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CHARACTERISTICS OF A VARIABLE SPACED PLANAR THERMIONIC CONVERTER WITH A TUNGSTEN EMITTER AND A NIOBIUM COLLECTOR

by V. C. Wilson and J. Lawrence

Prepared by
GENERAL ELECTRIC COMPANY
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for Lewis Research Center

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FOREWORD

The research described herein, which was conducted by the General Electric Research and Development Center, was performed under NASA Contract NAS 3-8511. The technical manager was Mr. J. F. Mondt, Space Power Systems Division, NASA Lewis Research Center. The report was originally issued as General Electric Report GEST-2094.

ABSTRACT

A parallel plane, variable spaced, thermionic converter was built with a polycrystalline tungsten emitter and a polycrystalline niobium collector. Current-voltage characteristics were obtained for a range of emitter temperatures from 1673 to 2153°K; collector temperatures from 873 to 1173°K; cesium reservoir temperatures from 583 to 683°K, and spacings from 1.0 to 20.0 mils. Over fifty families of curves consisting of over 190 load lines were obtained. Description of the converter processing procedure, test facility and experimental techniques is included. The output characteristics are compared with those of three converters with nickel collectors.

TABLE OF CONTENTS

CHARACTERISTICS OF A VARIABLE SPACED PLANAR THERMIONIC CONVERTER WITH A TUNGSTEN EMITTER AND A NIOBIUM COLLECTOR

SUMMARY

This topical report represents one of a series of reports to be prepared under Contract NAS 3-8511, Task III, Investigation of the Effect of Electrode Materials, Surface Treatments, and Electrode Spacing on Converter Performance.

Characteristics of a variable spaced,unguarded, planar, thermionic converter with a polycrystalline tungsten emitter and a polycrystalline niobium collector were determined. The diameters of the emitter and collector were 0.7 and 0.6 inch, respectively. A mechanical stage was used to vary the converter spacing. The emitter was heated by electron bombardment from a spiral-shaped tungsten filament positioned above the back side of the emitter. The emitter temperature was determined by observing blackbody cavities in the emitter with a calibrated micro-optical pyrometer. The collector temperature was measured with thermocouples positioned in the collector body close to the surface; the collector temperature was controlled by adding supplemental heat with a resistance heater. A resistance heater was used to control the

temperature of the cesium reservoir which was measured by a thermocouple.

A tungsten emitter vacuum work function of 4.58 eV was measured at 2105°K before introducing cesium into the converter. After admitting the cesium, a minimum cesiated collector work function of 1.55 eV was measured for the niobium collector.

A series of current-voltage characteristics was obtained for emitter temperatures, T_E, from 1673 to 2153°K; cesium reservoir temperatures, T_{Cs}, from 583 to 683°K; collector temperatures, T_C, from 873 to 1173°K; and interelectrode spacings from 1.0 to 20 mils. The converter was driven at 60 cycles and the electrode potential difference and current density were plotted on an XY recorder to yield a family of current-voltage curves for the various test conditions.

The effect of varying the emitter temperature on the converter performance with a 7-mil spacing and with optimum collector and cesium temperature is presented in Table I. For constant current density of 20 A/cm^2 the power density varies from 5.6 to 19 W/cm^2, at emitter temperatures of 1673 and 2153°K respectively. At a constant current density of 10 A/cm^2, the output voltage increases about 0.16 volt per each 100°K increase in emitter temperature.

TABLE I

THE EFFECT OF EMITTER TEMPERATURE ON CONVERTER PERFORMANCE

(Temperature Collector, T_C-Optimum; Temperature Cesium, T_{Cs}-Optimum; Spacing - 7 mils)

For Constant Current Density (20 A/cm^2)

T_E(°K)	Voltage (V)	Power Density (W/cm^2)
1673	0.28	5.6
1770	0.44	8.8
1866	0.55	11.0
1962	0.67	13.4
2057	0.80	16.0
2153	0.95	19.0

For Constant Current Density (10 A/cm^2)

T_E(°K)	Voltage (V)	Power Density (W/cm^2)
1673	0.35	3.5
1770	0.53	5.3
1866	0.68	6.8
1962	0.84	8.4
2057	0.98	9.8
2153	1.15	11.5

The effect of variations in collector temperature on the converter performance is presented in Table II under conditons of a constant emitter temperature of 2057°K and at a spacing of 10 mils. The power output is relatively insensitive to variations in collector temperature. For constant current densities of 20 and

10 A/cm^2, the change in converter performance as expressed in power density (watts per square centimeter) is approximately 20 and 10%, respectively, as the collector temperature is varied between 900 and 1100°K. At 10 A/cm^2, the optimum collector temperature is 973°K, whereas at a current density of 20 A/cm^2 the optimum is 1050°K. For increasing current densities, the optimum collector temperature increases.

TABLE II

THE EFFECT OF COLLECTOR TEMPERATURE ON CONVERTER PERFORMANCE

(Temperature Emitter, T_E-2057°K; Spacing - 10 mils)

Collector Temperature (T_C)°K	Voltage (V)	Power Density (W/cm^2)
For Constant Current Density (20 A/cm^2)		
900	0.55	11.0
1000	0.66	13.2
1100	0.65	13.0
For Constant Current Density (10 A/cm^2)		
900	0.86	8.6
1000	0.94	9.4
1100	0.87	8.7

The effect of spacing on converter performance at an emitter temperature of 2057°K, a collector temperature of 1023°K, optimum cesium temperature, and at constant current densities of 20 and 10 A/cm^2 is presented in Table III. At both the 10 and 20 A/cm^2 current densities, there is no gain in output by reducing the spacing from 2 to 1 mil. From the standpoint of mechanical design, there is little loss in converter performance in increasing the spacing from 5 to 7 mils. Beyond the 7-mil spacing, the power output starts to diminish substantially.

TABLE III

THE EFFECT OF SPACING ON CONVERTER PERFORMANCE

(Temperature Emitter, T_E-2057°K; Temperature Collector, T_C-1023°K; Temperature Cesium, T_{Cs} Optimum)

For Constant Current Density of 20 A/cm^2

Spacing (mils)	Power Density (W/cm^2)
1	17.5
2	17.5
5	16.8
7	16.0
10	13.5
20	7.0

For Constant Current Density of 10 A/cm^2

Spacing (mils)	Power Density (W/cm^2)
1	10.5
2	10.5
5	10.2
7	9.9
10	9.3
20	6.5

In comparing the output characteristics of the W-Nb converter with those of three converters with Ni collectors, the results indicate that Nb is inferior to Ni as a collector material. Depending upon the spacing, emitter temperature, and current density, the output voltage of a W-Nb converter was from 0.1 to 0.16 volt less than for a W-Ni converter under similar conditions. In terms of T_E to obtain equal outputs, the W-Nb converter must operate from 50 to 100°K hotter. The operating temperature range of the Nb collector was essentially the same as that for a Ni collector.

In the region investigated, changing from a Nb collector to a Ni collector will produce approximately the same improvement as changing the spacing from 10 to 5 mils in a converter.

INTRODUCTION

This study is part of a program to compare the characteristics of thermionic converters with various emitter and collector materials and surfaces under Task III of contract NAS 3-8511. Previously, a 5-mil fixed spaced[(1)] and a 2-mil fixed spaced[(2)] converter with polycrystalline tungsten emitters and polycrystalline nickel collectors were tested.

For several reasons, it may be desirable to use niobium collectors for thermionic converters in nuclear reactors: for thermal reactors, niobium is desirable because it has a comparatively low thermal neutron capture cross section; niobium matches alumina in thermal expansion, and thus makes it possible to bond to the collector an electrically insulating layer that will conduct the unconverted heat with tolerable temperature drops; niobium is a refractory metal with a high melting point and low vapor pressure, and therefore, it can be operated at high temperatures.

Measurements of work functions of cesiated surfaces suitable for collector materials by Houston[(3)] indicate a minimum work function for niobium of about 1.8 eV. This value compared with his measured minimum for nickel of about 1.55 eV potentially indicated a considerable disadvantage in using niobium as a collector material. It has been suggested, however, that the collector surface in a converter generally is not atomically clean[4] and measurements of collector work function in a converter usually yield minimum values below those measured for atomically clean surfaces.

In spite of the possibility that a converter with a niobium collector would not perform as well as one with a nickel or molybdenum collector, it seemed important to test such a converter and compare the output with that from converters with nickel collectors. A design engineer needs this information so that he can decide if the improved electrical characteristics of a system with nickel collectors outweigh the nuclear and thermal disadvantages of nickel or if the development cost of a composite niobium structure with a nickel collector will be justified by the improved performances.

DESCRIPTION OF CONVERTER

A variable spacing, planar converter was used to evaluate niobium as a collector material. A polycrystalline tungsten emitter was used to make a direct comparison of performance data with previous measurements on devices with nickel collectors.[1,2] A cross section of the converter and the mechanical stage for spacing adjustment is shown in Figure 1. The converter is mounted upon

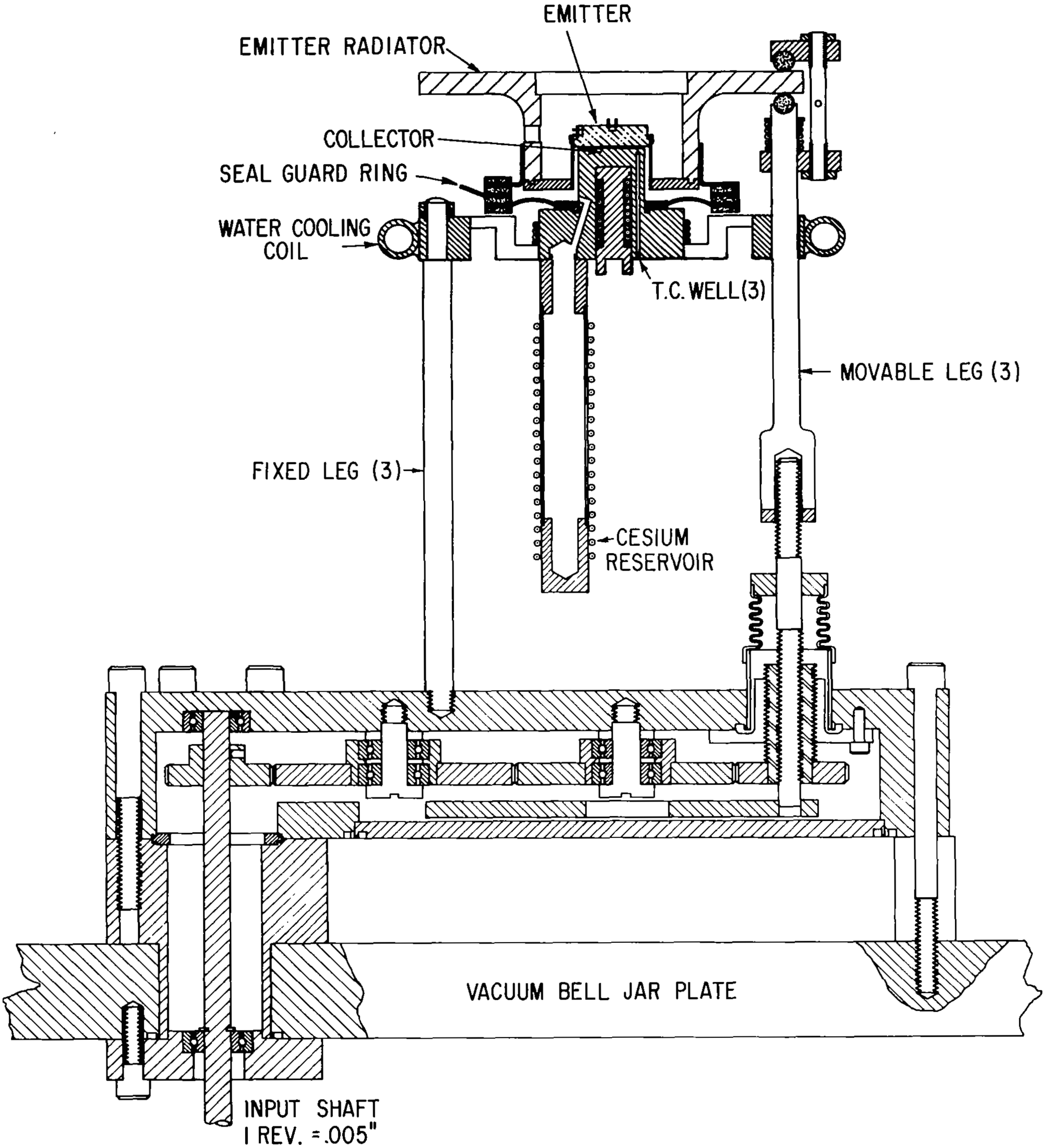

FIGURE 1. CROSS SECTION OF PARALLEL PLANE CONVERTER VG12

three fixed legs which in turn are attached to the mechanical stage. Relative position between the emitter and collector surfaces is controlled by collectively raising or lowering three movable legs clamped to the emitter radiator. Each leg contains a micrometer adjustment which is used to set the initial planar relationship between emitter and collector. Thereafter, the legs are moved collectively and the planar relationship is preserved. The motion of the movable legs is controlled by the input shaft. The system was designed so that 1 revolution of the input shaft causes a 0.005-inch change in the converter spacing. As a result of differential expansion in the converter structure, a zero spacing reference point must be determined for each temperature distribution during operation. This point is found by momentarily shorting the converter electrodes. Three small bumpers, extending 0.0002 inch above the collector surface were provided so that shorting would occur at these points and therefore minimize the possibility of electrode contamination caused by large area contact at elevated temperatures.

Heat which flows down the emitter lead is rejected by radiation from the emitter support structure. The collector is conduction cooled through six webs which connect the collector to the water-cooled mounting ring. The collector temperature is measured with thermocouples positioned close to the collector surface and its temperature is controlled by adding supplemental heat with resistance heaters. The emitter temperature is determined by observing blackbody cavities in the emitter with a calibrated micro-optical pyrometer.

EMITTER TEMPERATURE

The emitter was 1/4 inch thick and 0.7 inch in diameter. A similar emitter heated in vacuum showed that the radial temperature distribution was extremely flat, perhaps $\pm 5^\circ K$, in the area facing the collector. Since the emitter temperature was measured on the back side, a correction for the temperature gradient through the emitter must be made to determine emitter surface temperature. Calculations of the heat flow and axial thermal gradients as a function of temperature and thermionic converter current density were made. Results of these calculations are shown in Figure 2. Observations of the blackbody cavity temperature were corrected by using the data shown in Figure 2.

Further details of the experimental techniques used in this investigation are presented in Appendix A.

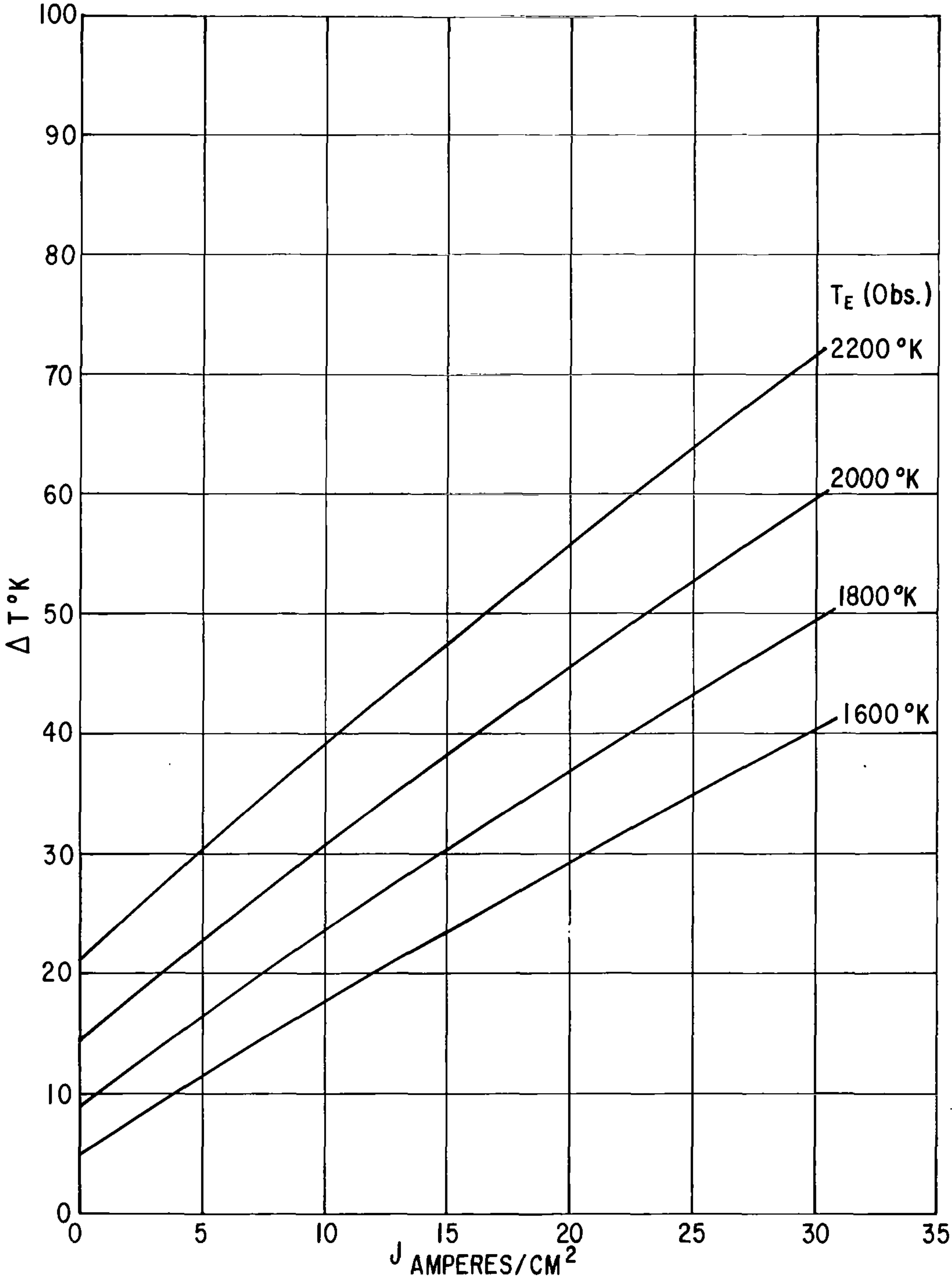

FIGURE 2. ESTIMATED DIFFERENCE IN TEMPERATURE BETWEEN BLACKBODY HOLE AND EMITTER SURFACE

RESULTS AND DISCUSSION

Work function Measurements

Emitter Work Function

While processing the converter and before admitting cesium vapor, the emission from the tungsten emitter was measured. The following table gives the results of the measurements, assuming an A value of 120 in the Richardson-Dushman Equation.

T(°K)	Φ(eV)
1995	4.57 ± .04
2105	4.58 ± .04
2210	4.58 ± .04

Rather large probable errors had to be put on these Φ values because this converter has no guard ring and the emitting area is not well defined.

Collector Work Function

After admitting the cesium, several curves, j versus v, were run of the thermionic emission from the collector. The squares of Figure 3 show the measured work function of the niobium collector versus the ratio T/T_{Cs}, collector surface temperature over cesium reservoir temperature. The saturated emission density from the collector was not well defined due to the lack of a guard ring around the collector; however, the values of collector work function reported here are probably accurate to within 0.05 eV. Part of

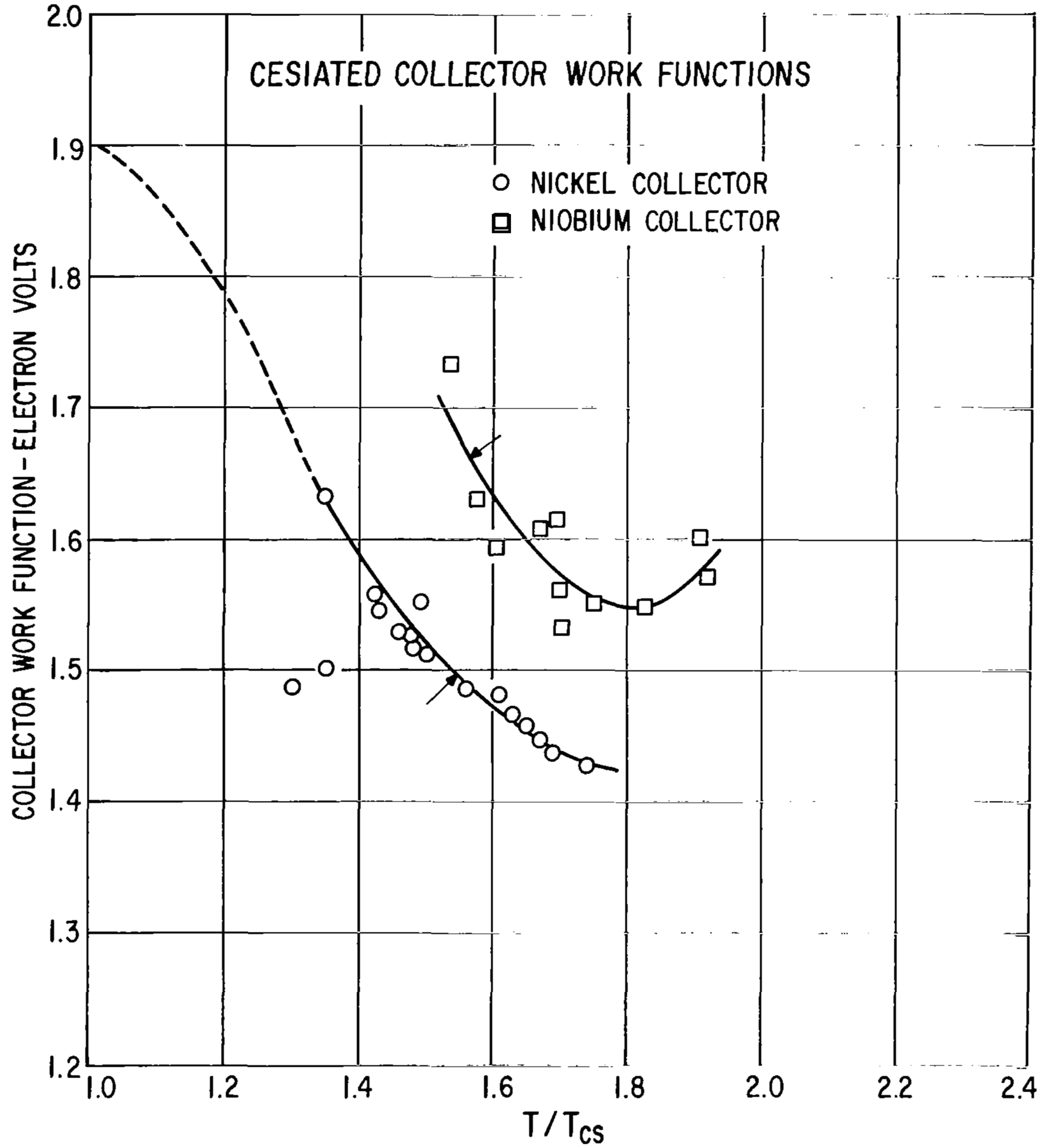

FIGURE 3. ϕ_C vs T_C/T_{Cs}

the spread in these data is the result of the difficulty in making the measurement, i.e., lack of a collector guard ring, and part of the spread is because the data were taken over a wide variation in cesium reservoir temperature. Rasor's[5] original theory that Φ is dependent upon T/T_{Cs} was approximate. Data from earlier tubes have shown that observed points of Φ versus T/T_{Cs} fall on a smooth curve for one value of T_{Cs}. For a different value of T_{Cs} the curve is usually displaced toward lower or higher Φ values. Kitrilakis[6] has made the same observations.

The circles in Figure 3 are data from the W-Ni converter with fixed 2-mil spacing.[2] It is apparent that the work function of cesiated Nb under similar conditions of T/T_{Cs} is a little more than a tenth of a volt greated than that of cesiated Ni. The minimum work function for cesiated Nb is 1.55 volts compared with 1.42 for cesiated Ni.

Converter Characteristics

Load lines, output voltage versus current density, were taken for emitter temperatures, T_E, from 1673 to 2153°K; cesium reservoir temperature, T_{Cs}, from 583 to 683°K; collector temperatures, T_C, from 873 to 1173°K; and spacings from 1.0 to 20 mils. The converter was driven at 60 cycles and the electrode potential difference and current density were simultaneously observed. These 60-cycle load lines were plotted on an XY recorder with the aid of a sampling circuit driven at a frequency slightly different from 60 cps so that the sampling circuit and recorder would draw a load line in about 3 seconds. Figure 4 shows a family of load lines with various cesium reservoir temperatures with all other parameters held constant. At low cesium pressure, T_{Cs} of 573 and 593°K, where the electron neutral atom mean free path of the electrons is about 2 mils, the result of the lack of a guard ring for this converter may be observed. At low output voltage (high internal voltage drop) some current may be collected from the emitter support structure. This causes those two load lines to start curving up near zero voltage. The lack of guard ring does not affect the operation in the region of interest; namely, along the envelope of the load lines.

The flow of heat and hence thermal gradient through the emitter varies with average current density because of electron cooling. The family of curves (Figure 4) was taken at constant blackbody cavity temperature on the back side of the emitter. When sweeping at 60 cycles out to 40 or 50 A/cm^2, the average direct current density was set at about 15 A/cm^2 by adjusting the load resistance. At low cesium pressures, an average current density of 15 A/cm^2 could not be drawn, therefore, the thermal

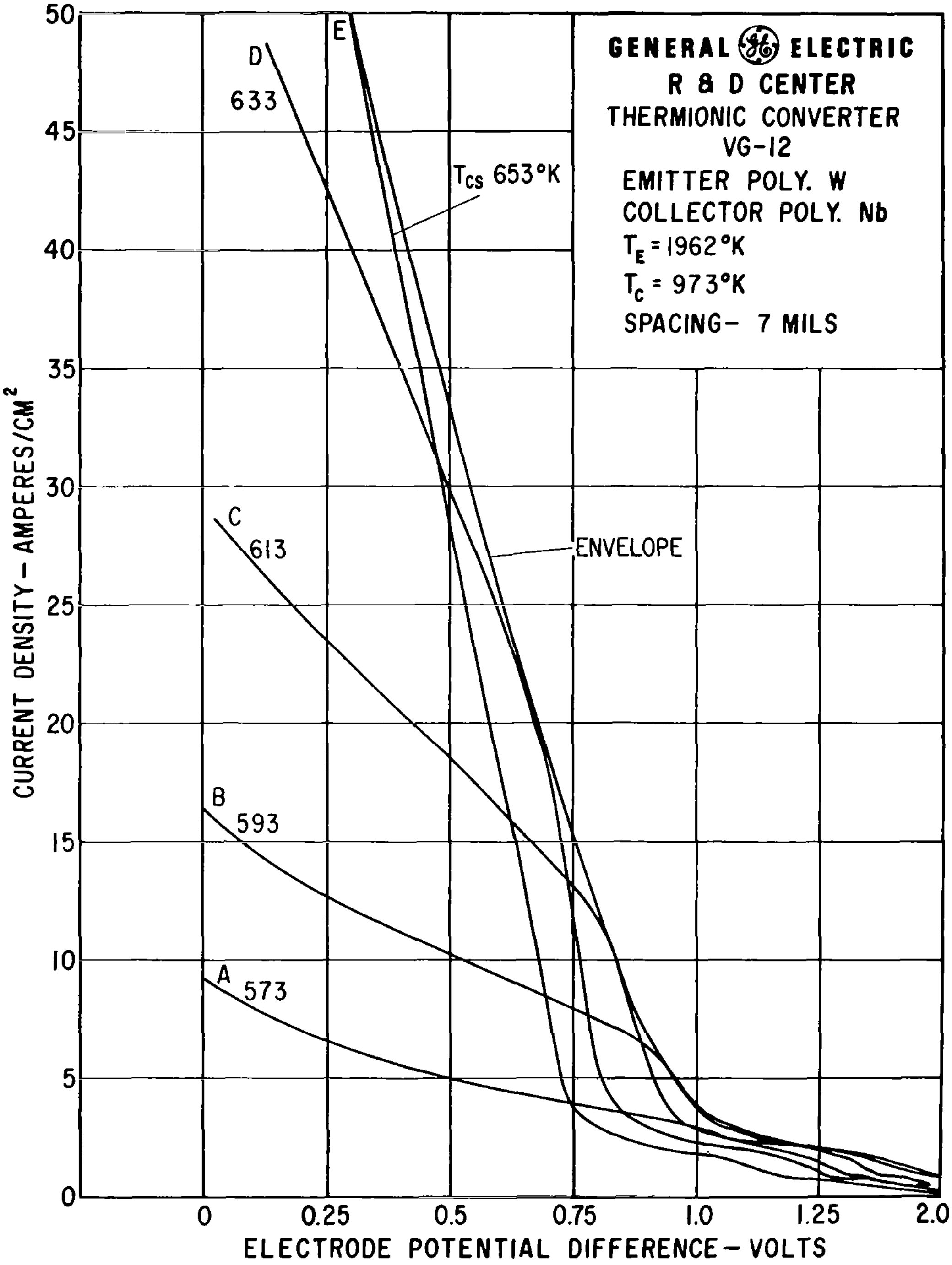

FIGURE 4. TYPICAL FAMILY OF LOAD LINES

gradient was less. Since the correction for thermal gradient through the emitter was made for an average current density of 15 A/cm^2, the low current end of the family of curves was taken at somewhat elevated emitter surface temperatures. If the average direct current varies from 15 to 5 A/cm^2, then from Figure 2 the emitter surface temperature would increase 18°K.

Figure 5 shows the envelopes of load lines for various emitter temperatures. At 10 A/cm^2 the output voltage increases about 0.16 volts per 100°K increase in emitter temperature.

Figure 6 shows the effect of spacing on the output of the converter. Notice that there is no gain in output, by reducing the spacing from 2 to 1 mil until a current of 35 A/cm^2 is exceeded. The curves show that for T_E = 2057°K and T_{Cs} optimum there is very little to be gained by going closer than 5 mils. This fact is also illustrated in Figure 7.

The effect of variations in the collector temperature is shown in Figure 8. At open circuit the voltage decreases with increasing collector temperature. The decrease is a result of the increased back emission from the collector. At 10 A/cm^2 the optimum collector temperature is 973°K. For increasing current densities the optimum collector temperature increases. For example, at 25 A/cm^2 optimum T_C is at 1023°K; at 45 A/cm^2, 1073°K.

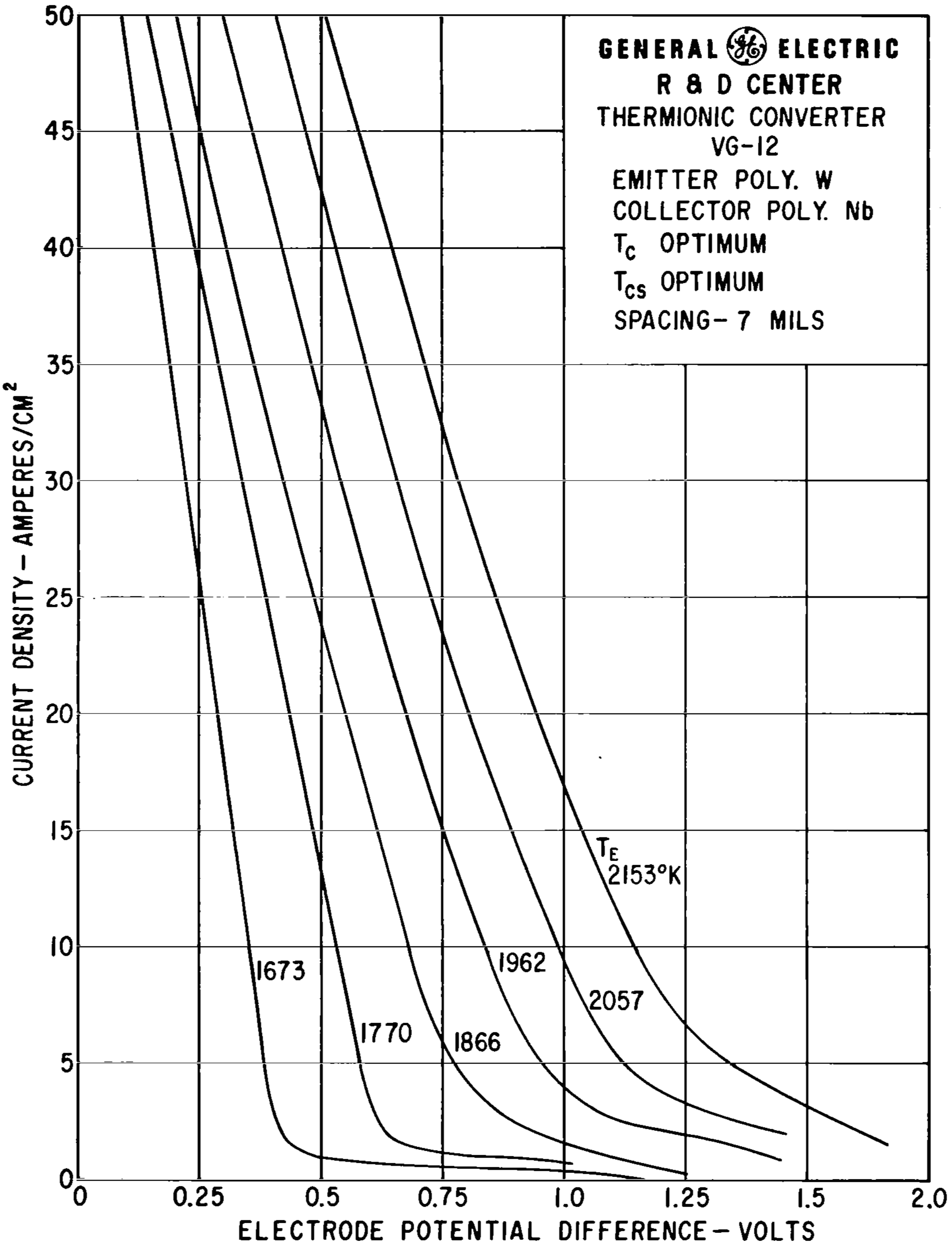

FIGURE 5. ENVELOPES OF LOAD LINES FOR VARIOUS EMITTER TEMPERATURES

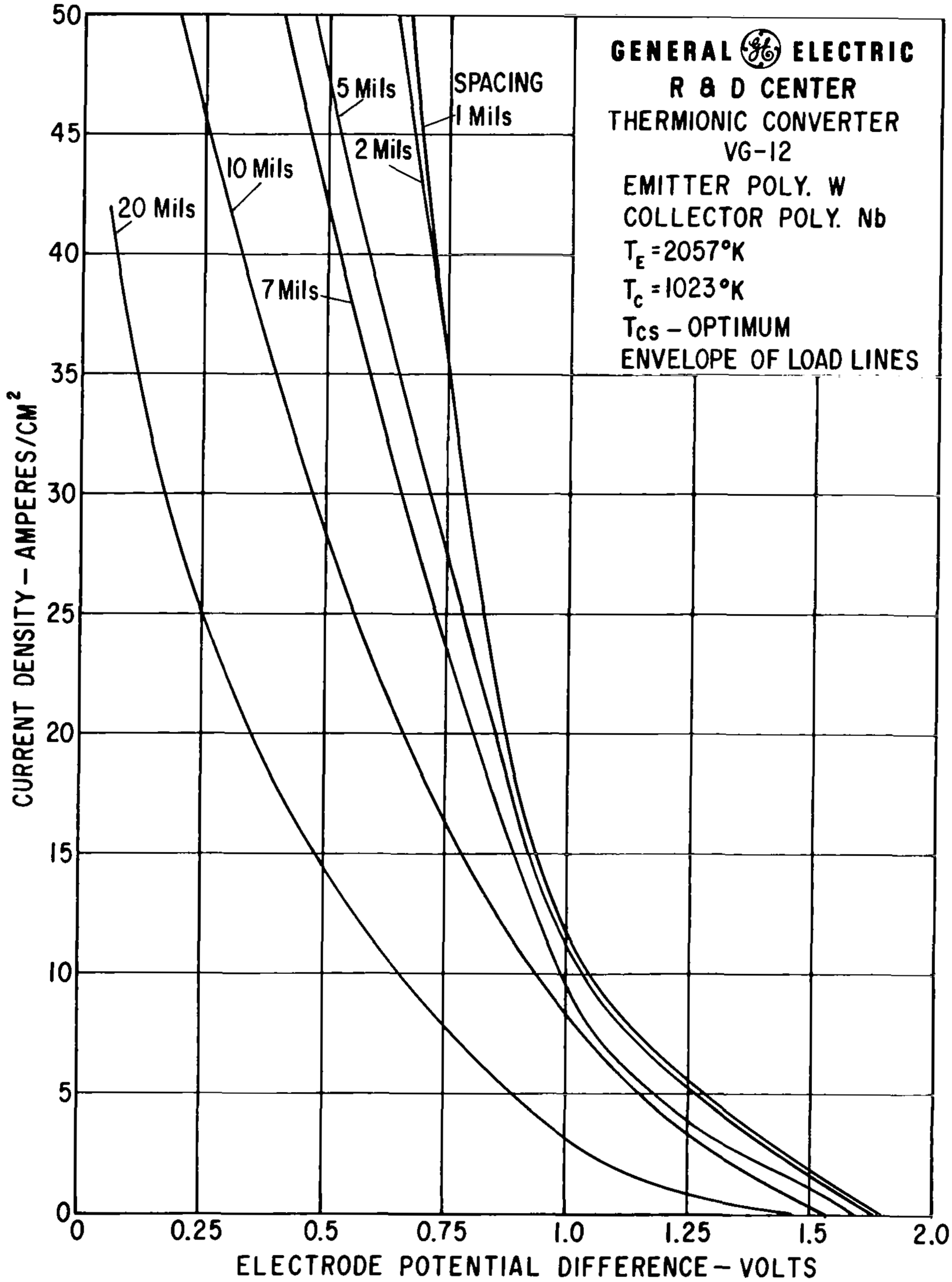

FIGURE 6. ENVELOPES OF LOAD LINES FOR VARIOUS SPACINGS

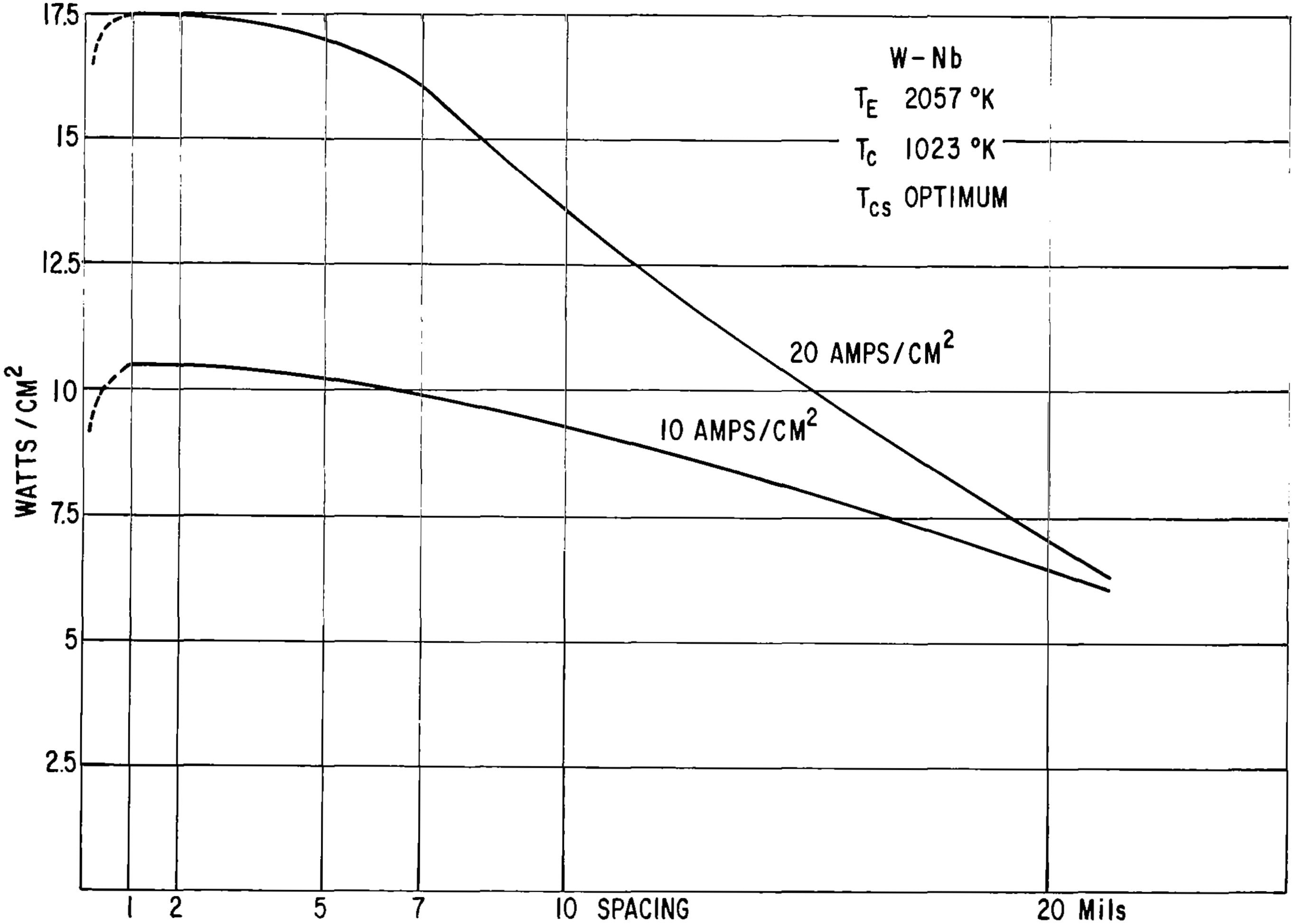

FIGURE 7. OUTPUT POWER AS A FUNCTION OF SPACING AT T_E = 2057°K

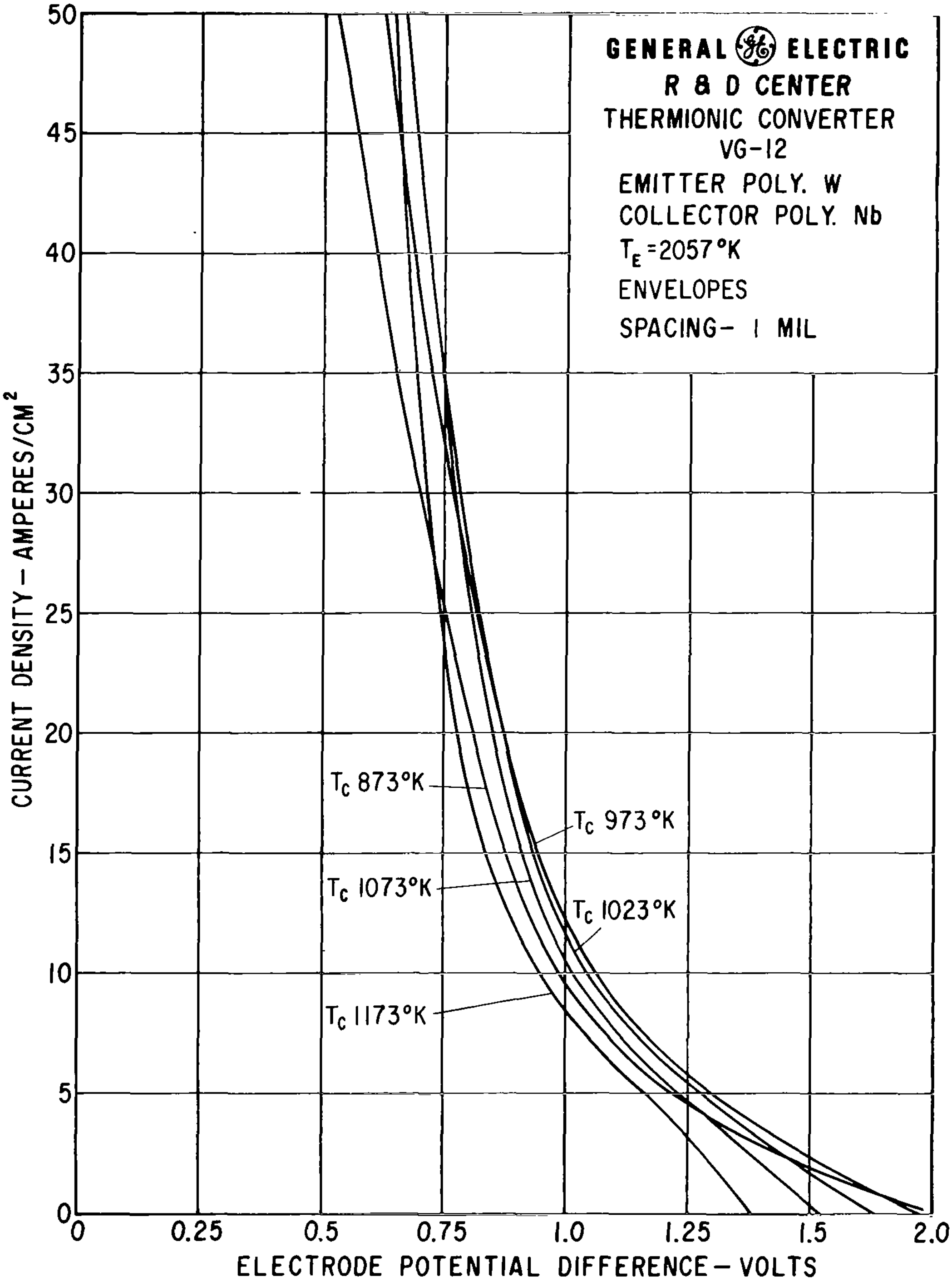

FIGURE 8. EFFECT OF COLLECTOR TEMPERATURE VARIATIONS ON THE ENVELOPES OF LOAD LINES

Curves similar to those shown in Figure 8 have been drawn for other spacings. The lower half of Figure 9 is a replot of the data given in Figure 8. The upper half is for a 10-mil spacing.

A qualitative explanation for the broad maximum in output power versus T_C can be made by referring to Figures 3 and 11. At the cesium pressures and collector temperatures of Figure 11 the ratio T_C/T_{Cs} varies from 1.36 to 1.8 with increasing T_C. From Figure 3 it may be seen that the work function of the collectors decrease as T_C/T_{Cs} increases. At constant T_{Cs} as T_C increases. This effect should improve the output voltage of the device. However, simultaneously the back emission from the collector increases greatly with increasing T_C. This produces a detrimental effect. The observed variation in output with variations of T_C is the difference between the two effects.

A complete set of load lines for T_E from 1673 to 2153°K; T_{Cs}, 583 to 683°K; T_C, 873 to 1173°K and spacing of 1 to 20 mils is presented in Appendix B.

COMPARISON OF Nb AND Ni FOR COLLECTORS

Data have been previously published for two converters with Ni collectors and 5-mil spacings.[1,7] One converter had a polycrystalline W emitter; the other a polycrystalline W-25% Re emitter. Both these converters were processed similarly to the processing of

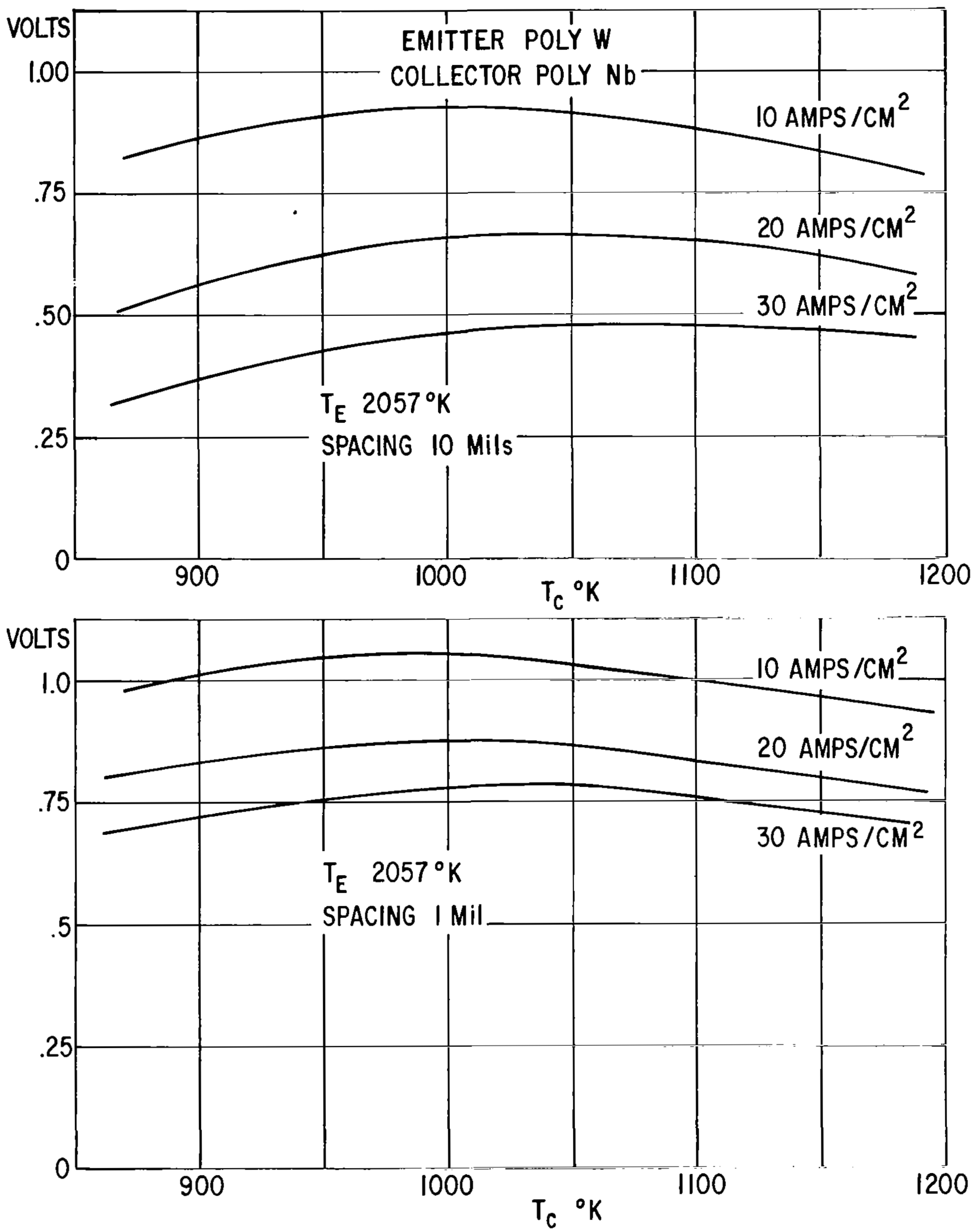

FIGURE 9. OUTPUT POTENTIAL vs COLLECTOR TEMPERATURE FOR THREE CURRENT DENSITIES AT 1- AND 10-MIL SPACING

this W-Nb converter. Both converters had been operated at T_E = 2130°K. This emitter temperature was not corrected for a temperature drop through the emitters as was accomplished for the results shown in Figure 2. It is estimated that under these conditions the emitter surfaces were at 2115°K. Therefore, for comparison the W-Nb converter was operated at 2116°K and at 5-mil spacing to compare the three converters. The results are shown in Figure 10. At all current densities the output voltage of the W-Nb converter is about 0.1 volt less than for the other two converters. Figure 11 shows the effect of collector temperature for Ni and Nb collectors. Notice that the Ni collector permits the same output power at an emitter temperature 50°K lower.

Figure 12 shows a comparison with a W-Ni converter with 2-mil spacing.[(2)] Here the superiority of the nickel collector seems greater than in Figure 10. The work function versus T/T_{Cs} of these collectors for these two converters are shown in Figure 3. At 20 A/cm^2 the W-Ni converter had optimum output at T_C = 948°K and T_{Cs} = 613°K. The W-Nb converter at 20 A/cm^2 had T_C = 1023°K and T_{Cs} = 653°K. These two load lines are shown dashed in Figure 12. Also these two operating points are indicated by arrows on Figure 3. The work function difference is 0.16 volt; the output difference at 20 A/cm^2 is 0.19 volt. The lower T_{Cs} value for W-Ni indicates

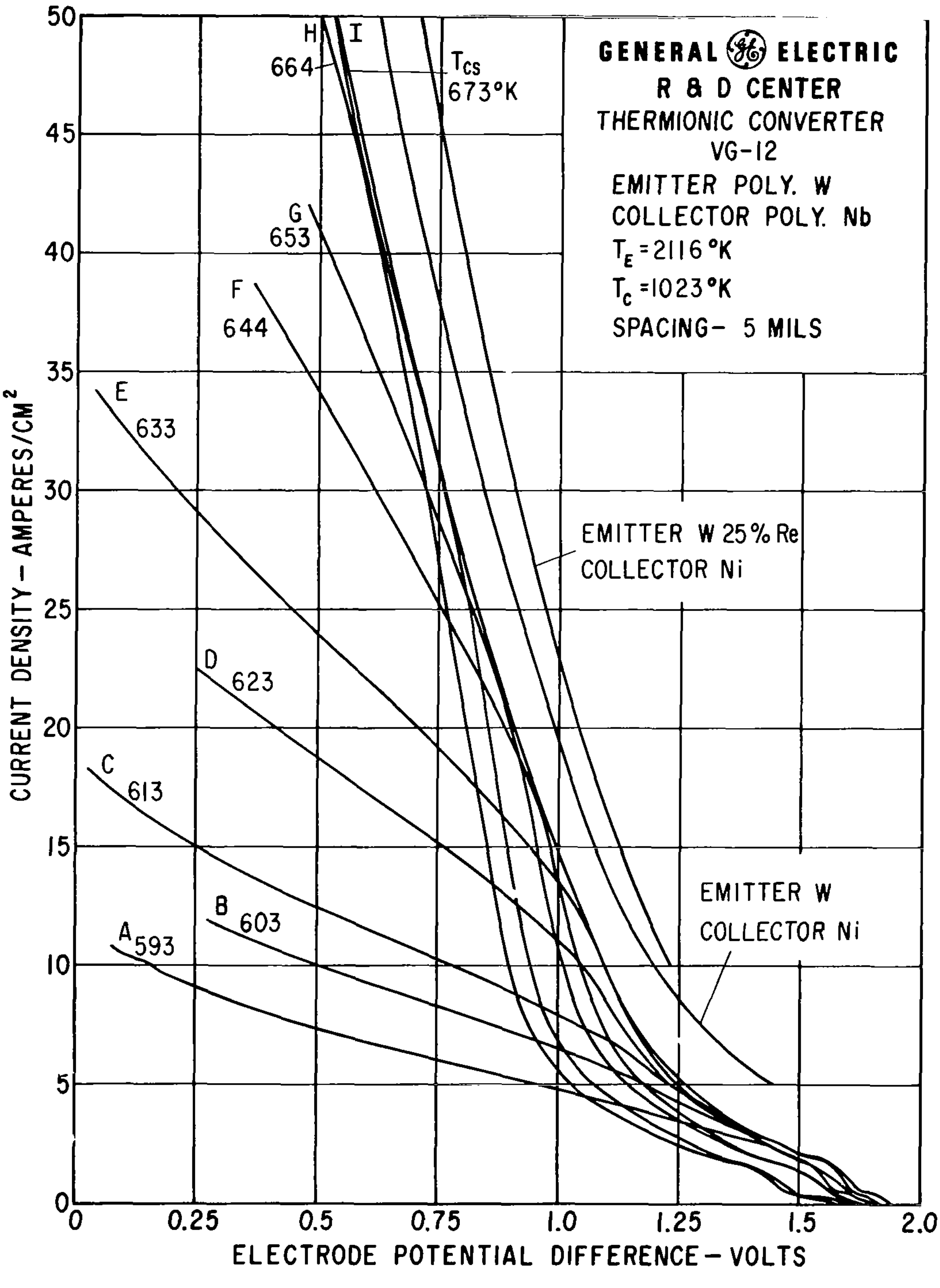

FIGURE 10. A FAMILY OF LOAD LINES FOR THE W-Nb CONVERTER AND FOR COMPARISON, TWO ENVELOPES OF LOAD LINES FOR TWO CONVERTERS WITH Ni COLLECTORS

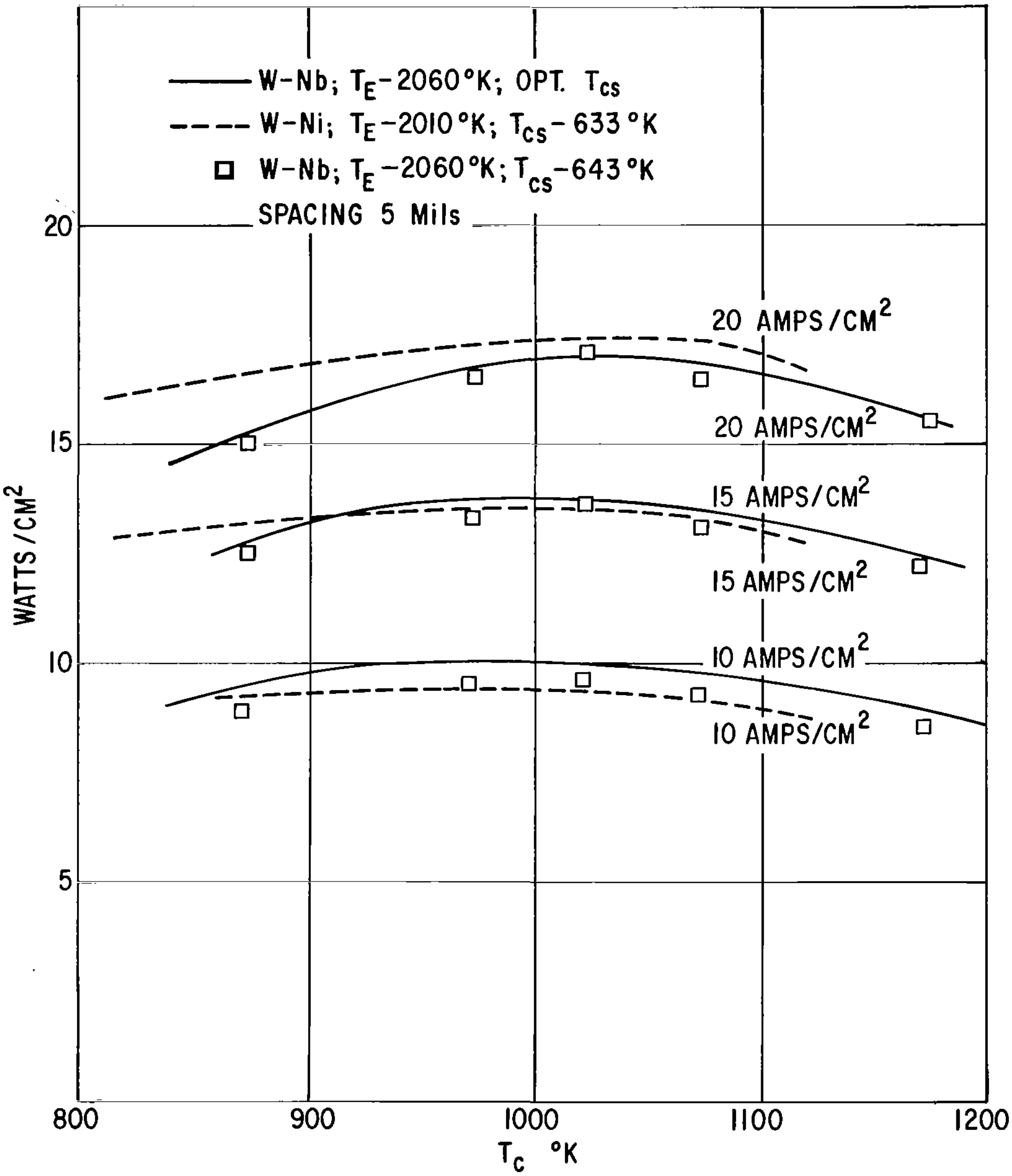

FIGURE 11. OUTPUT POWER vs COLLECTOR TEMPERATURE FOR A Nb COLLECTOR AND A Ni COLLECTOR. (Notice the W-Ni tube has T_E 50°C lower.)

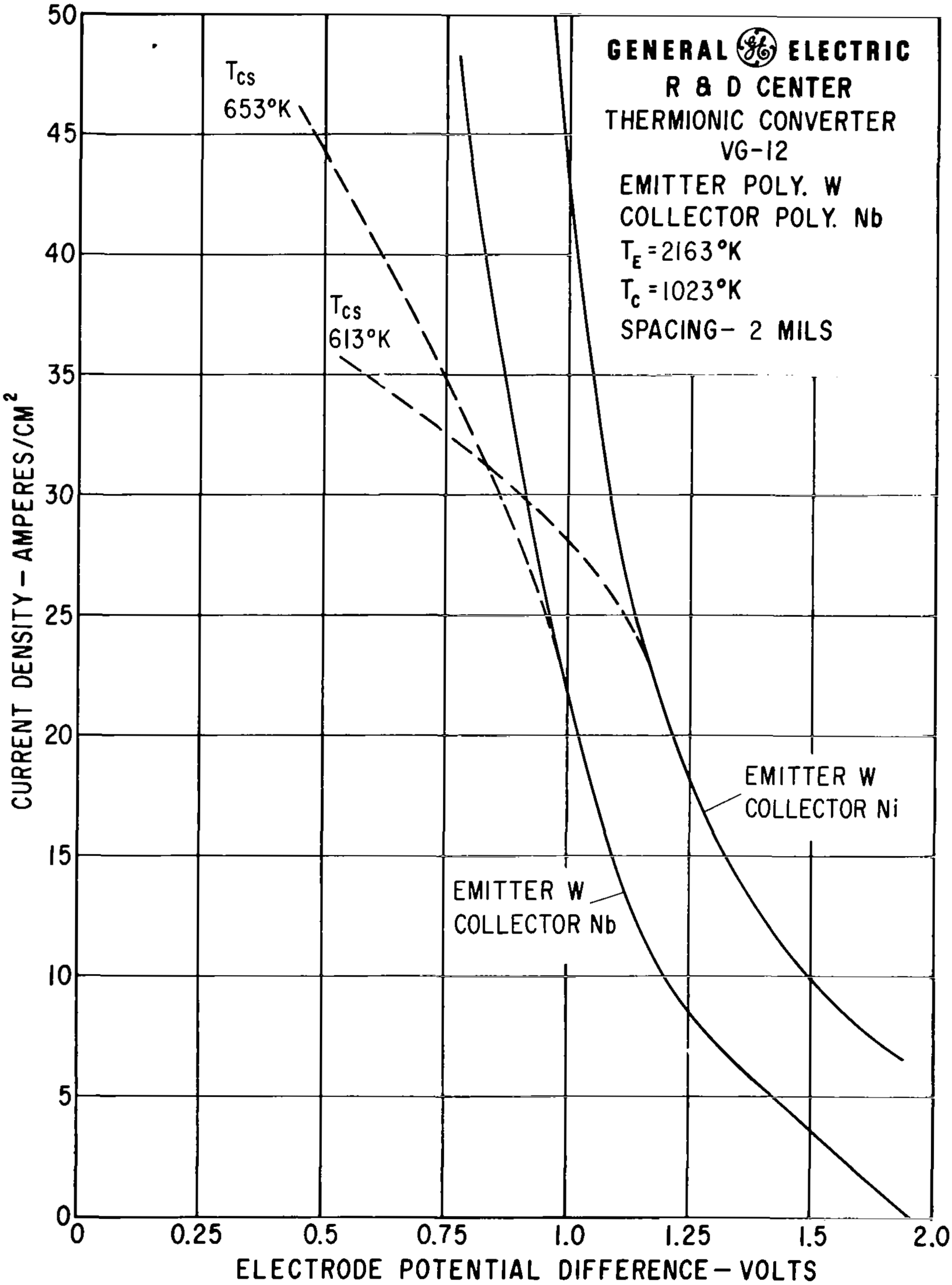

FIGURE 12. COMPARISON OF THE ENVELOPES OF LOAD LINES FOR W-Ni AND W-Nb CONVERTERS WITH 2-MIL SPACINGS

that the emitter adsorbed cesium more strongly than did the emitter in the W-Nb converter. The lower cesium pressure in the W-Ni converter means less electron scattering and could easily explain the difference between 0.16 and 0.19 volt. Thus one might conclude that the Ni collector accounted for 0.16-volt improvement and lower cesium pressure as a result of a superior emitter surface caused 0.03-volt improvement for the W-Ni converter.

CONCLUSIONS

The vacuum work function of polycrystalline tungsten emitter was measured at emitter temperatures of 1995, 2105, and 2210°K and the work functions were 4.57, 4.58, and 4.58 ± .04 eV, respectively.

A minimum work function of 1.55 ± .05 eV was measured for the cesiated polycrystalline niobium collector.

Output voltage versus current density (amperes per square centimeter) curves were taken for emitter temperatures, T_E, from 1673 to 2153°K; collector temperatures, T_C, from 873 to 1173°K; cesium reservoir temperature, T_{Cs}, from 583 to 683°K; and interelectrode spacings from 1.0 to 20 mils.

For various emitter temperatures and at a current density of 10 A/cm^2, the output voltage increases about 0.16 volt per 100°K increase in emitter temperature.

The converter performance was affected by varying the interelectrode spacing. By reducing the spacing from 2 to 1 mil, there was no gain in converter output until a current of 35 A/cm^2 was exceeded. At an emitter temperature of 2057°K and an optimum cesium temperature, the improvement in performance was slight in going closer than 5 mils. From a practical design standpoint a 7-mil spacing is desirable and the decrease in performance compared to that at a 5-mil spacing is small.

In comparing the output characteristics of the W-Nb converter with those of three converters with Ni collectors, the results indicate that Nb is inferior to Ni as a collector material. Depending upon the spacing, emitter temperature, and current density, the output voltage of a W-Nb converter was from 0.1 to 0.16 volt less than for a W-Ni converter under similar conditions. In terms of T_E to obtain equal outputs, the W-Nb converter must operate from 50 to 100°K hotter. The operating temperature range of the Nb collector was essentially the same as that for a Ni collector.

In the region investigated, changing from a Nb collector to a Ni collector will produce approximately the same improvement as changing the spacing from 10 to 5 mils in a converter.

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7. Loc. Cit., Wilson, V.C., Webster, H.F., and Lawrence J., Figure 5.

APPENDIX A

EXPERIMENTAL TECHNIQUE

To keep the main body of this report concise, many details concerning experimental techniques and the test facility have been omitted. For completeness, additional information is included in this appendix.

FABRICATION, ASSEMBLY, AND OUTGASSING

The converter consists of the collector assembly with the cesium reservoir; the emitter assembly, and the ceramic to metal seal with a flexible diaphragm.

Materials: The emitter was ground from a rolled sheet of GE Lamp Metals Department weldable grade tungsten. The niobium collector was cut from vacuum arc melted rolled sheet. All of the molybdenum parts were vacuum arc melted. The large nickel emitter radiator was induction melted nickel. The nickel foils for the seal assembly were grade A vacuum tube quality.

The seal was made of high purity alumina rings ground planar. Ten mil thick nickel foils were cleaned in an ultrasonic bath in acetone and subsequently in grain alcohol. All parts were cleaned this way. All nickel and molybdenum parts were fired in hydrogen at 1000°C about 20 minutes. The nickel foils were pressed flat and smooth between hardened steel dies. The seal was assembled by stacking the ceramic and nickel pieces with 0.0002" thick foils of titanium between the parts. The assembly was fixtured with a spring force to press the parts together and vacuum brazed in a molybdenum susceptor at 1275°C. R.H. Bristow has shown[A1] that the NiTi alloy formed in this seal may be extremely brittle if the firing cycle is not carefully controlled. For subsequent tubes, Bristow has supplied ceramic pieces pre-metalized (see Ref. A_1) and we have copper brazed either nickel or tantalum parts to the metalized surfaces.

The Niobium Collector was diffusion bonded to the molybdenum collector body by placing a 1/2 mil foil of nickel between the pieces and firing at 1400°C for 1/2 hour. During this bonding the niobium disc was considerably oversize to avoid nickel flowing onto the collector surface. The collector was then ground and polished with a diamond powder. This surface probably has a relatively high emissivity because of the surface imperfections and strains.

Surfaces of the molybdenum collector body that were to have heaters or other parts brazed to them were "brush plated" with copper. Most of the joints in the collector and cesium reservoir assemblies were copper brazed in vacuum at 1100°C. During these operations the collector surface was protected from copper deposition by appropriate shields.

The emitter was ground planar and polished with diamond paste. Subsequent heat treatment probably thermally etched the emitter and removed the surface strains. The emitter was mounted on its tantalum support section and outgassed by electron bombardment in vacuum. Finally the assembly was brought up to about 2500°C for five minutes to braze the tungsten emitter to the tantalum tube with niobium. This operation probably causes some recrystallization of the tungsten and thermally etches the surface slightly.

The final assembly was done with care to avoid finger prints, dust, or other contamination. The closure was an electron beam weld between the emitter radiator and the upper foil on the seal.

The converter was mounted in a vacuum bell jar with a mercury vapor pump. The inside of the converter was pumped with a sorption pump and vacuum ion pump. The cesium was in a glass pellet in a temporary side arm later to be removed. Using electron bombardment to heat the emitter and collector and cesium reservoir heaters, the entire converter was heated so that each part was about 100°C above the anticipated operating temperature. During the outgassing the inside of the converter was about 10^{-6} Torr and the bell jar pressure about 10^{-5} Torr. The final pressures were about 10^{-7} and 10^{-6} Torr with all the parts hot.

The bell jar was let down to air, and the converter sealed off by heating a glass constriction. The cesium pellet was broken and the cesium distilled into the converter. Finally the temporary cesium side arm was sealed off by pinching a cold weld in a copper tube section. This technique may leave a small amount of hydrogen in the converter. The hydrogen comes from a reaction between cesium and water on the inner surface of the glass pellet. However, probably the hydrogen diffuses out through the hot tantalum emitter support during the first few minutes of operation of the converter.

In filling a converter without a hot tantalum section, it would be preferable to break the pellet and pump for a few minutes before sealing off the converter from the pumps.

Finally the converter is remounted in the vacuum bell jar ready for operation.

TEST FACILITY

The converters are operated in a vacuum bell jar which provides a protective external environment during processing and testing. Electrical leads as well as cooling water and a vacuum line for evacuating the inside of the converter during converter processing are provided through the bell jar base plate. The vacuum bell jar is exhausted through a Three Stage 3-inch Mercury Diffusion Pump with a pumping speed of about 50 liters/sec. Typical system pressure with the converter operating is in the 10^{-7} Torr range. A 25 liter/sec vacuum ion pump is used to exhaust the inside of the converter during processing.

INSTRUMENTATION

Emitter Temperature Control and Measurement

Power is supplied to the emitter by electron bombardment from a spiral-shaped tungsten filament positioned above the back side of the emitter. The accelerating potential is provided by a 1500-volt, 5 A d-c power supply. The bombardment system is operated such that the electron bombardment current is limited by the filament temperature. This mode of operation is unstable for this application because of the feedback of thermal energy from the emitter to the filament. Stability is achieved by incorporating a circuit which continuously senses the bombardment current and adjust the a-c filament heating power to maintain constant emission current. The bombardment current can be adjusted and maintained within a few milliamperes of a desired value.

The emitter temperature is determined by measuring the brightness of a blackbody cavity in the back side of the emitter with a micro-optical pyrometer. This cavity is formed by welding a lid over a 0.050-inch diameter by 0.100-inch deep hole in the emitter. A 0.020-inch diameter hole in the lid is provided for pyrometry. The electron bombardment filament is on the same side of the emitter and therefore telescoping shields are provided around the blackbody cavity to prevent light from the filament from affecting the emitter temperature determination. One shield is integral with the lid on the blackbody cavity and one is attached to an electrostatic shield over the bombardment filament. See Figure A-1. The effectiveness of this shielding is determined by observing the brightness in the blackbody cavity when the emitter is cool and the bombardment filament is hot. The effect of scattered light into the blackbody was found to be neglgible for this configuration.

One correction of the emitter temperature which is necessary is caused by the optical path. Light from the blackbody cavity passes through a flat window in the top of the bell jar and is then reflected by a front surface mirror before it enters the pyrometer. The correction for losses caused by this path is determined directly by measuring the apparent temperature difference of a flat ribbon lamp with and without the mirror and window in the optical path. A correction curve was determined as a function of apparent temperature and used to calculate the true temperature of the emitter. It is believed that measured values of temperature of the back side of the emitter obtained by the use of the blackbody cavity are within ±5°K.

An additional correction is necessary to arrive at the emitter surface temperature. There will be a temperature gradient through the emitter since the energy input is at the back side and most of the energy is removed from the emitter face. Part of the energy removed from the emitter will be dependent upon the average converter current because of electron cooling. Calculations of heat flow and axial thermal gradients as a function of temperature and thermionic converter current density were made. Results of these calculations are shown in Figure 2 of this report.

In taking the A.C. data the load resistance may be adjusted so that as one shifts from D.C. to A.C. there is no apparent change or drift in the temperature of the blackbody cavity. Presumably under these conditions the average power loss from the emitter over the A.C. cycle is the same as for the D.C. condition. If this adjustment is made the observed temperature is probably accurate to ±10°C. This allows for ±5° in making the temperature measurement plus an error of about ±8° in estimating the thermal gradient through the emitter.

For most of the load lines of Appendix B time did not permit carefully adjusting the load resistor to obtain equal D.C. and A.C. losses. Therefore, for most of the load lines in this report the probable error in T_E was about ±15°C.

COLLECTOR TEMPERATURE (CONTROL AND MEASUREMENT)

The collector surface is at one end of a cylindrical molybdenum pedestal and consists of a 0.050-inch-thick disk of niobium bonded to the molybdenum. The collector is conduction cooled through 6 symmetrically placed heat chokes at the base of the pedestal to a water-cooled mounting ring. The collector temperature is adjusted by adding heat with two resistance heaters. Three thermocouples are positioned near the collector surface through the support pedestal. Two thermocouples are Chromel-Alumel and one is Pt-(Pt-10% Rh). The Pt-(Pt-10% Rh) thermocouple is fed to a recording potentiometer. The power to one of the heater windings in the collector is automatically controlled to maintain a constant collector temperature. The second heater on the collector is used as an auxiliary and is manually adjusted. This provision causes the dynamic range of the proportional temperature controller to be shifted. Typically, the collector temperature is maintained within ±2% which is adequate for most aspects of thermionic converter operation; however, it can be held within a few degress when necessary as in the determination of the collector work function through thermionic emission techniques.

CESIUM RESERVOIR

The cesium reservoir consists of a 0.500-inch-diameter, thin wall, nickel cylinder with a heavy nickel block at the base. A heating coil is wrapped around the cylinder in such a way as to make the heavy block the coolest portion of the reservoir. The cesium reservoir temperature is measured by one of two thermocouples attached to the nickel block. One thermocouple is Pt-(Pt-10%Rh) and one is Chromel-Alumel. A radiation shield operating at reservoir temperature is placed over the thermocouple junctions to minimize the possibility of errors from conduction and radiation from the thermocouple leads. Readings from the two thermocouple pairs are compared as a check on reservoir temperature. In addition, a thermistor is imbedded in the nickel block. The thermistor is connected to a proportional controller which regulates the amount of power input to the heater winding on the reservoir. Cesium reservoir temperatures can be maintained within ±1°K with this technique.

EXPERIMENTAL DATA

Emitter Work Function

During converter processing, while the device was still being exhausted internally with the vacuum ion pump, and before cesium was introduced, thermionic emission measurements were taken from the clean tungsten surface. In converter VG-12, data from which are reported in the main text of this report, there is no active guard ring in the device. There is a very sharp thermal gradient in the heat choke on which the converter emitter is mounted. Collection from the heat choke was minimized by making the vacuum emission measurements at very close spacing, i.e., 0.0005 inch. Since areas extraneous to the emitter which might possibly be considered to contribute to the measured emission were at distances greater than 0.030 inch from the collector, an effect from these areas would only be seen when strong accelerating potentials were applied. For the values reported on page 11 the emitter area was used. If the collector area had been used, at 2210°K the reported Φ of 4.58 eV would have been 4.54 eV. Probably a true Φ value is between these two extremes. A guard ring was included in the ceramic seal; therefore, leakage currents between emitter and collector could be eliminated. Emitter work functions were determined from emission densities found by the extrapolation of Schottky plots to zero field.

Values of current density J in amperes per square centimeter were then substituted in the Richardson-Dushman equation.

$$\Phi = \frac{KT}{e} [\ln A \frac{(1-R)T^2}{J}] \text{ volt}$$

where
- Φ is the effective work function;
- K is the Boltzmann constant in joules per degree Kelvin;
- e is the electron charge in coulombs;
- T is the true surface temperature in degrees Kelvin;
- A is a universal constant used as 120;
- R is a refection coefficient assumed as 0.

Tabular values of effective work function as a function of current density and absolute temperature have been generated by Read.* These tables were used in the determination of effective work function.

Upon completion of the measurements of the bare work function of the emitter, cesium was introduced into the device and the converter was sealed off.

COLLECTOR WORK FUNCTION DETERMINATION

As mentioned in the main text of the report, the colllector work function was determined from measurements of saturated emission from the collector. Leakage currents were eliminated by the guard ring electrode in the ceramic-to-metal seal. The emitting area of the collector was not well defined since there was no guard ring around the collector to prevent emission from the cylindrical sides. The geometry of the device did, however, allow for a reasonably good measurement of the collector work function. The gap between the side of the collector was the order of 0.030 inch while the interelectrode spacing during emission measurements was about 0.0005 inch. Since the applied voltage across each gap was the

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*Read, P.L., "Tables of Effective Work Function," General Electric Research and Development Center Report No. 64-RL-3605E, March 1964.

same and the electric field is inversely proportional to the spacing, the field in the converter region would have been 60 times greater than that on the side. From examination of Schottky plots of the experimental data and from estimates of the accuracy in measuring T_C, it is estimated that the values of collector work function should be accurate to ±0.05 eV.

THERMIONIC CONVERTER DATA

In determining output characteristics, the device was connected in a test circuit as shown in Appendix A, Figure A-2. Emitter, collector, and cesium reservoir temperature controls were maintained in the manner previously described. The emitter is operated at ground potential as a safety precaution since it runs approximately 1500 volts positive relative to the bombardment filament. Connected between the emitter and collector is a sweep transformer, adjustable load resistor, and a current shunt.

After the operating parameters, such as emitter, collector, and cesium reservoir temperatures are set, the load resistor is adjusted so that a desired direct current flows in the circuit. Then the a-c sweep is applied and converter voltage and current are driven about the d-c operating point. This technique allows the converter load characteristics to be investigated while maintaining a fixed d-c operating point.

Potential leads for voltage are attached to the converter electrodes. Current values are measured as a potential drop across a calibrated shunt. Since these potentials are varying at a 60-cps rate, they are fed to a sampling circuit[A2] which transforms the outputs to slowly varying d-c functions which are recorded directly on an "X-Y" recorder. The entire system is calibrated by applying known potentials measured by student type slide wire potentiometers at the inputs to the sampling system. Calibration adjustments allow the converter current to be displayed as current density. The load characteristic curves included in this report have been reproduced directly from the original data with no corrections needed.

REFERENCES

A_1 - R.H. Bristow, GE Report No. GEST-2029 Part III, Bureau of Ships Contract No. 88578, October 1963.

A_2 - J.G. Metro, "Two-Channel Sampling System," General Electric Research and Development Center Report No. 65-C-180.

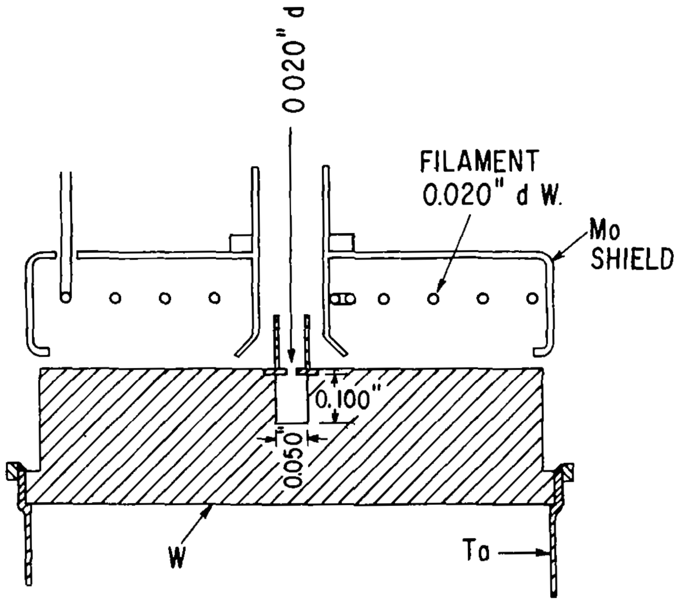


FIGURE A-1. CROSS SECTION OF BLACKBODY CAVITY, ELECTRON BOMBARDMENT FILAMENT AND OPTICAL AND ELECTROSTATIC SHIELDS

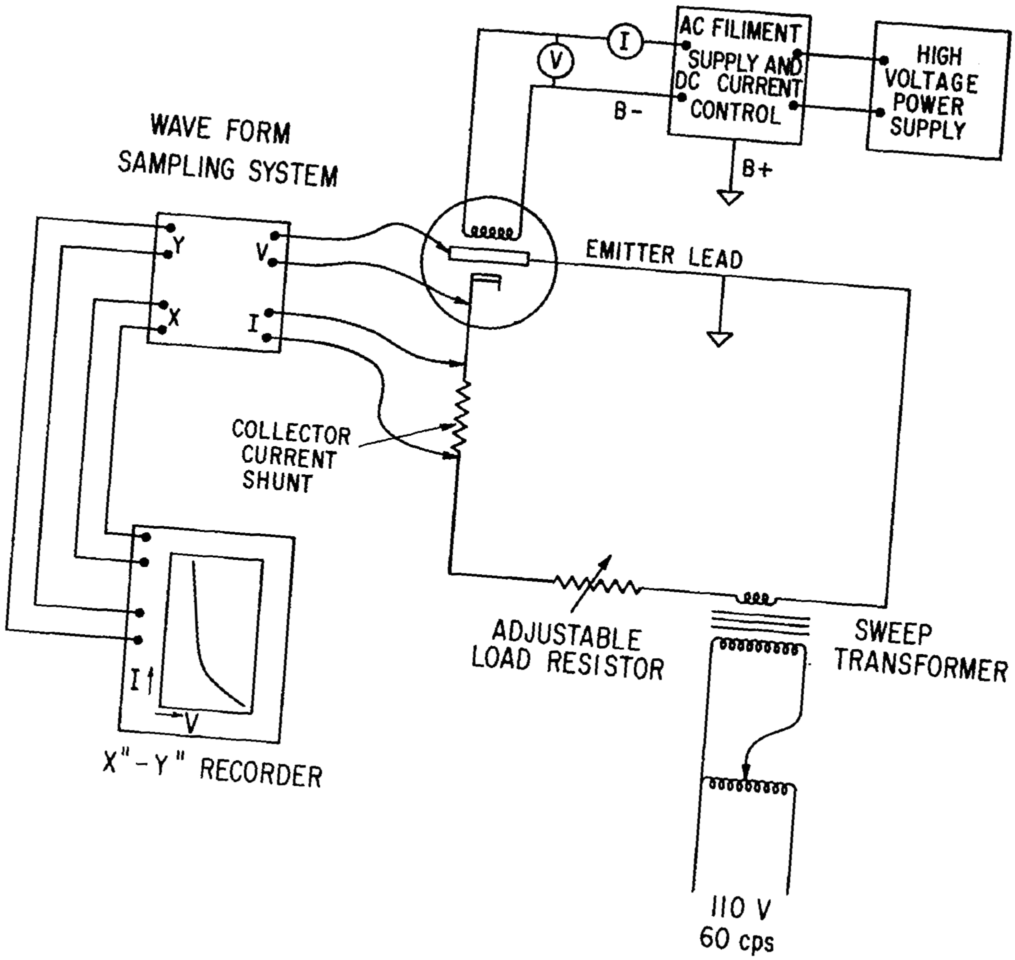


FIGURE A-2. THERMIONIC CONVERTER TEST CIRCUIT

APPENDIX B

CONVERTER DATA

A complete set of load lines is included for temperature emitter, T_E, from 1673 to 2153°K; temperature cesium, T_{Cs}, 583 to 683°K; temperature collector, T_C, 873 to 1173°K; and spacings 1.0 to 20 mils. A few load lines were taken at 0.5-mil spacing.

The following table lists the figures.

Figure	T_E(°K)	T_C(°K)	Spacing (mils)
B-1	1673	973	1
B-2	1673	973	2
B-3	1673	973	5
B-4	1673	973	7
B-5	1673	973	10
B-6	1673	973	20
B-7	1770	973	0.5
B-8	1770	973	2
B-9	1770	973	5
B-10	1770	973	7
B-11	1770	973	10
B-12	1770	973	20
B-13	1866	973	7
B-14	1962	995	0.5
B-15	1962	995	2
B-16	1962	995	5
B-17	1962	973	7
B-18	1962	995	10
B-19	1962	995	20
B-20	2057	873	1
B-21	2057	873	2
B-22	2057	873	5
B-23	2057	873	10
B-24	2057	873	20

Figure	T_E(°K)	T_C(°K)	Spacing (mils)
B-25	2057	973	1
B-26	2057	973	2
B-27	2057	973	5
B-28	2057	973	10
B-29	2057	973	20
B-30	2057	1023	1
B-31	2057	1023	2
B-32	2057	1023	5
B-33	2057	1023	7
B-34	2057	1023	10
B-35	2057	1023	20
B-36	2057	1073	1
B-37	2057	1073	2
B-38	2057	1073	5
B-39	2057	1073	10
B-40	2057	1073	20
B-41	2057	1173	1
B-42	2057	1173	2
B-43	2057	1173	5
B-44	2057	1173	10
B-45	2057	1173	20
B-46	2150	1023	1
B-47	2153	1023	2
B-48	2153	1023	5
B-49	2153	1023	7
B-50	2153	1023	10
B-51	2153	1023	20
B-52	Power Density Grid		

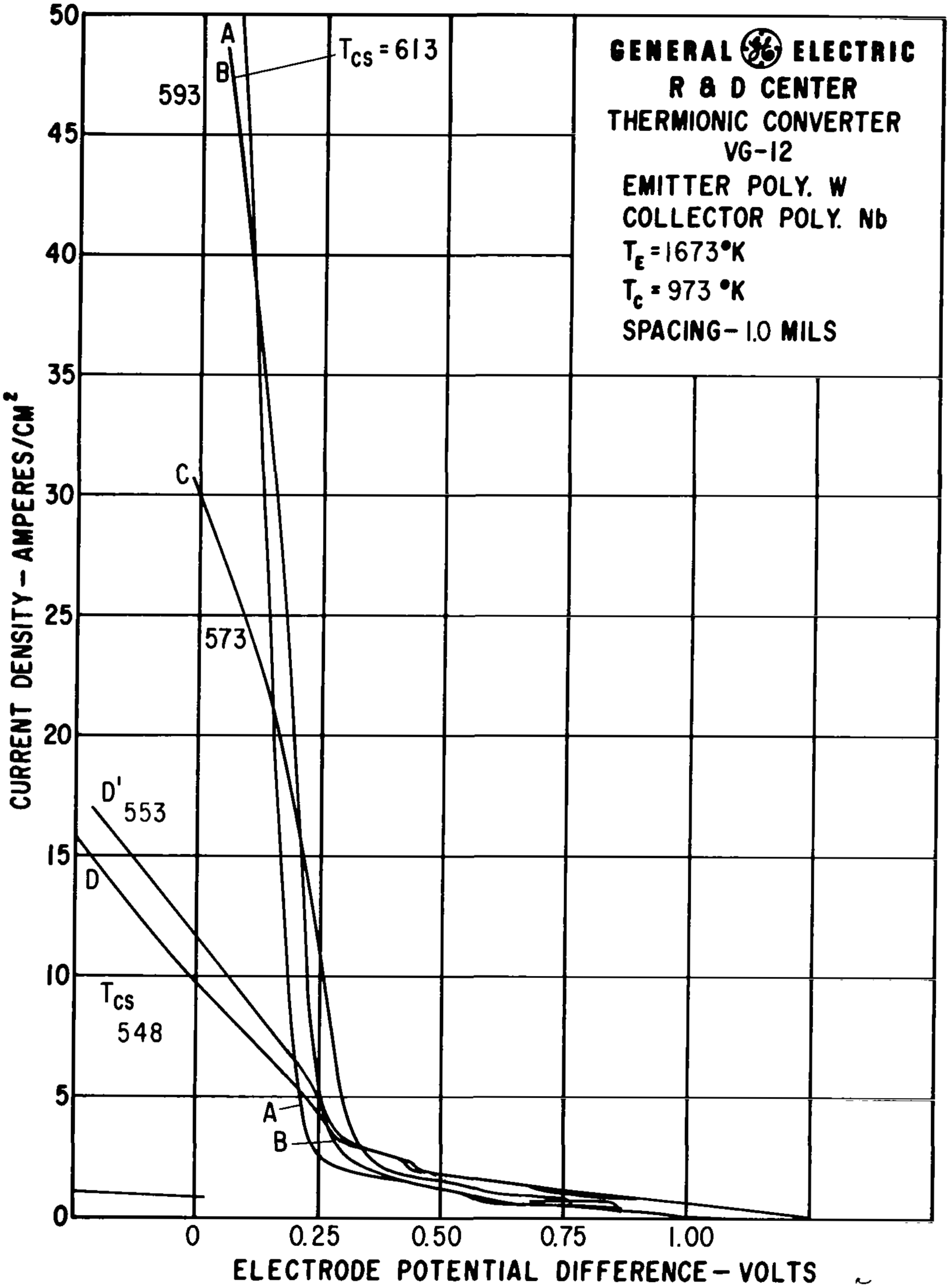

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1673°K
T_c = 973 °K
SPACING - 1.0 MILS
T_{CS} = 613
593
573
D' 553
T_{CS} 548
A
B
C
D
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.50
0.75
1.00

FIGURE B-1

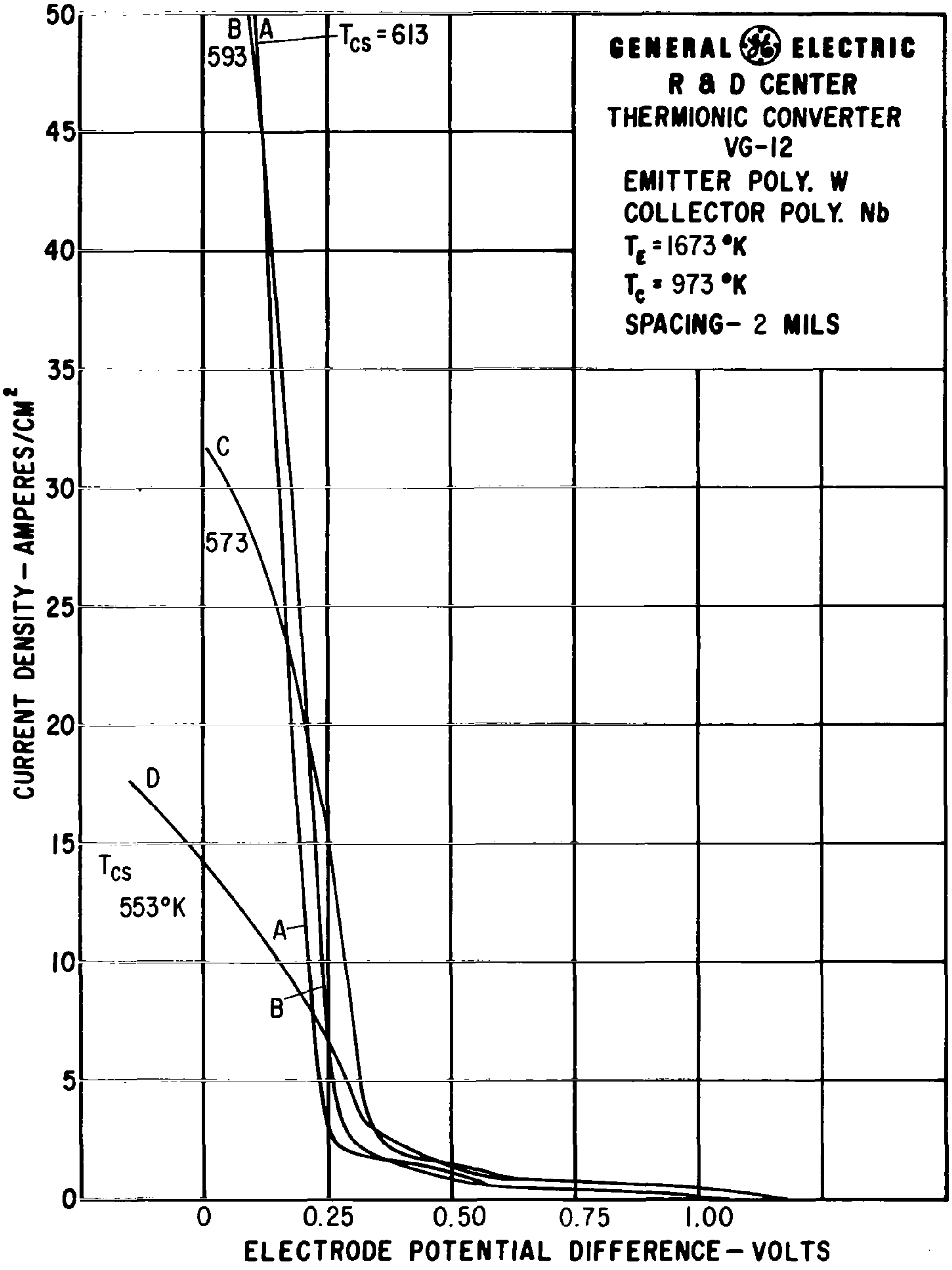

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1673 °K
T_C = 973 °K
SPACING– 2 MILS
B
593
A
T_{CS} = 613
C
573
D
T_{CS}
553°K
A
B
CURRENT DENSITY – AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE – VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.50
0.75
1.00

FIGURE B-2

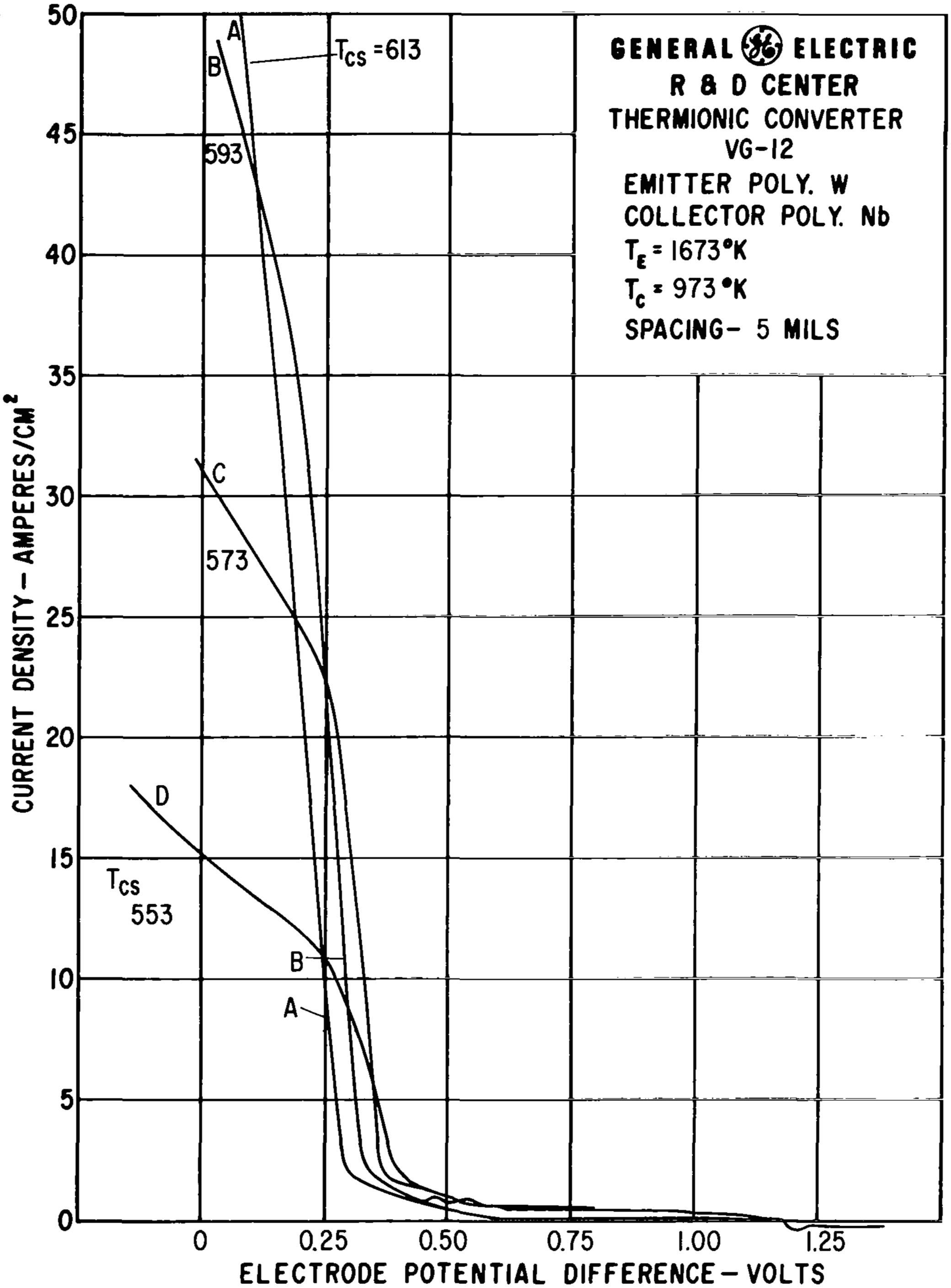

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1673°K
T_C = 973°K
SPACING- 5 MILS
A
B
T_{CS} =613
593
C
573
D
T_{CS}
553
B
A
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.50
0.75
1.00
1.25

FIGURE B-3

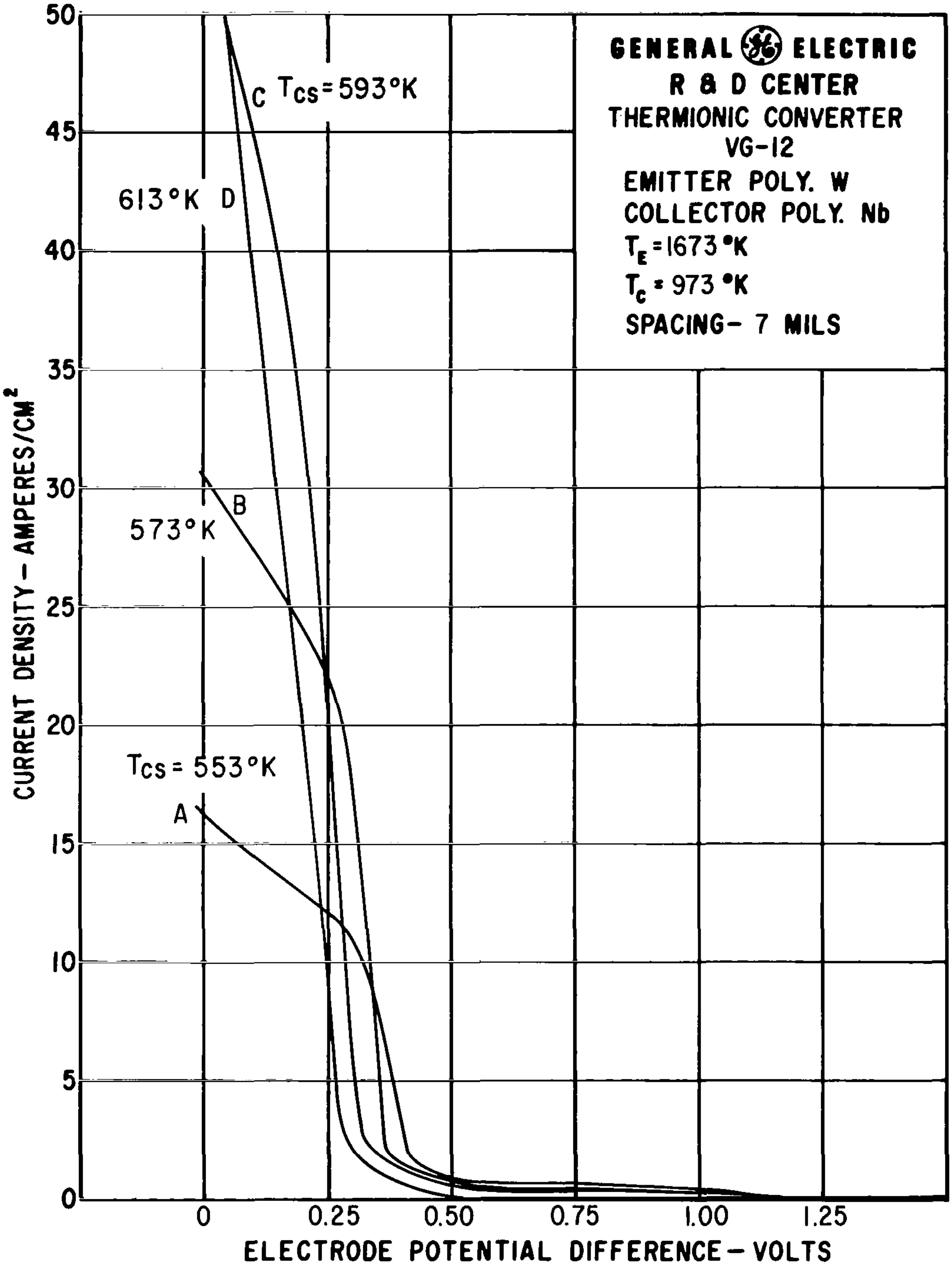

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1673 °K
T_C = 973 °K
SPACING- 7 MILS
C T_{CS} = 593°K
613°K D
573°K
B
T_{CS} = 553°K
A
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.50
0.75
1.00
1.25

FIGURE B-4

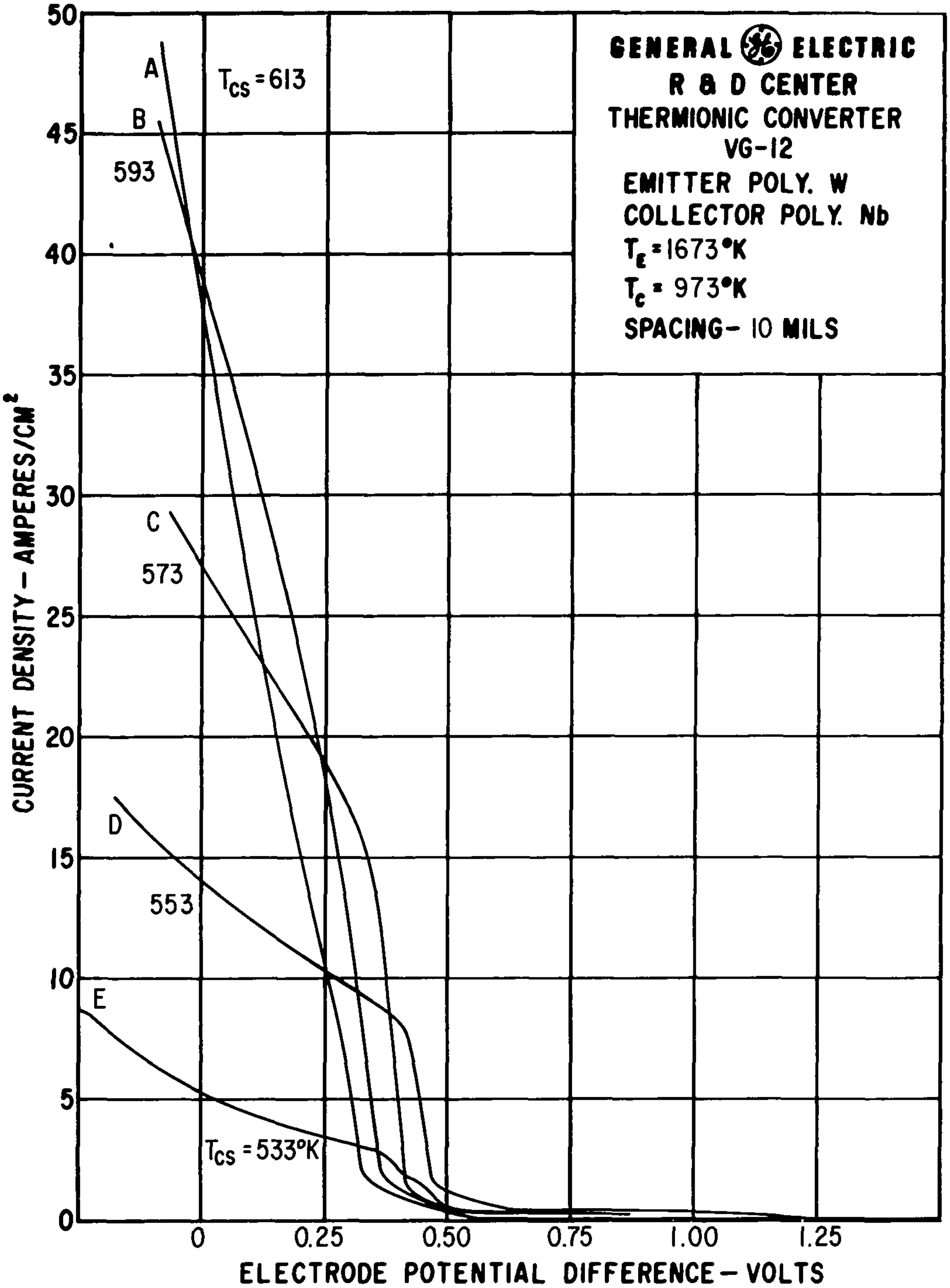

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1673°K
T_c = 973°K
SPACING – 10 MILS
A
T_{CS} = 613
B
593
C
573
D
553
E
T_{CS} = 533°K
CURRENT DENSITY – AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE – VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.50
0.75
1.00
1.25

FIGURE B-5

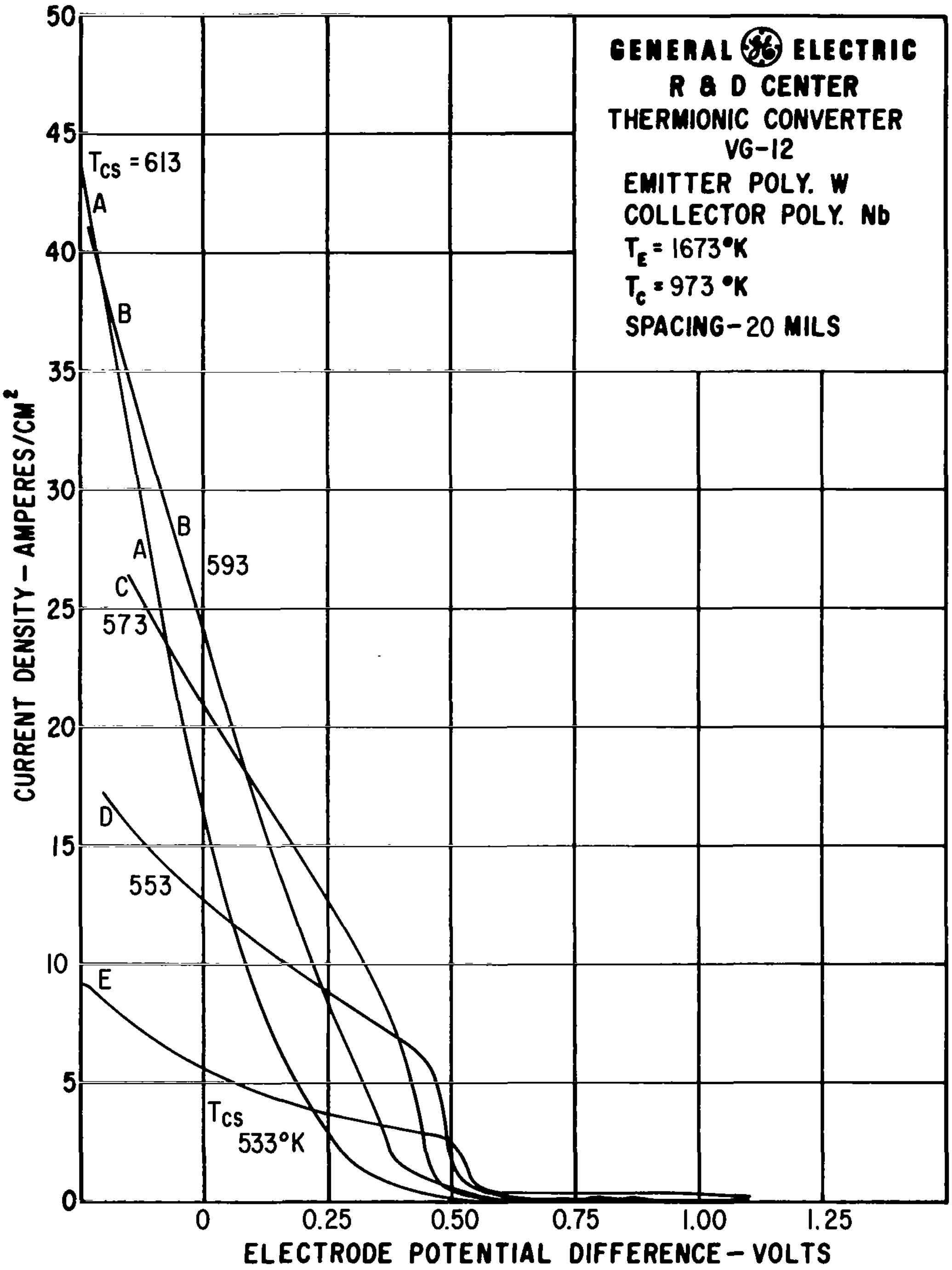

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1673°K
T_C = 973 °K
SPACING–20 MILS
T_{CS} = 613
A
B
593
C
573
D
553
E
T_{CS}
533°K
CURRENT DENSITY – AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE – VOLTS
50
45
40
35
30
25
20
15
10
5
0
0
0.25
0.50
0.75
1.00
1.25

FIGURE B-6

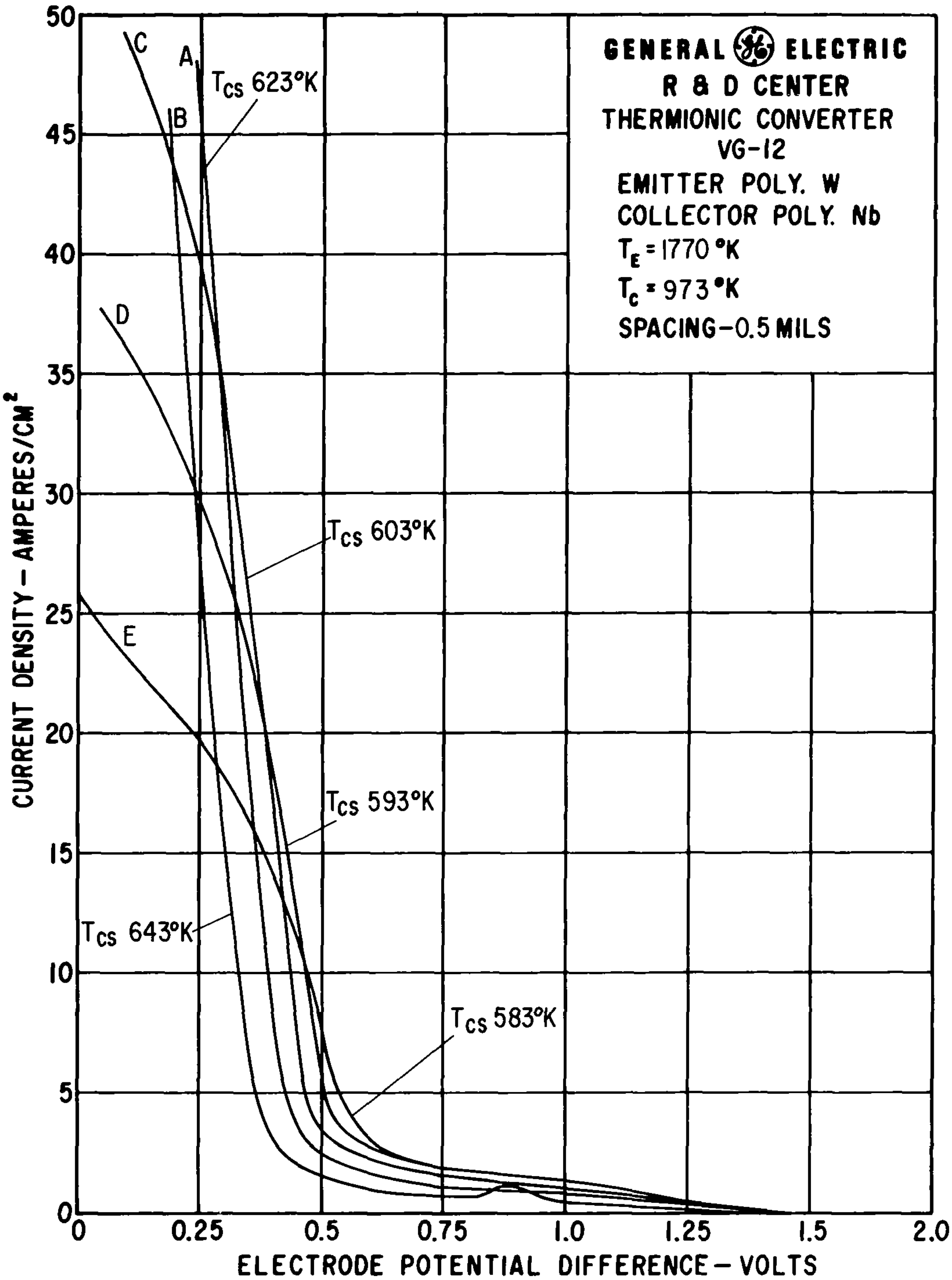

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1770 °K
T_C = 973 °K
SPACING-0.5 MILS
A
B
C
D
E
T_{CS} 623°K
T_{CS} 603°K
T_{CS} 593°K
T_{CS} 643°K
T_{CS} 583°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-7

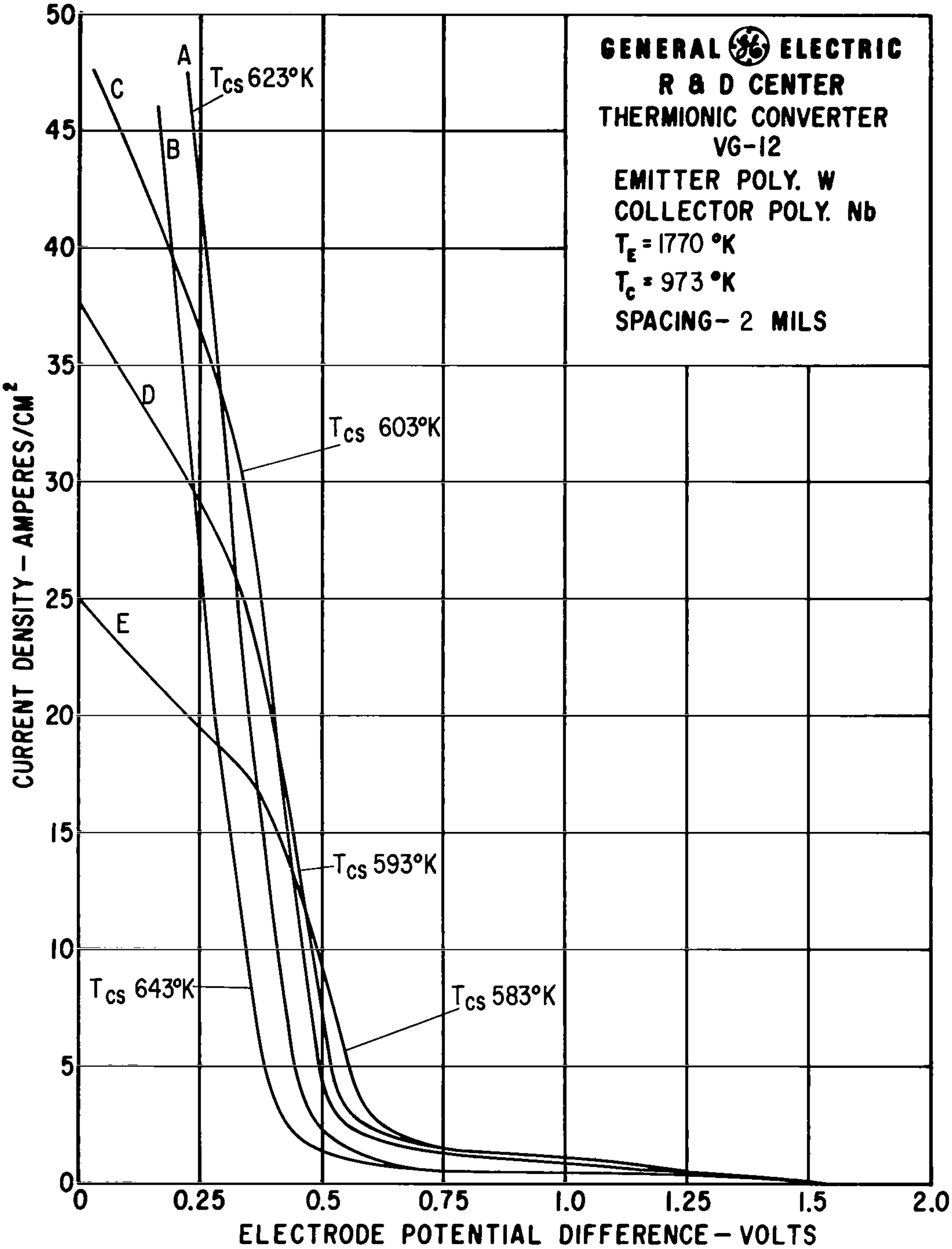

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1770 °K
T_C = 973 °K
SPACING– 2 MILS
A
B
C
D
E
T_{CS} 623°K
T_{CS} 603°K
T_{CS} 593°K
T_{CS} 583°K
T_{CS} 643°K
CURRENT DENSITY – AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE – VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-8

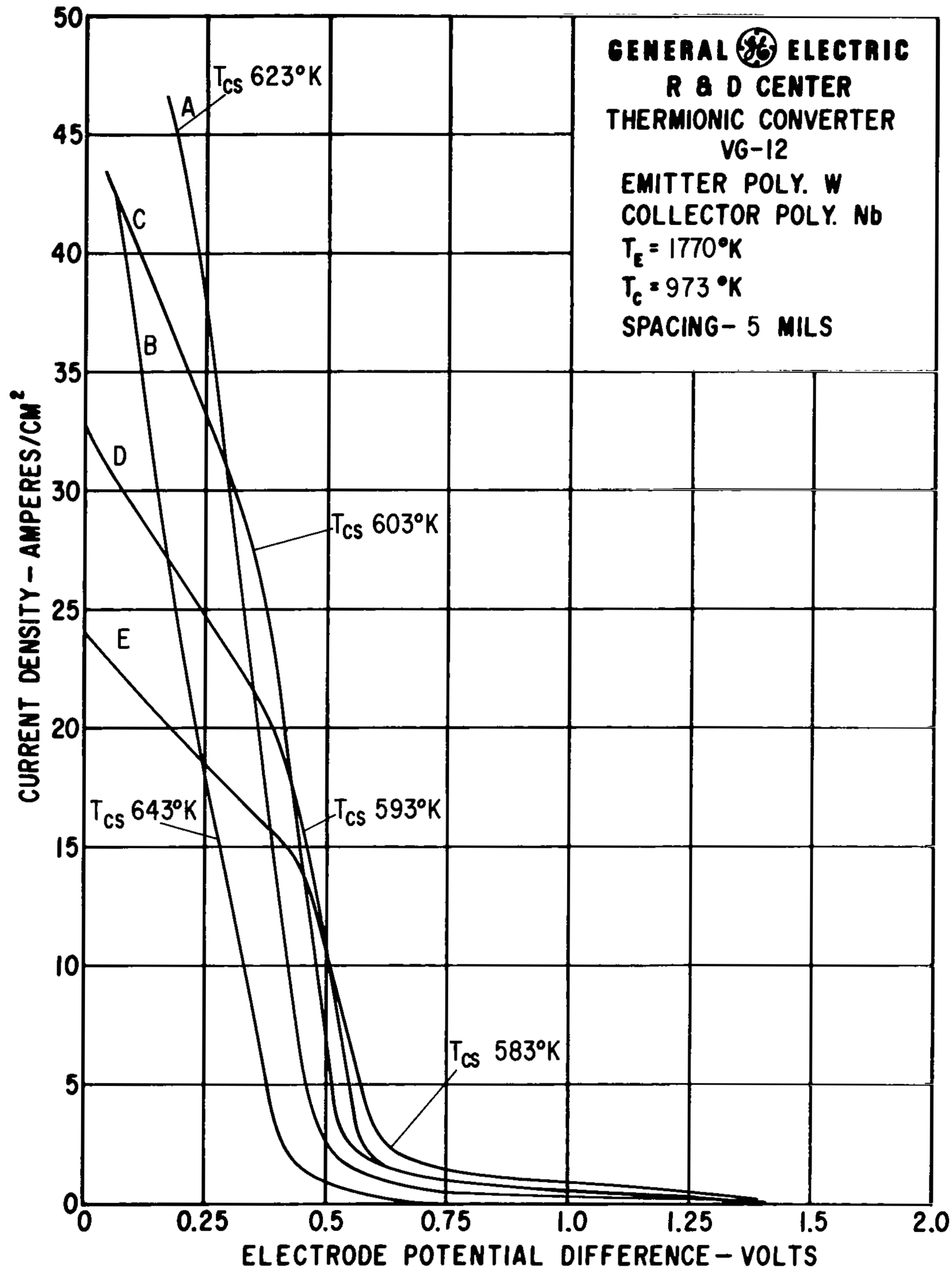

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1770°K
T_C = 973 °K
SPACING- 5 MILS
T_{CS} 623°K
T_{CS} 603°K
T_{CS} 643°K
T_{CS} 593°K
T_{CS} 583°K
A
B
C
D
E
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-9

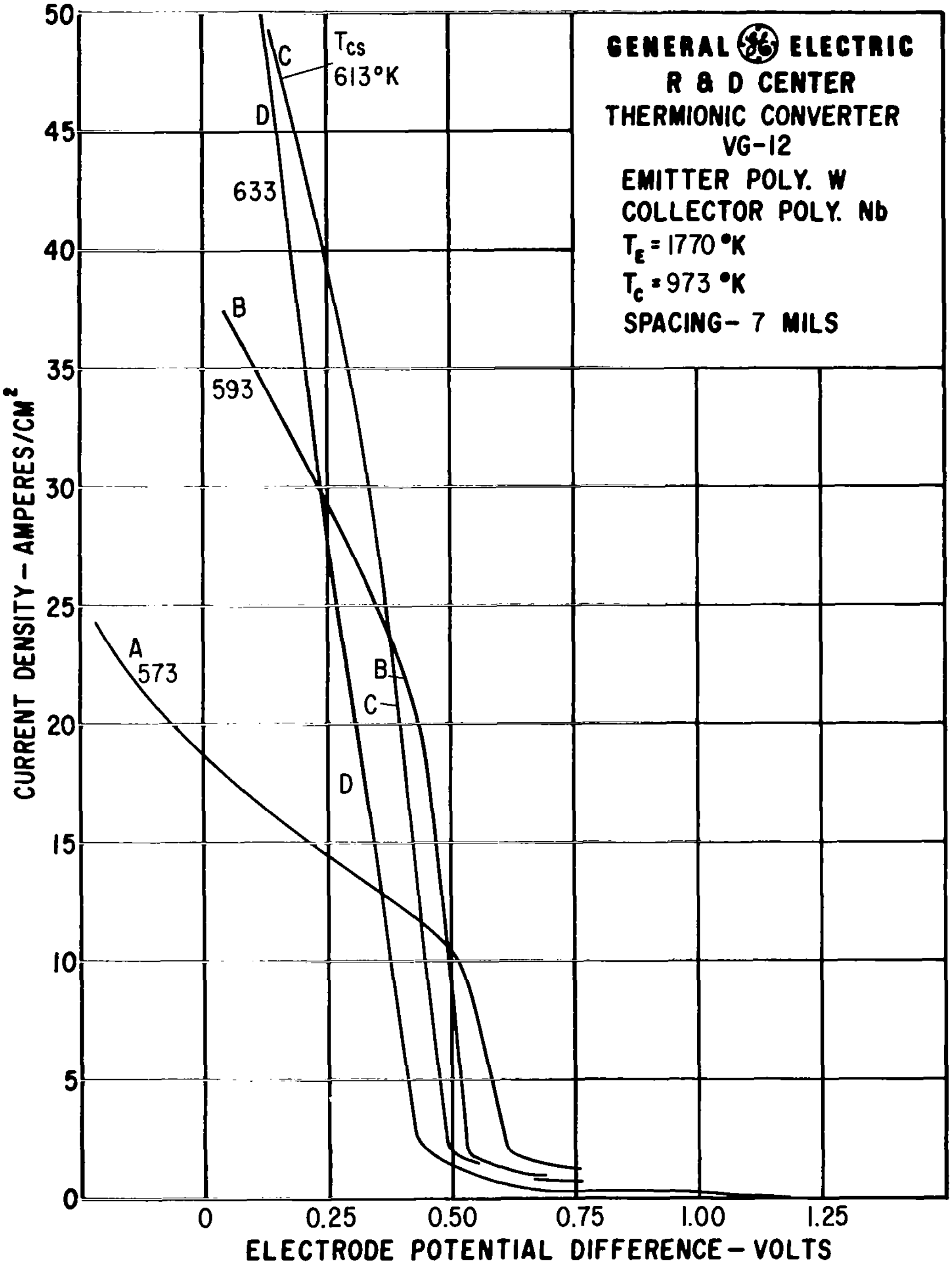
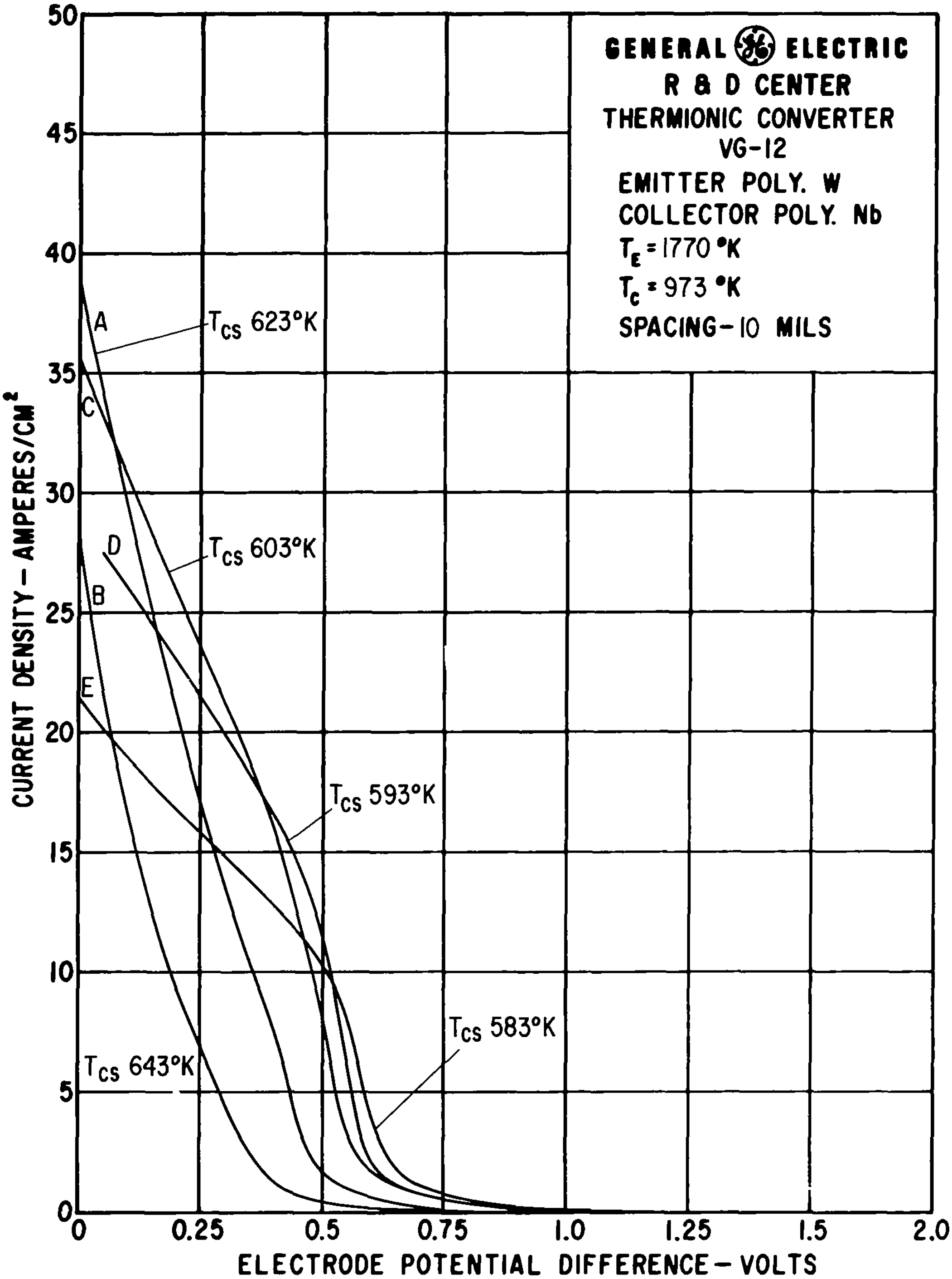

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1770 °K
T_C = 973 °K
SPACING - 7 MILS
T_{CS}
613°K
633
593
573
A
B
C
D
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
0.25
0.50
0.75
1.00
1.25
5
10
15
20
25
30
35
40
45
50

FIGURE B-10



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1770 °K
T_C = 973 °K
SPACING-10 MILS
A
B
C
D
E
T_{CS} 623°K
T_{CS} 603°K
T_{CS} 593°K
T_{CS} 583°K
T_{CS} 643°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-11

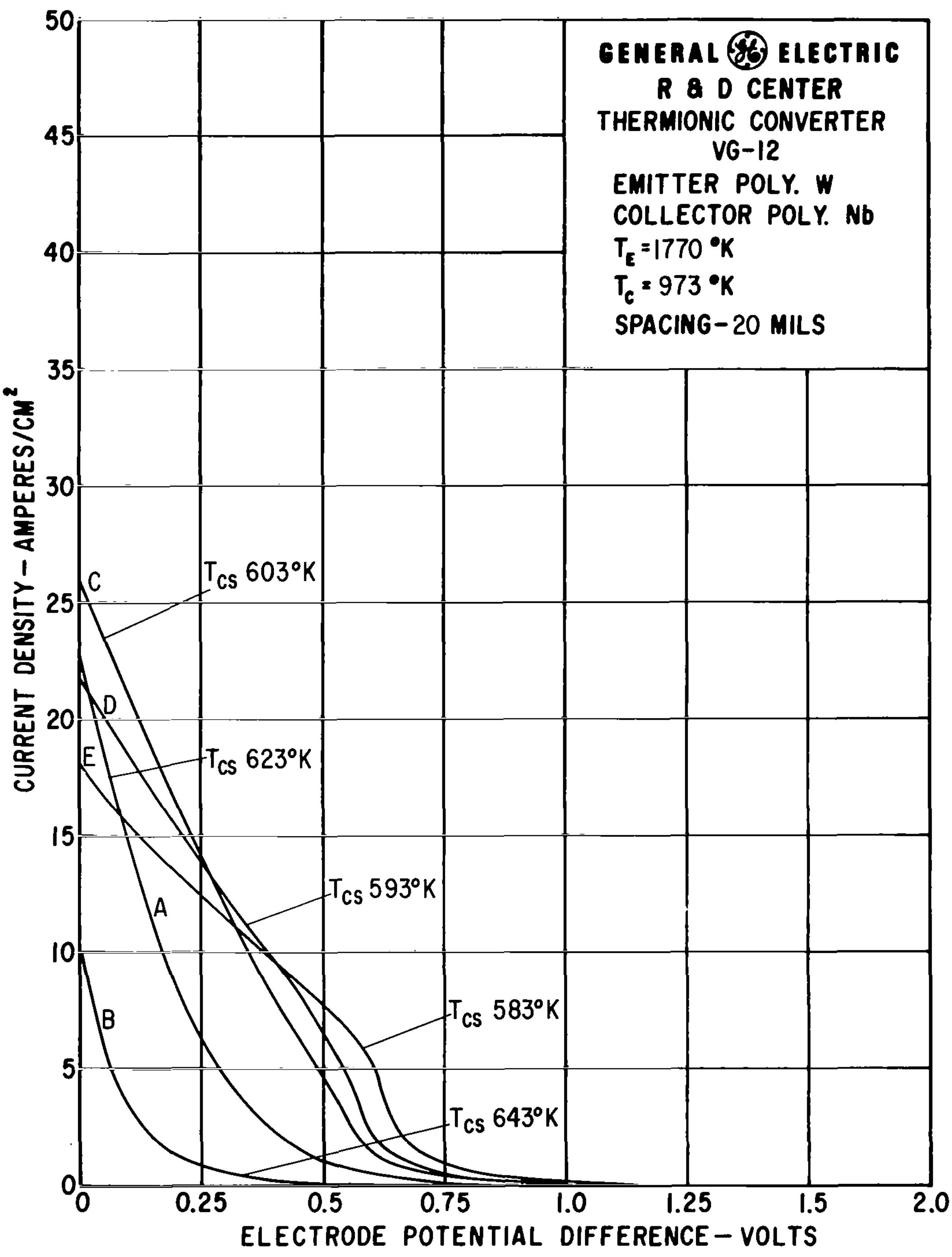

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1770 °K
T_c = 973 °K
SPACING-20 MILS
T_{CS} 603°K
T_{CS} 623°K
T_{CS} 593°K
T_{CS} 583°K
T_{CS} 643°K
C
D
E
A
B
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-12

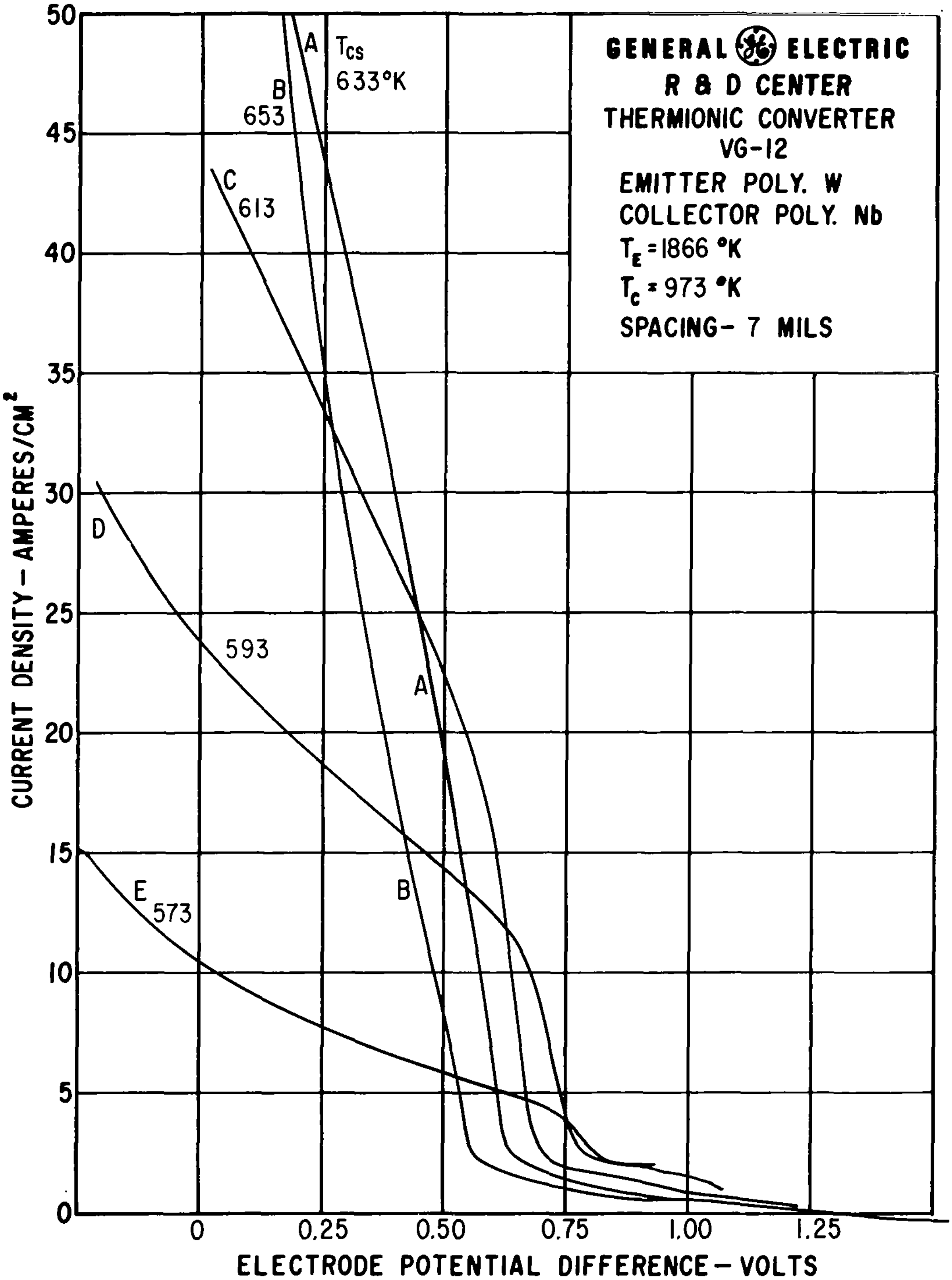

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1866 °K
T_C = 973 °K
SPACING- 7 MILS
T_{CS}
633°K
A
B
653
C
613
D
593
E
573
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
0.25
0.50
0.75
1.00
1.25
5
10
15
20
25
30
35
40
45
50

FIGURE B-13

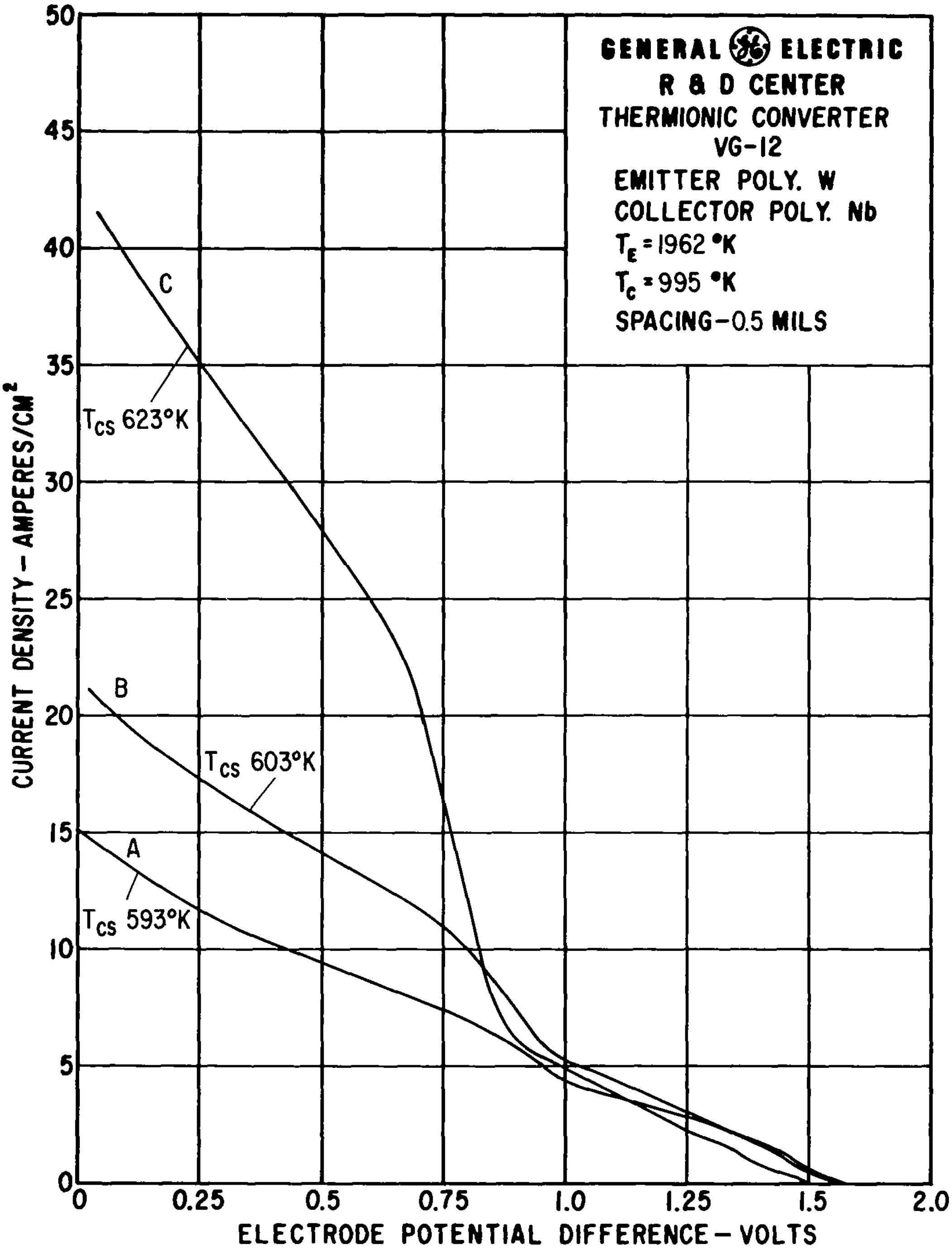

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1962 °K
T_c = 995 °K
SPACING-0.5 MILS
C
T_{CS} 623°K
B
T_{CS} 603°K
A
T_{CS} 593°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-14

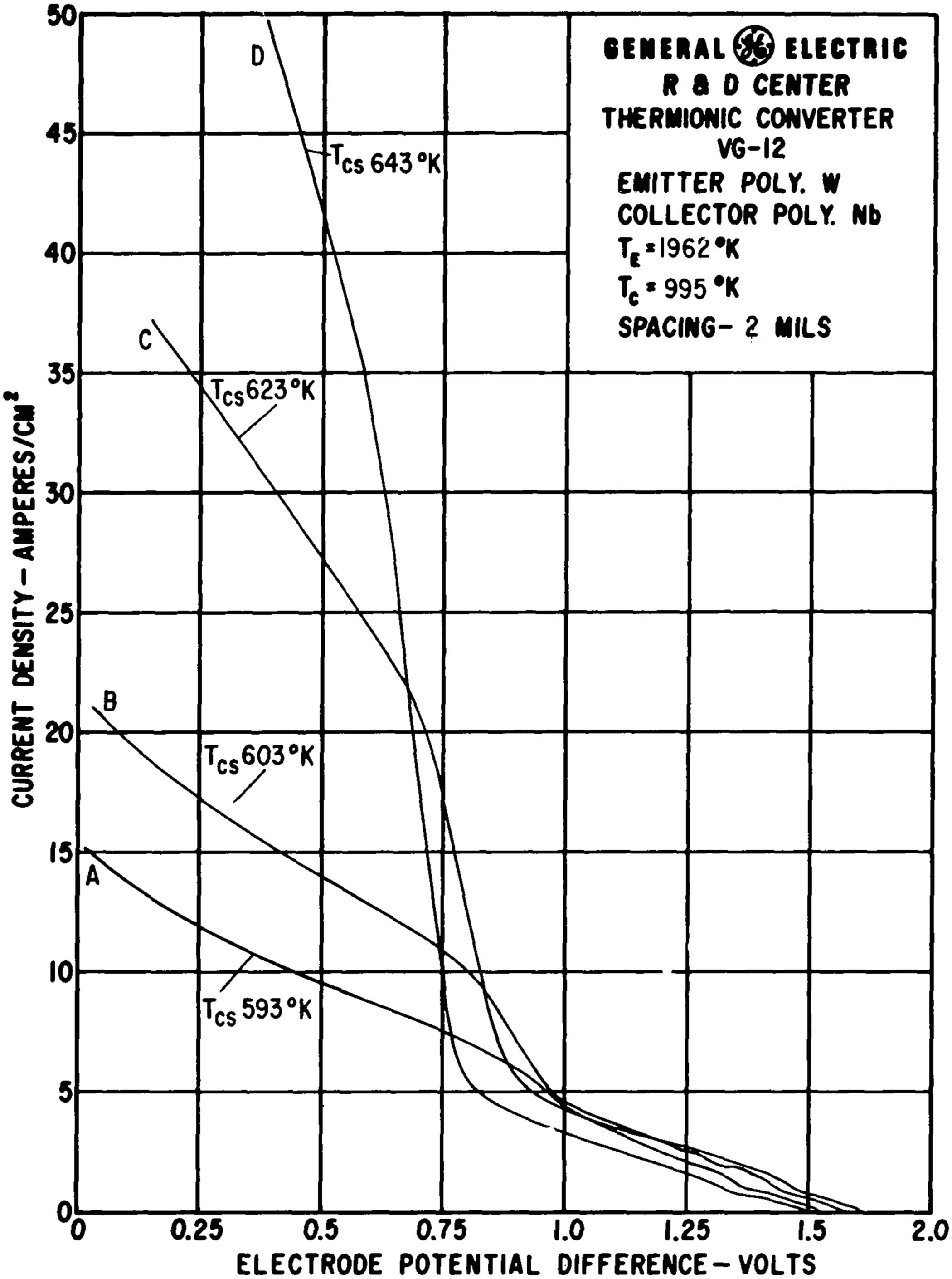

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1962 °K
T_C = 995 °K
SPACING- 2 MILS
D
T_{CS} 643 °K
C
T_{CS} 623 °K
B
T_{CS} 603 °K
A
T_{CS} 593 °K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-15

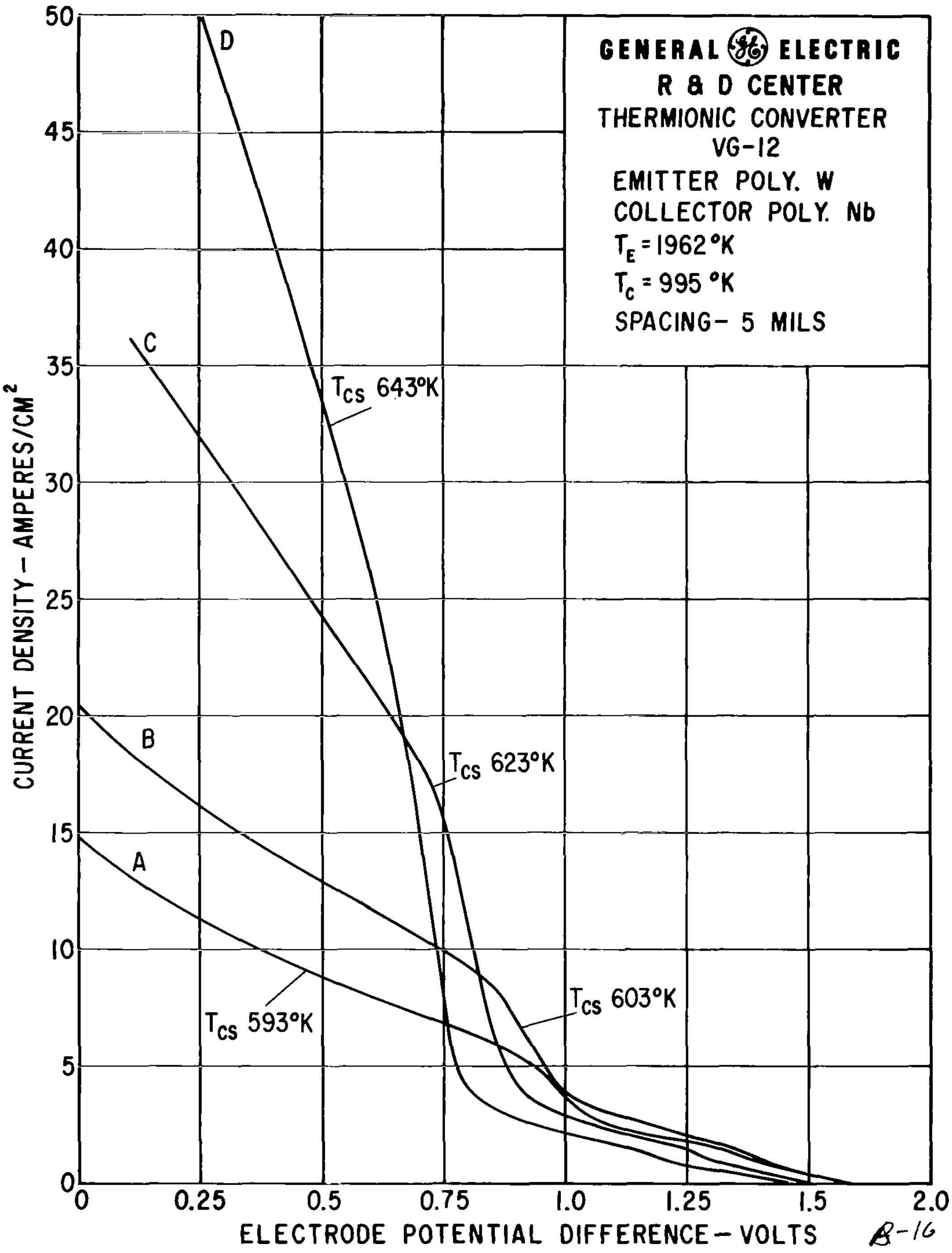

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1962 °K
T_c = 995 °K
SPACING - 5 MILS
D
C
B
A
T_{CS} 643°K
T_{CS} 623°K
T_{CS} 603°K
T_{CS} 593°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0
B-16

FIGURE B-16

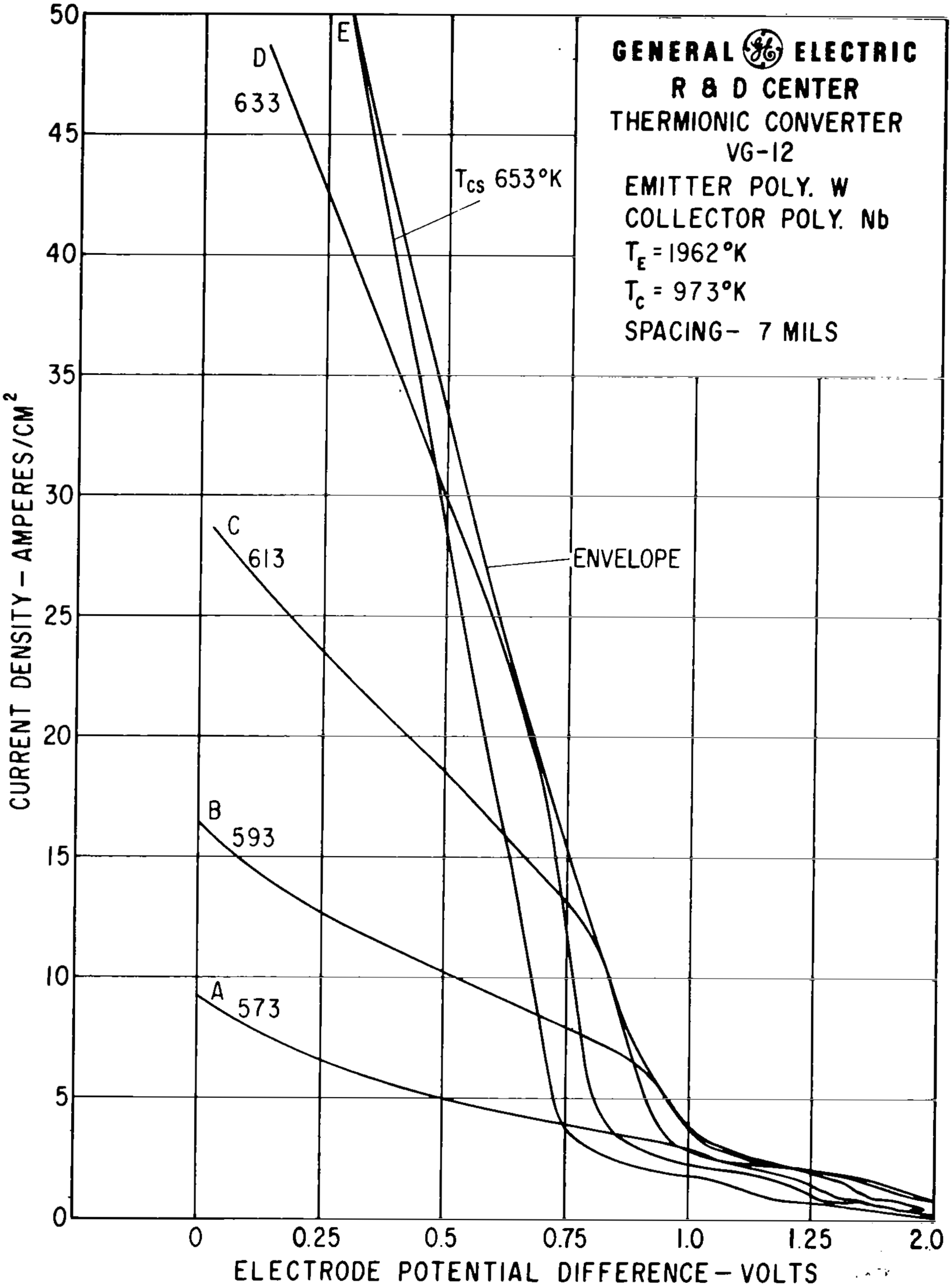

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1962°K
T_C = 973°K
SPACING- 7 MILS
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
A 573
B 593
C 613
D 633
E
T_{CS} 653°K
ENVELOPE
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
2.0

FIGURE B-17

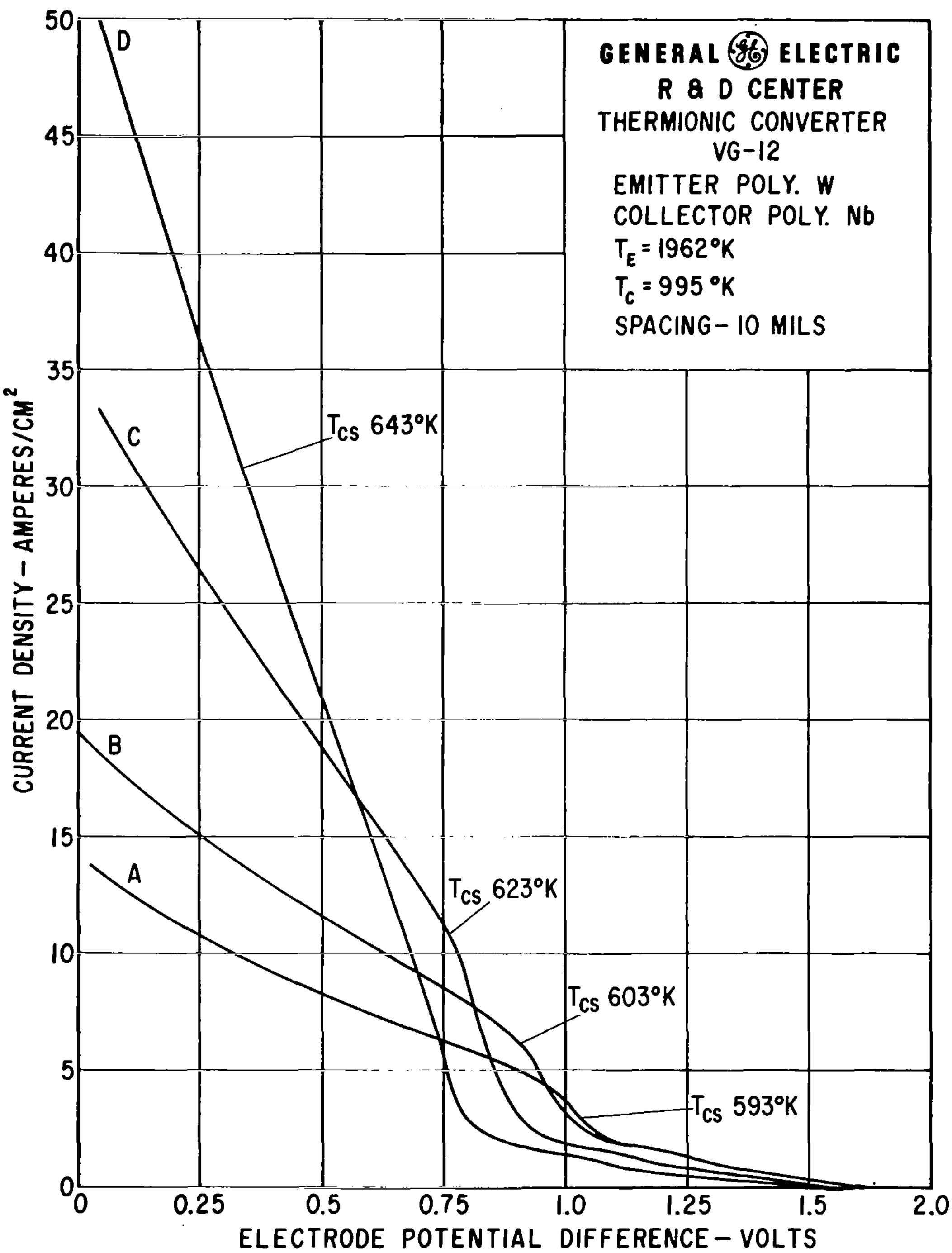
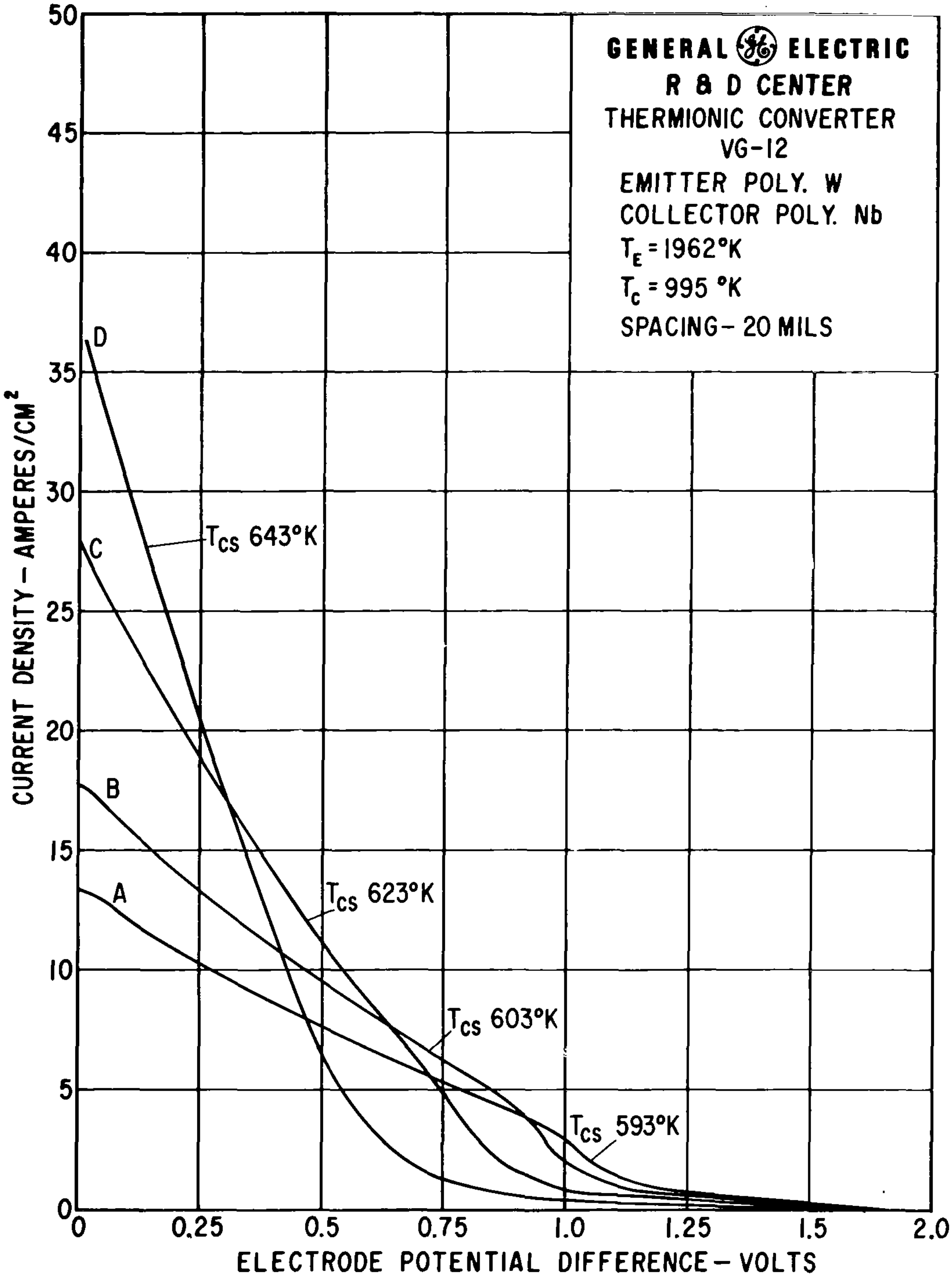

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1962°K
T_C = 995 °K
SPACING- 10 MILS
D
C
B
A
T_{CS} 643°K
T_{CS} 623°K
T_{CS} 603°K
T_{CS} 593°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE- VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-18



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 1962°K
T_c = 995 °K
SPACING - 20 MILS
D
C
B
A
T_{CS} 643°K
T_{CS} 623°K
T_{CS} 603°K
T_{CS} 593°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-19

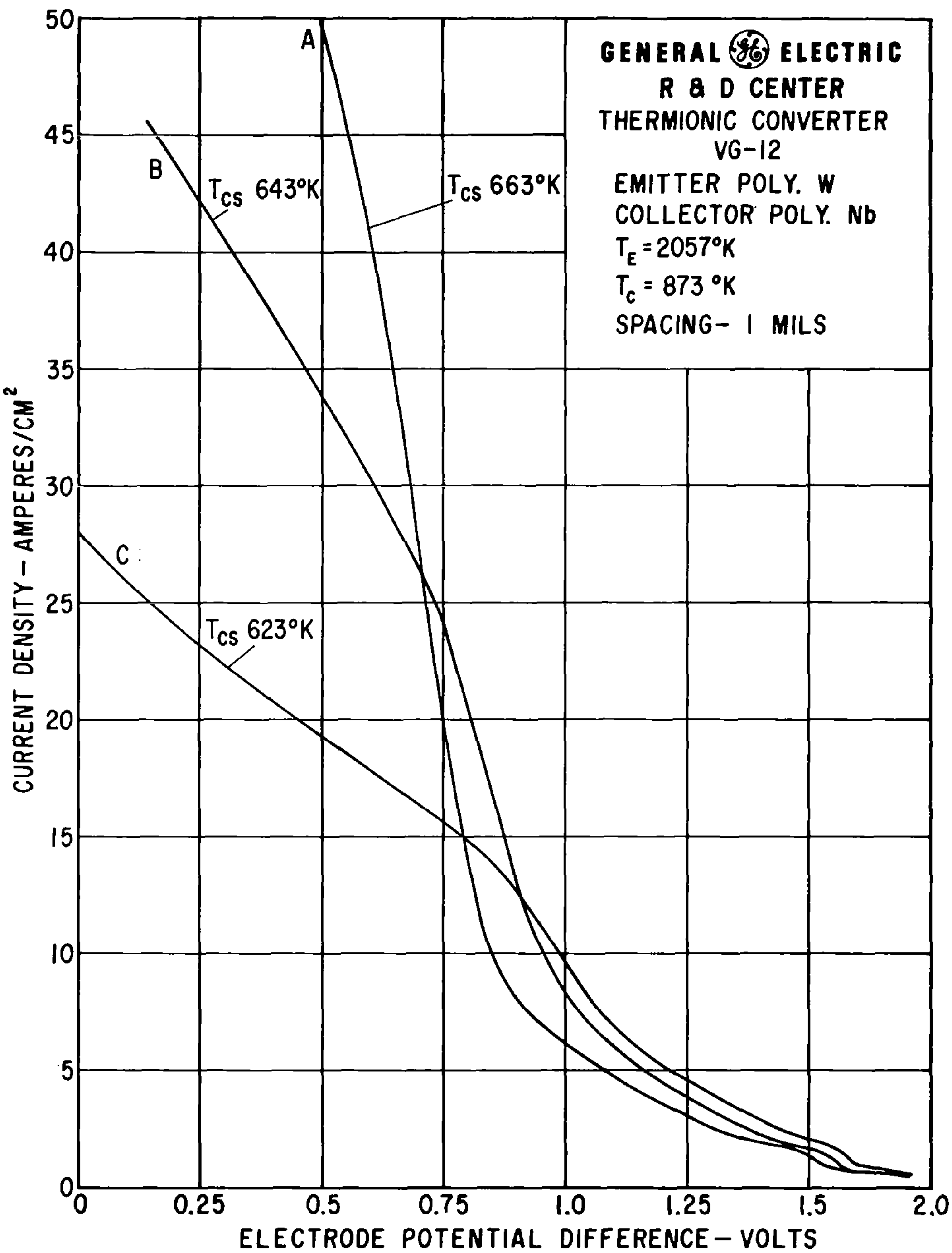
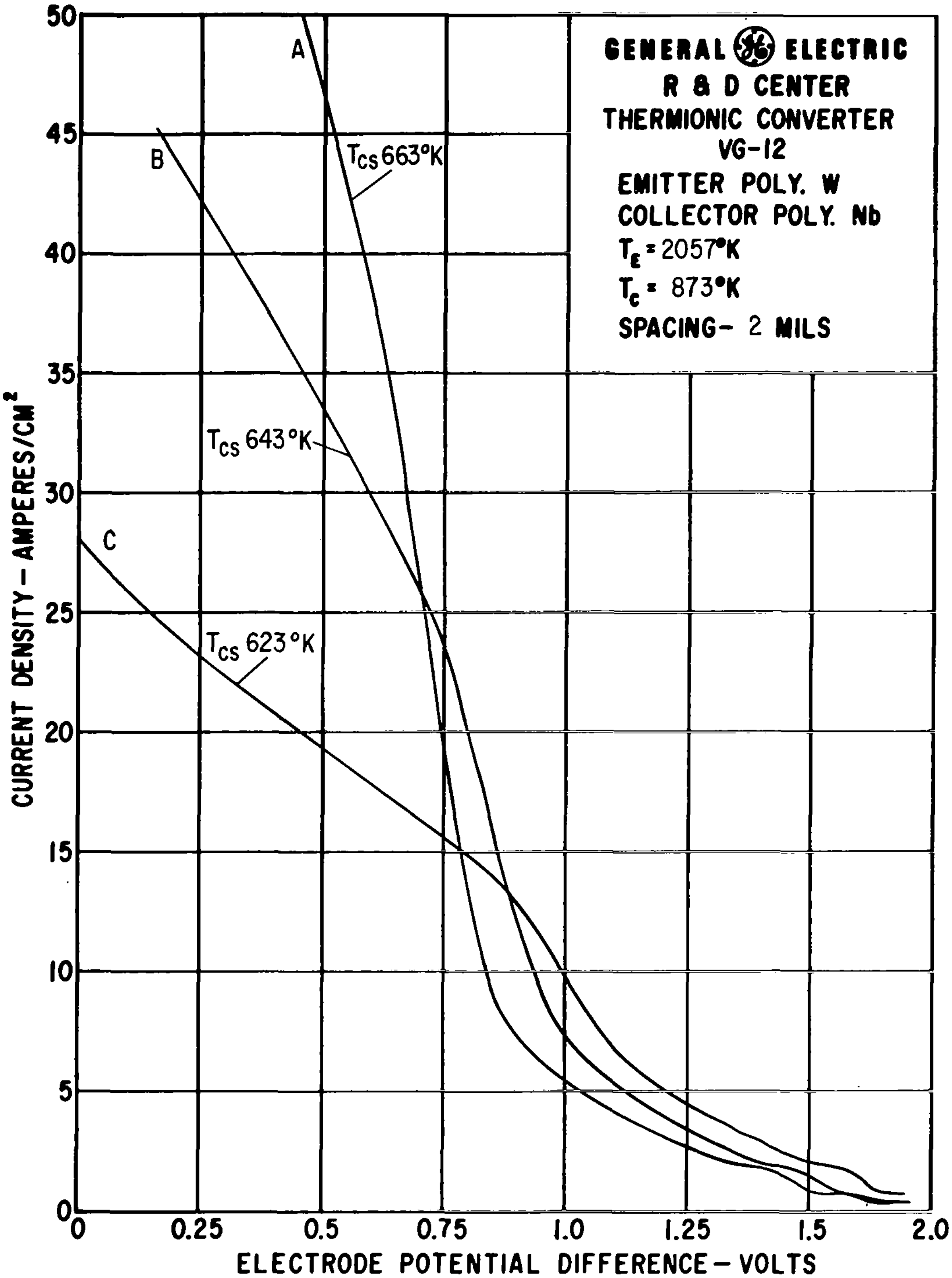

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 873 °K
SPACING- 1 MILS
A
B
C
T_{CS} 663°K
T_{CS} 643°K
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-20



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_c = 873°K
SPACING- 2 MILS
A
B
C
T_{CS} 663°K
T_{CS} 643°K
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-21

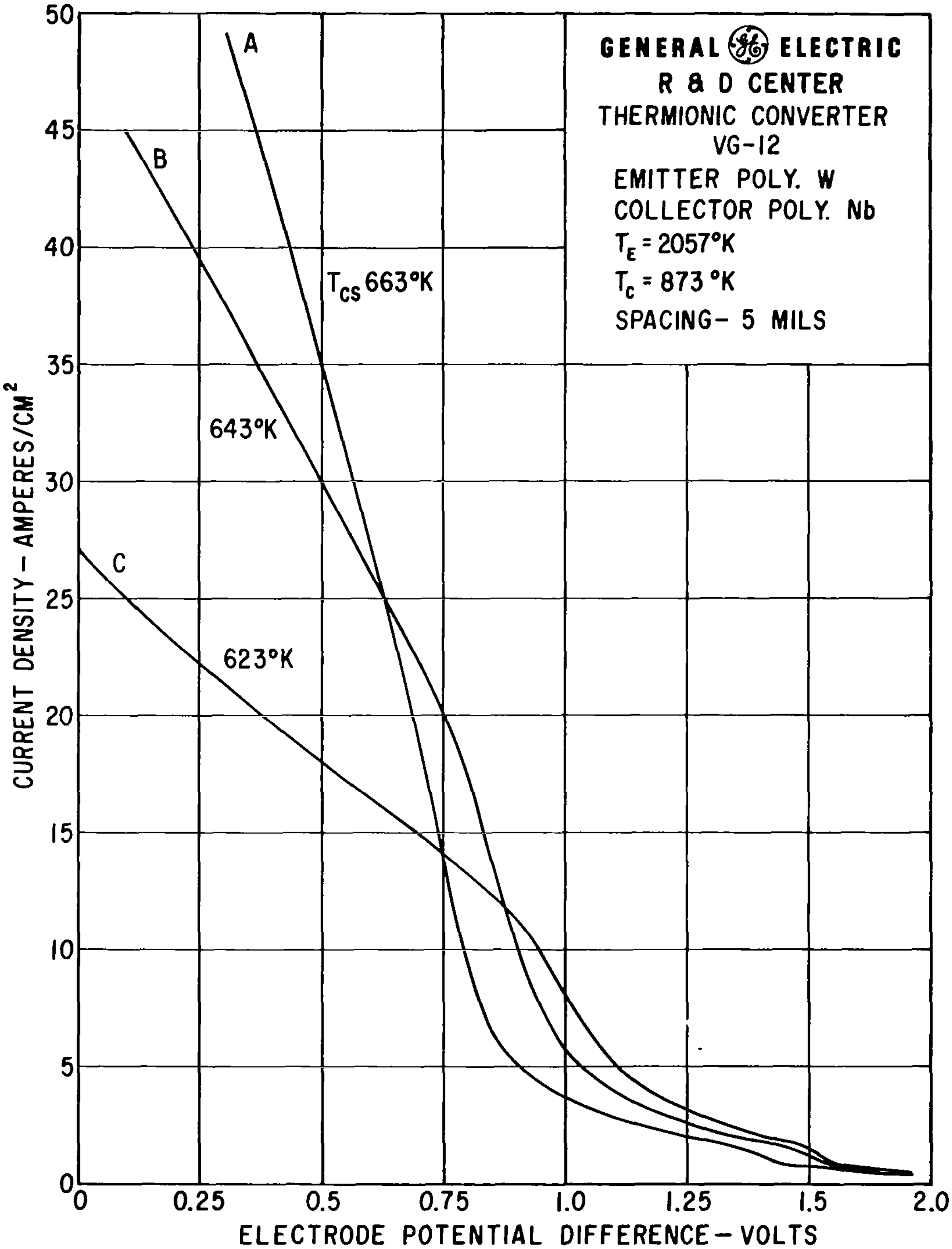

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_c = 873 °K
SPACING- 5 MILS
A
B
C
T_{CS} 663°K
643°K
623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-22

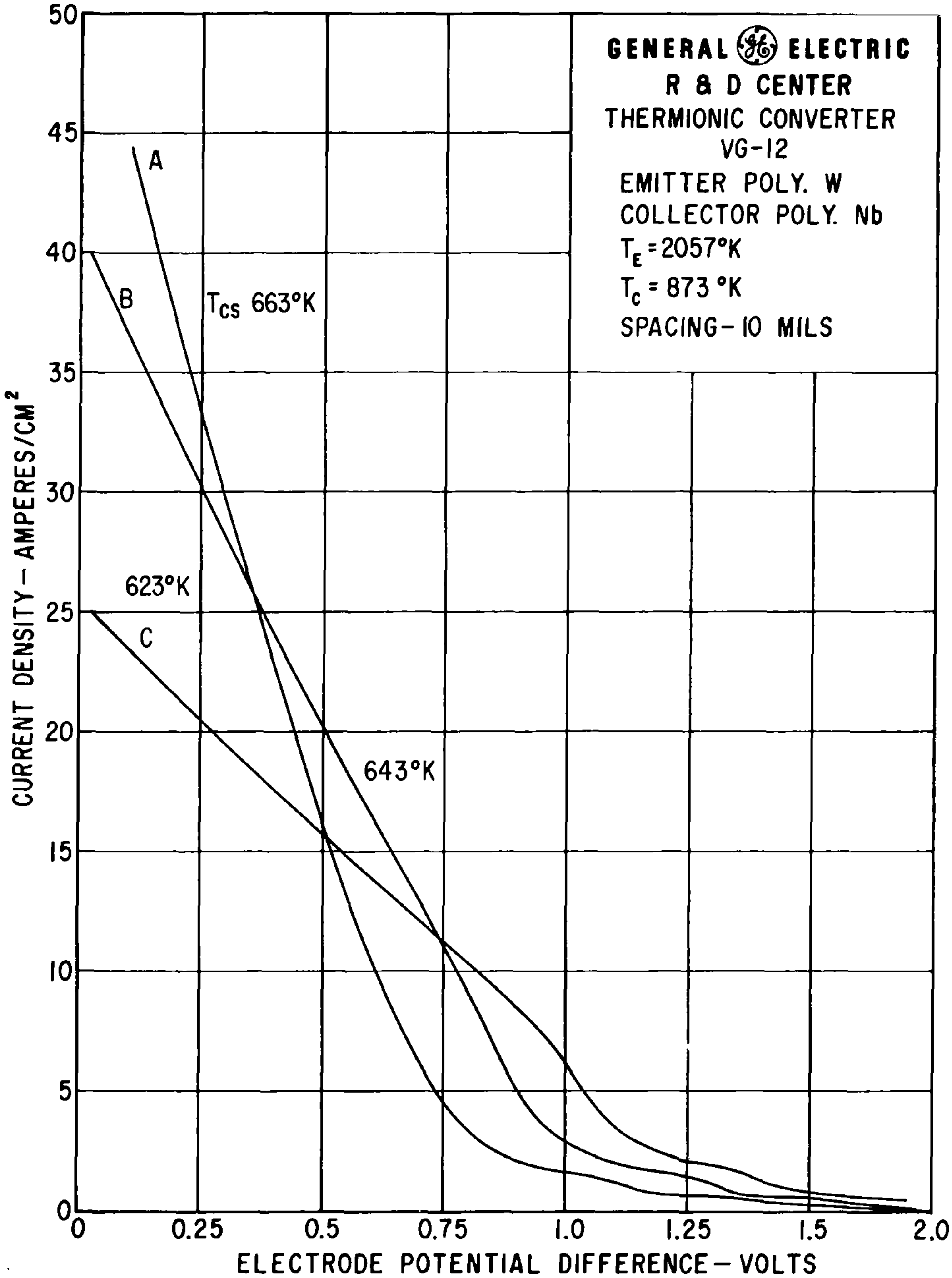

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_c = 873 °K
SPACING - 10 MILS
A
B
C
T_{CS} 663°K
623°K
643°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-23

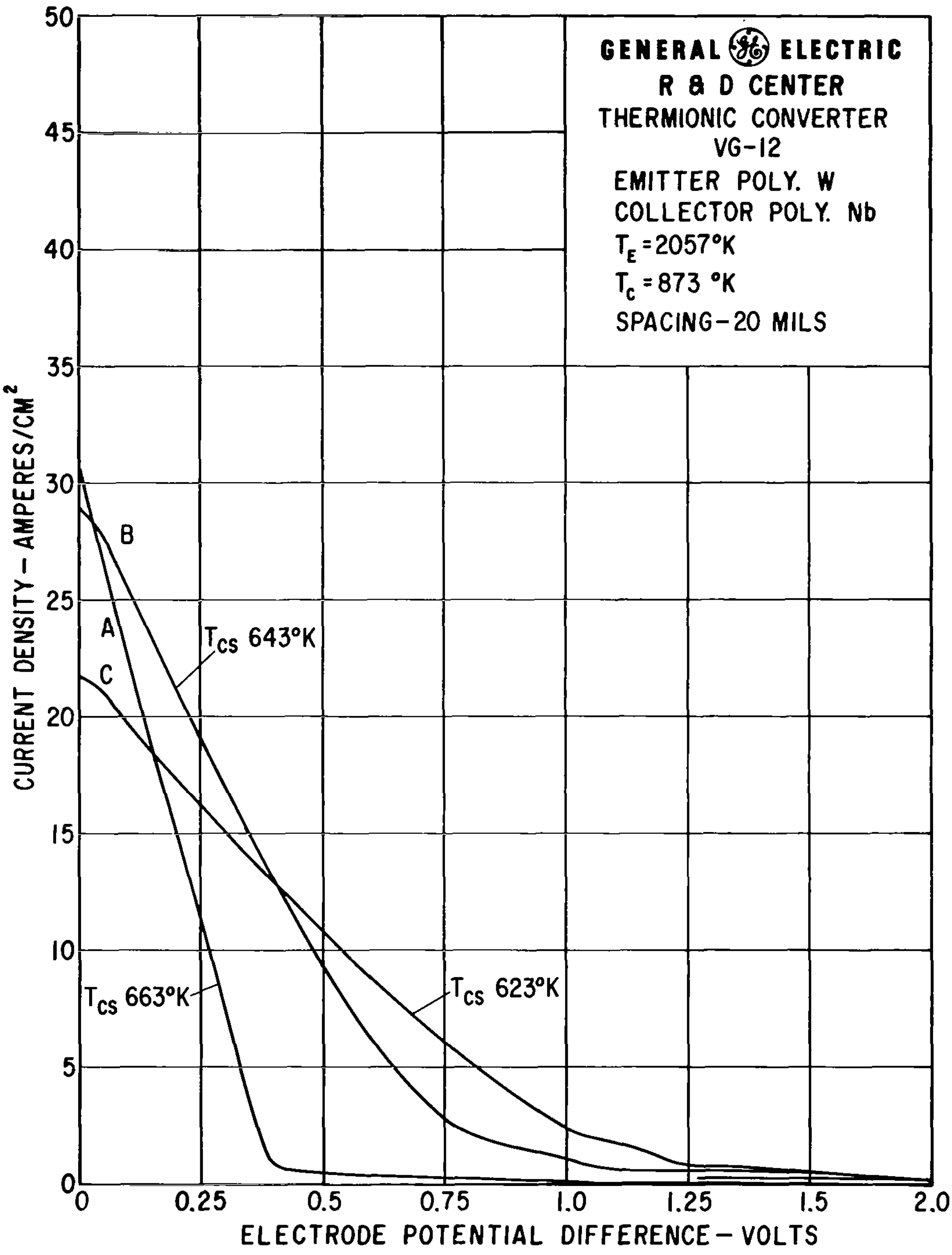

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 873 °K
SPACING-20 MILS
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
A
B
C
T_{CS} 643°K
T_{CS} 663°K
T_{CS} 623°K
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-24

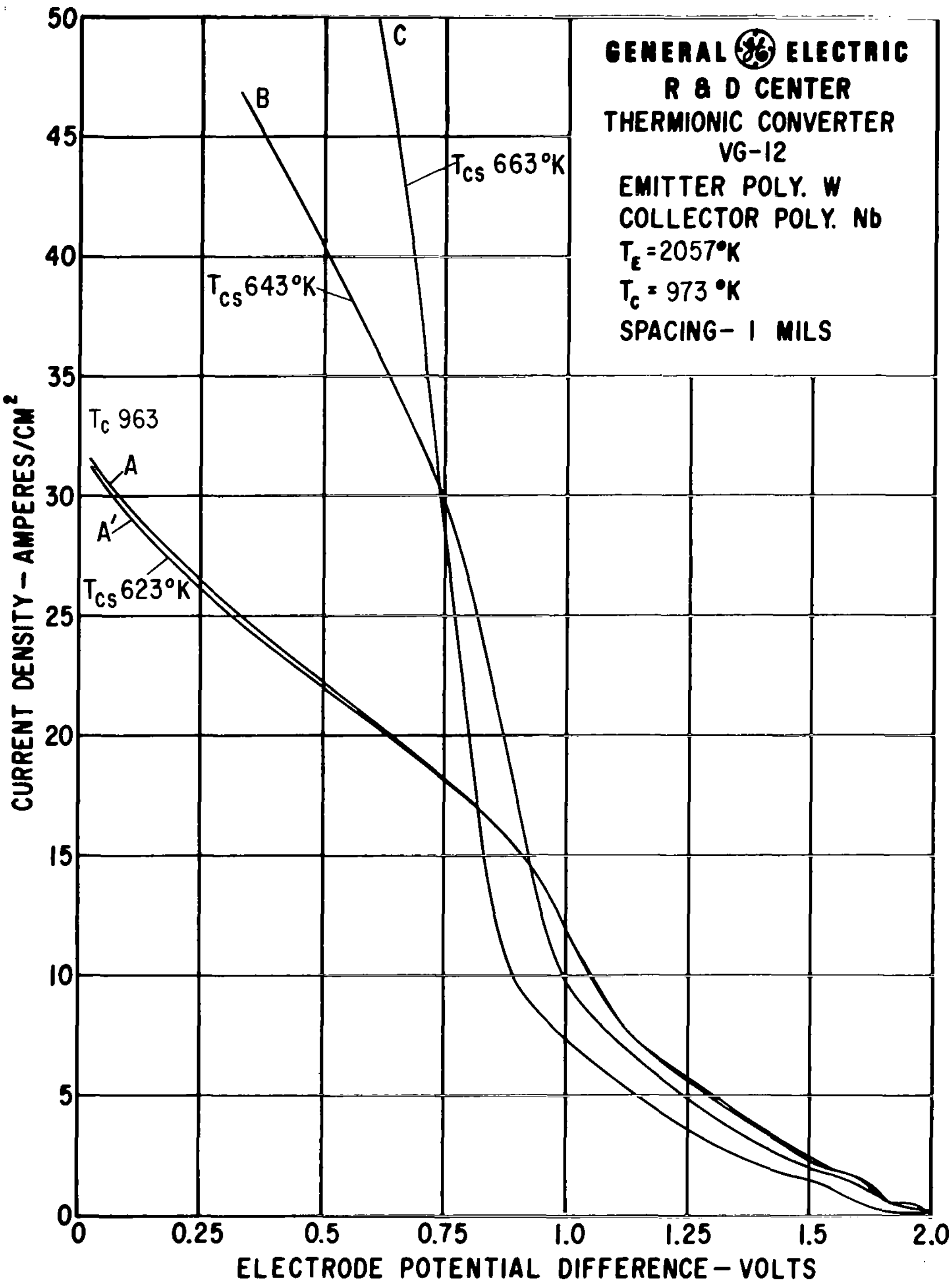
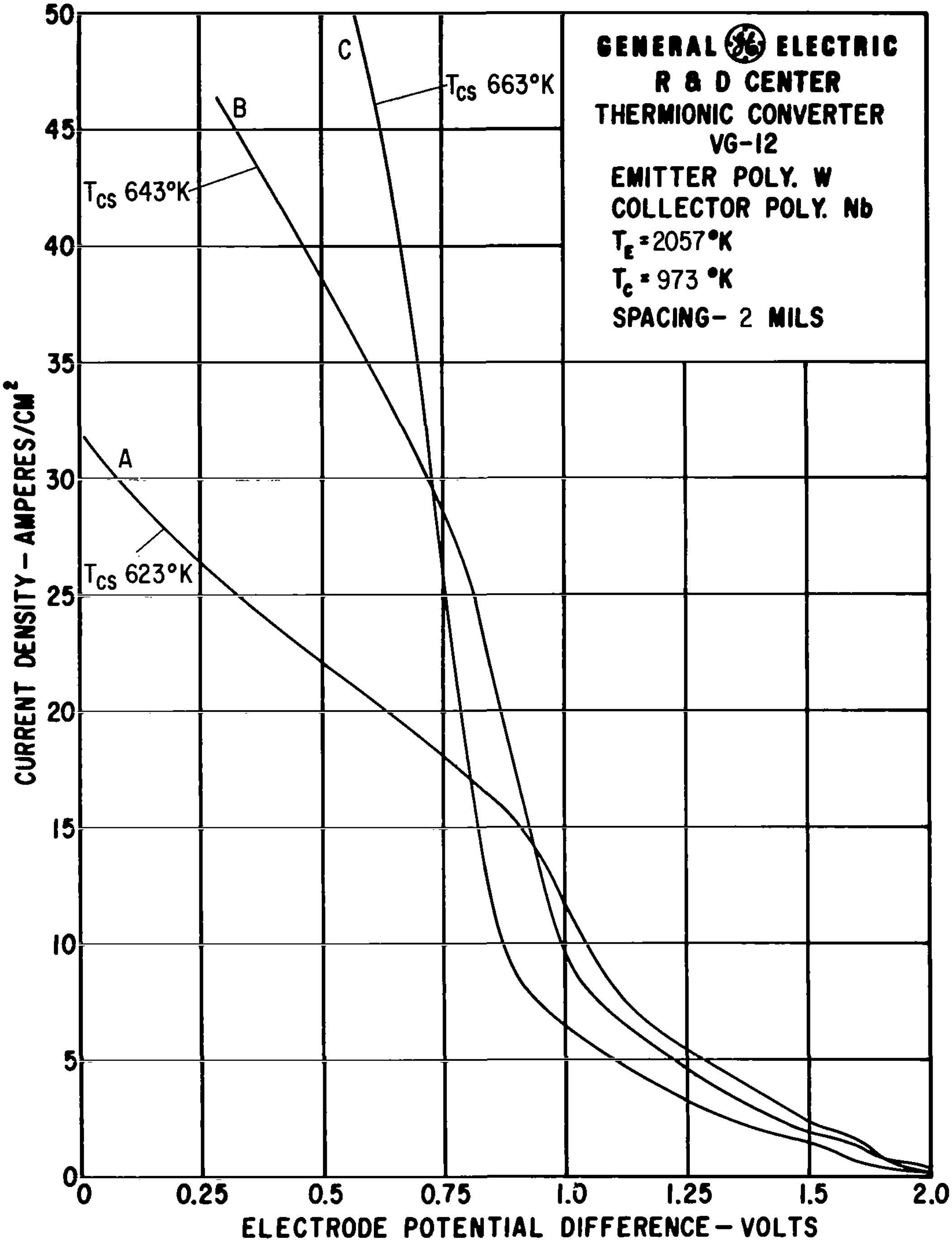

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 973 °K
SPACING- 1 MILS
C
B
T_{CS} 663°K
T_{CS} 643°K
T_C 963
A
A'
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
50
45
40
35
30
25
20
15
10
5
0
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-25



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057 °K
T_c = 973 °K
SPACING- 2 MILS
A
B
C
T_{CS} 623°K
T_{CS} 643°K
T_{CS} 663°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0
5
10
15
20
25
30
35
40
45
50

FIGURE B-26

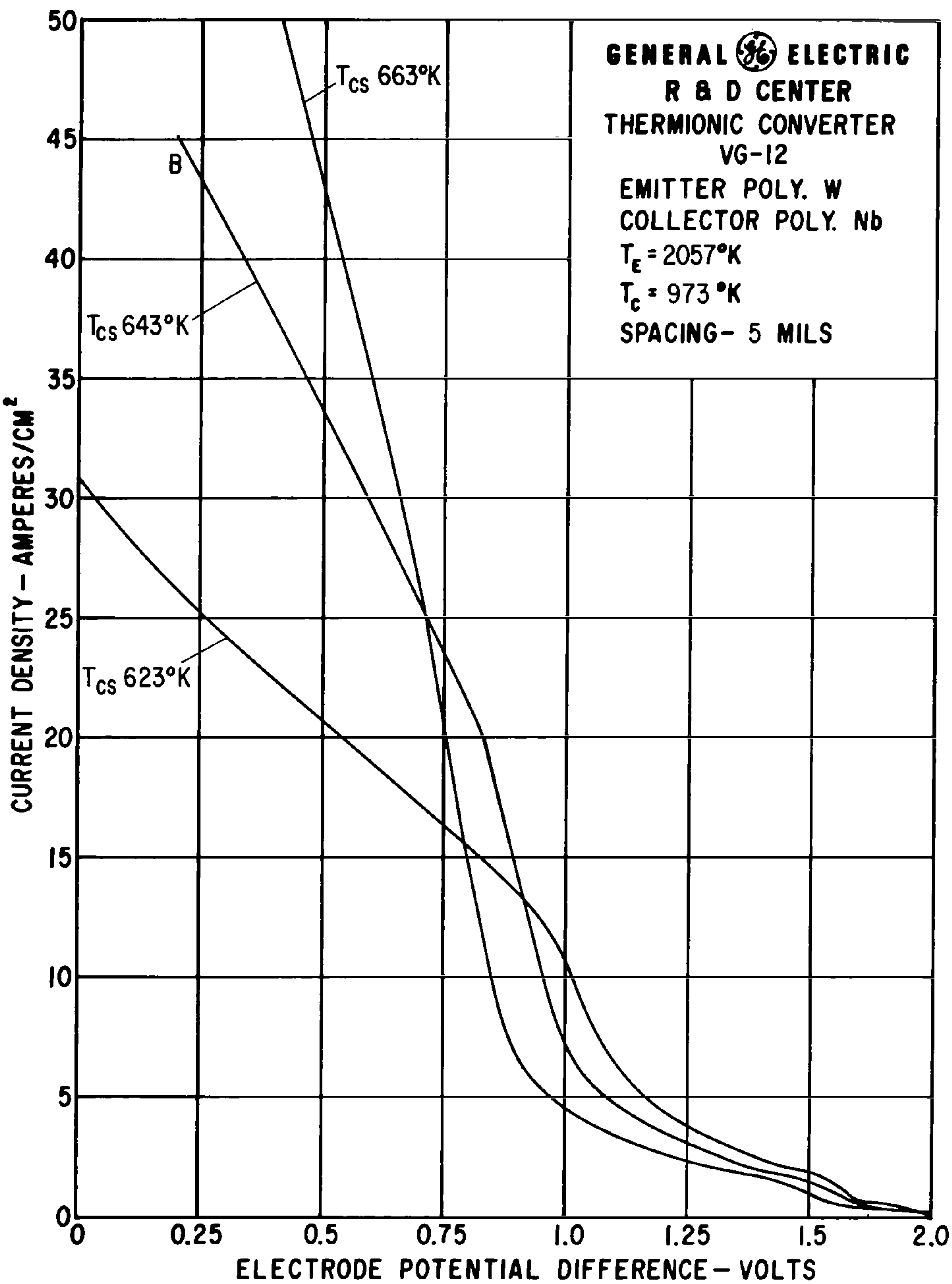

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 973 °K
SPACING- 5 MILS
T_{CS} 663°K
B
T_{CS} 643°K
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-27

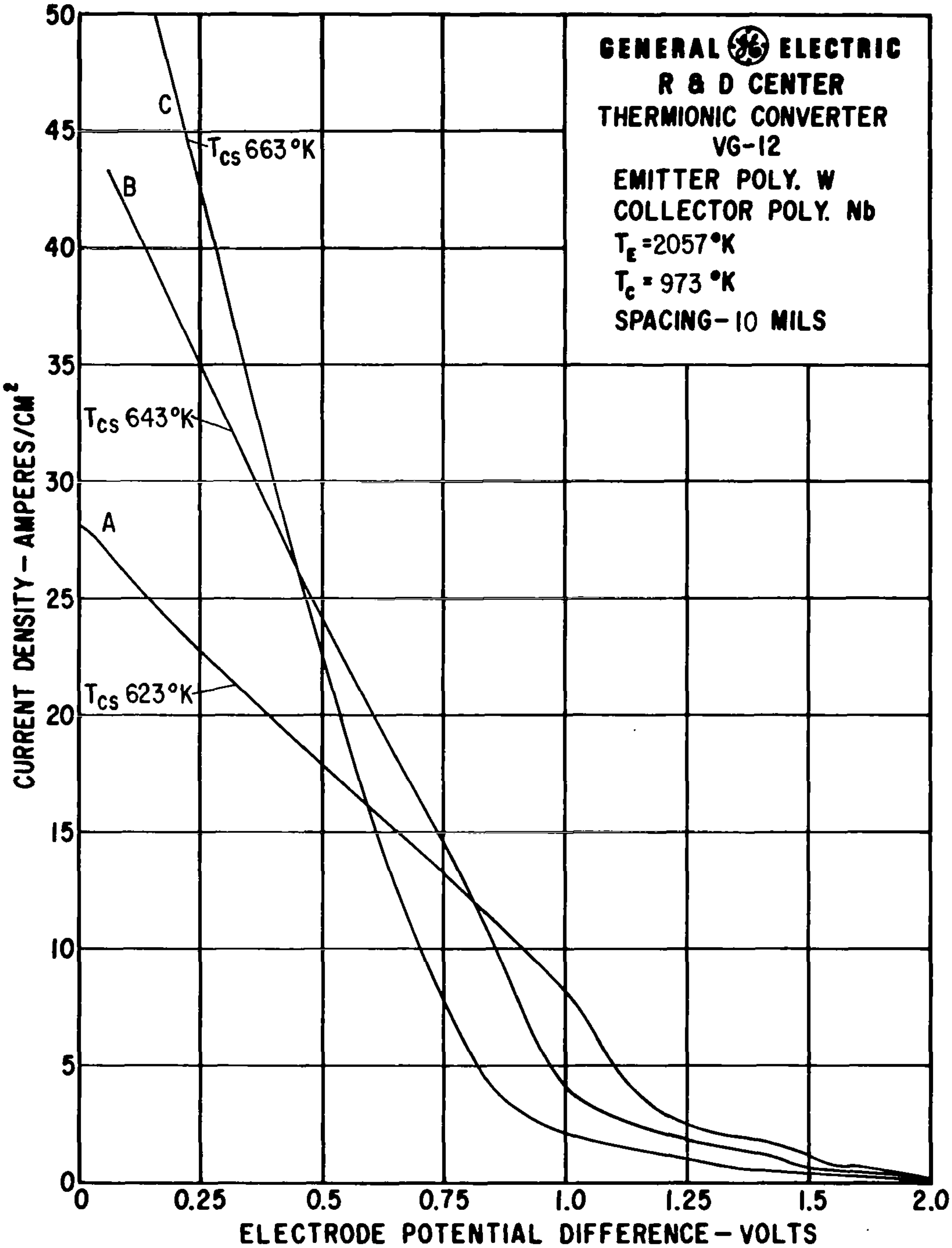
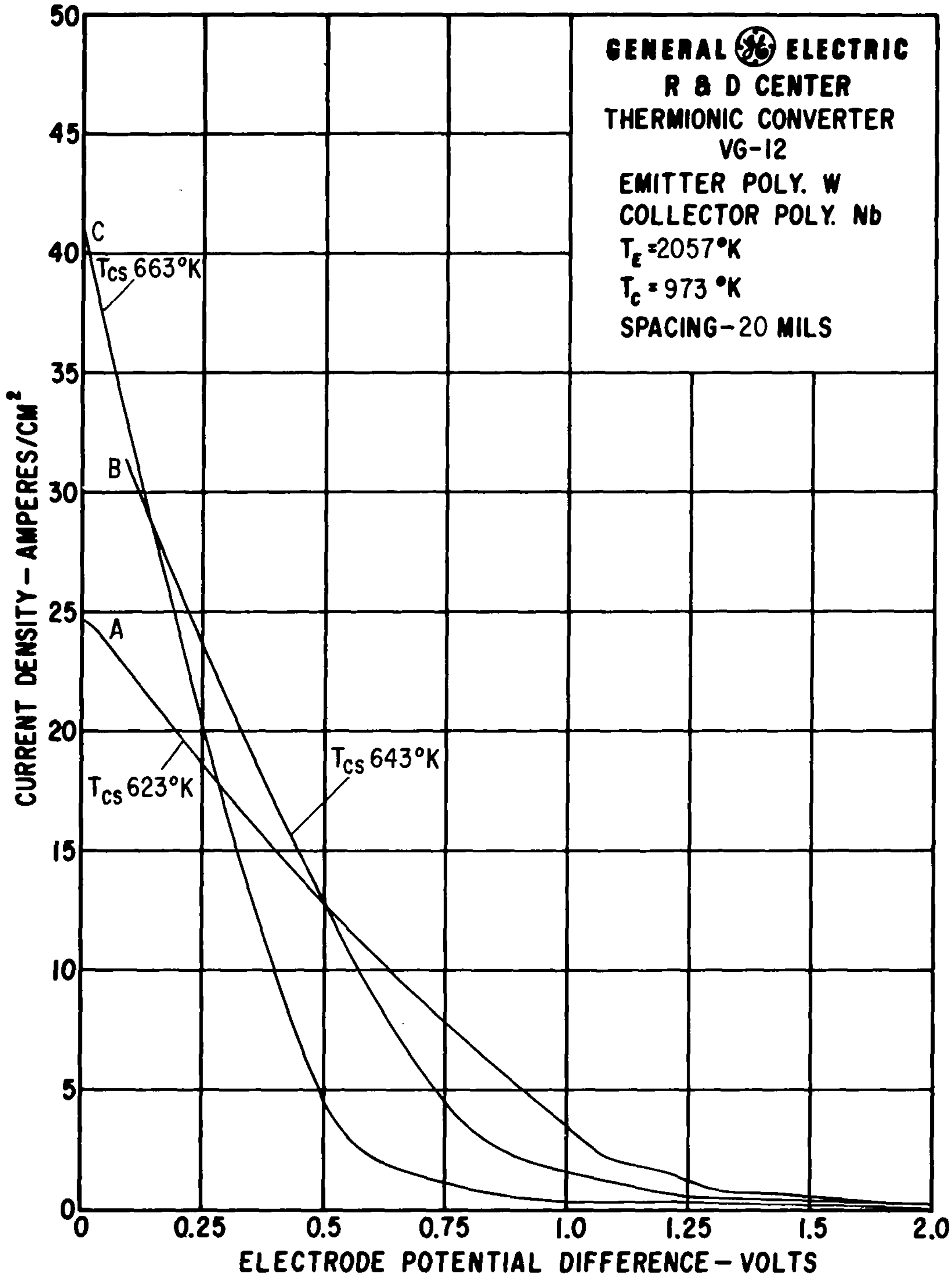
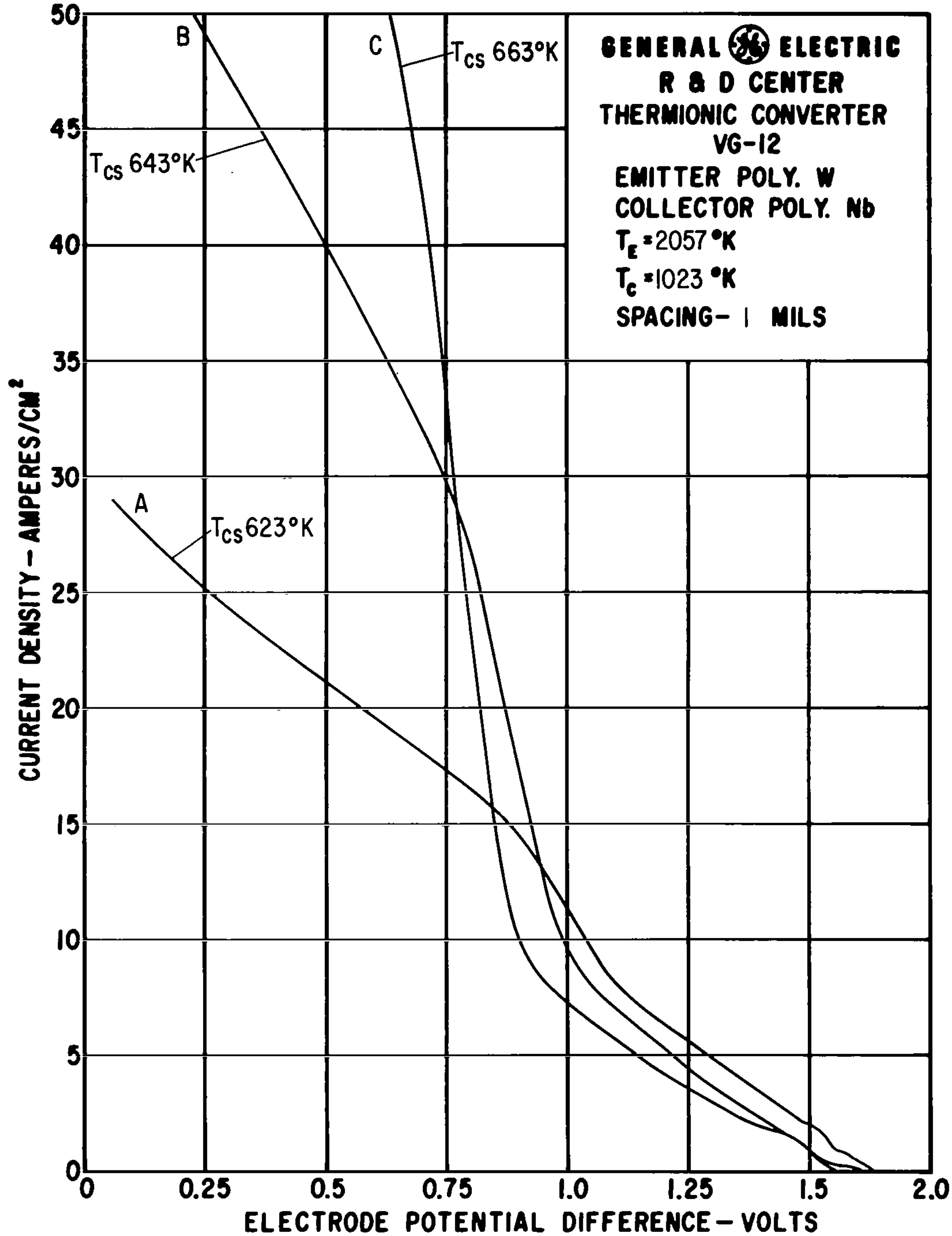
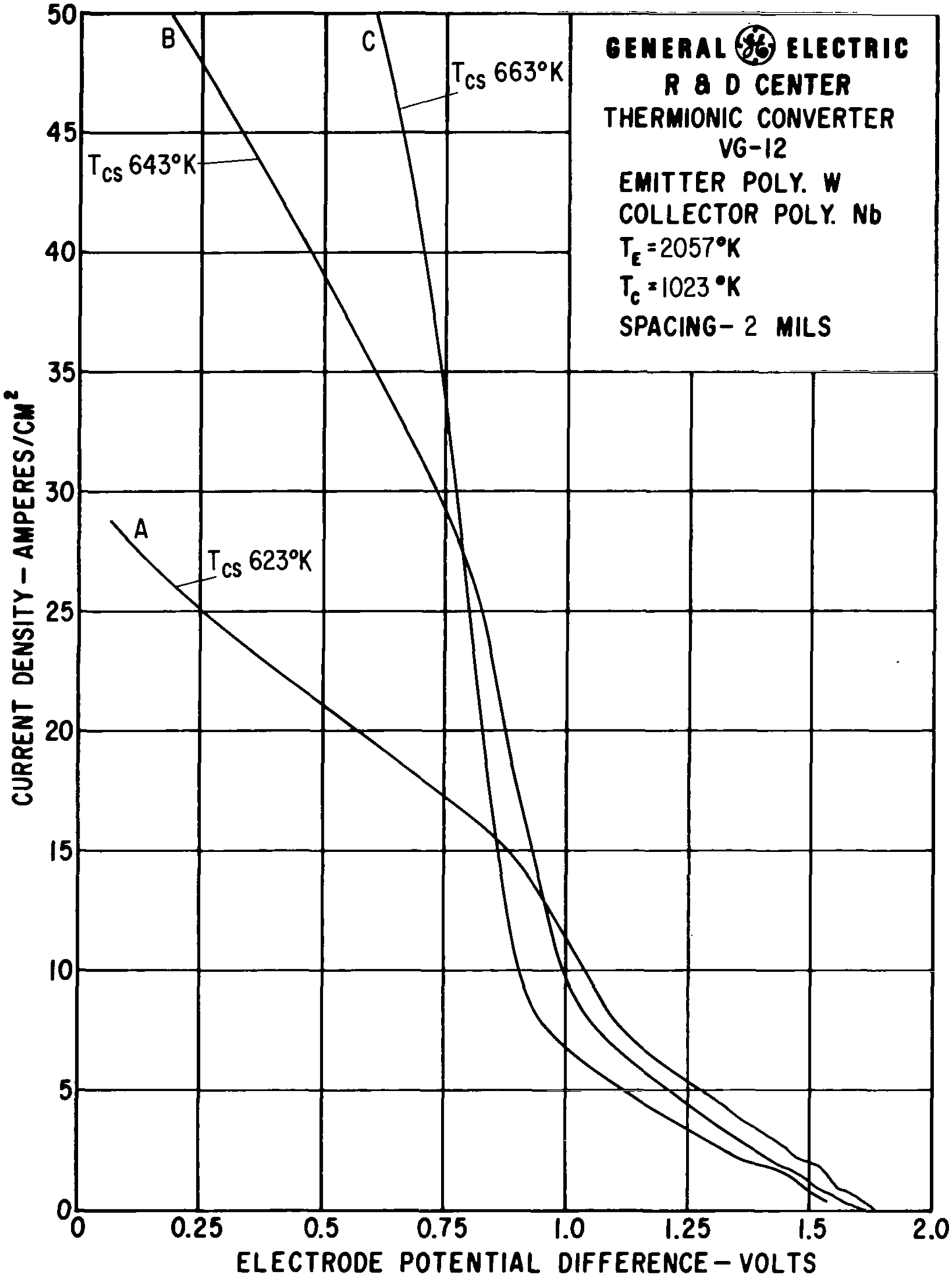
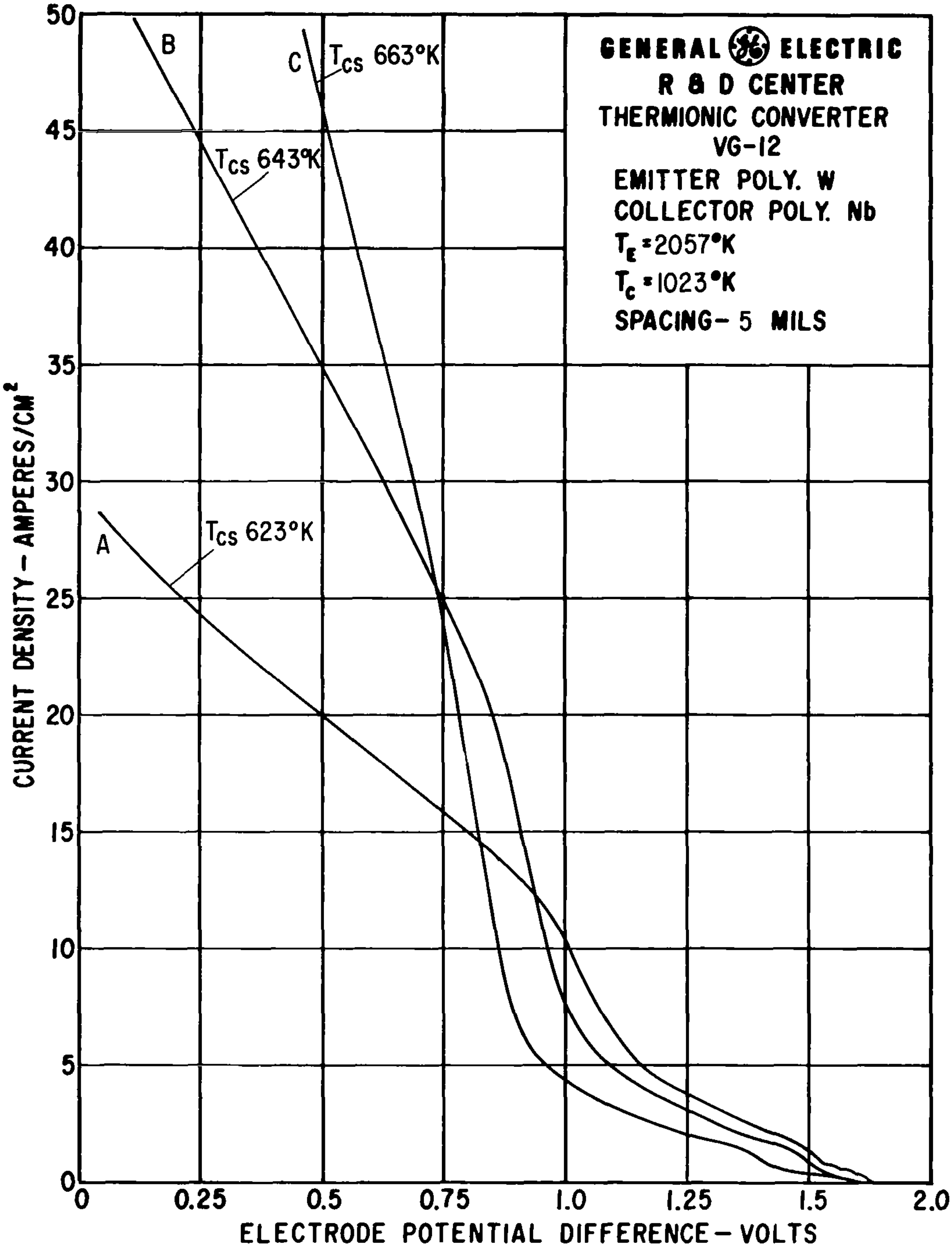

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E=2057°K
T_c = 973 °K
SPACING-10 MILS
C
T_{cs} 663°K
B
T_{cs} 643°K
A
T_{cs} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-28

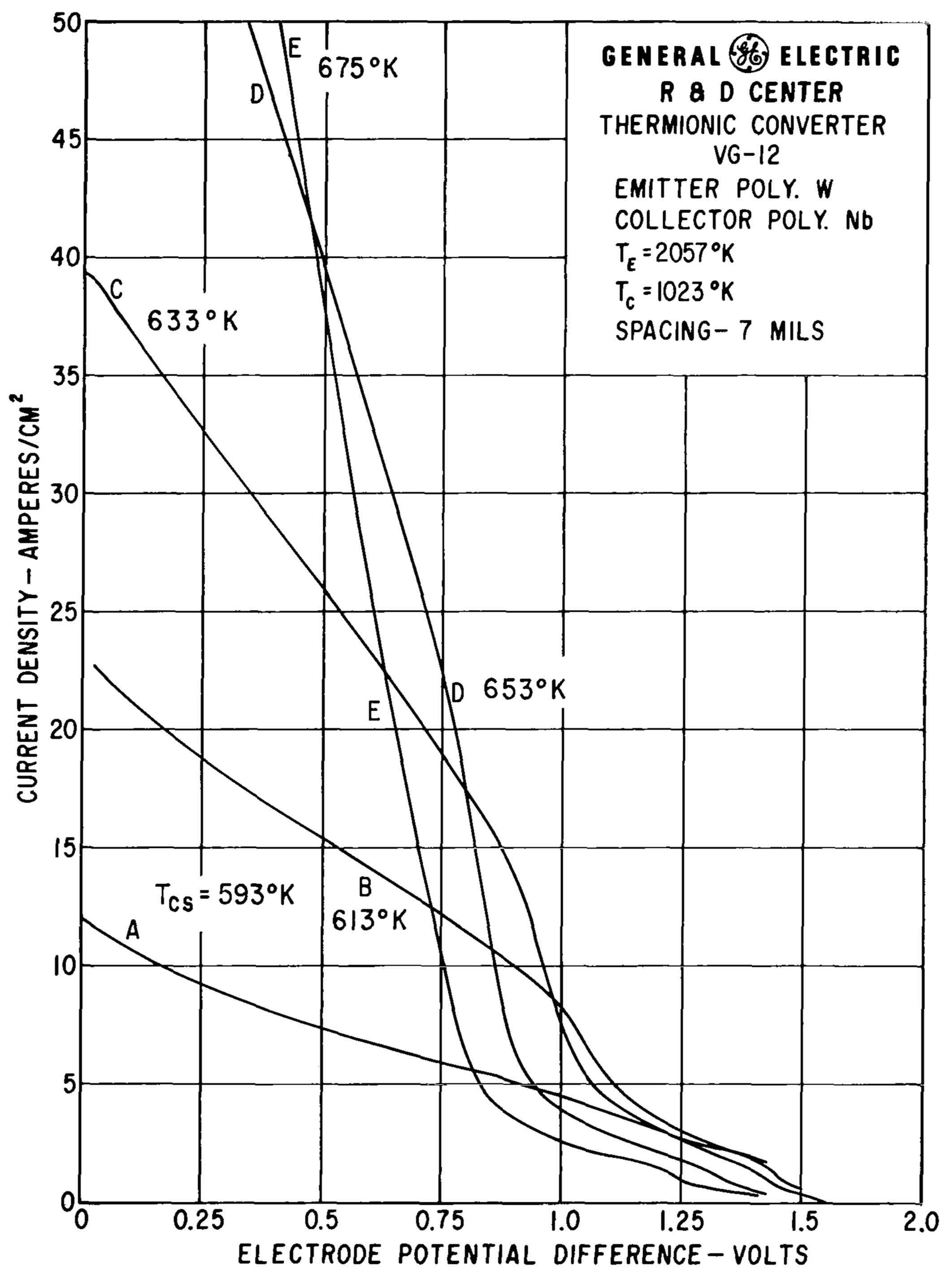

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 973°K
SPACING-20 MILS
C
T_{CS} 663°K
B
A
T_{CS} 623°K
T_{CS} 643°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0


GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057 °K
T_C = 1023 °K
SPACING- 1 MILS
A
B
C
T_{CS} 623°K
T_{CS} 643°K
T_{CS} 663°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

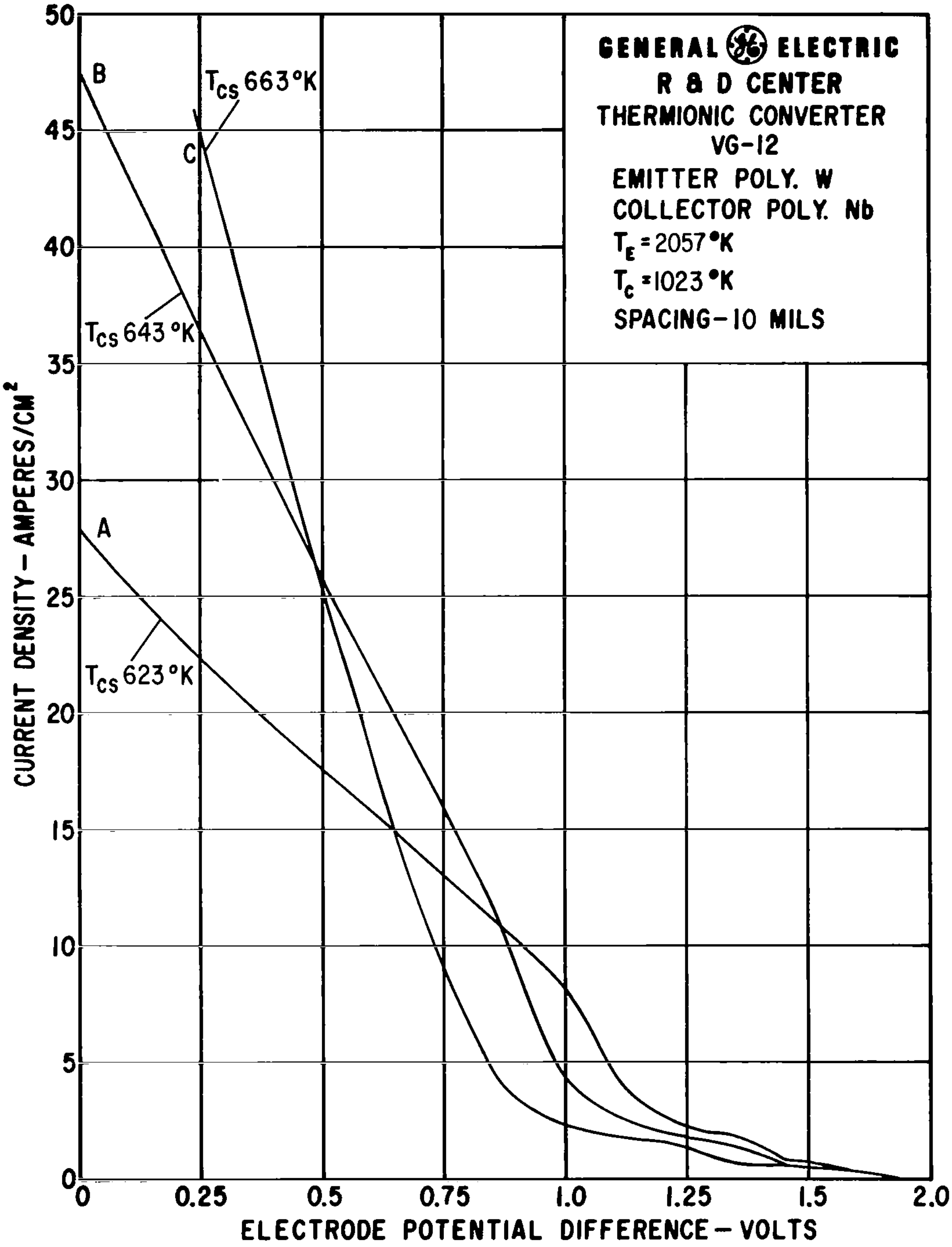

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 1023 °K
SPACING- 2 MILS
A
B
C
T_{CS} 623°K
T_{CS} 643°K
T_{CS} 663°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_c = 1023°K
SPACING - 5 MILS
A
B
C
T_{cs} 623°K
T_{cs} 643°K
T_{cs} 663°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057 °K
T_c = 1023 °K
SPACING - 7 MILS
E 675 °K
D
C 633 °K
D 653 °K
E
B 613 °K
T_{CS} = 593 °K
A
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0


GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057 °K
T_C = 1023 °K
SPACING - 10 MILS
B
T_{CS} 663 °K
C
T_{CS} 643 °K
A
T_{CS} 623 °K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

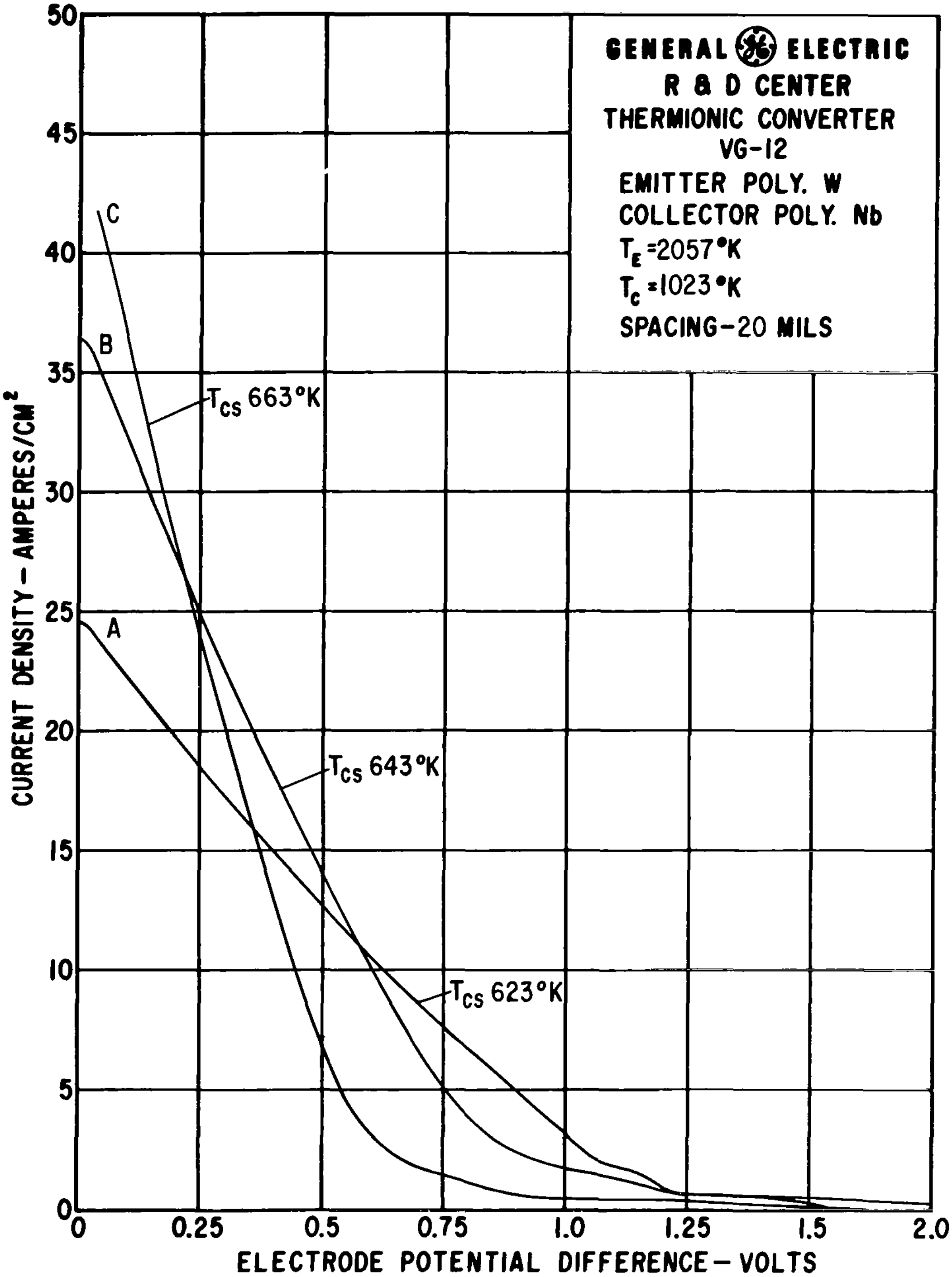

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E =2057°K
T_C =1023°K
SPACING-20 MILS
C
B
A
T_CS 663°K
T_CS 643°K
T_CS 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
50
45
40
35
30
25
20
15
10
5
0
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-35

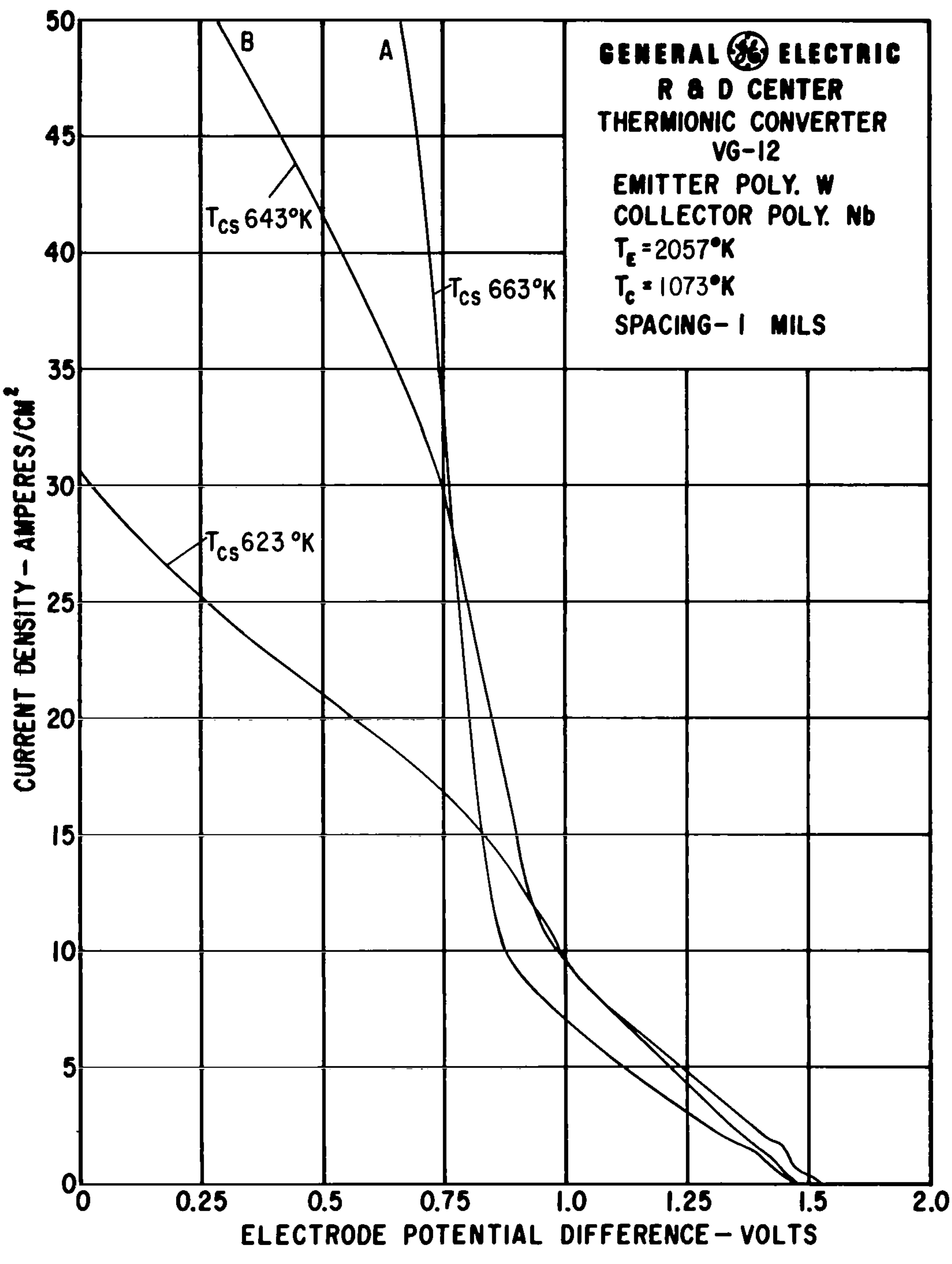

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 1073°K
SPACING - 1 MILS
B
A
T_{CS} 643°K
T_{CS} 663°K
T_{CS} 623 °K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
50
45
40
35
30
25
20
15
10
5
0
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-36

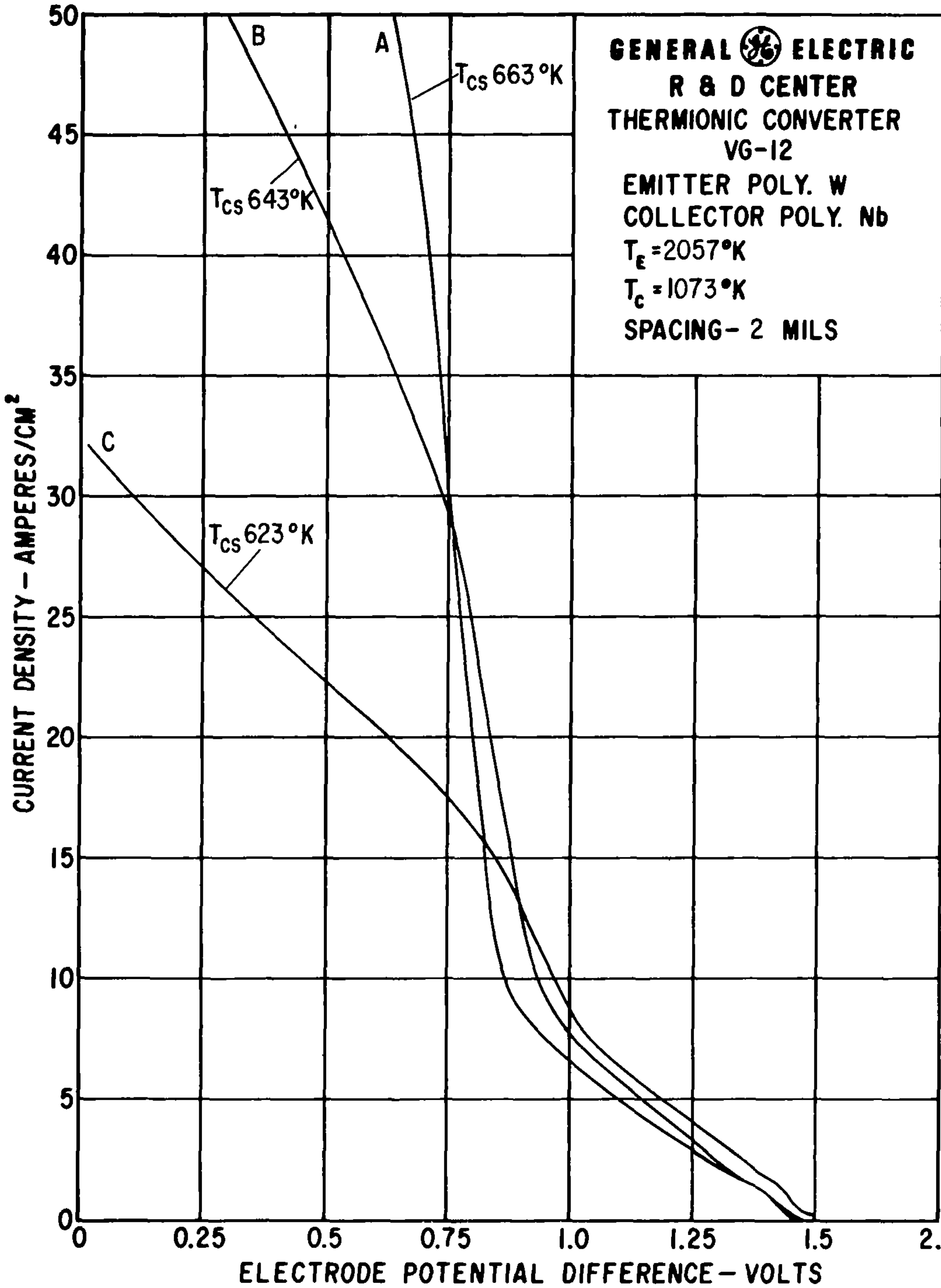
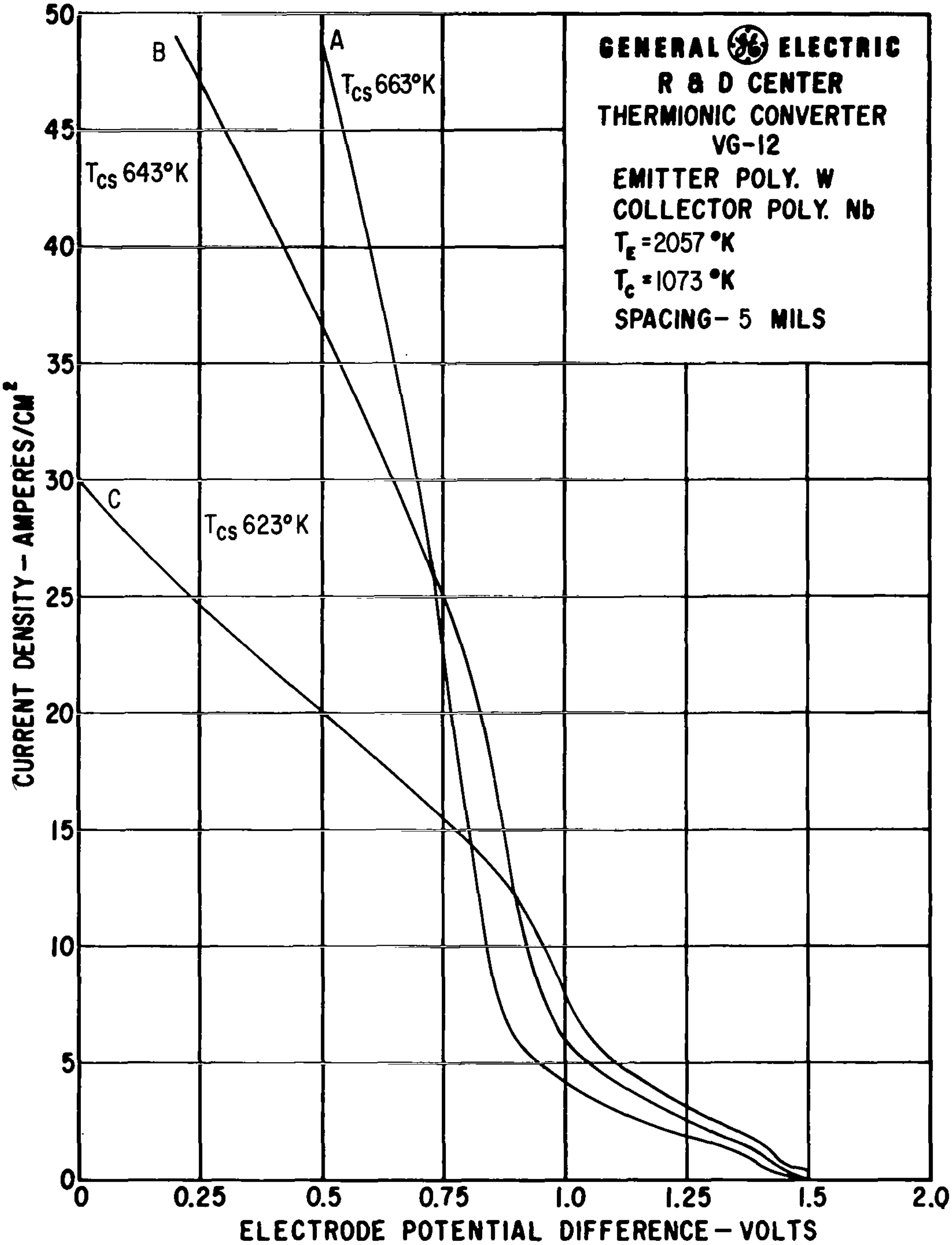

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 1073°K
SPACING - 2 MILS
A
B
C
T_{CS} 663°K
T_{CS} 643°K
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-37



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057 °K
T_C = 1073 °K
SPACING - 5 MILS
A
T_{CS} 663°K
B
T_{CS} 643°K
C
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-38

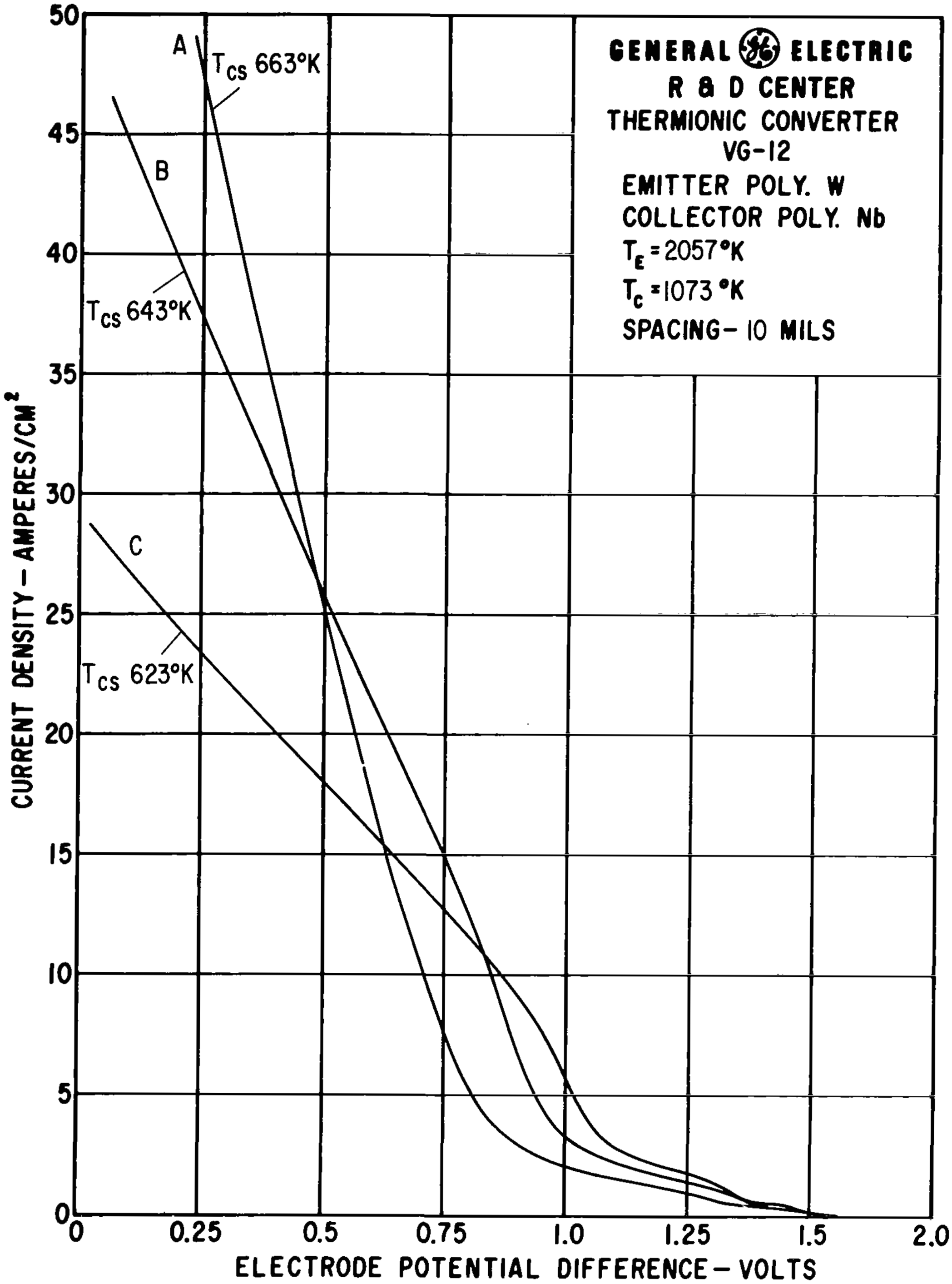

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 1073 °K
SPACING- 10 MILS
A
T_{CS} 663°K
B
T_{CS} 643°K
C
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-39

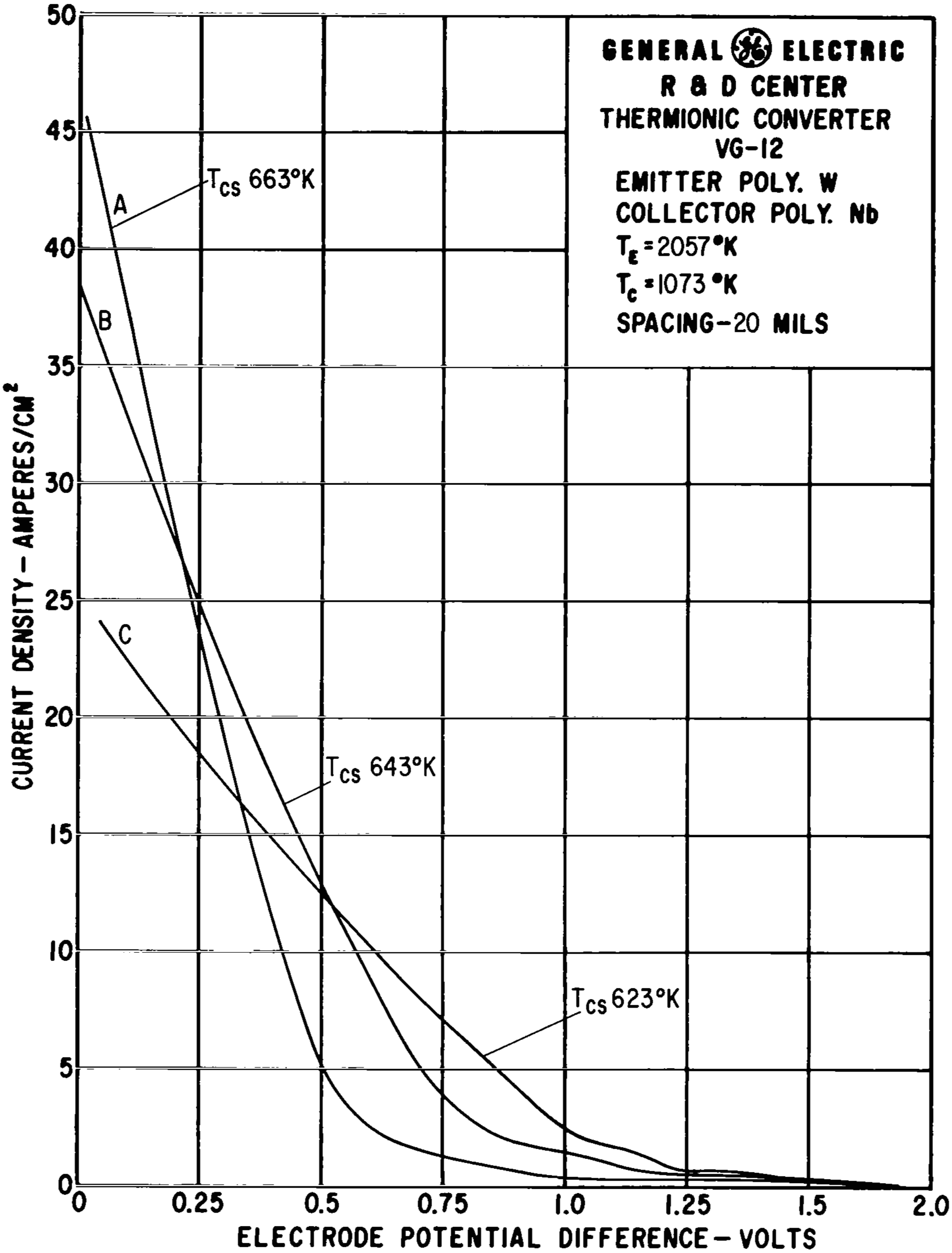
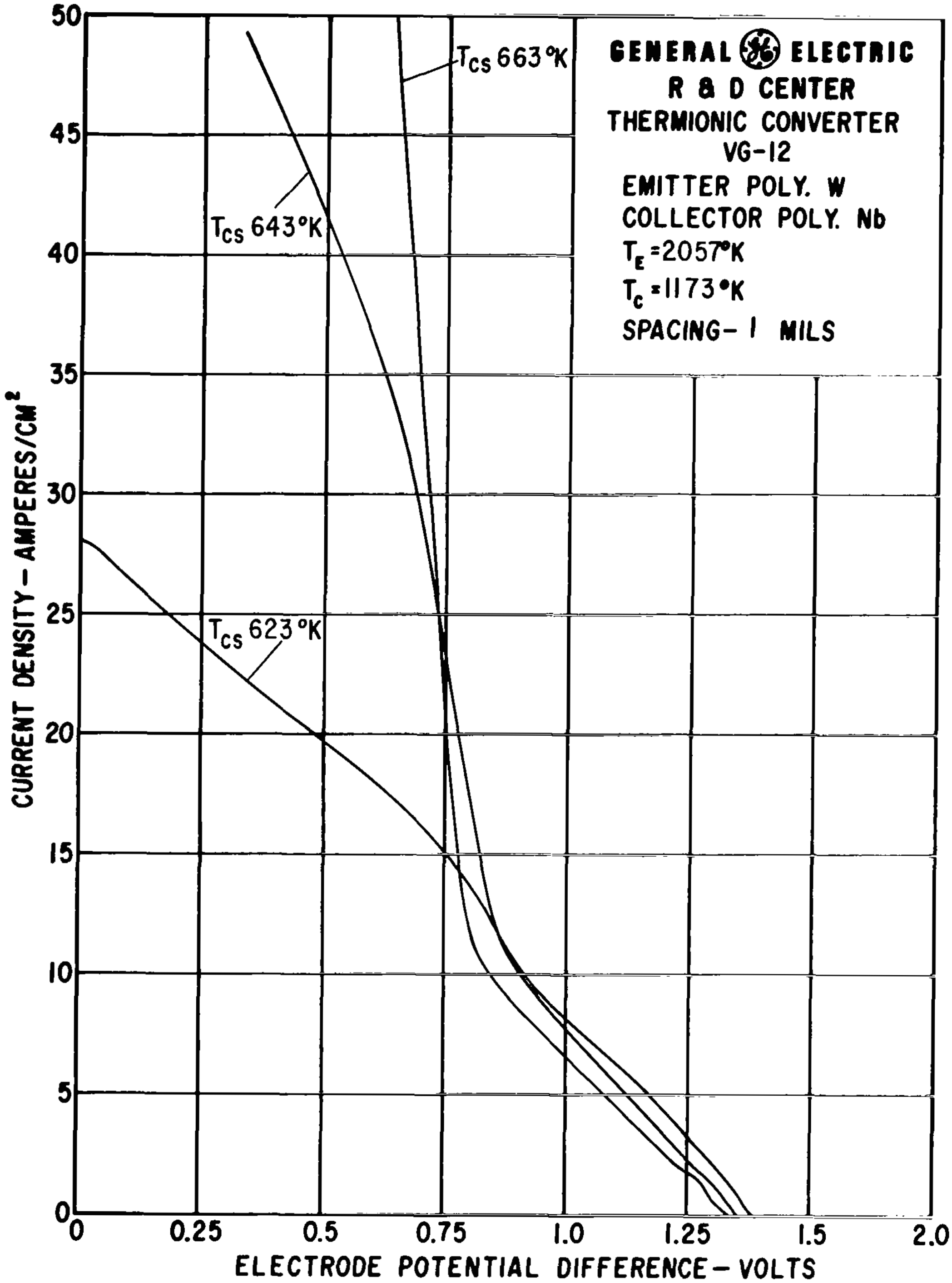

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057 °K
T_c = 1073 °K
SPACING-20 MILS
T_{CS} 663°K
T_{CS} 643°K
T_{CS} 623°K
A
B
C
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-40



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E =2057°K
T_C =1173°K
SPACING- 1 MILS
T_CS 663°K
T_CS 643°K
T_CS 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-41

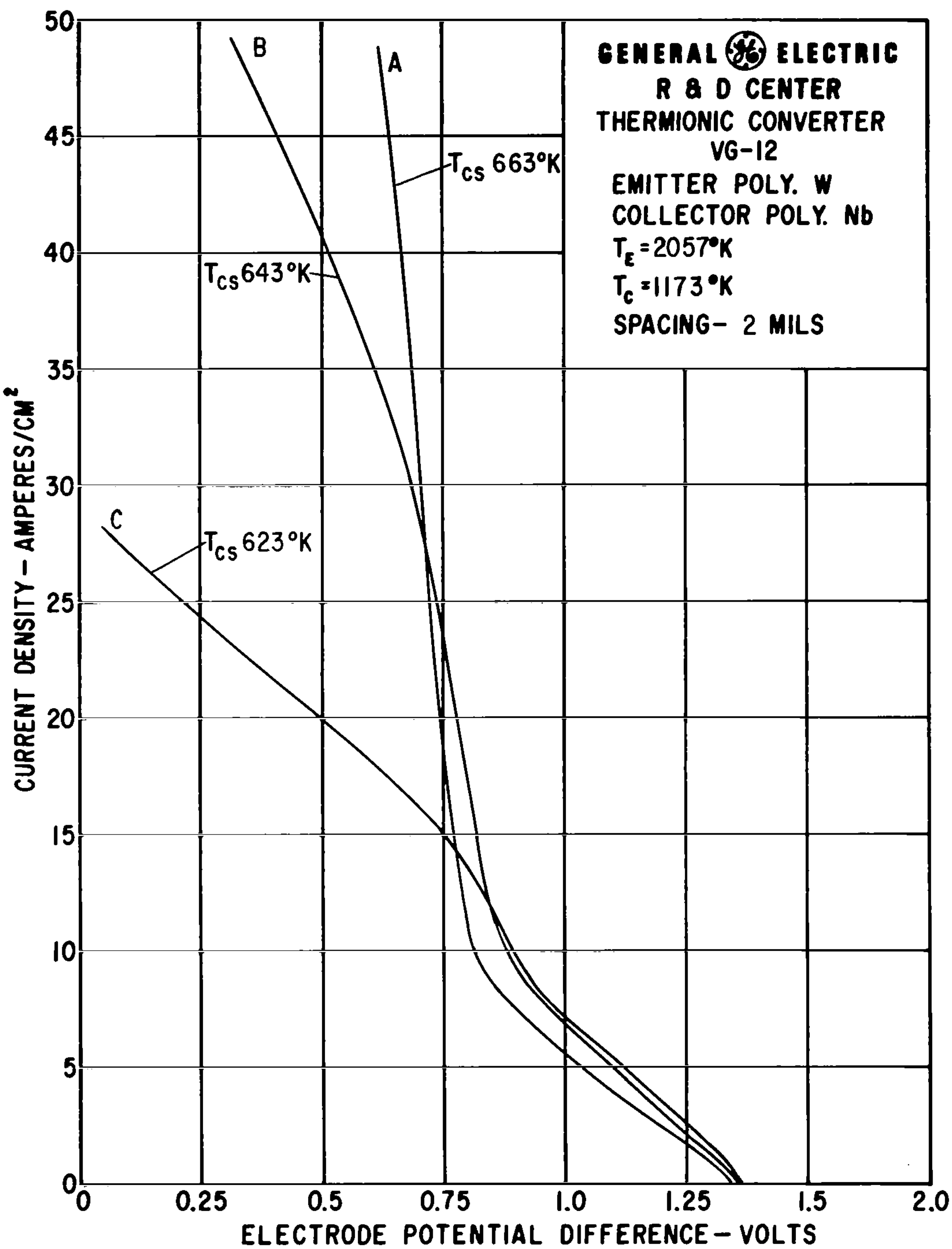
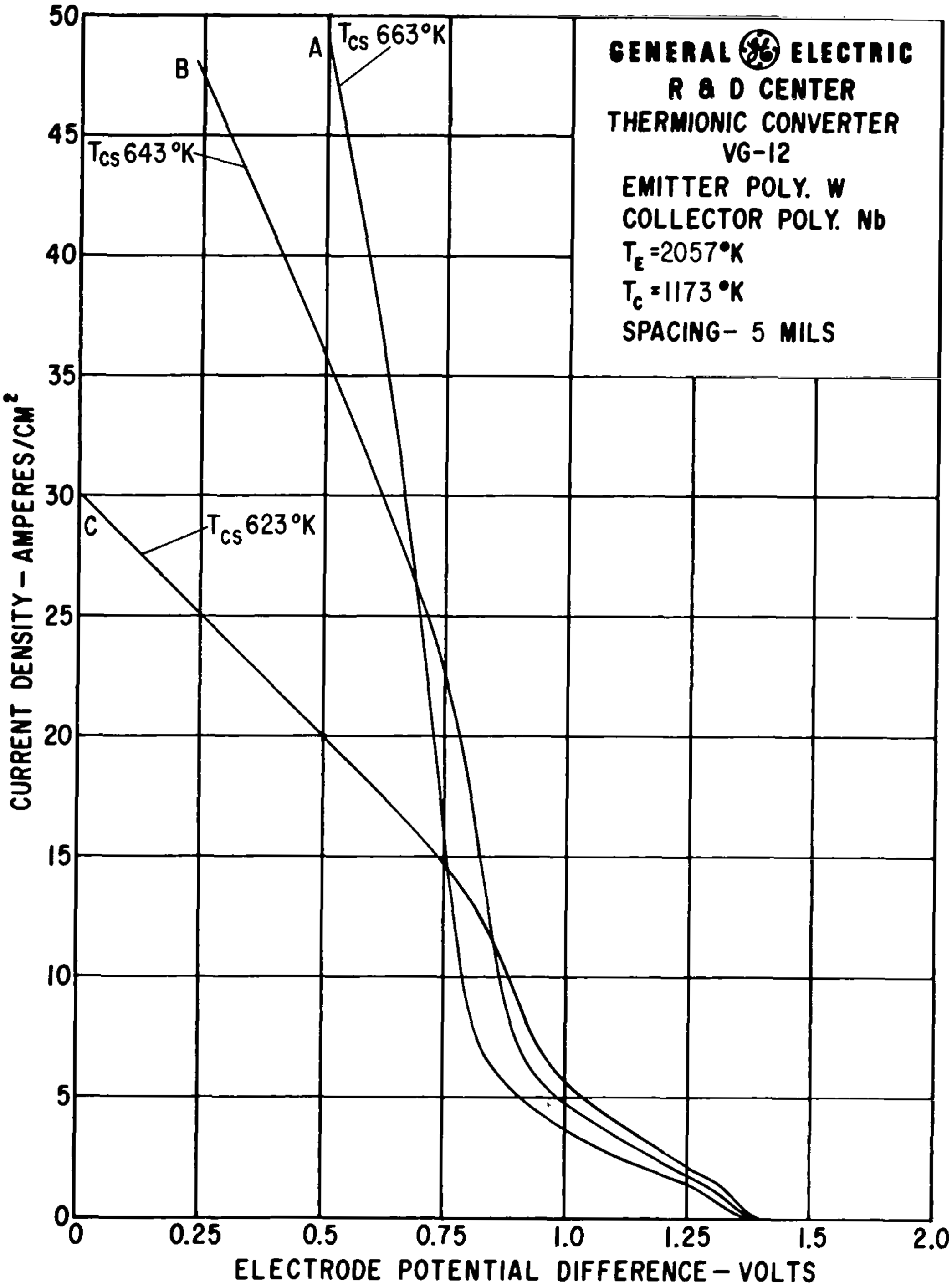

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_C = 1173°K
SPACING – 2 MILS
A
B
C
T_{CS} 663°K
T_{CS} 643°K
T_{CS} 623°K
CURRENT DENSITY – AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE – VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-42



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E =2057°K
T_C =1173 °K
SPACING- 5 MILS
A
B
C
T_{CS} 663°K
T_{CS} 643°K
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-43

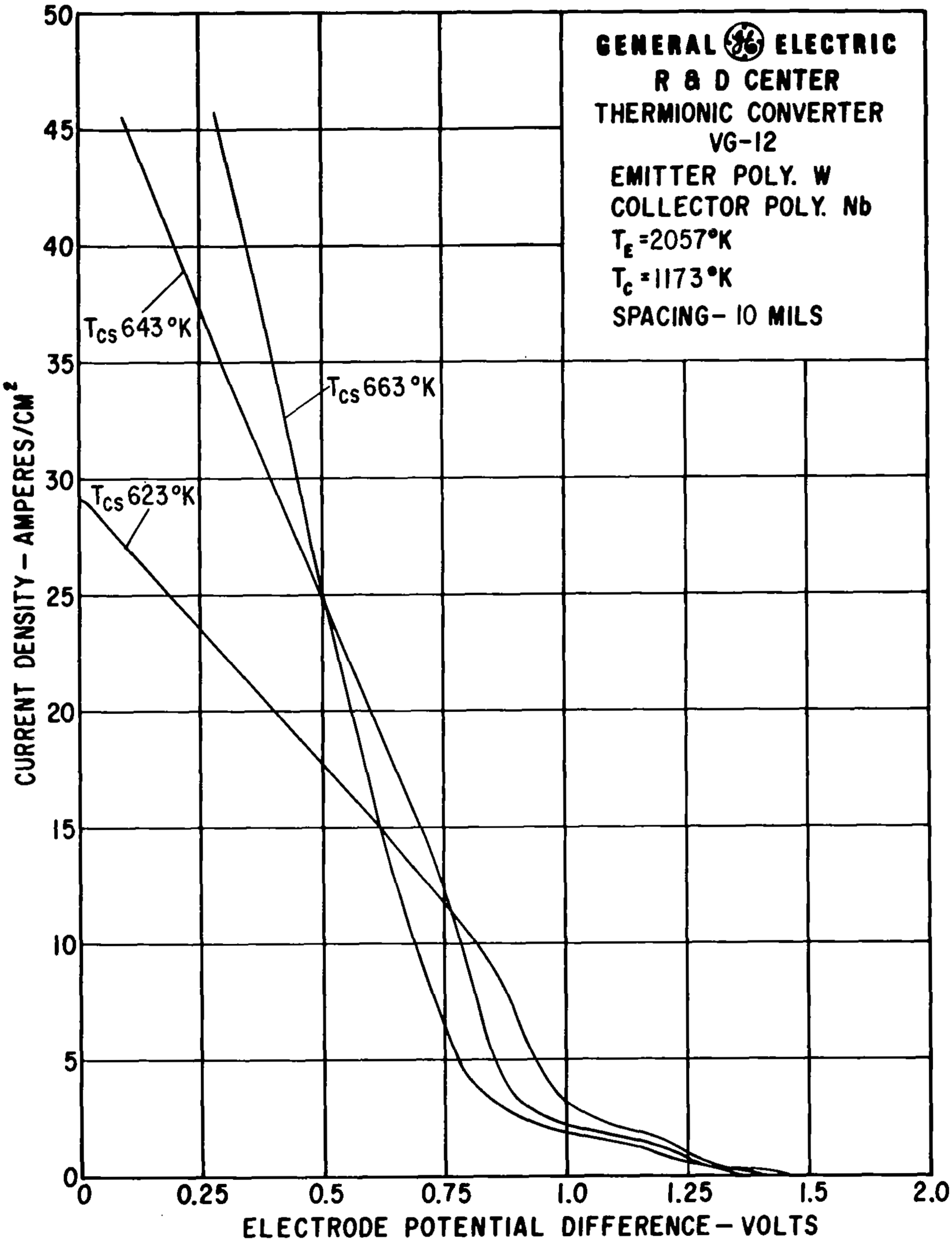

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E =2057°K
T_C =1173°K
SPACING- 10 MILS
T_{CS} 643 °K
T_{CS} 663 °K
T_{CS} 623 °K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-44

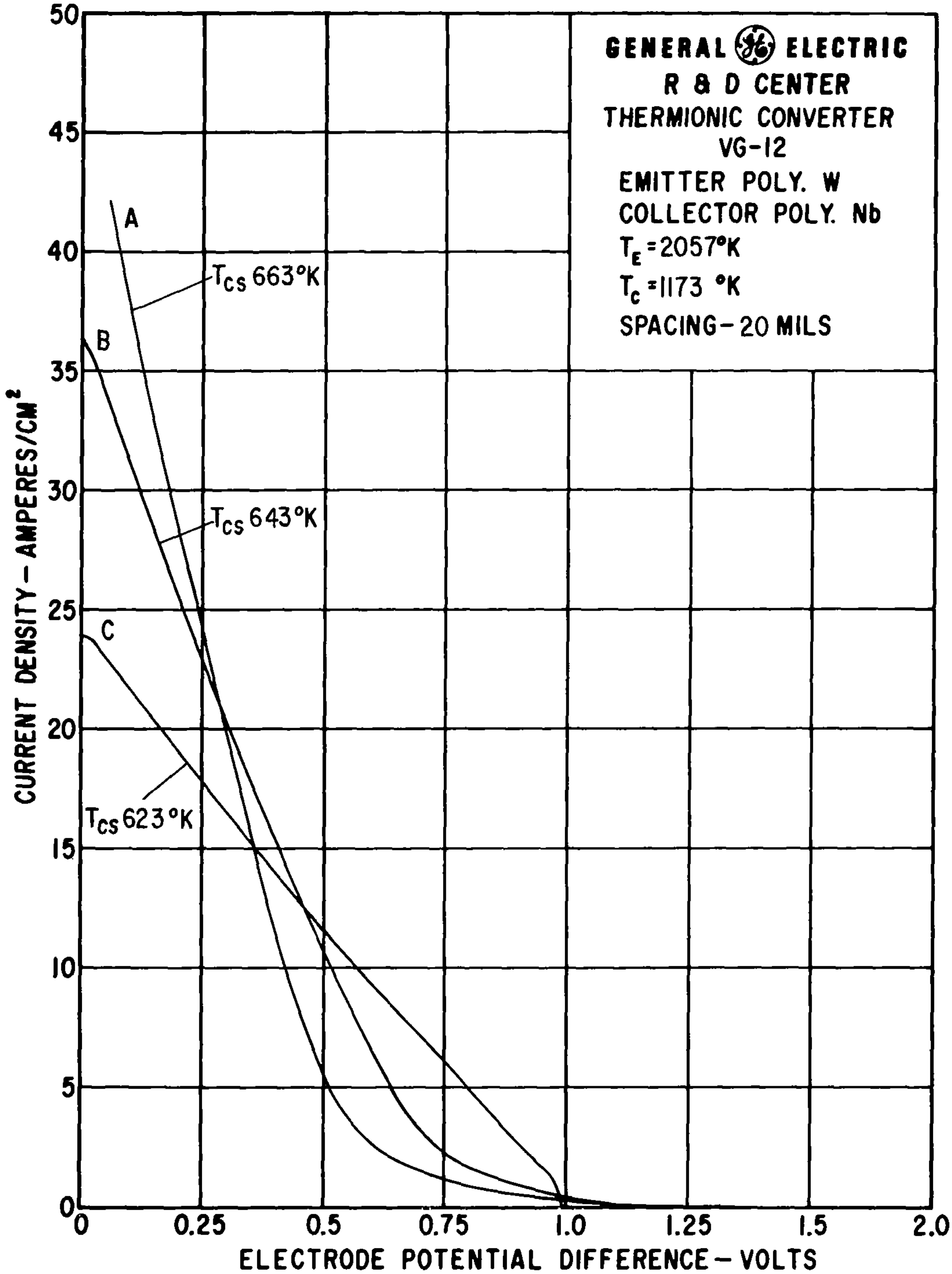

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2057°K
T_c = 1173 °K
SPACING - 20 MILS
A
T_{CS} 663°K
B
T_{CS} 643°K
C
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-45

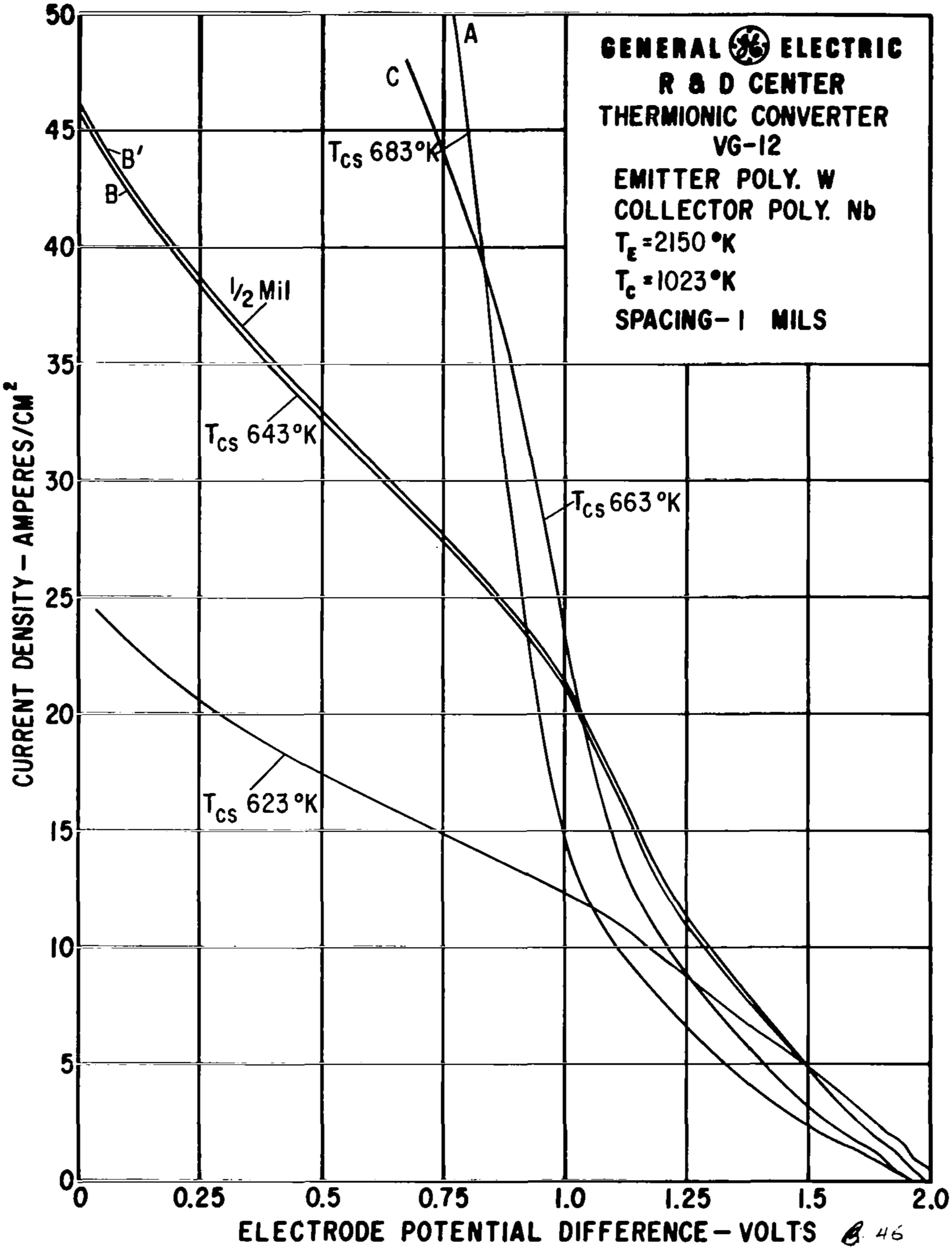

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2150 °K
T_C = 1023 °K
SPACING - 1 MILS
A
C
B'
B
T_{CS} 683°K
1/2 Mil
T_{CS} 643°K
T_{CS} 663°K
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-46

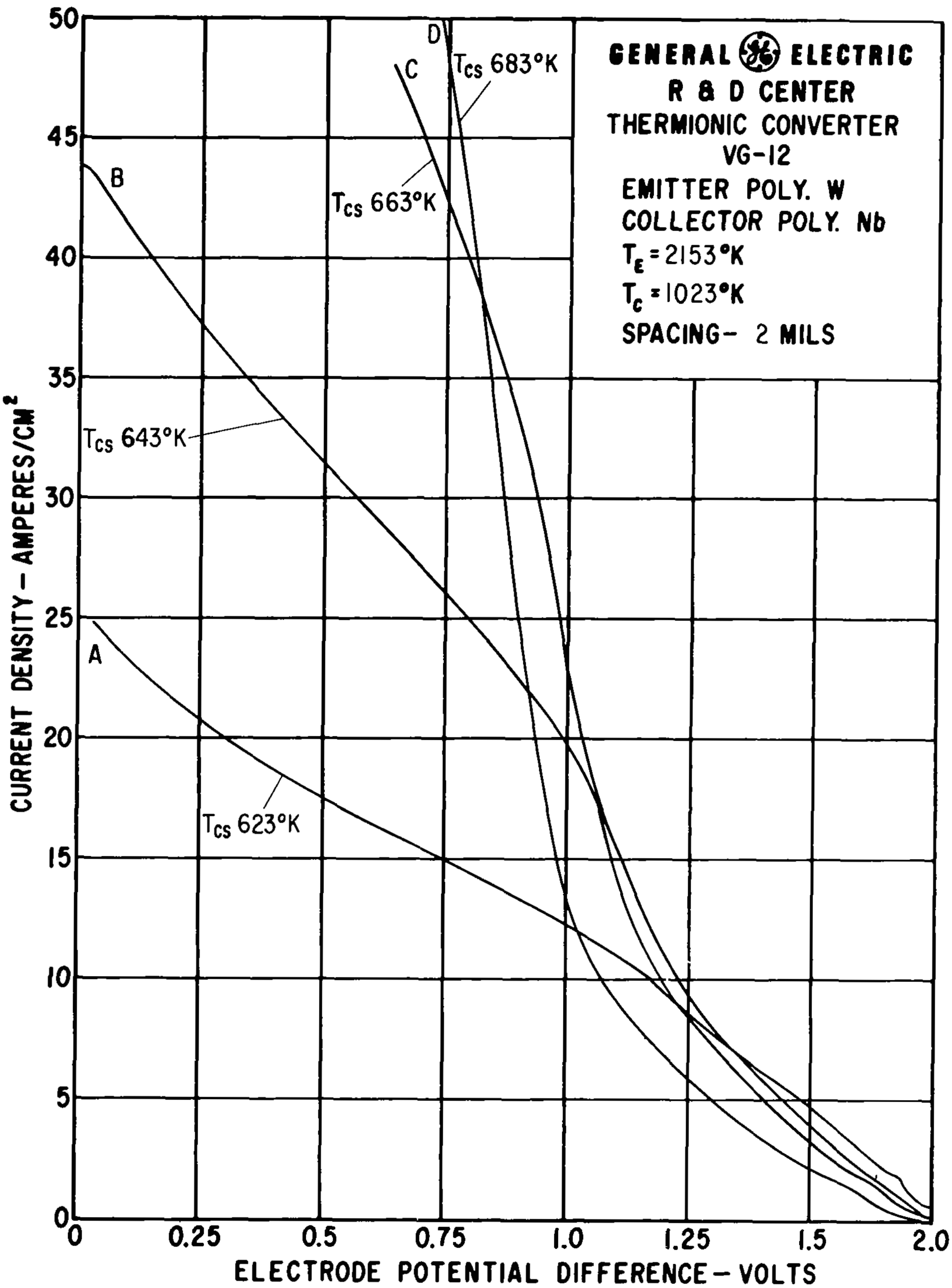

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
$T_E = 2153°K$
$T_C = 1023°K$
SPACING- 2 MILS
A
B
C
D
T_{cs} 623°K
T_{cs} 643°K
T_{cs} 663°K
T_{cs} 683°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-47

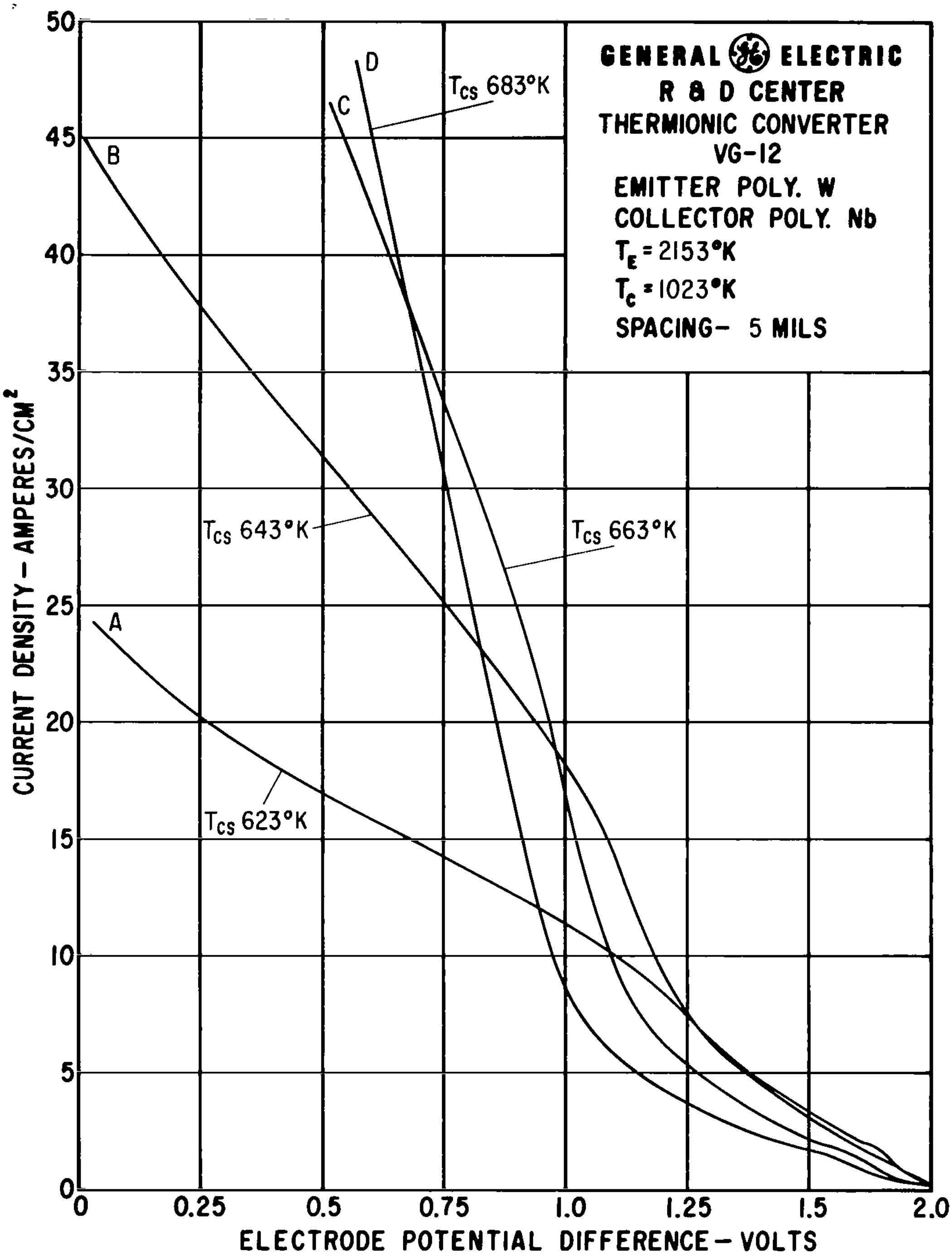

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2153°K
T_c = 1023°K
SPACING- 5 MILS
A
B
C
D
T_{CS} 623°K
T_{CS} 643°K
T_{CS} 663°K
T_{CS} 683°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-48

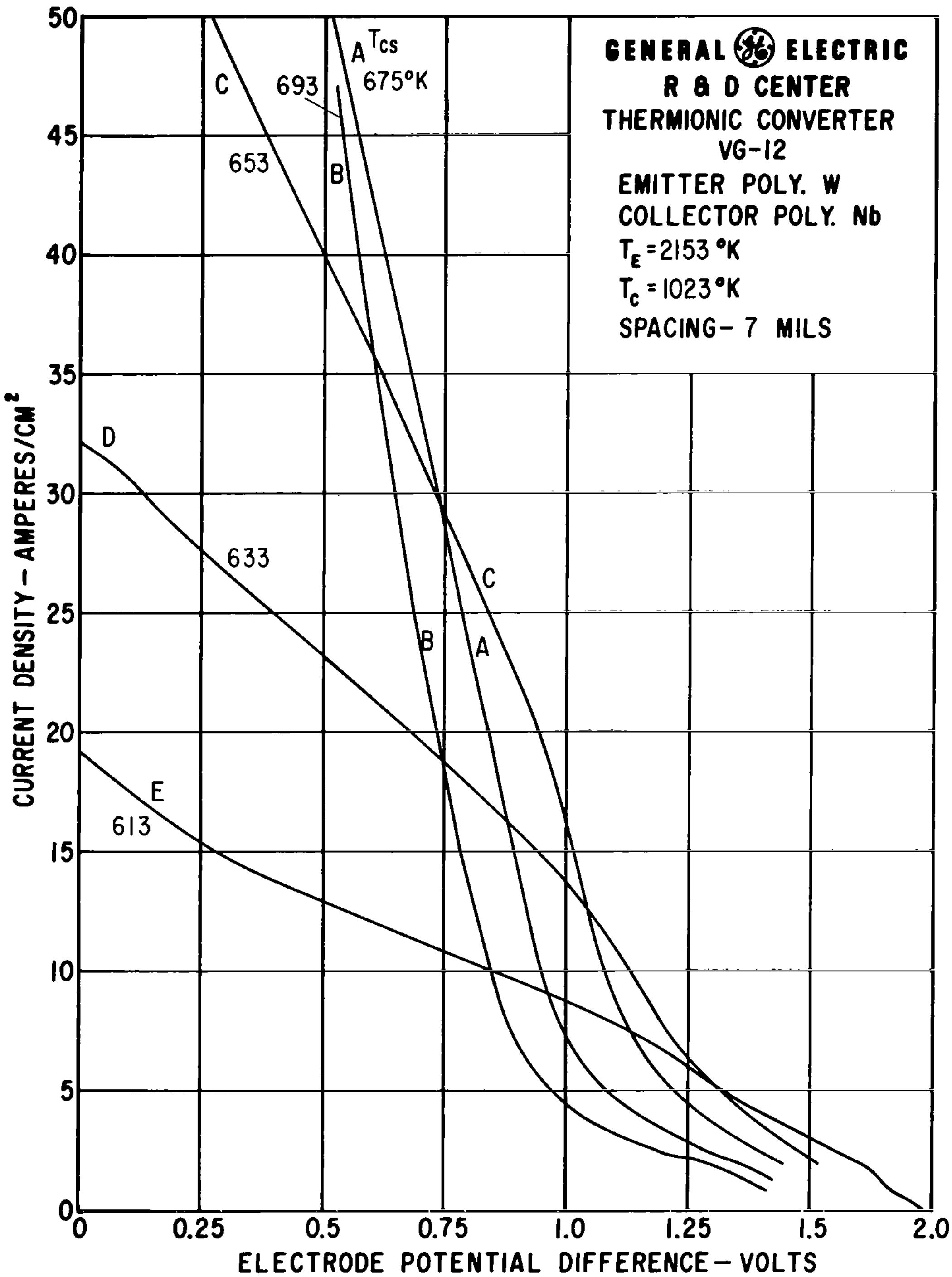

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2153 °K
T_C = 1023 °K
SPACING - 7 MILS
T_{CS}
A 675°K
B 693
C 653
D 633
E 613
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-49

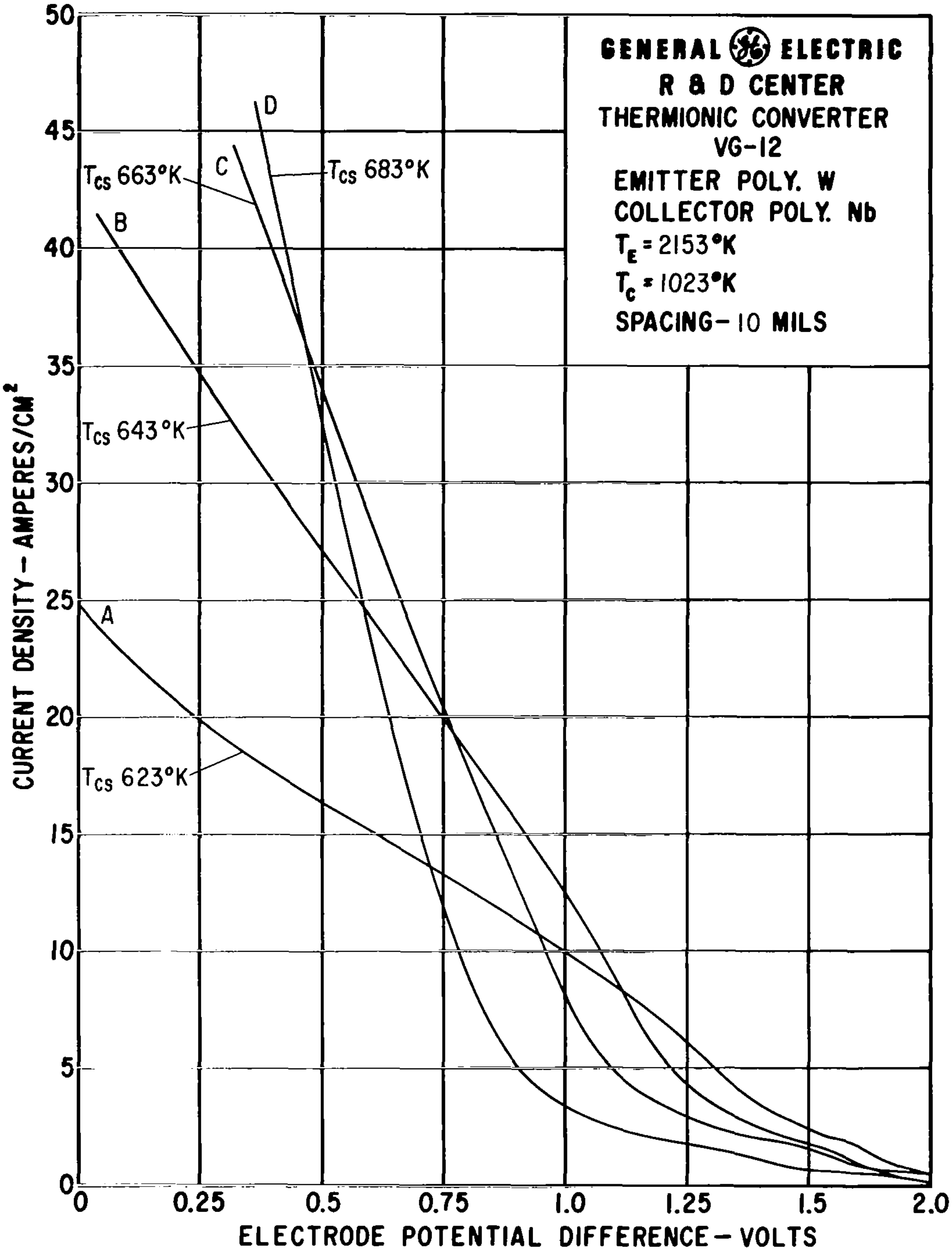
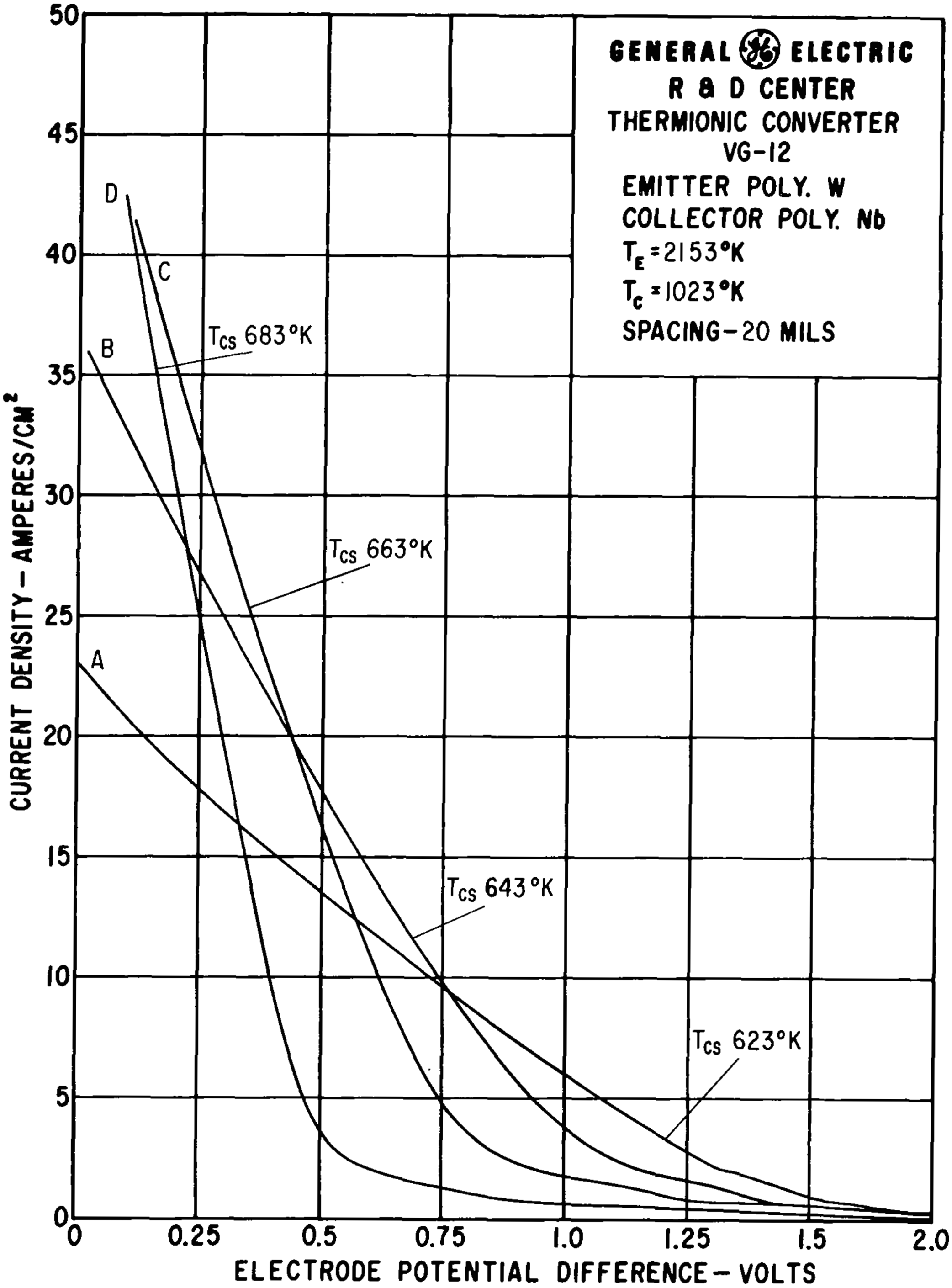

GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2153°K
T_C = 1023°K
SPACING - 10 MILS
A
B
C
D
T_{CS} 623°K
T_{CS} 643°K
T_{CS} 663°K
T_{CS} 683°K
CURRENT DENSITY - AMPERES/CM²
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-50



GENERAL ELECTRIC
R & D CENTER
THERMIONIC CONVERTER
VG-12
EMITTER POLY. W
COLLECTOR POLY. Nb
T_E = 2153°K
T_C = 1023°K
SPACING - 20 MILS
D
C
B
A
T_{CS} 683°K
T_{CS} 663°K
T_{CS} 643°K
T_{CS} 623°K
CURRENT DENSITY - AMPERES/CM^2
ELECTRODE POTENTIAL DIFFERENCE - VOLTS
0
5
10
15
20
25
30
35
40
45
50
0.25
0.5
0.75
1.0
1.25
1.5
2.0

FIGURE B-51

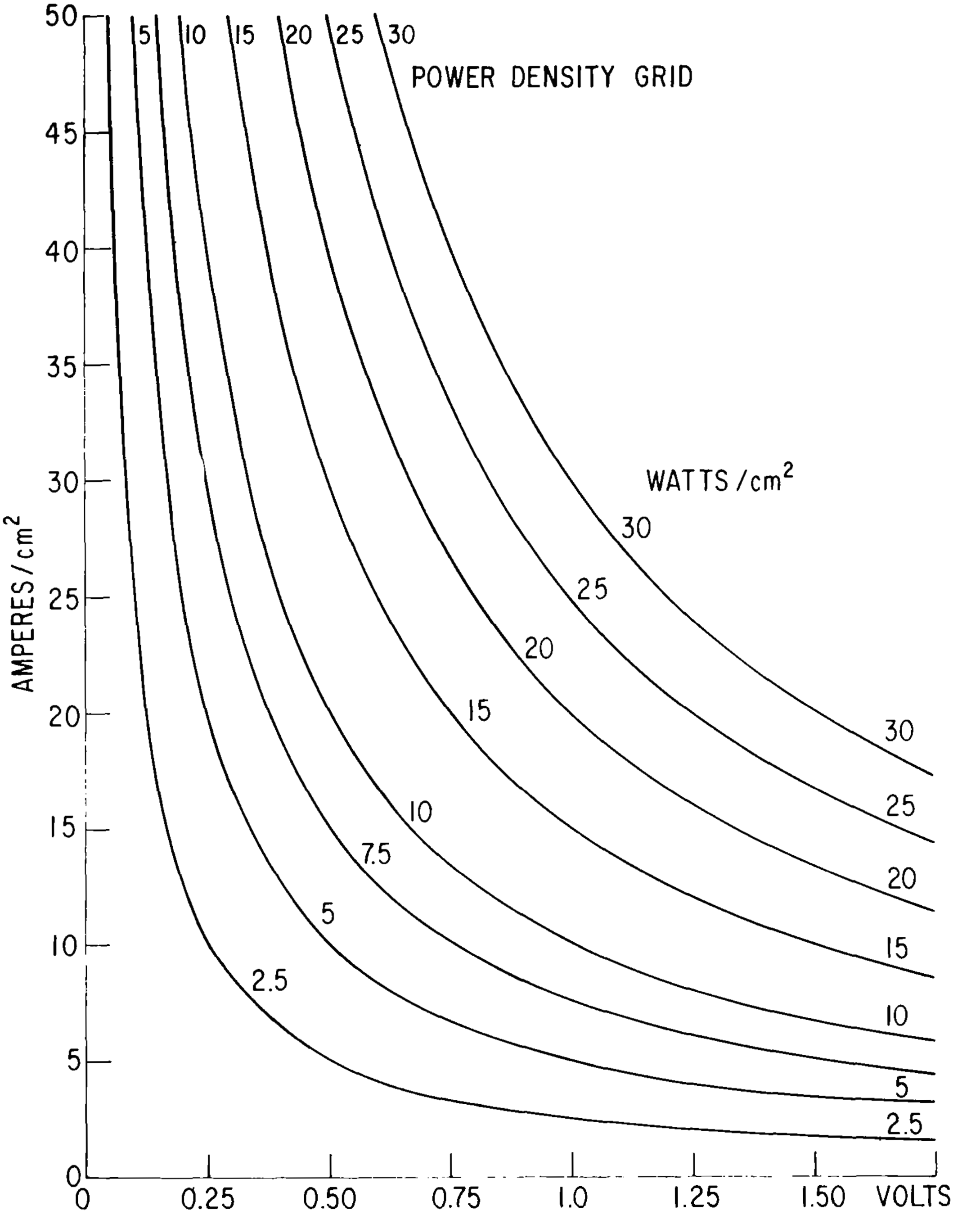

POWER DENSITY GRID
WATTS /cm²
AMPERES/cm²
VOLTS
0
0.25
0.50
0.75
1.0
1.25
1.50
5
10
15
20
25
30
35
40
45
50
2.5
7.5

FIGURE B-52

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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