducing Cs into the converters are given in the box at the bottom of the figure. Notice that at high emitter temperatures the output voltage at 10 Amp/cm^2 is in the same order as the work function. This is in agreement with the general concept that, neglecting a patchy emitter surface, the higher the bare work function of the emitter surface the better.

Less effort has been made to carefully prepare and characterize collectors than emitters. Figure A-5 shows output powers with W(110) emitters. The collector surface for curve C was a mixture of Mo and Nb,

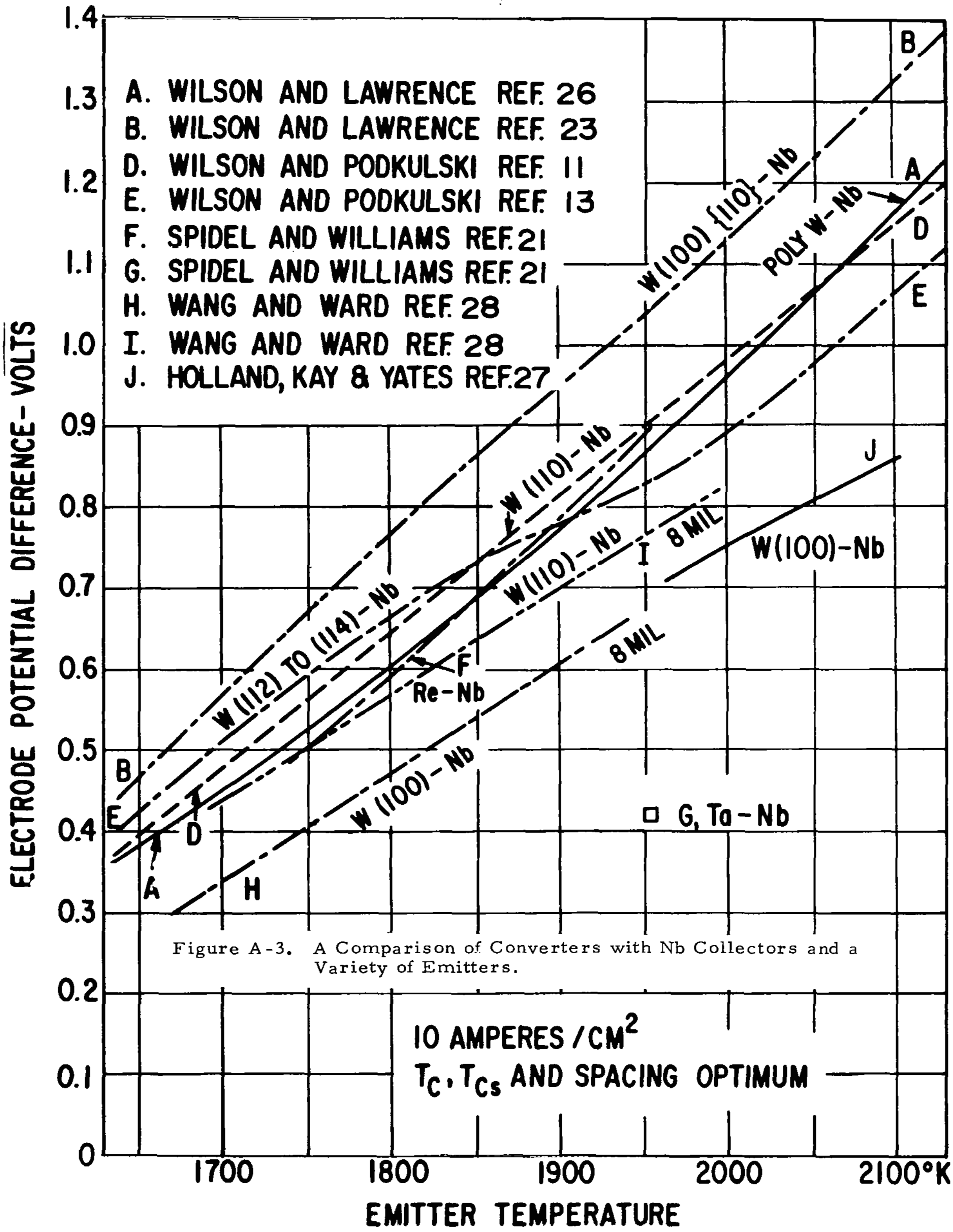

Figure A-3. A Comparison of Converters with Nb Collectors and a Variety of Emitters.

and probably curve E is low because there is something different about the composite fluoride plus chloride vapor deposits. Assuming that curves A, B, and D represent nearly identical emitters, one may say that for a collector Mo is considerably better than Nb and Ni is slightly better than Mo. The curve (average ΔV of Ni over Nb from curves A and D) at the bottom of the figure shows that Ni produces about 0.1 Volt more output than does Nb. The Thermo Electron Corporation[33] reports that Re increases the output 0.1 Volt above that of Mo. Holland, Kay and Yates[27, 34] report that Mo is superior to Nb as a collector material. The general consensus of the workers in the field is that Nb is not a good collector material.

For maximum converter output, the ϕ_c must be a minimum at the Cs pressure adjusted for optimum Cs coverage of the emitter. The lowest work function with Cs has been reported by Maly, Rapp, and Kluge[38] of 1.25 eV for Al-Al_2O_3-Cs at T_C/T_{Cs} = 1.4 and T_{Cs} = 250°C; T_C than is 445°C which may be a little low for thermionic space reactor systems. The low work function surface appears to be an Al-Al_2O_3-Cs semiconductor which is unstable above 450°C. After 150 hours of operation, the work function at T_{Cs} = 225°C increased to a minimum of 1.7 eV.

The work function of Ni in several converters has remained consistently low, usually below 1.5 eV. Houston and Dederick[36] have shown that Ta and AISI type 304 stainless steel have low work functions when coated with Cs. The cylindrical converters with stainless steel collectors life tested by Lawrence and Wilson[37] had low output voltages suggesting high collector work functions. Figure A-6 taken from Maly, Rapp and Kluge[38] may explain why Ni is better than stainless steel for a high temperature collector. The low work function of the Cr-Ni steel comes at T_{Cs} = 473°K and T_C = 590°K. The dashed line was taken from Lawrence and Perdew.[5] Their T_C was 830°K at the minimum in the curve. No one has been able to accurately measure T_C under normal thermionic converter operating conditions of T_C = 1000°K. Presumably Ni with a trace of oxygen in a converter maintains a low cesiated work function under the usual operating

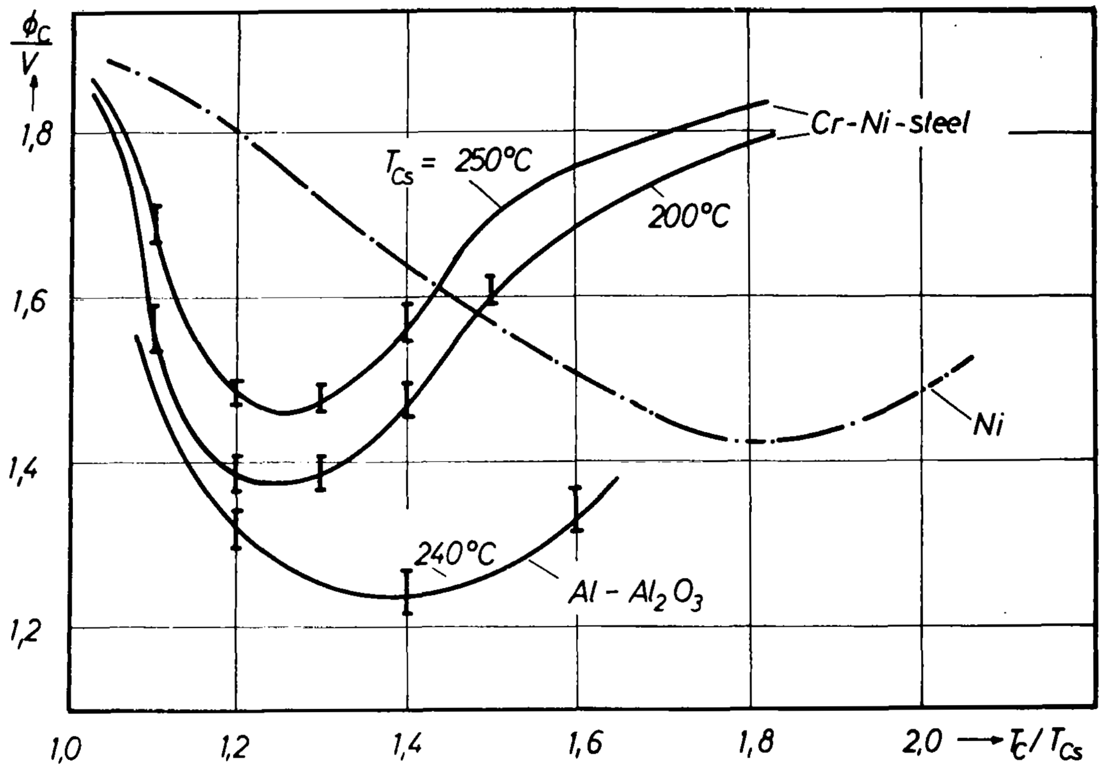

Figure A-6. Collector Work Function Comparison

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