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DEVELOPMENT OF HIGH-TEMPERATURE VAPOR-FILLED THYRATRONS AND RECTIFIERS

by Arthur W. Coolidge, Jr.

Prepared by
GENERAL ELECTRIC COMPANY
Schenectady, N. Y.
for Lewis Research Center

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FOREWORD

The work described herein was done at the General Electric Tube Department under NASA Contract NAS 3-6005 with Mr. Ernest A. Koutnik, Space Power Systems Division, NASA-Lewis Research Center, as Technical Manager. The report was originally issued as General Electric Report G-E S-23-467, February 1966.

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ABSTRACT

High-temperature vapor-filled diodes and thyratrons were studied for potential use as power-conditioning elements in future space applications. A 600°C thallium-filled diode was developed using a barium-system cathode. Alkali-halide fills intended for use at 600°C did not produce successful results. Cesium-filled diodes for use at 300°C were also studied. After the accumulation of extensive data from the investigation of diodes, a cesium-filled thyratron was designed and three sample tubes -- rated at 15 amperes average, 300 volts forward, and 500 volts inverse -- were constructed. One thyratron tube was operated for 1500 hours.

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DEVELOPMENT OF HIGH-TEMPERATURE VAPOR-FILLED THYRATRONS AND RECTIFIERS

by
Arthur W. Coolidge, Jr.

General Electric Company
Tube Department

SUMMARY

In the design of electrical equipment for use aboard space ships, the operating temperature of the equipment determines the amount of heat that must be rejected by means of a cooling loop and reradiation.

By using high-temperature-resistant envelope materials and a suitable vapor fill, diodes and thyratrons show promise for use as power conditioning elements that may be operated at a temperature of several hundred degrees centigrade.

Specifically, cesium vapor, which has been used extensively in thermionic converters, is a leading candidate for realizing high-temperature operation, low-power loss, and simplicity of tube design.

At the 15-ampere average current level, the many operating characteristics of cesium diodes and thyratrons were examined and recorded. It was found that satisfactory tube operation could be achieved when the anode and grid rejected heat to a sink in the range of 250° to 300°C, and the condensed cesium temperature (or reservoir) was maintained in the range of 200°C to 250°C. Feasibility was demonstrated by a 1500-hour endurance run.

INTRODUCTION

At the present time, available large power-controlled rectifiers are incapable of operating in the 300°C to 600°C temperature range -- the range which will be required for power conditioning of the large nuclear space-power systems currently being developed. This investigation was conducted to develop thyratron and rectifier tubes capable of operating reliably at these temperatures and under spacecraft environmental conditions for thousands of hours.

In the first phase of the work, a diode tube was used to investigate various vapor-fill, electrode, and structural materials. The diode cathode was simply heated from an external heat source. Although both alkali halides and pure metals were investigated as vapor-fill materials, most of the work was conducted with cesium vapor. Anode materials used were zirconium carbide, hafnium, and molybdenum. Cathode emission characteristics were determined through the use of barium, thoriated tungsten, tungsten, and molybdenum as cathode materials. Seal alloys for reliably joining the structural parts to the ceramic housing were also investigated. Reverse potential characteristics were determined from measurements of inverse voltage breakdown.

The second phase of the work essentially consisted of constructing and testing a cesium-filled thyratron tube, based upon information from the diode work. This tube was approximately 3 inches high and contained a copper grid. Endurance tests were run for 1500 hours at 15 amperes average current. Although the objective 300 volts forward holdoff potential was achieved, the approximate 500 volts reverse potential limit was lower and the deionization time of about 400 microseconds was longer than desired. Additional work is being performed under Contract NAS3-9423 to further improve the design in these two areas.

In the course of this work, hitherto unavailable data were obtained which, although not used for the final-design tube, are reported in the Appendices for future reference.

SELECTION OF VAPOR FILL

The ideal high-temperature vapor-filled tube, either diode or thyratron, should have long life, operate with a low tube-voltage-drop during conduction, and represent a reasonably good open circuit when current conduction is not wanted. For the diode, there should be no inverse current from the anode when the maximum negative voltage imposed by the circuit is applied to the anode. In addition to this requirement, the thyratron must have inherently low emission from its grid so that when the maximum positive voltage imposed by the circuit is applied to the anode, a small discharge will not be initiated from grid-to-anode and thus cause complete loss of grid control.

Previous experience with industrial-type thyratrons indicates that the vapor pressure, at operating temperature, should be in the range of 0.01 to 0.5 torr. Two commonly used vapor-fill materials, mercury and cesium, have been used at temperatures up to 100°C and 300°C, respectively (refer to Figures 1 and 2). However, four elements and four halides of cesium have interesting vapor pressures in the 600°C range. They are:

(1) Thallium
(2) Lead
(3) Bismuth
(4) Antimony
(5) Cesium Iodide
(6) Cesium Fluoride
(7) Cesium Bromide
(8) Cesium Chloride

Vapor pressure data for the listed materials are presented in Figures 3 and 4.

To preclude arc-back or loss of grid control in a thyratron, the work function of the anode and grid should be high enough to limit the unwanted emission to a maximum of 10^{-6} amperes per square centimeter. This requires a work function of at least 3 electron volts at a temperature of 1150°K.

Tube drop during conduction is a function of the ionization potential of the vapor fill, and will typically be 1 to 5 volts higher than the published value. The excess voltage over the ionization potential is required to compensate for losses that occur within the plasma and the small voltage loss that occurs at the cathode as the current passes through any cathode emission coating.

A wealth of background information from thermionic converters indicated that a cesium-filled thyratron could be made for use at approximately 250°C with great design simplicity, durability, and long life. Primary among the assets of cesium is its ability to produce a low-work-function

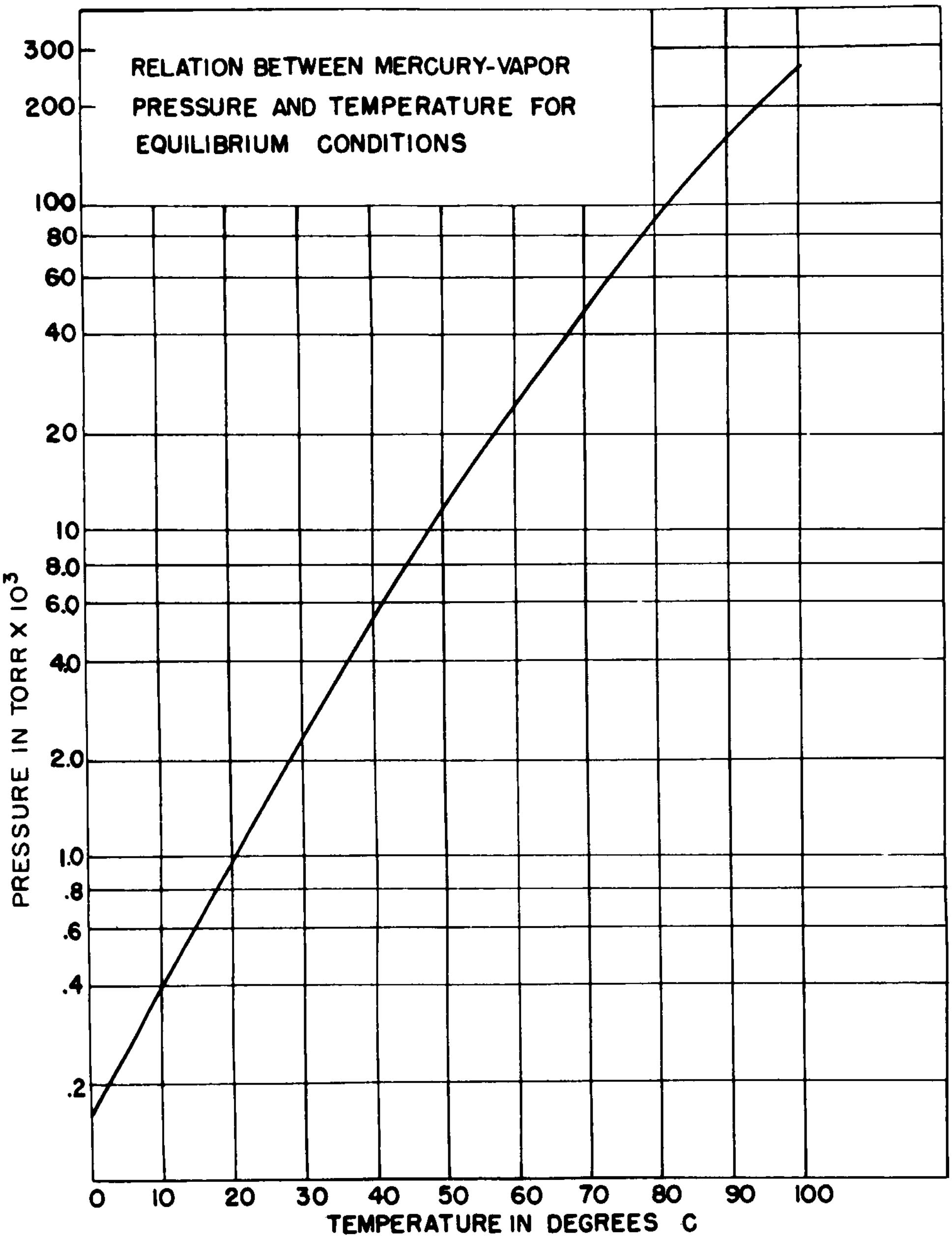

Figure 1 - Relationship Between Mercury-Vapor Pressure and Temperature for Equilibrium Conditions

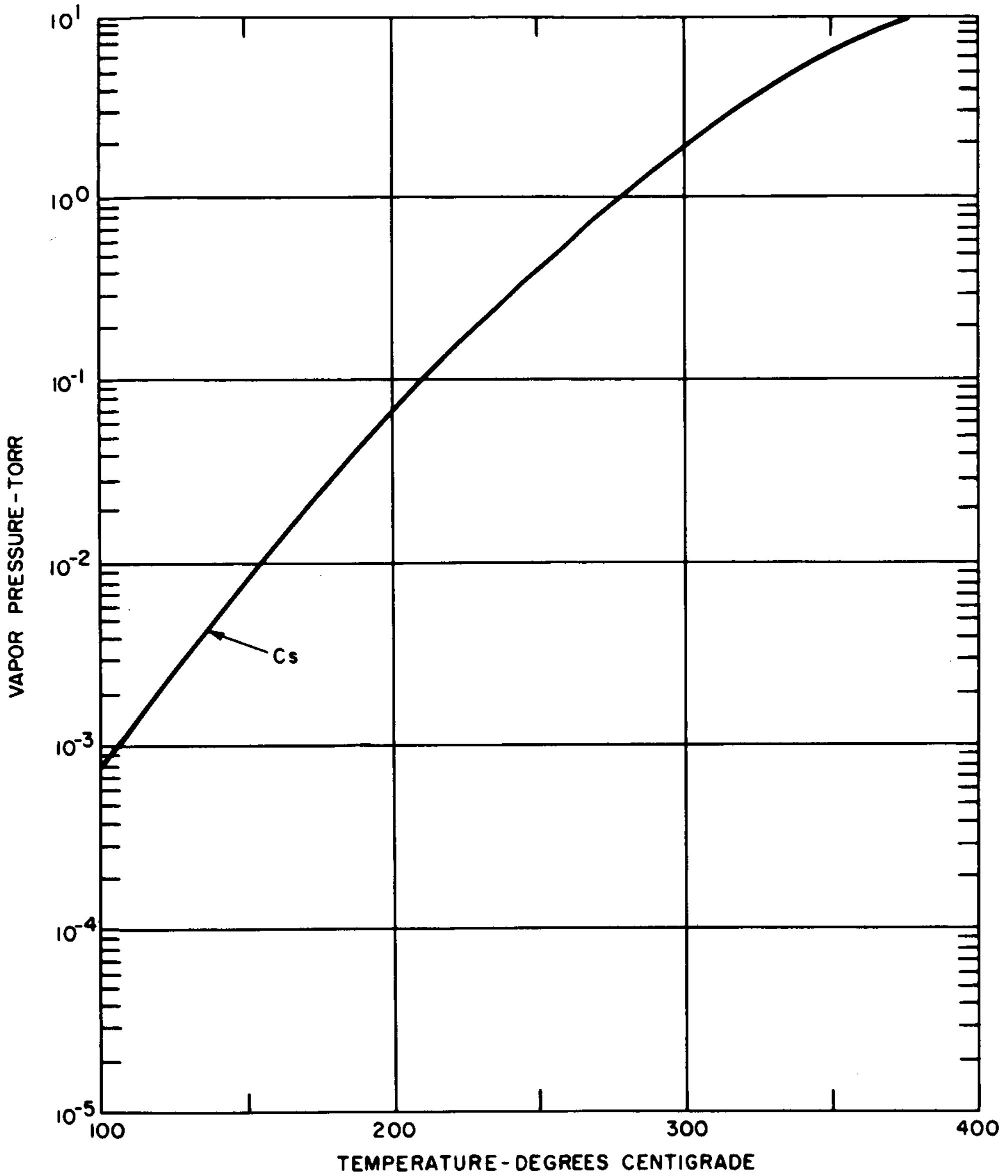

Figure 2 - Relationship Between Cesium-Vapor Pressure and Temperature for Equilibrium Conditions

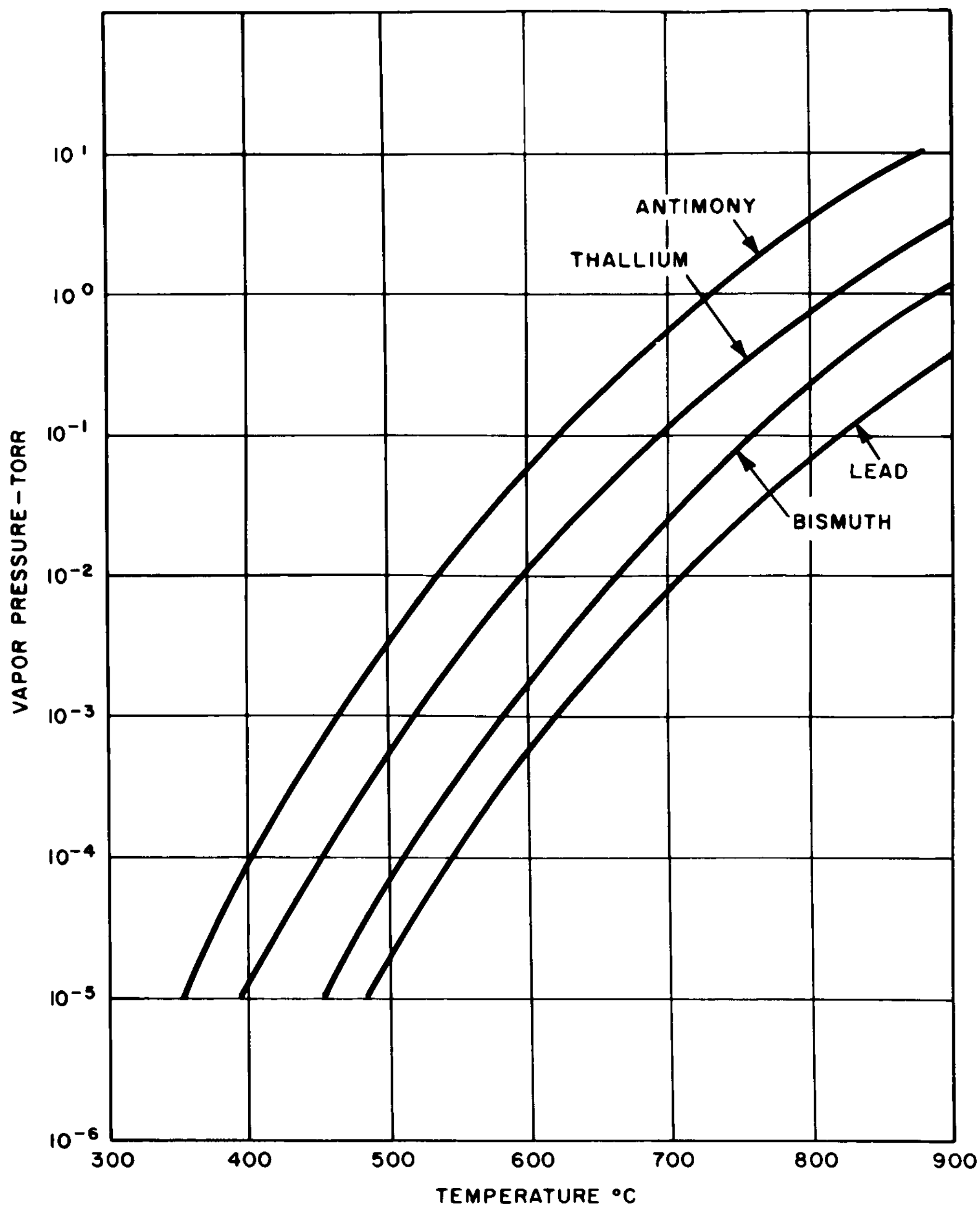

Figure 3 - Relationship Between Antimony, Thallium, Lead and Bismuth Vapor Pressures and Temperature for Equilibrium Conditions

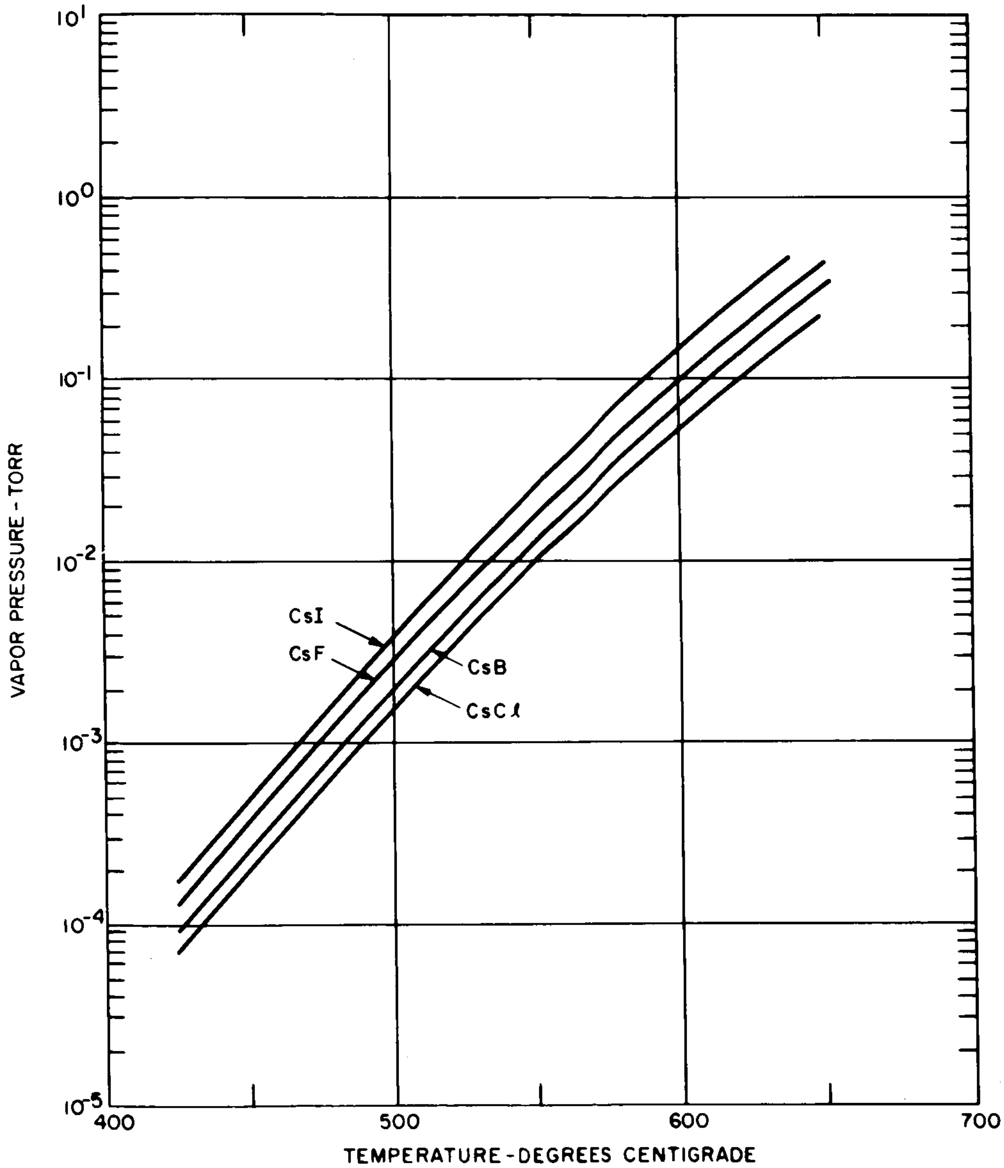

Figure 4 - Relationship Between Alkalide-Halide-Vapor Pressure and Temperature for Equilibrium Conditions

surface when it is attached in the form of a very thin layer to a high-work-function refractory metal. Thus, the cathode in a thermionic converter or thyratron need be nothing more than a heated refractory metal substrate with a thin overlayer of cesium formed by the arrival of cesium atoms from the cesium vapor within the tube.

Cesium has the lowest ionization potential (3.87 volts) of all the known elements and, therefore, promises to produce the lowest-loss tube with respect to tube drop.

If, by the process of partial dissociation, one of the aforementioned cesium halides produced a free cesium complement, a tube could be realized having not only the desirable characteristics of a cesium tube but also the capability of operating to a temperature of 600°C.

Three vapor fills were investigated:

(1) An alkali halide, which might lead to a tube with cesium characteristics in the 600°C operating range.

(2) One of the metals in the thallium, lead, bismuth, antimony group.

(3) Cesium which has many desirable properties but requires a lower operating temperature.

INITIAL TEST VEHICLES

For initial test vehicles, a simple diode design (Figure 5) was selected. Refractory metals and high-alumina-content ceramics, both known to have good resistance to cesium attack, were used as the basic structural materials.

A molybdenum cathode, heated by an external oven, was arranged closely to a molybdenum anode. Attached to the anode was a tantalum tubulation containing a reservoir of alkali halide, the temperature of which was controlled by a second oven. The main body of the tube was placed inside of a third oven. By means of independent oven-temperature control, it was possible to operate the main structure in an ambient temperature to 800°C and increase the emitter temperature to 1400°C. Because of its remote location, the reservoir could be operated in the temperature range from about 200°C to 600°C.

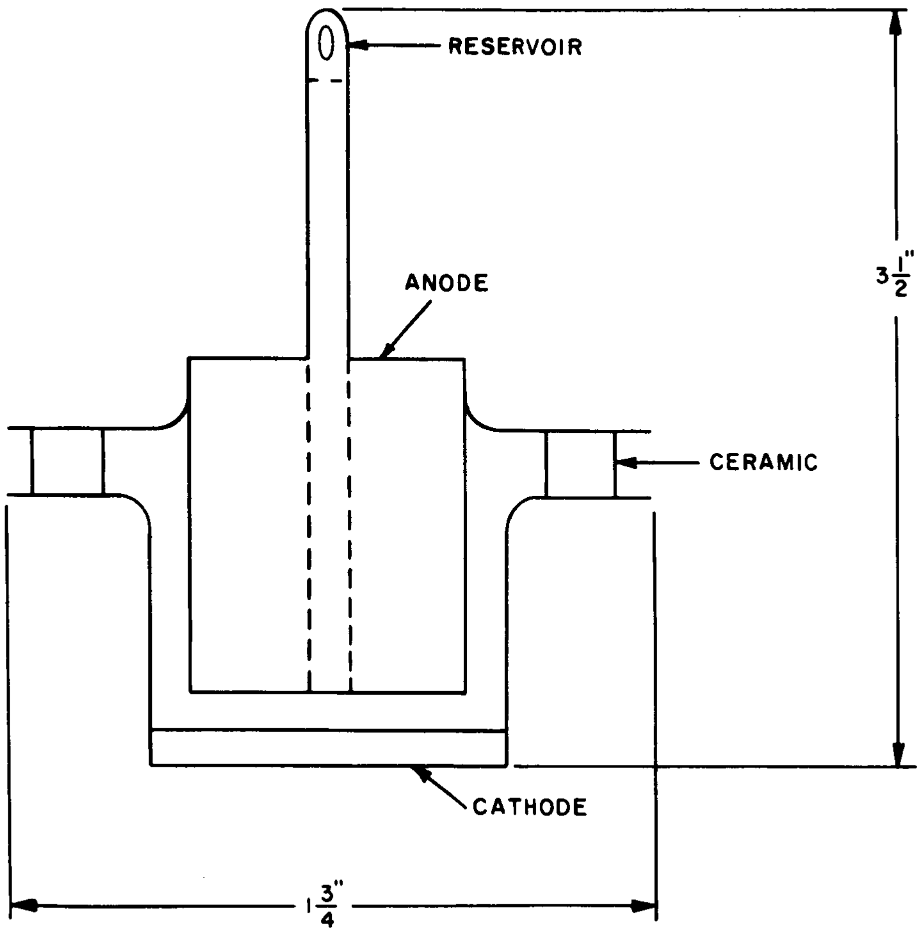

Figure 5 - Schematic of Initial Test Diode

TESTING OF SELECTED VAPORS

ALKALI HALIDE

Four tubes incorporating a cesium-iodide fill were investigated. Although some of the apparent problems were resolved, at no time was there evidence of good, cesiated-cathode emission, such as is readily realized in thermionic converters. Thus, further work with cesium halides was halted. The details and results of the cesium-halide work are given in Appendix A.

THALLIUM

With the removal of alkali halides from further consideration, selection of one of the four metals -- thallium, lead, bismuth, or antimony -- was thus necessary for achieving a 600°C vapor-filled tube. Two important considerations in this regard are materials compatibility and ionization potential.

The compatibility of these metals with other materials commonly used in high-temperature tubes cannot be completely predicted. Phase diagrams giving the constitution of binary alloys (to the extent that such information is available) can be used as a guide to the compatibility problem, but, as in the case of previous experience with cesium, actual compatibility cannot be established without long-term testing.

The ionization potentials for the four elements are as follows:

Thallium	6.1 Volts
Lead	7.4 Volts
Bismuth	8.0 Volts
Antimony	8.5 Volts

Since the minimum tube drop would be determined by the ionization potential, thallium was selected for trial.

Unlike cesium, none of the four elements possesses the characteristic of appreciably lowering the work function of a substrate material. Therefore, a tube using any of these as a fill material would require a prepared cathode, such as a barium-coated substrate. In this case, cathode life would be limited as a function of the time required to evaporate the barium material from the cathode.

A tube bearing the designation Z-7009, No. 19, was made with the combination of thallium fill and a barium-system cathode (Figure 6). This tube was operated successfully for 500 hours. Over this period of time, the results indicated that thallium was a very promising vapor-fill material for tubes capable of operating in an ambient temperature of 600°C to 700°C. The principal handicap, at least when compared to cesium, was the vulnerability of the prepared cathode to depletion before the objective life of 20,000 hours could be achieved.

Detailed data and test results for Type Z-7009, Tube No. 19, are given in Appendix A.

CESIUM

The early cesium-filled diodes utilized a structure similar to a thermionic converter (Figure 5) with a molybdenum cathode and anode.

Type Z-7009, Tube Nos. 2 and 3, were identical except that Tube No. 2 had an anode-to-cathode spacing of 0.030 inch, while in Tube No. 3 the spacing was 0.010 inch.

When these tubes were operated at currents up to 15 amperes average, extremely low arc drops were observed. Indeed, at low average currents and high cathode temperature, the tube drop was actually negative, indicating that the tube was capable of "generating" in a manner similar to that of a thermionic converter. Emission data is summarized in Figures 7, 8, 9 and 10. As can be seen from these illustrations, the tube with the closest anode-to-cathode spacing exhibited the lowest drop. Under pulse conditions, the tube was loaded with a current of 104 amperes, equivalent to approximately 20 amperes per square centimeter, with a tube drop of 1.6 volts. The tube drop for a thyratron would necessarily be higher because of losses at the grid and increased plasma losses attending the longer path between cathode and anode.

Additional emission data (Figure 11) was taken on Tube No. 7 to determine the most efficient cathode temperature. This tube contained a cathode identical to that used in Tube Nos. 2 and 3. It can be seen that there is little change in tube drop as the cathode temperature is lowered from 1300°C to 900°C. Thus, from the standpoint of efficiency, it would appear wasteful to provide the extra power needed to heat the cathode to a temperature of 1200°C to 1300°C.

An analysis of efficiency may be made by:

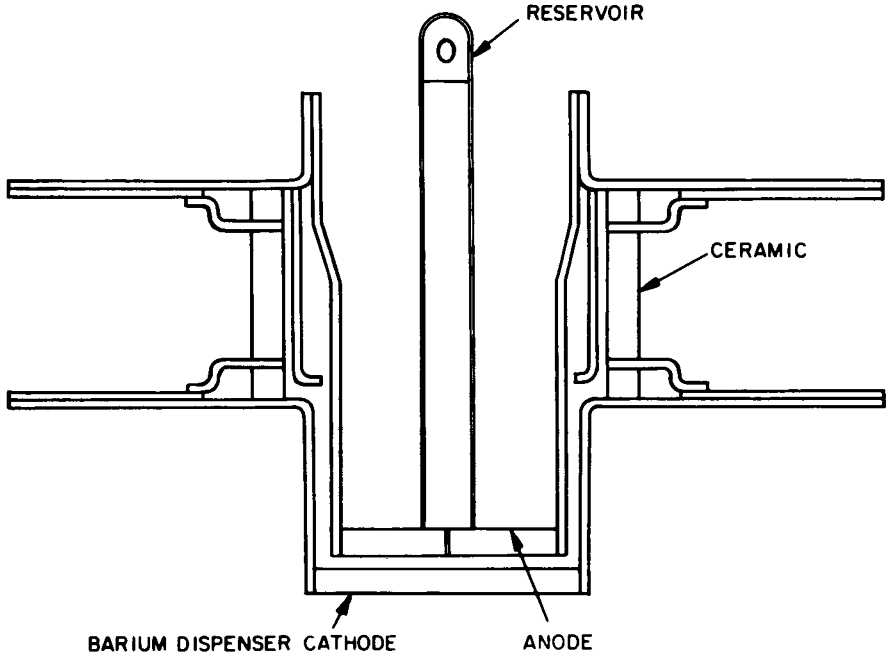

Figure 6 - Schematic of Thallium-Filled Diode

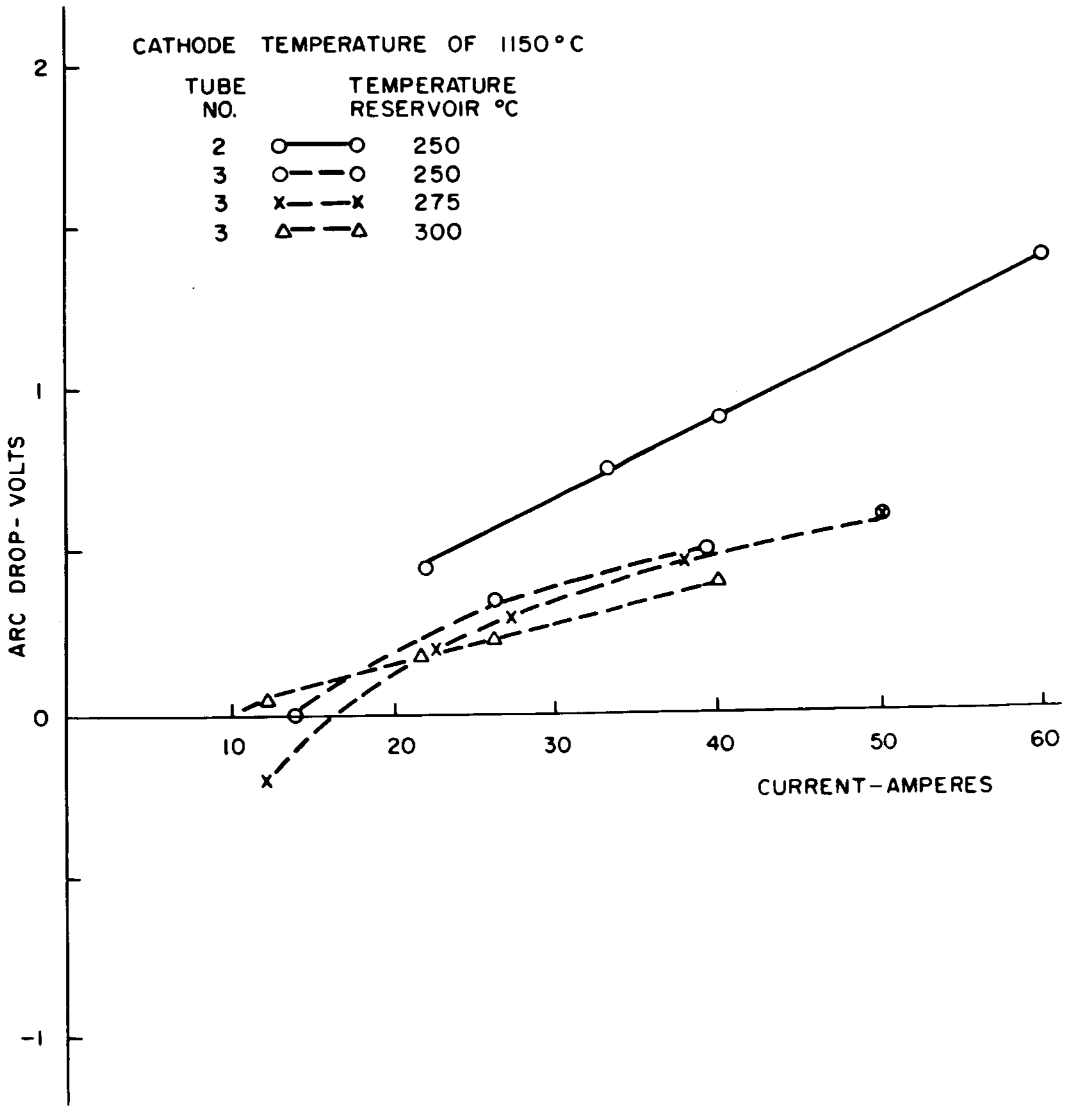

Figure 7 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1150°C

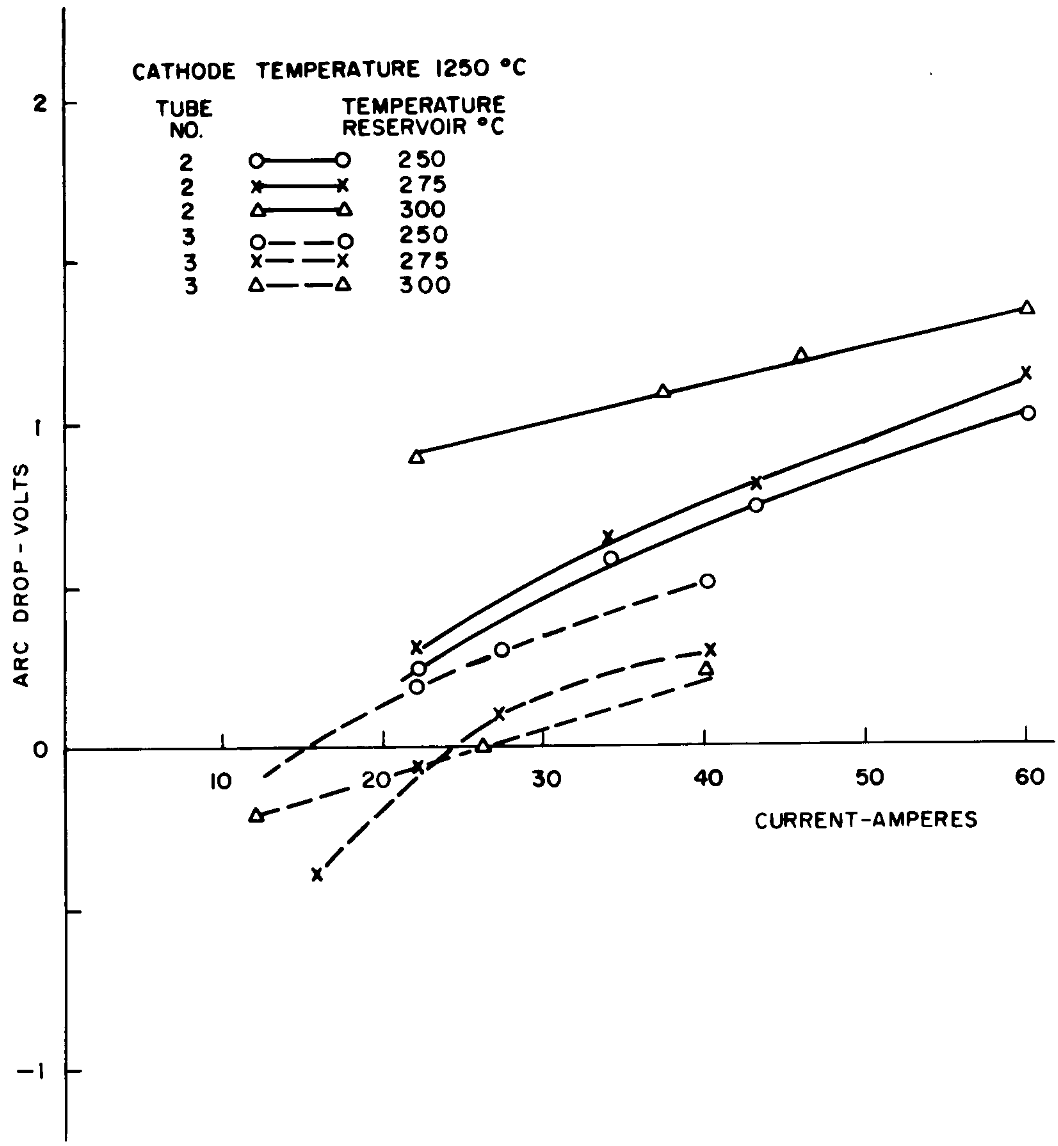

Figure 8 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1250°C

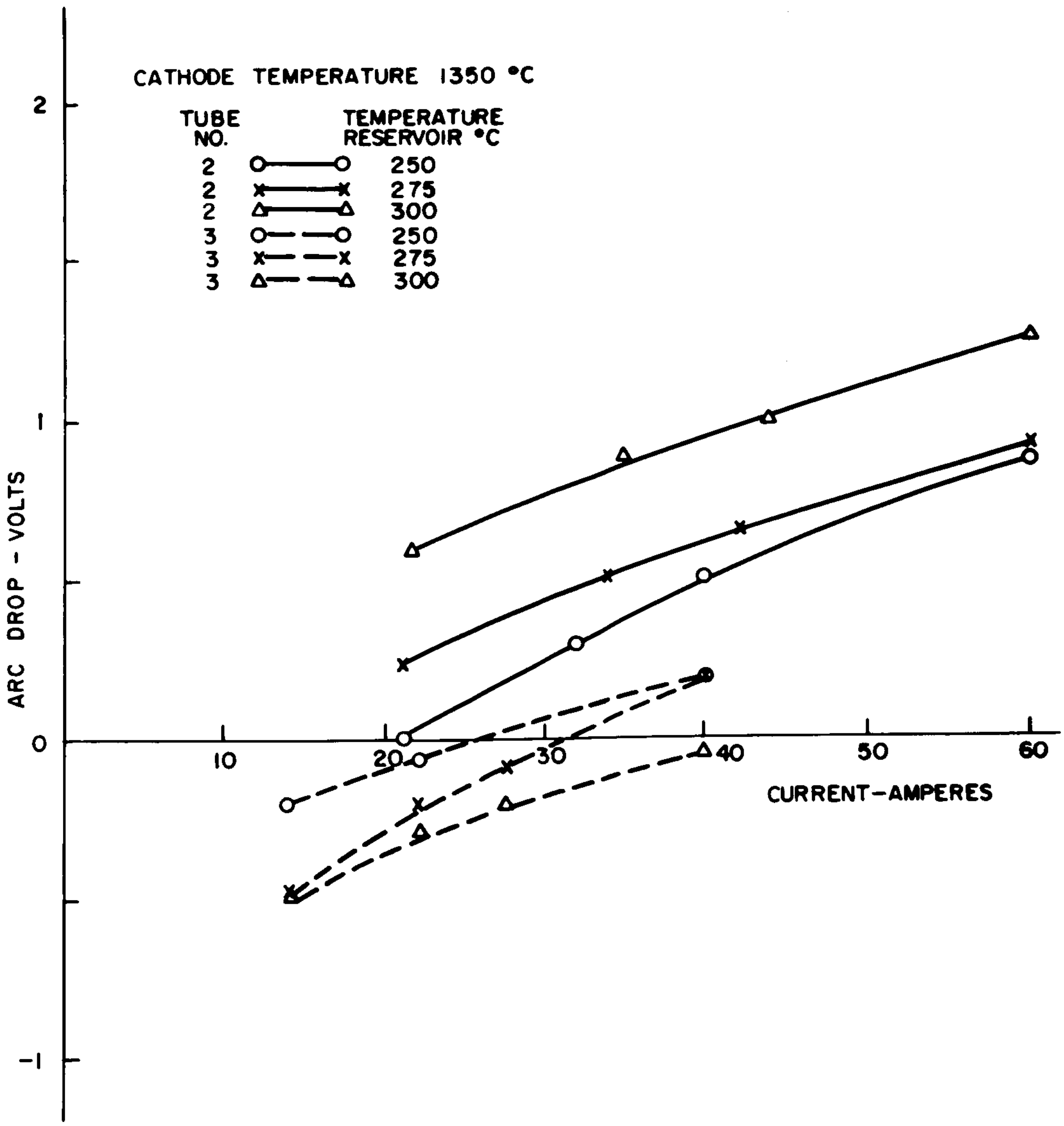

Figure 9 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1350°C

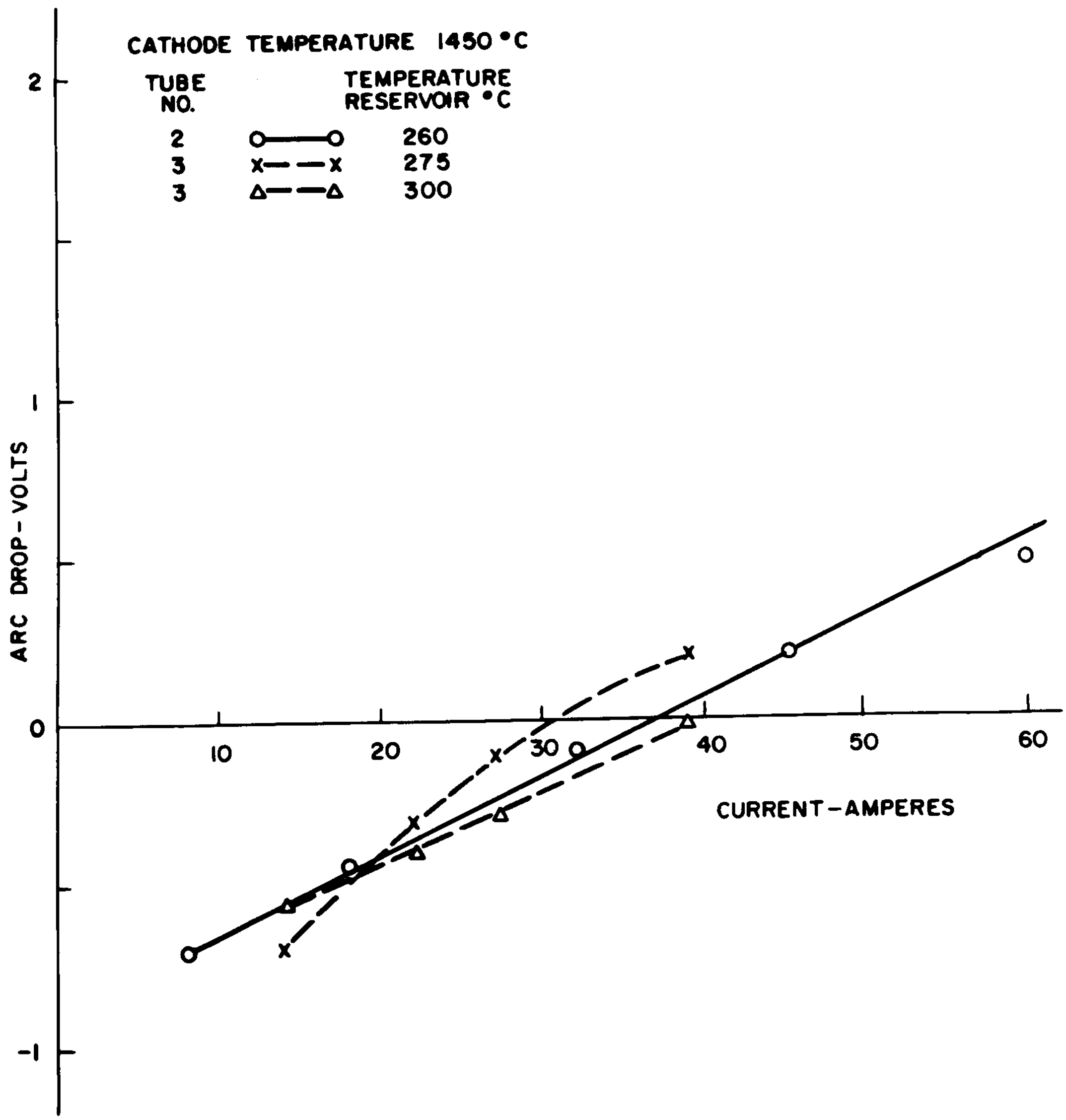

Figure 10 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1450°C

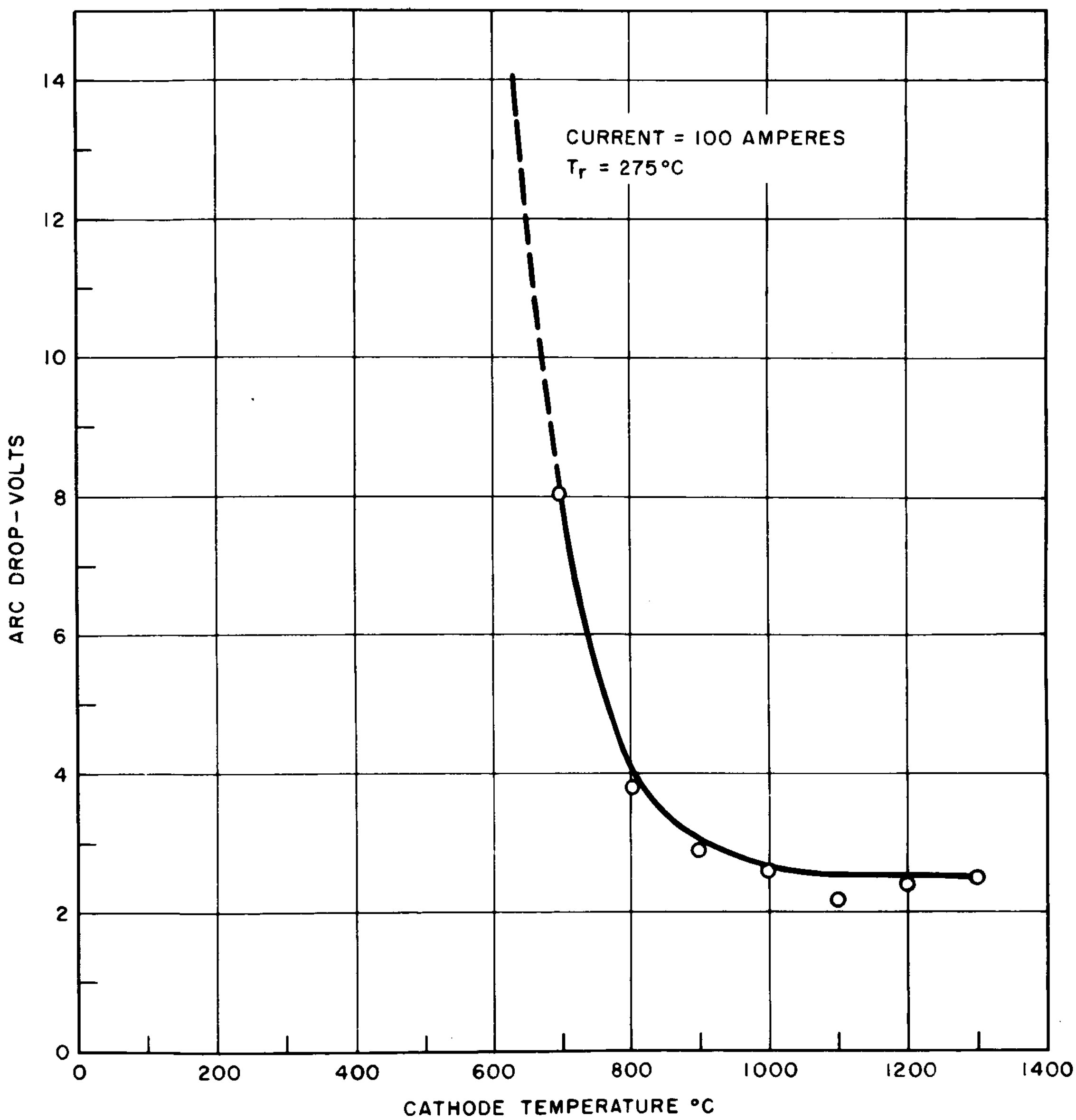

Figure 11 - Peak Drop Versus Cathode Temperature, Type Z-7009, Tube No. 7

(1) Measuring the relationship of heater power to cathode temperature. This constitutes an external power loss.

(2) Calculating an internal power loss, from the curve of Figure 11, multiplied by the objective average current of 15 amperes.

(3) Obtaining the total power loss, which is equal to the sum of the internal and external losses.

Figure 12 exhibits, as a function of cathode temperature, the component and total losses. As can be seen in this figure, the most efficient point of operation occurs at a cathode temperature of 800°C. In practice, it would be advisable to operate the cathode at about 900°C to allow for variations between tubes, as well as for electron cooling at the cathode, which produces a power loss of

$$I_b \, (W.F. + 2\, KT/e)$$

where:

	W.F.	=	work function of the cathode, in volts
	K	=	Boltzman constant
		=	1.3708×10^{-23} watt-second/degree K
	T	=	cathode temperature, in degrees K
	e	=	charge of electron
		=	1.590×10^{-19} coulomb

Since the 2 KT/e term is only about 0.1 volt in magnitude, it may be neglecteu without serious error, yielding I_b (W.F.) as the approximate power loss due to electron cooling. At an average current level of 15 amperes, and an assumed cesiated work function of 2 volts, the electron cooling factor amounts to 30 watts. Therefore, the heater power should be at least 30 watts higher than the power required to produce a quiescent temperature of 800°C.

The ability of a thyratron to hold off high anode voltage depends upon the suppression of grid emission to a low value. Moreover, if the tube is to withstand high inverse voltages, reverse current caused by emission from the anode must be negligible. Cold breakdown will occur when the voltage exceeds the "PD" or Paschen limitation, regardless of the electrode temperatures.

Figure 13 illustrates the inverse-current measurements taken on

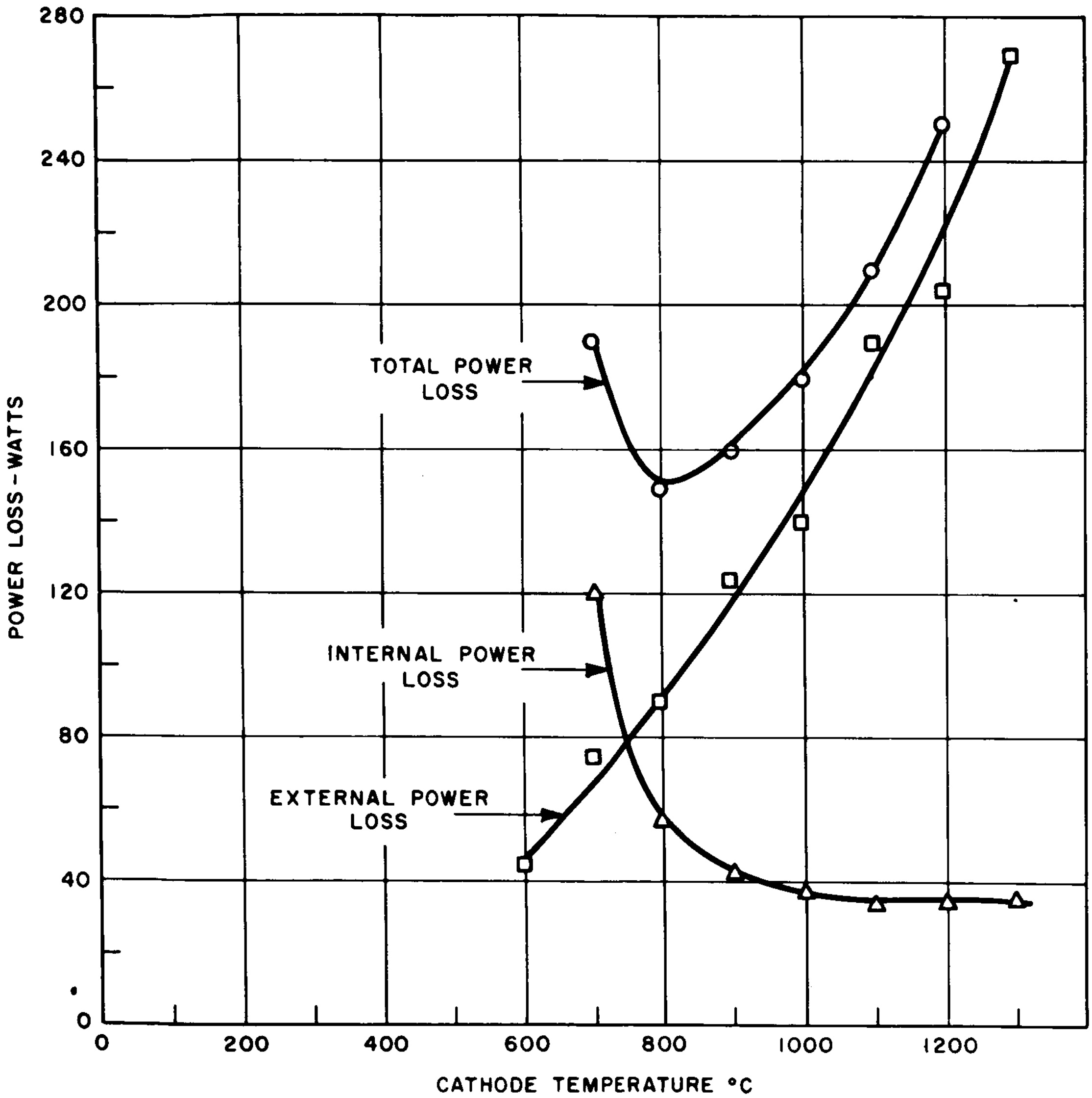

Figure 12 - Power Loss Versus Cathode Temperature, Type Z-7009, Tube No. 7

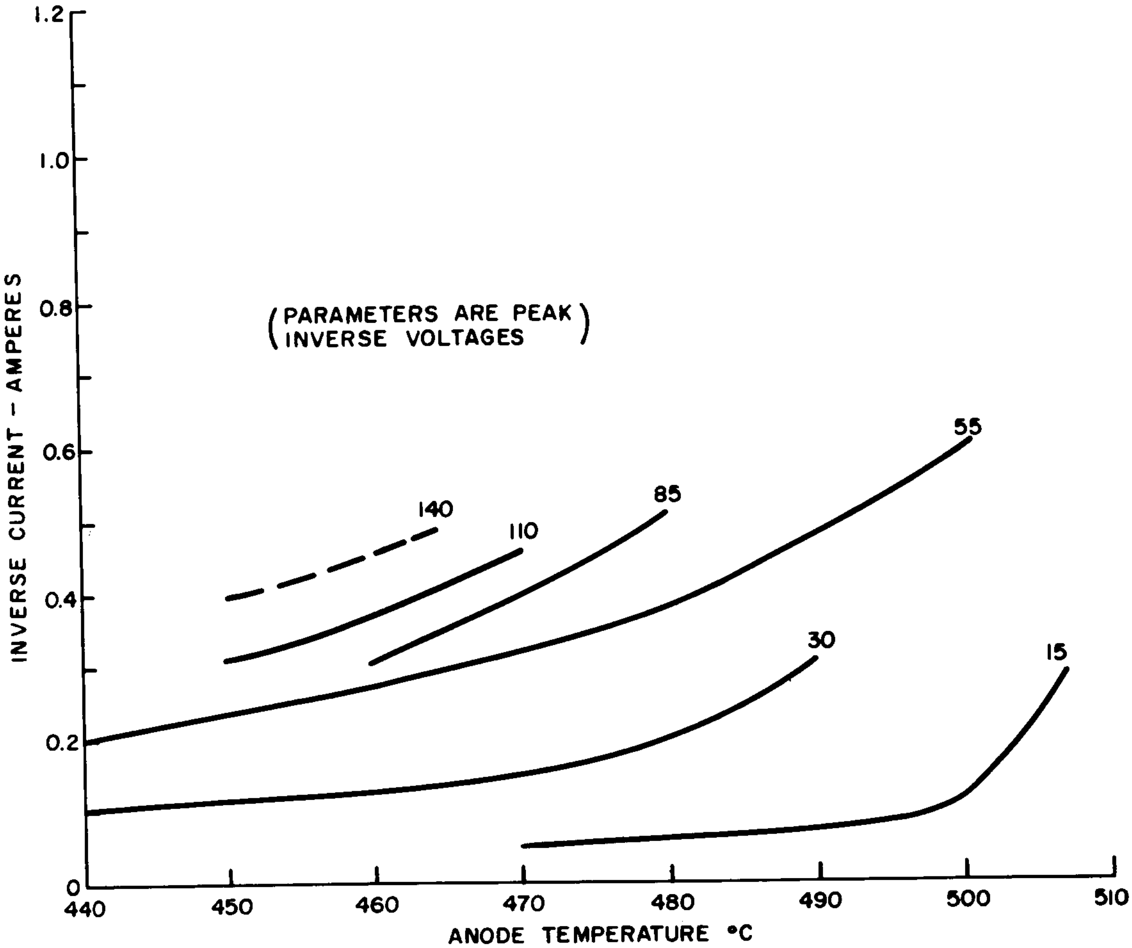

Figure 13 - Inverse Current Versus Temperature as a Function of Inverse Voltage, Type Z-7009, Tube No. 2

Type Z-7009, Tube No. 2. Inverse current became excessive when the anode temperature approached 500°C. The failure of the curves to approach zero current at low temperature indicated that the tube exhibited a leakage path (probably cesium) of about 300 ohms. The data are limited to peak inverse voltages of 140 volts because inverse breakdown occurred at 150 volts. Assuming a temperature drop of about 100°C between a heat sink external to the tube and the hottest part of an electrode connected to the heat sink, an arbitrary rating of 125 volts inverse and 350°C ambient might be applied to this particular diode.

It is of interest to contemplate how poor an emitter, an anode, or a grid surface must be to prevent spurious ionization. One estimate can be made by computing the saturation current from cesiated molybdenum at 500°C, these conditions corresponding to the runaway threshhold of Type Z-7009, Tube No. 2. Although the work function of bare molybdenum is about 4.4, its work function when cesiated drops to about 2.0. The curves in Figure 14, drawn for Richardson's equation, indicate a saturation current of about 10^{-5} amperes per square centimeter. This would imply the necessity of keeping anode and grid emission to a fraction of a microampere per square centimeter if spurious ionization is to be avoided.

When a substrate material is coated with a thin layer of another material, the work function of the combination is generally different from the work functions of either of the individual materials. For example, cathode emission is enhanced by a layer of thorium on tungsten. When a monolayer of cesium resides on a refractory metal such as molybdenum or tungsten, both of which have work functions higher than 4.0, the work function of the combination is reduced to a value of 2.0 or lower.

Spurious emission from a grid or anode in a cesium tube cannot be predicted without an established relationship between the substrate work function and the cesiated work function over the range of interest.

Rasor and Warner[1] attempted to establish such a relationship, and Figure 15 displays a family of curves computed for it. It may be noted from Figure 15 that for a low-work-function substrate, the cesiated work function remains the same, but as the substrate work function increases through the range of 3 to 5, the cesiated work function becomes lower. Therefore, the

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1. Rasor, N. J., Warner, C., Correlation of Emission of Processes for Adsorbed Alkali Films on Metal Surfaces, Journal of Applied Physics, Volume 35, No. 9 (September 1964), pp 2589-2600.

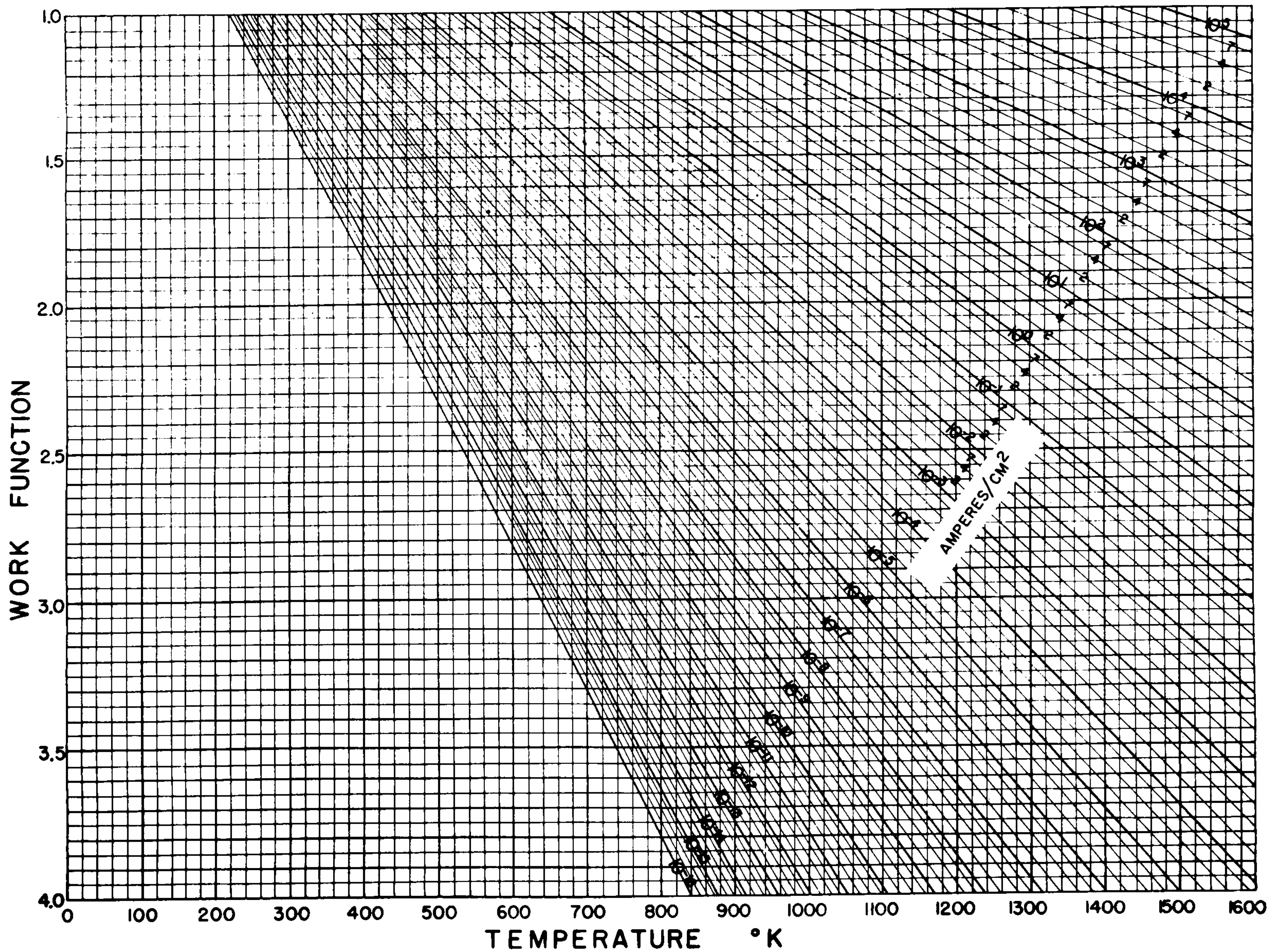

Figure 14 - Relationship Between Work Function, Temperature, and Saturation Emission (Richardson's Equation)

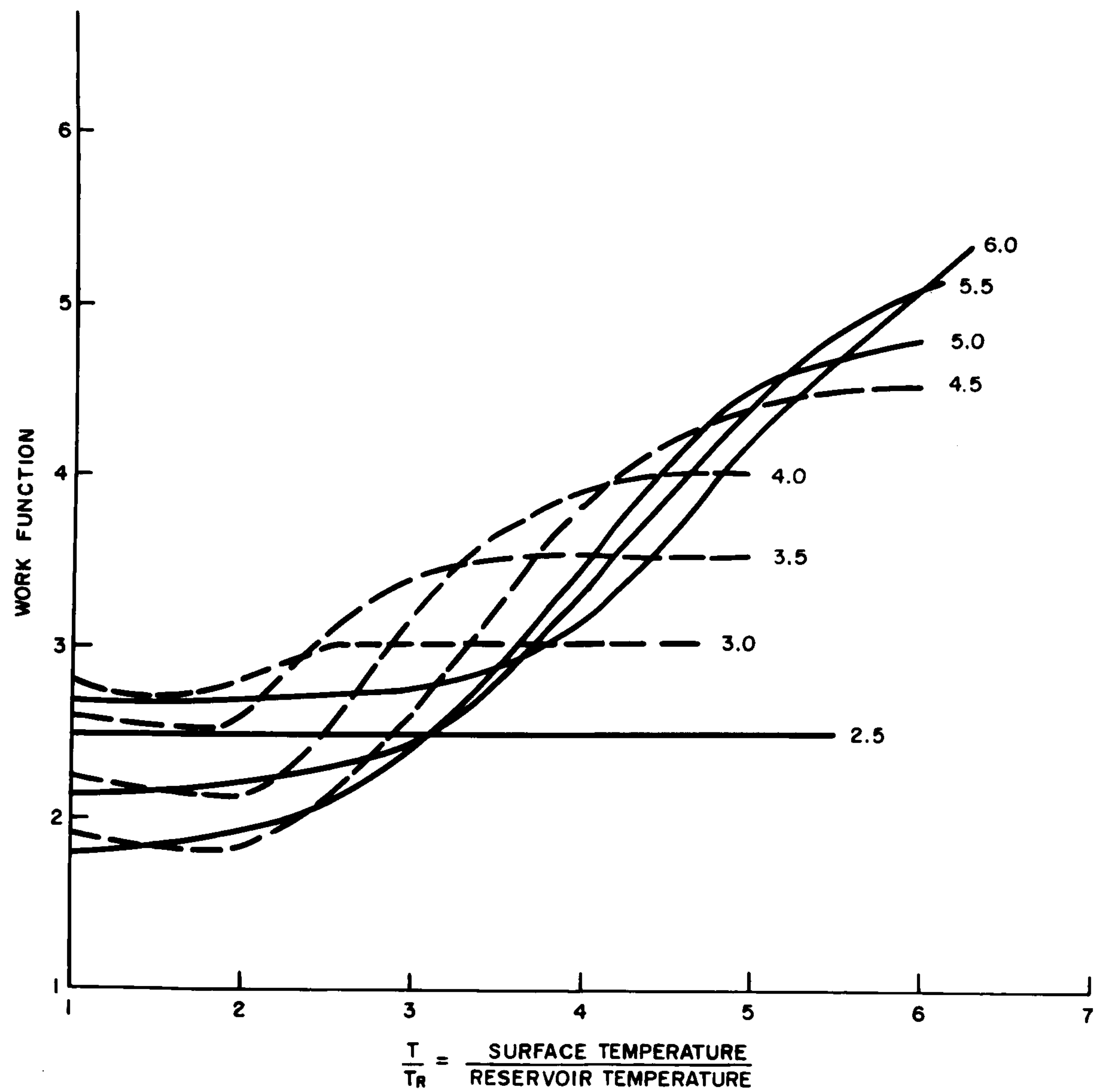

Figure 15 - Cesiated Work Function Versus Surface Temperature with Substrate Work Function as Parameter

highest cesiated work function corresponds to a substrate work function of mid-value, approximately 3.0 to 3.5. By combining the information given in Figures 14 and 15, a new series of curves may be drawn. These curves (Figures 16, 17, 18 and 19) illustrate the relationship between saturation current and substrate work function. For convenience, the same data are presented in Figure 20 in terms of cesiated emission versus bare substrate work function for the temperature range pertinent to a tube working into a 600°C heat sink.

From Figure 20, it is obvious that a work function of 3.0 would be preferable for the anode or grid surfaces. While a substrate work function of 6.0 would also be fairly good (for low emission), few conductors have such a high work function. Platinum has a work-function range of 4.7 to 6.3, depending upon the exact crystalographic arrangement at its surface; however, platinum does not seem dependable, because if its work function decreased to 4.7, it would become an excellent emitter.

As a result of the above study, two additional anode materials -- zirconium carbide and hafnium -- and one additional fill material -- rubidium -- were chosen for evaluation. Test results indicated no substantial improvement over the case of molybdenum in cesium; therefore, these new materials were not considered for adoption in the first thyratrons to be constructed. The test results from these materials are given in Appendices B and C.

Sufficient data were available for estimating the maximum ambient or heat-sink temperatures to which alkali-vapor tubes might be used. The maximum heat-sink temperature is considered to be the maximum permissible electrode temperature less the thermal drop between the electrode and the heat sink. For a 15-ampere structure, in which anode dissipation might be on the order of 100 watts, it was computed that the thermal drop could be held to approximately 100°C. Thus, with this figure and the summary comparison of Figure 21, maximum heat-sink temperatures become:

Combination	Heat-Sink Temperature (°C)
Molybdenum Anode, Cesium Fill	280
Zirconium-Carbide Anode, Cesium Fill	240
Hafnium Anode, Cesium Fill	310
Molybdenum Anode, Rubidium Fill	240

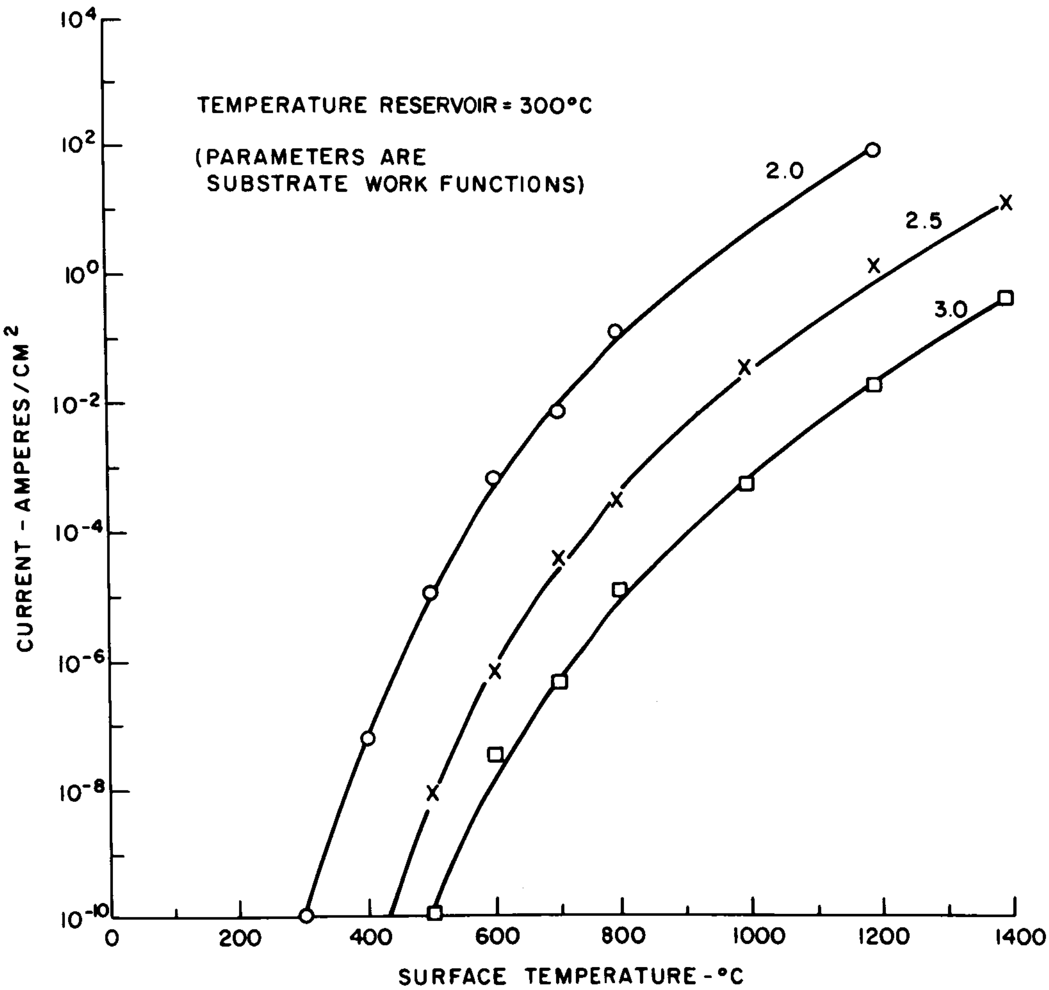

Figure 16 - Cesiated Emission Curves for Low-Range Bare Work Functions

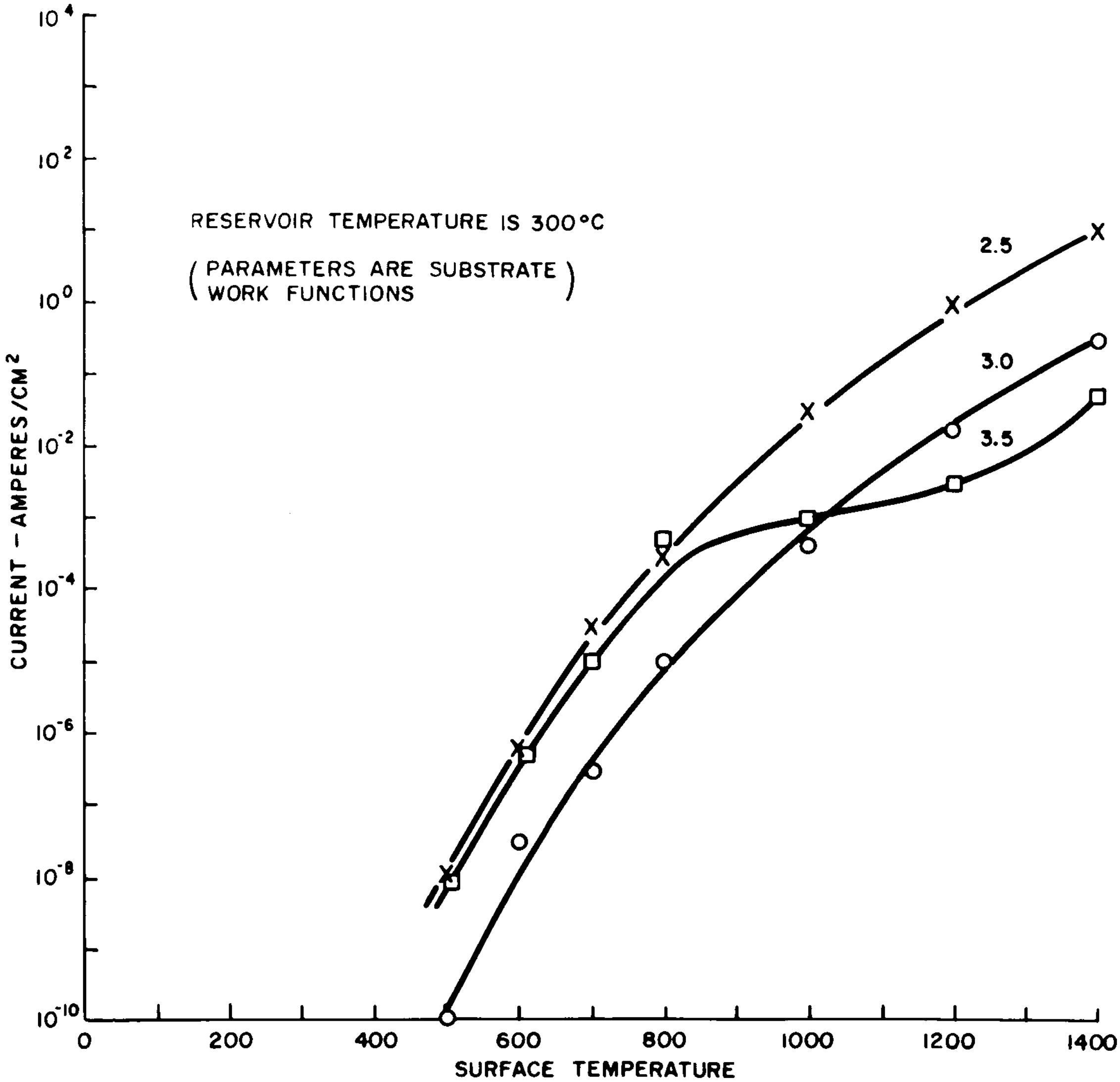

Figure 17 - Cesiated Emission Curves for Middle-Range Bare Work Functions

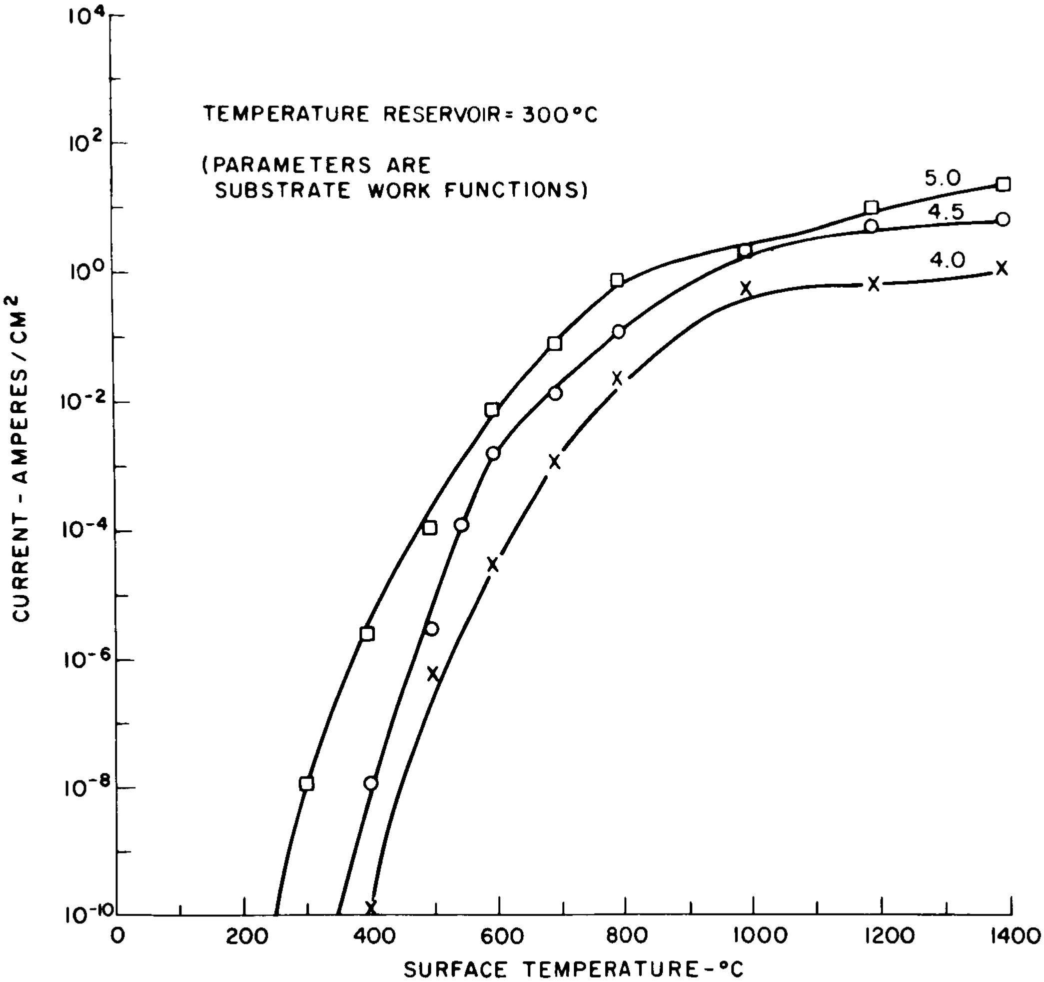

Figure 18 - Cesiated Emission Curves for Middle-to-High-Range Bare Work Functions

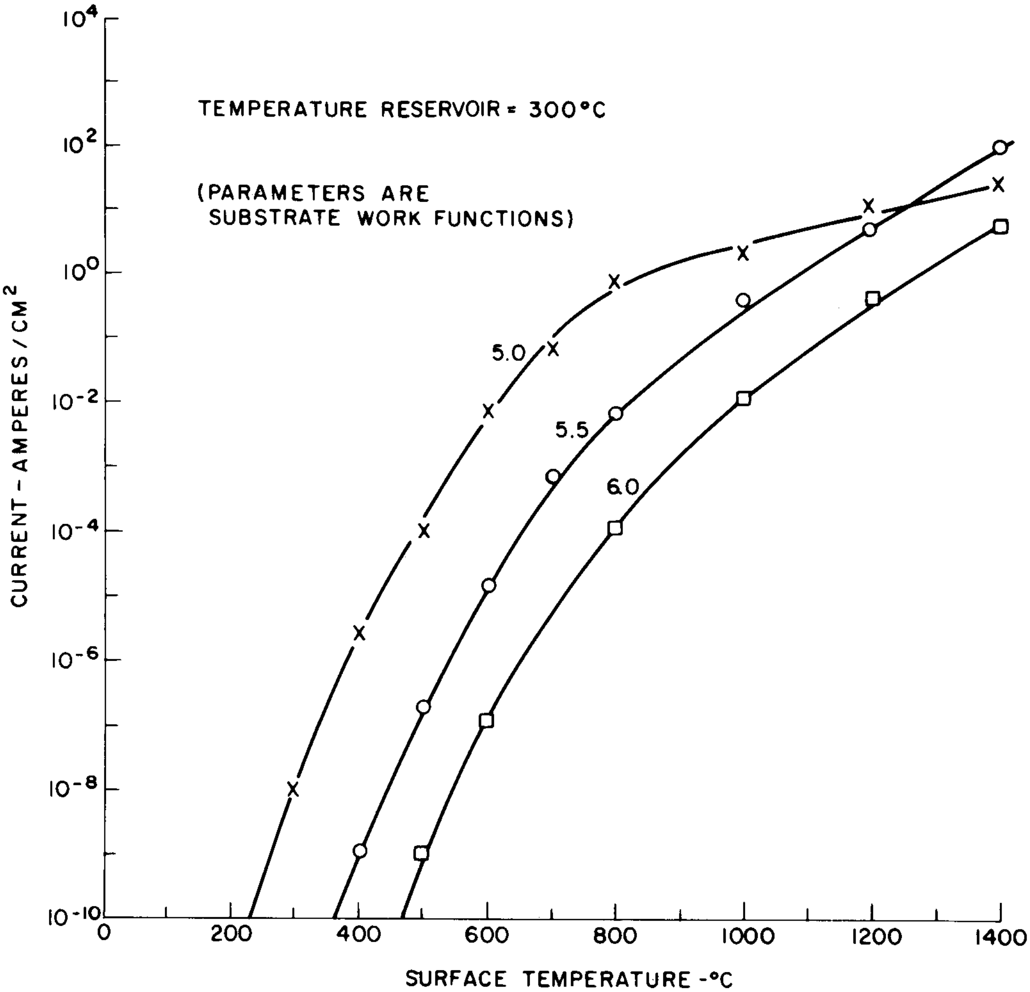

Figure 19 - Cesiated Emission Curves for High-Range Bare Work Functions

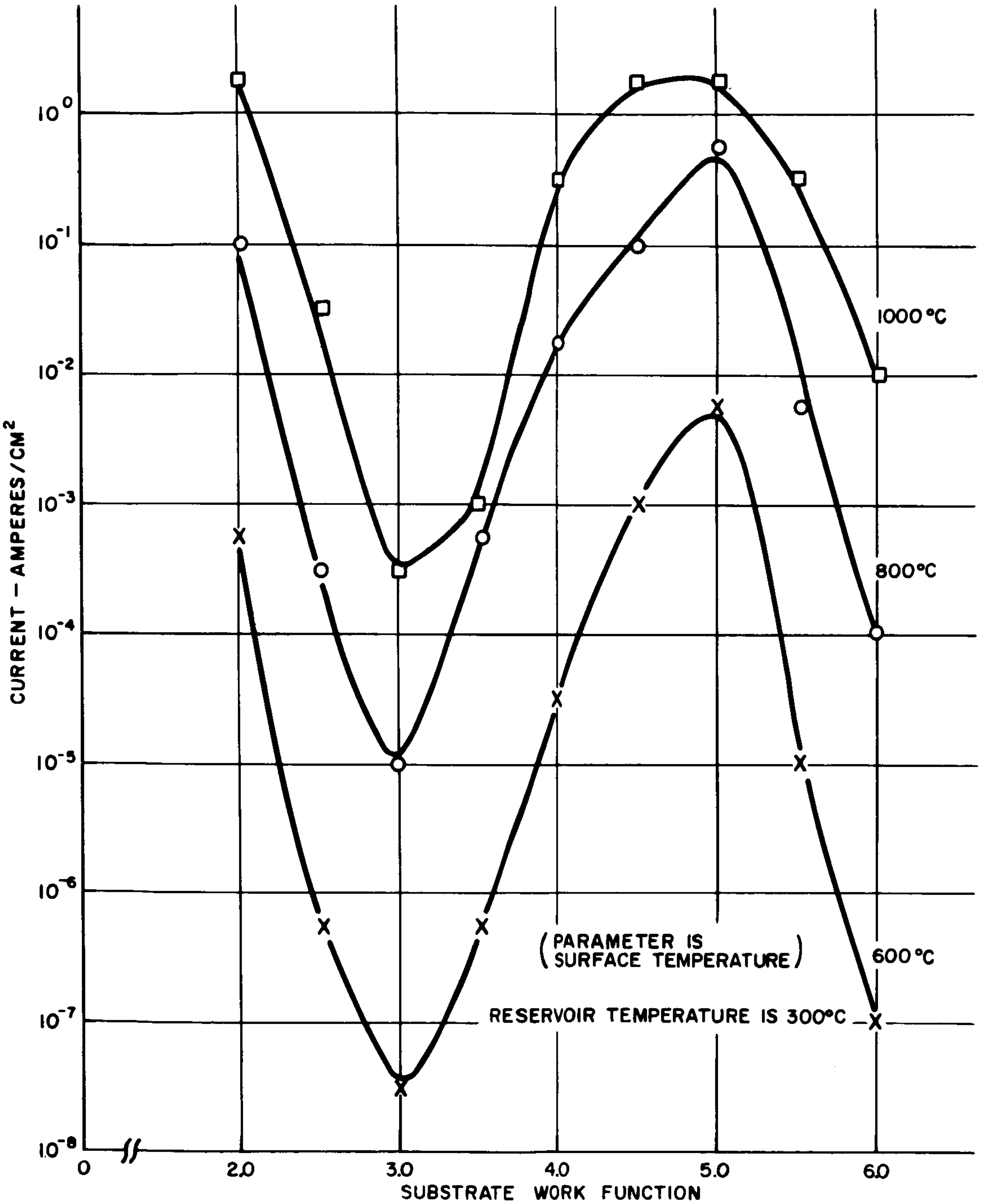

Figure 20 - Cesiated Emission Versus Substrate Work Function

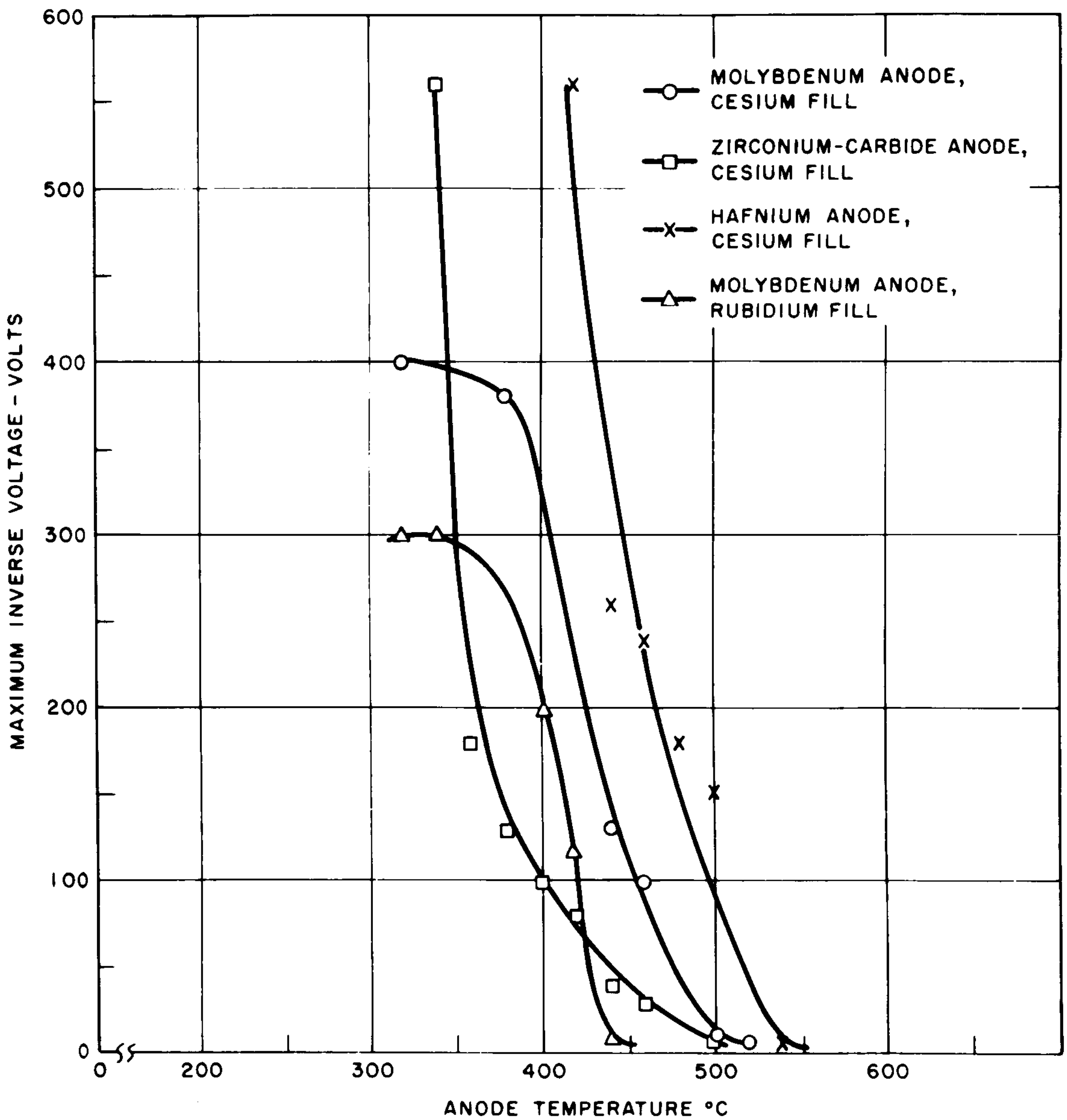

Figure 21 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature for Various Anode and Fill Combinations

With the background generated by the evaluation of cesium in diodes, attention was now focused on the evaluation of cesium in thyratrons operating in the 300°C range.

THYRATRONS

For the evaluation of cesium in thyratrons operating in the 300°C range, objective ratings for the thyratron were:

Average Current	15 Amperes
Peak Current.	50 Amperes
Forward Voltage	300 Volts
Inverse Voltage.	750 Volts

A simple thyratron structure was designed using electrodes and ceramics of the same size as had been used in the diode program. There were three structural details new to the thyratron, however, as may be seen by referring to Figure 22:

(1) A thick disc grid with parallel slots was positioned between the anode and cathode.

(2) The cathode took the form of a directly-heated tungsten filament, spiral shaped, mounted between two tungsten pins and having an emitting area in excess of 5 square centimeters.

(3) The thyratron assembly was not assembled in one brazing operation. Rather, ceramic and flange assemblies were brazed separately and final assembly was effected by welding six pairs of mating flanges.

The anode material was tantalum at the collecting surface, backed by a heavy molybdenum cylinder for conducting heat to the anode heat-sink disc. The grid in the first design was cold-rolled steel. Ceramic cylinders were of the high-alumina variety, and metallized at the ends. Molybdenum flanges were brazed to the ceramics with a palladium-cobalt brazing alloy.

OPERATING CHARACTERISTICS

Of the three thyratrons constructed (Type Z-7009, Tube Nos. 20, 21, and 22), two were of identical design. The third, Tube No. 22, contained a design modification based upon the test results of the first two tubes, Nos. 20 and 21.

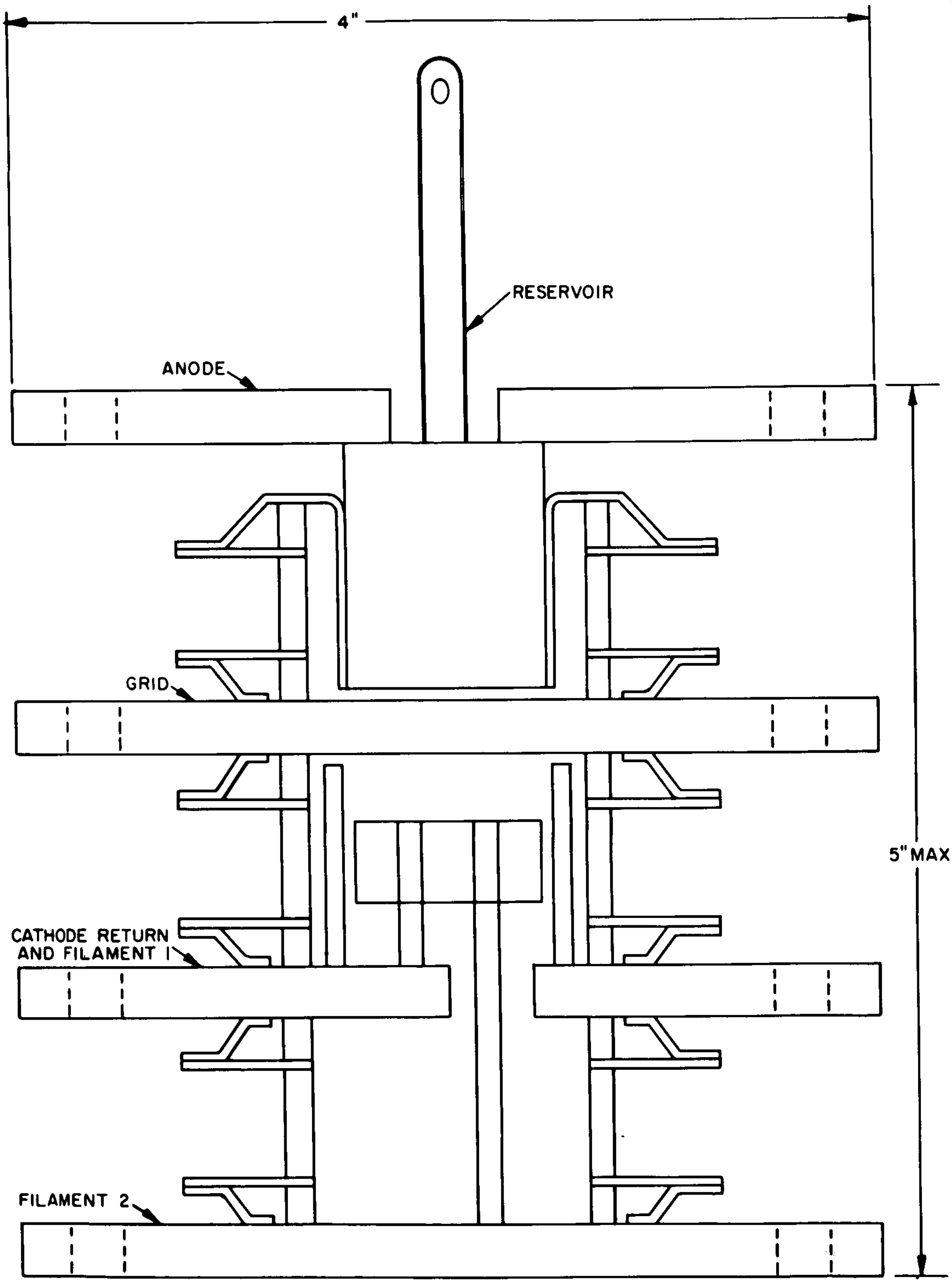

Figure 22 - Conceptual Design for High-Temperature Thyratron

Peak and average current emission capability of these thyratrons is represented in Figures 23 and 24. The selection of a filament voltage input of 1 volt is reasonable; Figure 25 indicates that this is 0.2 volt higher than the voltage at which tube drop rapidly increases, yet no gain is realized by increasing the voltage higher than 1 volt.

Anode dissipation was investigated from two standpoints: the maximum temperature to which it could be operated without arc-back, and whether or not proposed heat-sink connections were adequate for holding anode temperature below the critical value at full average current conduction. The thyratrons were subsequently constructed such that the thermal path for carrying away anode dissipation consisted of:

(1) A molybdenum block about one-inch diameter by one-inch long, extending from the inner anode surface to the top of the tube.

(2) A four-inch diameter, 1/4-inch thick, copper disc.

(3) Two additional copper discs for bridging the gap between the four-inch disc and the heat sink. (In an actual application, these two discs could be bolted together with a thin mica insert between them, the insert providing the necessary insulation between heat-sink and anode potentials.) The diameters of the above discs were $6\frac{1}{2}$ and $8\frac{1}{2}$ inches, respectively.

In lieu of actually operating the tubes inside of a 300°C chamber, anode dissipation was studied synthetically. A heat-sink linkage (disc) was bolted to the tube, and the tube was operated at full-rated average current. Additional power was injected by means of an external heater to provide a means of raising the temperature of the anode system further. With the edge of the anode system (or the part of the disc that would ordinarily be bolted to a heat sink) at 300°C, it was determined that the tube was free from arc-back at 150 volts inverse.

From another measurement, without a copper disc connected to the molybdenum anode, it was shown that the tube would arc-back at 150 volts inverse if the anode surface temperature reached 410°C. Further, by raising the temperature of the full anode system (with disc) until arc-back occurred, an estimate of the temperature drop (for an actual application) between the anode and a heat sink could be made. This is based upon the difference (Δt) between 410°C (the internal arc-back temperature) and the temperature at the outer edge of the disc. Pursuing this course, an arc-back occurred when the edge of the disc reached 380°C, yielding an apparent

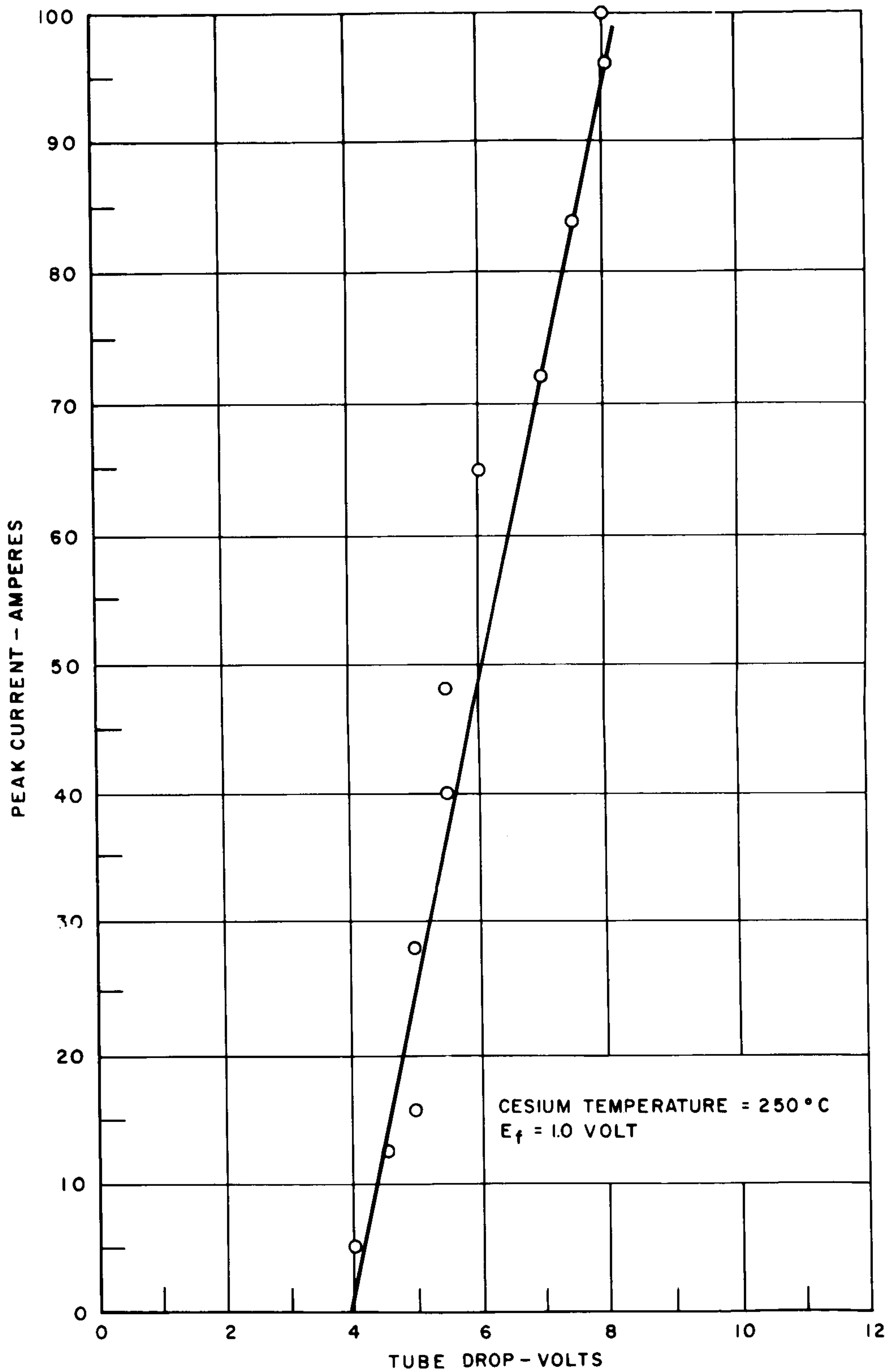

Figure 23 - Current Versus Voltage, Type Z-7009, Tube No. 22

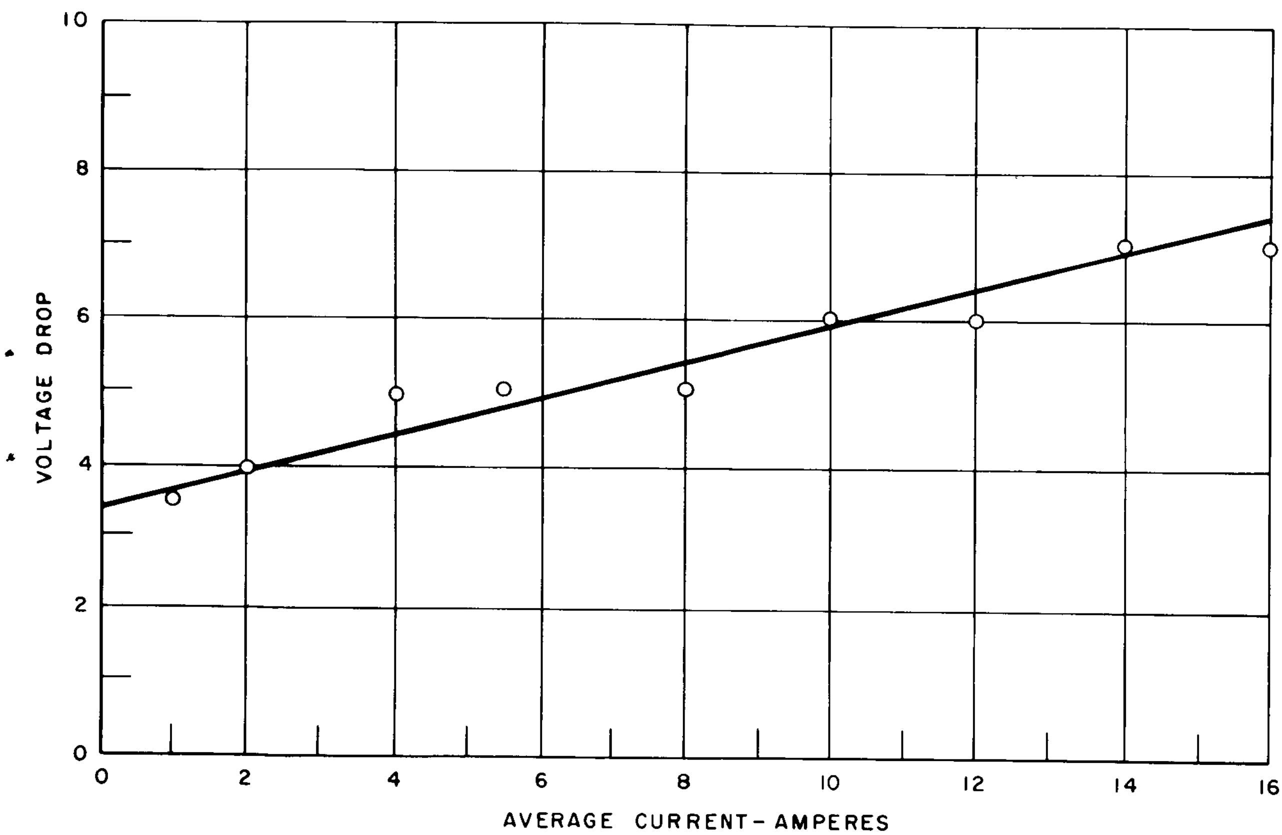

Figure 24 - Voltage Drop Versus Average Current, Type Z-7009, Tube No. 22

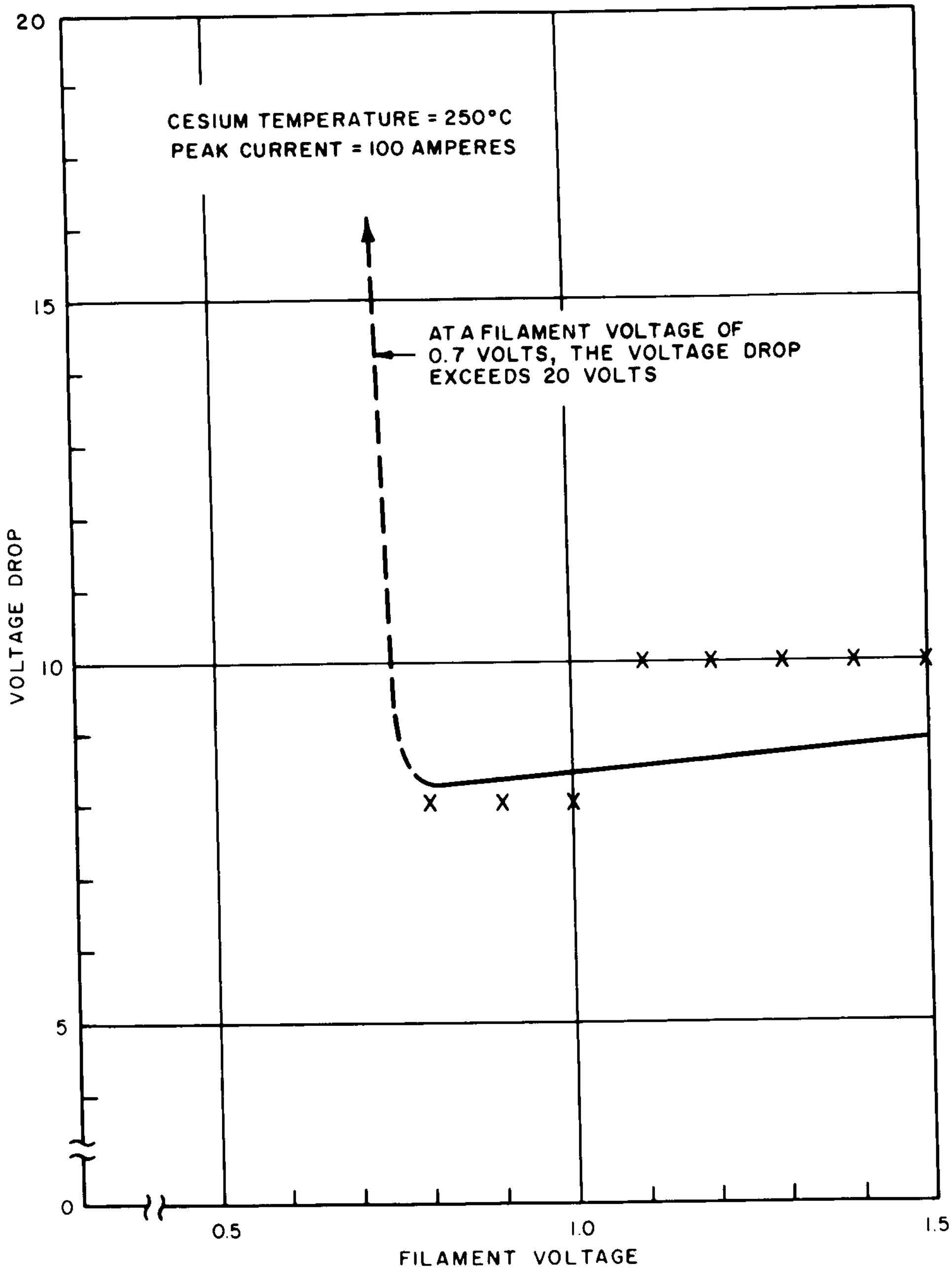

Figure 25 - Voltage Drop Versus Filament Voltage, Type Z-7009, Tube No. 22

Δt of 30 degrees. If the tube were contained within an actual 300-degree heat sink, this Δt would be doubled, becoming approximately 60 degrees, the reason for this being that in an actual high-temperature application, all of the heat flow from the anode would be conducted through the linkage to the heat sink. In the synthetic test described, the average heat flow traversing the heat disc is actually closer to one-half of the heat flow entering it, since all of the heat is lost from the disc by radiation. Thus, the tube is capable of operating to 150 volts inverse, with a heat-sink temperature of 410°C minus 60°C (arc-back temperature less 2 Δt) = 350°C. From the curves of Figure 21, it would appear that an additional temperature reduction of 50 degrees is required to raise the critical anode voltage at which arc-back occurs from 150 to 750 volts. Thus, the tube is marginally capable of reaching 750 volts inverse, with a 300-degree heat sink.

By varying the number of heat-linkage discs, a radiator of 1, 4, $6\frac{1}{2}$, or $8\frac{1}{2}$ inches in diameter could be provided for the anode. Figure 26 demonstrates the relationship between anode system temperature and average current for these various-size radiating surfaces. The curves extend to an average current of 15 amperes, or to the point where an arc-back was observed (inverse voltage = 150). A plot of grid temperature is given in Figure 27.

Figure 28 presents the d-c grid control characteristic. The d-c control characteristic plots the anode voltage needed to fire the tube as a function of grid voltage, and a circuit such as the one shown in Figure 29 is used to obtain the data.

In using the circuit, the grid voltage is first set at a value which is negative to the extent that the tube will hold off the anode voltage that will be applied. After applying the desired anode voltage, the negative grid voltage is reduced to the point where the tube fires. The two voltages of interest are the grid and anode voltages, just prior to the firing of the tube. This procedure is repeated for different anode voltages until sufficient points are available for plotting a curve.

It will be noted that the curve flattens at an anode voltage of 300 volts. This represents the maximum voltage that may be impressed between anode and grid. Any further increase in negative bias will, in fact, reduce the anode voltage at which breakdown occurs; that is, if the control grid is driven to -100 volts, the maximum anode voltage becomes 200 volts. The breakdown voltage of a gap is dependent upon the product of electrode separation and gas or vapor pressure (Paschen's Law). Hence, the maximum forward and inverse voltages, as a function of cesium temperature, are

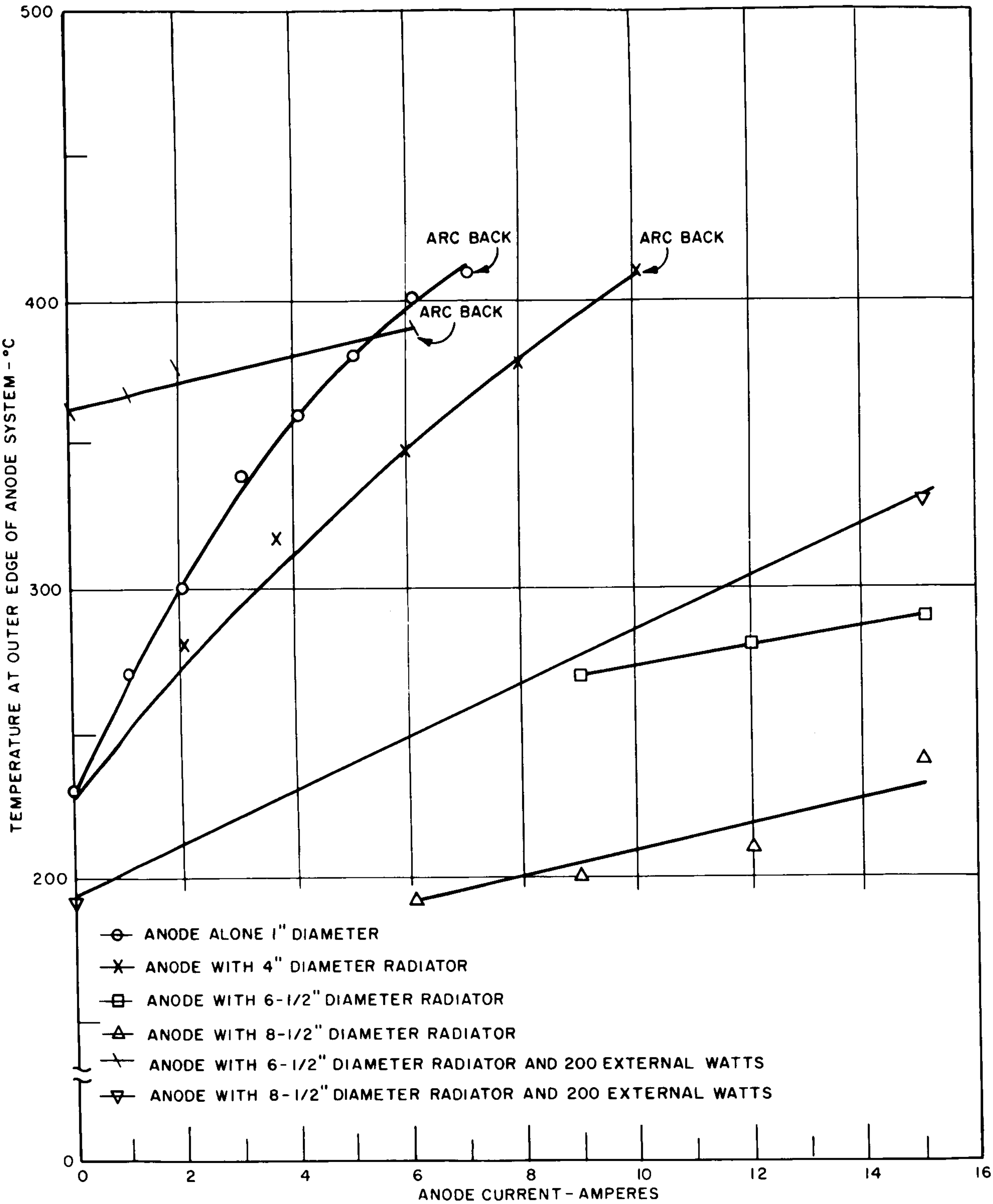

Figure 26 - Anode Temperature Versus Average Current, Type Z-7009, Tube No. 20

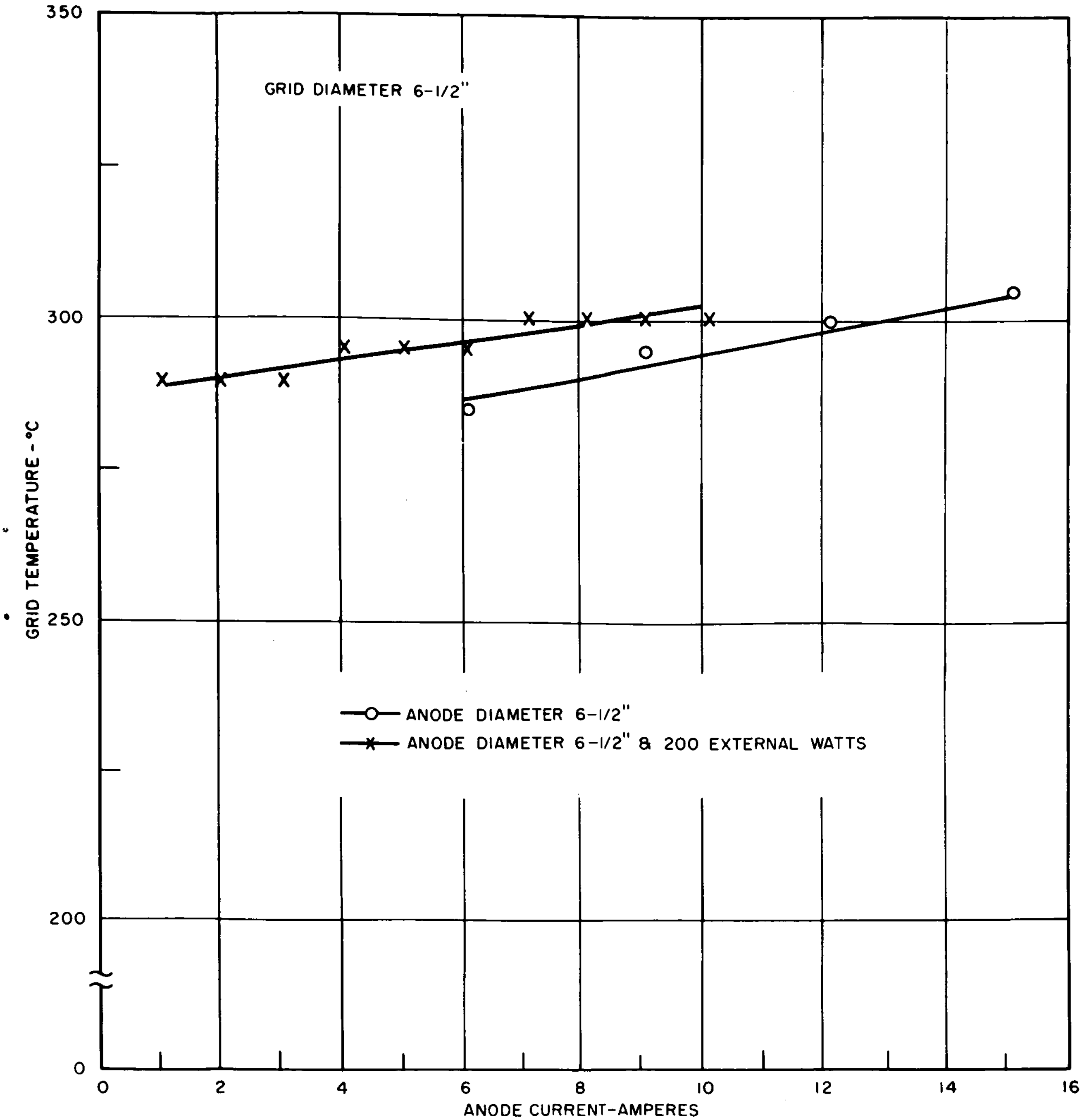

Figure 27 - Grid Temperature Versus Average Current, Type Z-7009, Tube No. 20

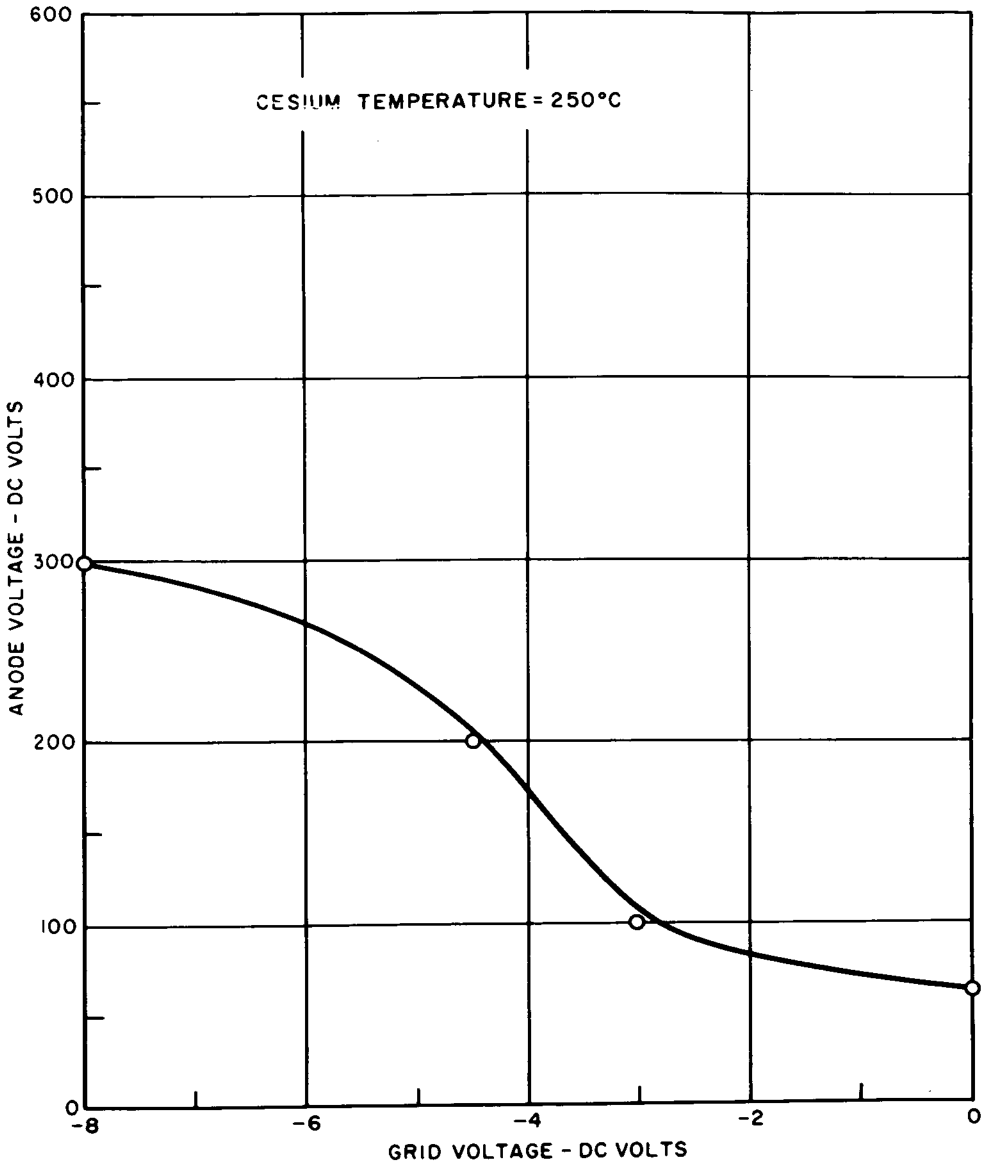

Figure 28 - D-C Control Grid Characteristic, Type Z-7009, Tube No. 21

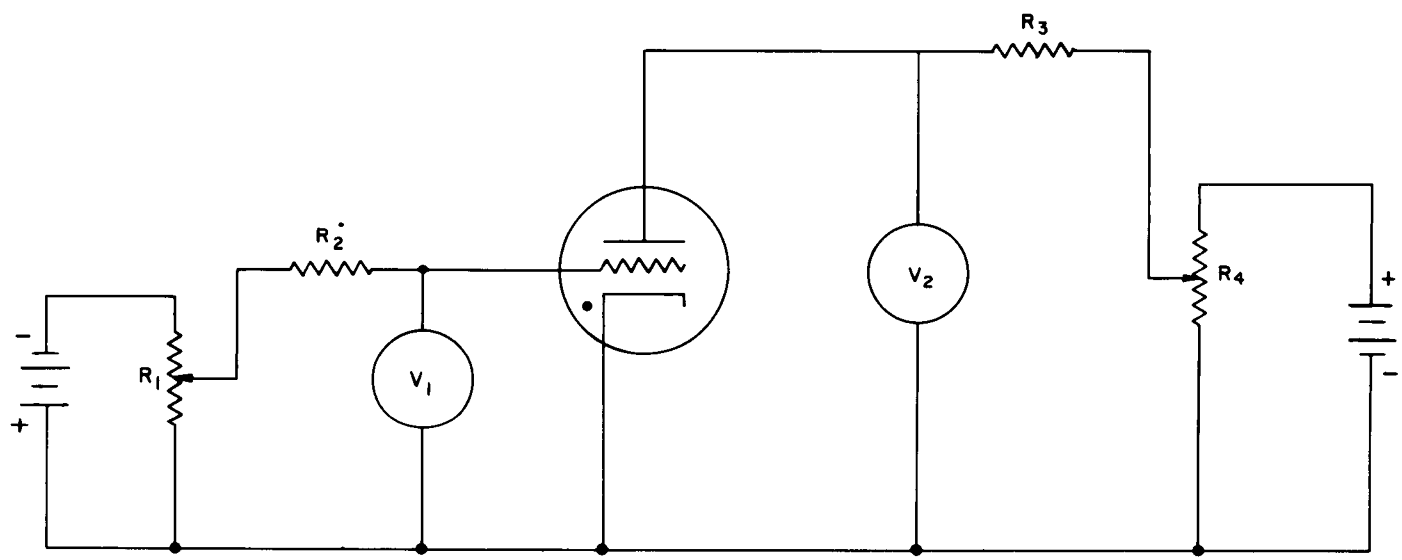

Figure 29 - Circuit for D-C Grid Control Characteristic

seen to vary as shown in Figure 30 and as a function of cesium pressure in Figure 31. The curve of breakdown voltage reaches a minimum of about 400 volts for a cesium pressure of 2 torr. We know of no published Paschen's curve related to cesium for comparison, but since most gases exhibit a minimum breakdown voltage in the general range of 5 for the product of PD (where P is pressure in torr, and D is gap length or electrode separation in millimeters), it is of interest to compare the cesium data to published data for air.[2] For this comparison, the inverse voltage curve (Figure 31) was used with the grid-anode spacing of 1/8-inch = three millimeters, Figure 32. The forward voltage curve, Figures 30 and 31, is displaced lower than the inverse voltage curve for two reasons:

(1) The effective spacing for the grid-anode gaps for the forward-voltage case is greater than the electrode spacing because of the openings in the grid.

(2) In the forward-voltage case, electrons emitted by the hot cathode are available for precipitating a discharge. For the inverse case, the electrons must emanate from the relatively cold anode.

Based upon the above data, two alternatives are open for achieving the objective rating of 750 volts inverse:

(1) Reduce the controlling temperature for the cesium below 300°C.

(2) Resort to the use of gradient grids.

Operation at 750 volts in a simple triode structure may be possible if the cesium reservoir temperature is held to a maximum of 230°C. Under these conditions, the grid and anode could still reject heat to a 300-degree heat sink because the cesium vapor pressure would be governed by the coolest spot in the tube.

Full-voltage operation at 300 degrees might be achieved by adding two gradient grids between the anode and control grid. Such an approach would provide three gaps in series to divide the inverse voltage. One gradient grid would be inadequate because experience with other thyratrons has shown that the addition of a gradient grid increases the voltage capability only about 50 percent above the capability of the triode.

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2. Cobine, J. D., Gaseous Conductors, 1st Edition, New York: McGraw-Hill Company (1941), p 164

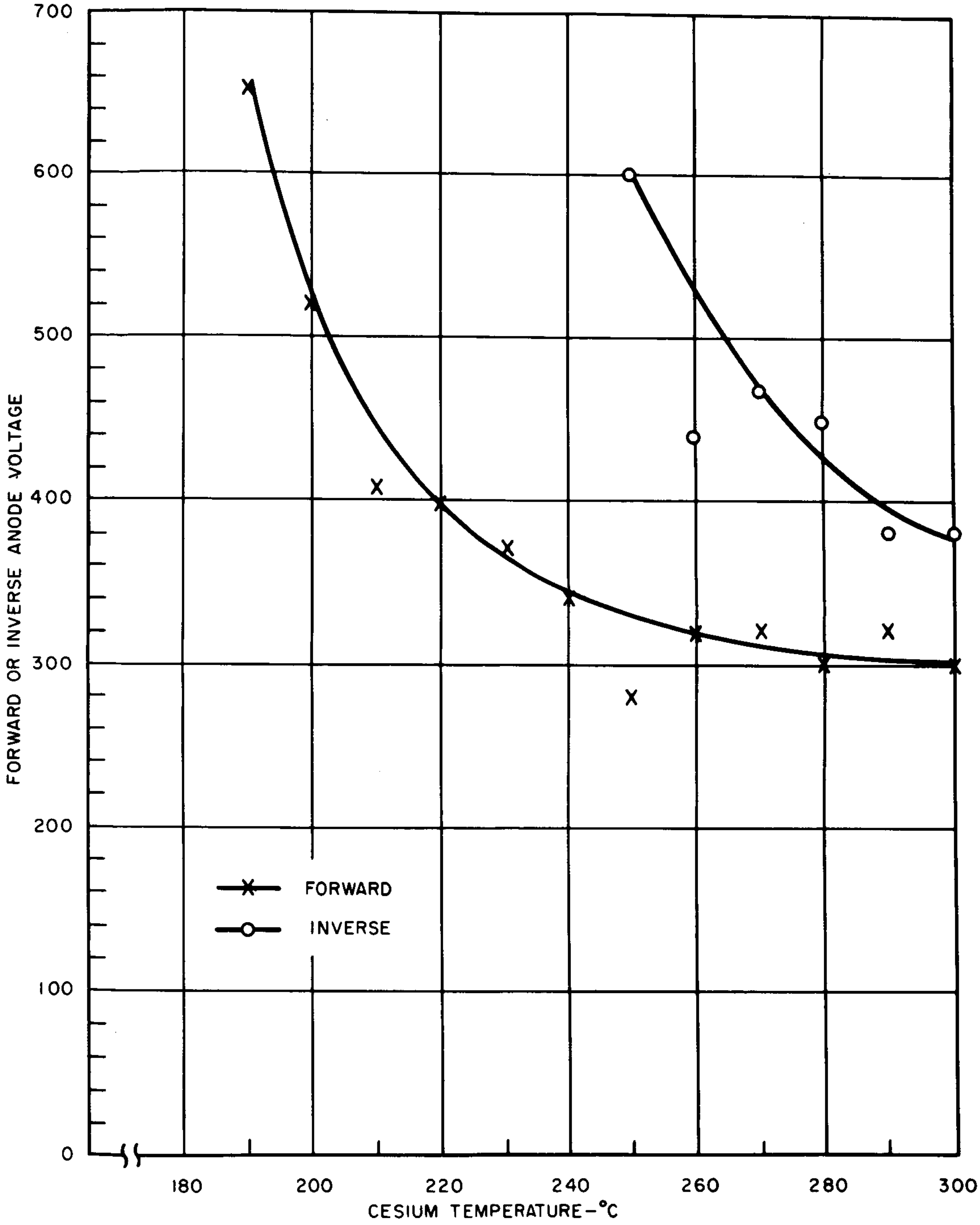

Figure 30 - Maximum Anode Voltage Versus Cesium Temperature, Type Z-7009, Tube No. 21

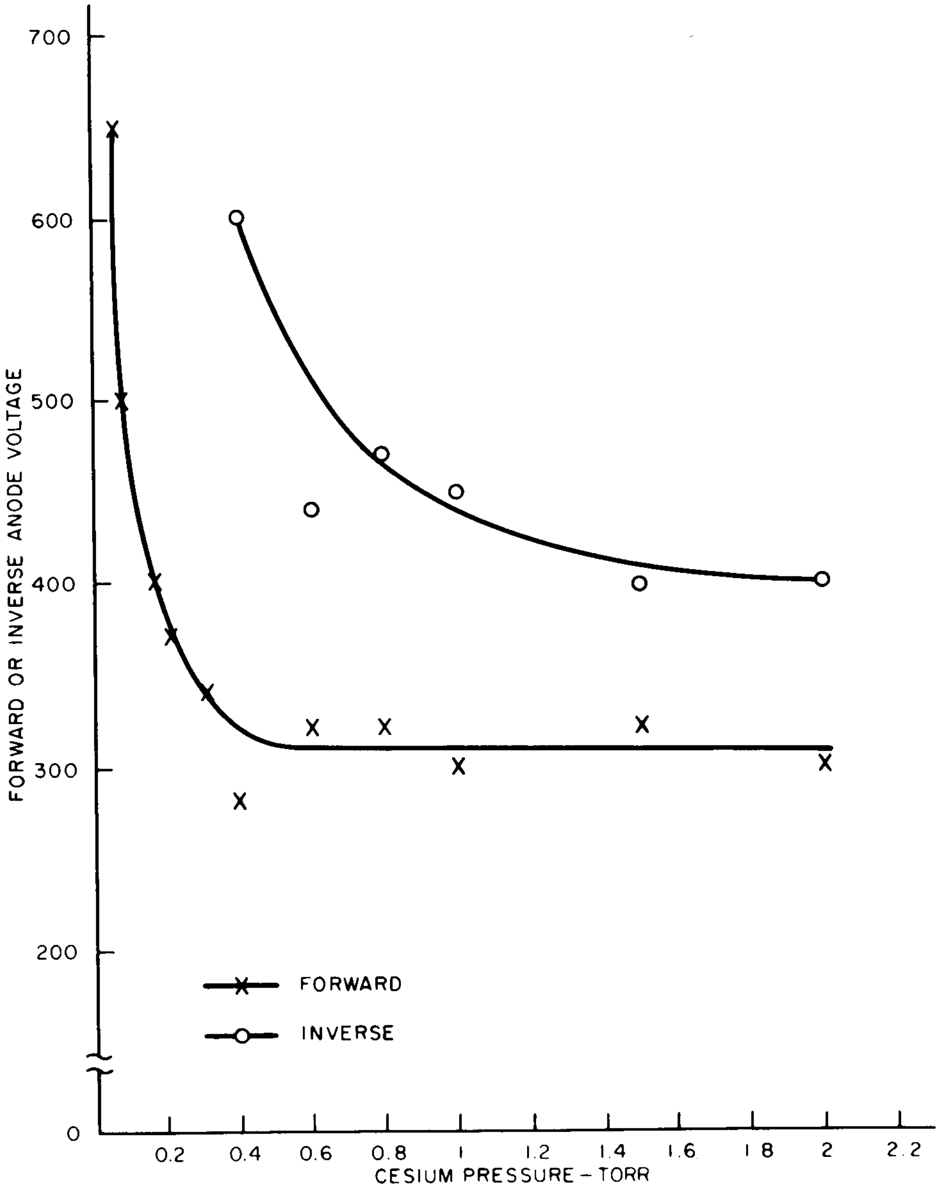

Figure 31 - Maximum Anode Voltage Versus Cesium Vapor Pressure, Type Z-7009, Tube No. 21

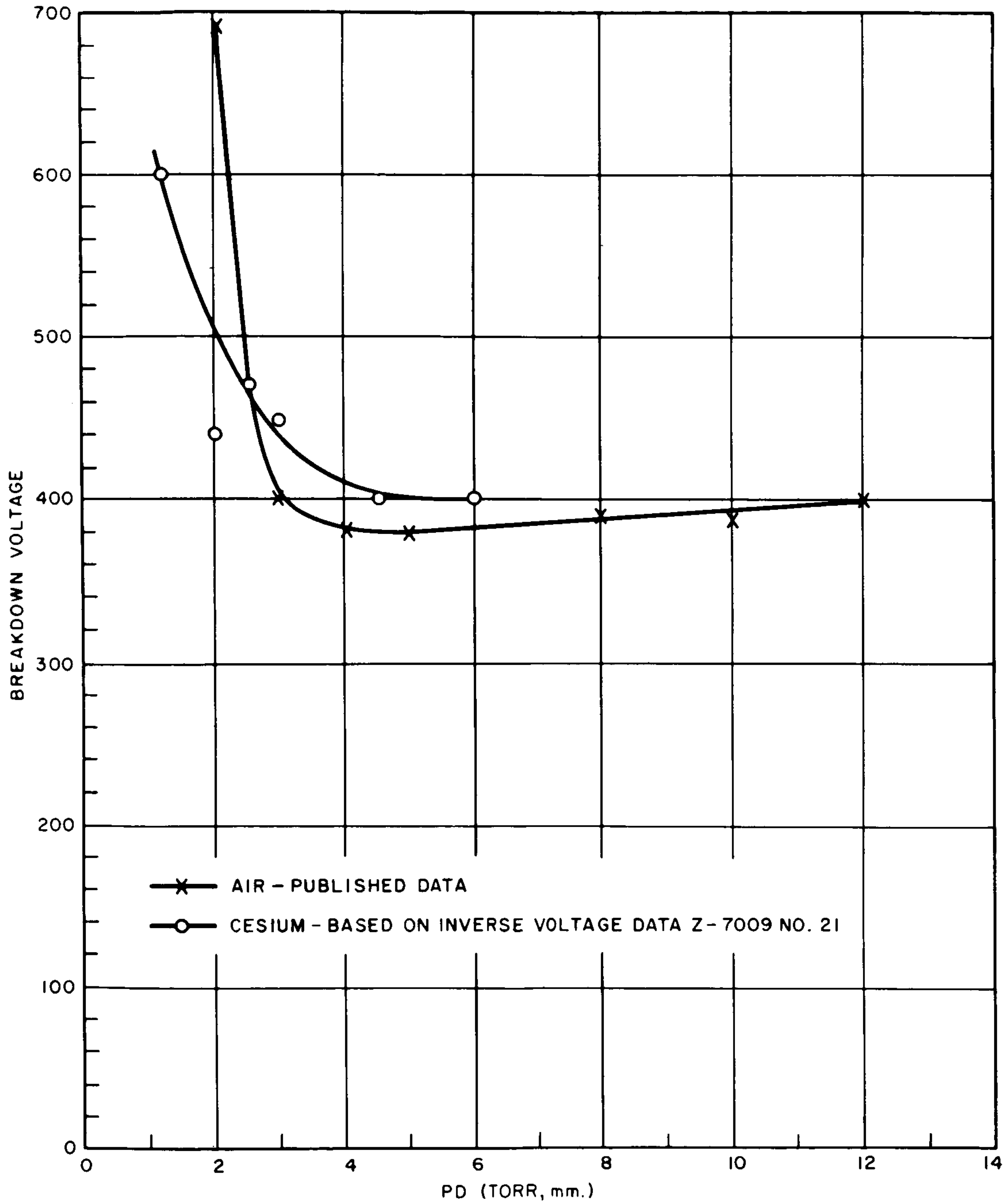

Figure 32 - Breakdown Voltage for Air and Cesium Versus PD

Two grid control problems were evident with respect to both Tube Nos. 20 and 21. A low leakage resistance between grid and anode, presumably created by the formation of a cesium film on the ceramic insulator, required an increase in bias and driving power. Grid emission occurred above a certain critical temperature and caused complete loss of control. These problems are discussed in the paragraphs which follow.

One of the desirable characteristics of a typical thyratron is its ability to control large quantities of power flow with a very small power input to the grid. Thus, it is commonplace for a thyratron grid to be energized from a high-impedance circuit -- as high as 10 megohms for some industrial applications. The grid-anode leakage resistance should be many times higher than the resistance of the grid driver circuit. If this is not the case, an excessive bias supply voltage must be provided to compensate for that portion of the anode voltage coupled to the grid as a result of internal leakage. The excess bias supply voltage requirement is approximately equal to the ratio of

$$(Rg/Rga)(Va)$$

where: Rg = resistance of grid circuit in ohms

Rga = grid-anode leakage in ohms

The general case has been derived for predicting the grid bias supply voltage required to prevent conduction in a thyratron, as follows:

$$V_b = Va + Va\left[\frac{Rga + Rg}{Rga + Rgc}\right] - (Va + Vg)\left[\frac{Rga + Rg}{Rga}\right]$$

where: V_b = bias supply voltage

Va = peak anode voltage

Vg = critical grid voltage corresponding to Va and obtained from d-c control-grid characteristic.

Rga = grid-anode leakage resistance

Rgc = grid-cathode leakage resistance

Rg = internal resistance of grid driving circuit

Leakage paths measuring from 1 ohm to 1 megohm were observed, the magnitude of the leakage depending upon ceramic and electrode temperatures and the previous history of operation. Figure 33 presents a

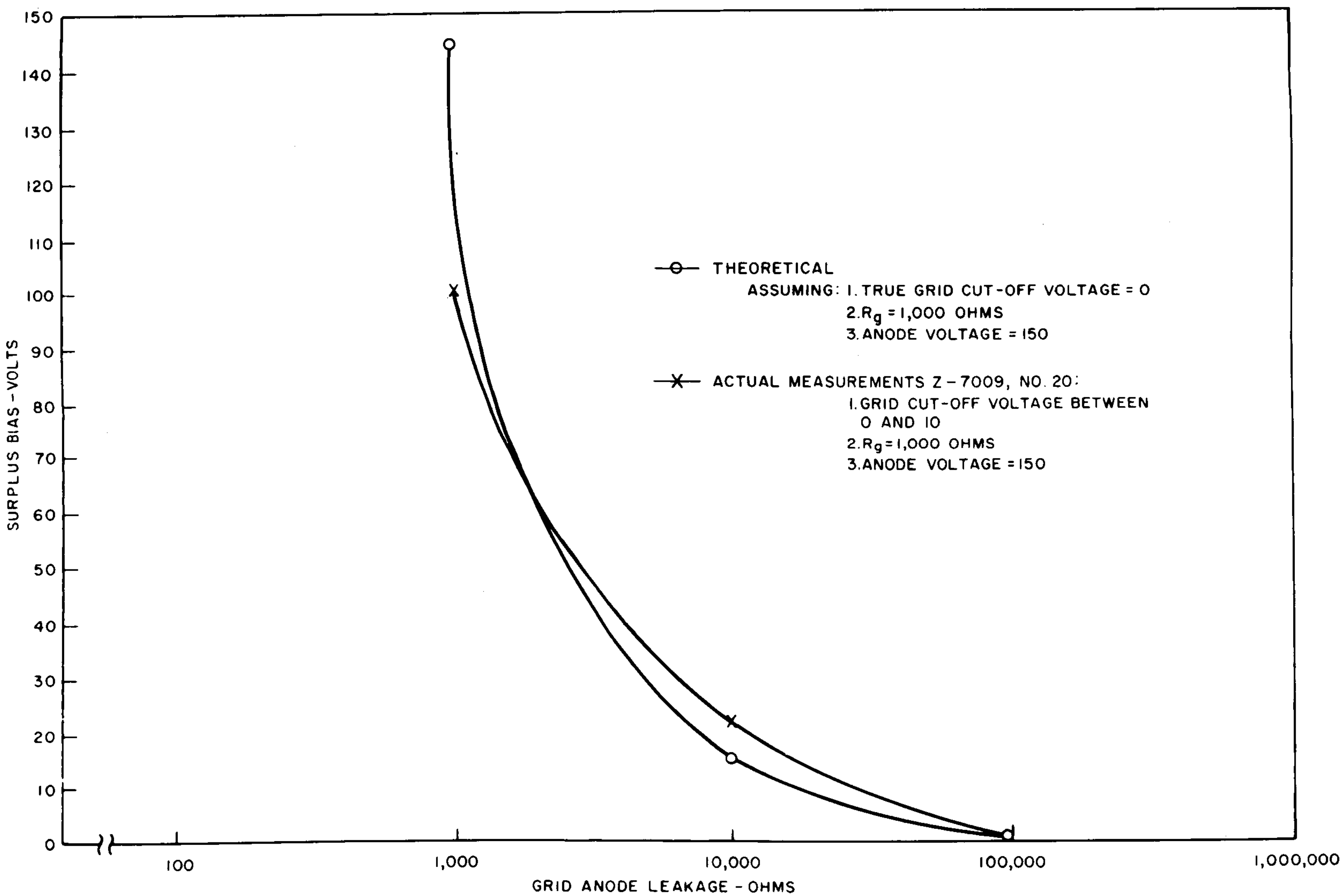

Figure 33 - Surplus Bias Supply Voltage Needed to Compensate for Grid-to-Anode Leakage

comparison of actual and theoretical excess or overvoltage required at the grid supply. When the leakage equals the grid circuit resistance, as many bias supply volts are required as there are anode volts to be held off.

Heat was supplied to the grid-anode ceramic in an attempt to reduce the cesium coverage. With a one-turn heater looped around the midpoint of the ceramic, the leakage resistance was studied as the heater power input was varied. Because of the random nature of the cesium-film deposition, the results were not perfectly repeatable. However, a typical account of the leakage resistance, as a function of heater input voltage and average current, is given in Figure 34. In this figure, the abscissa changes were made at 5-minute intervals. With the application of external heat, the leakage path could be controlled so that the grid-anode impedance minimum was typically 10,000 ohms. By increasing the amount of heating, the minimum impedance could be raised. It appears that any final-design cesium thyratron should have a heating circuit directly attached to the grid-anode ceramic. One way of fulfilling this requirement may be to print the heating circuit onto the ceramic by metallizing.

Tube Nos. 20 and 21 exhibited grid control only if the average current was low and the temperature at the edge of the grid was below 300°C, Figure 35. The thermal problem was emphasized by the fact that higher average currents could be controlled for the time required to raise the temperature at the center of the grid to the critical emitting temperature. At 16 amperes, this time was only about 2 seconds, Figure 36.

The grids of Tube Nos. 20 and 21 were devised from 1/8-inch iron and slotted in such a way as to leave 1/16-inch wide bars, Figure 37, at the center. These bars were the most vulnerable part of the grid, with respect to a significant temperature gradient. A temperature gradient was calculated based upon the following assumptions:

(1) Anode dissipation is 100 to 150 watts.

(2) About 10 percent of the above or 10 watts of dissipation appears at the grid because of the discharge going through the grid.

(3) All of the discharge might concentrate at one slot, thus causing the dissipated energy to divide equally between the two boundary bars for the particular slot.

(4) The energy being dissipated in each bar enters the bar at a point in the center, and one-half of this energy flows out of each end.

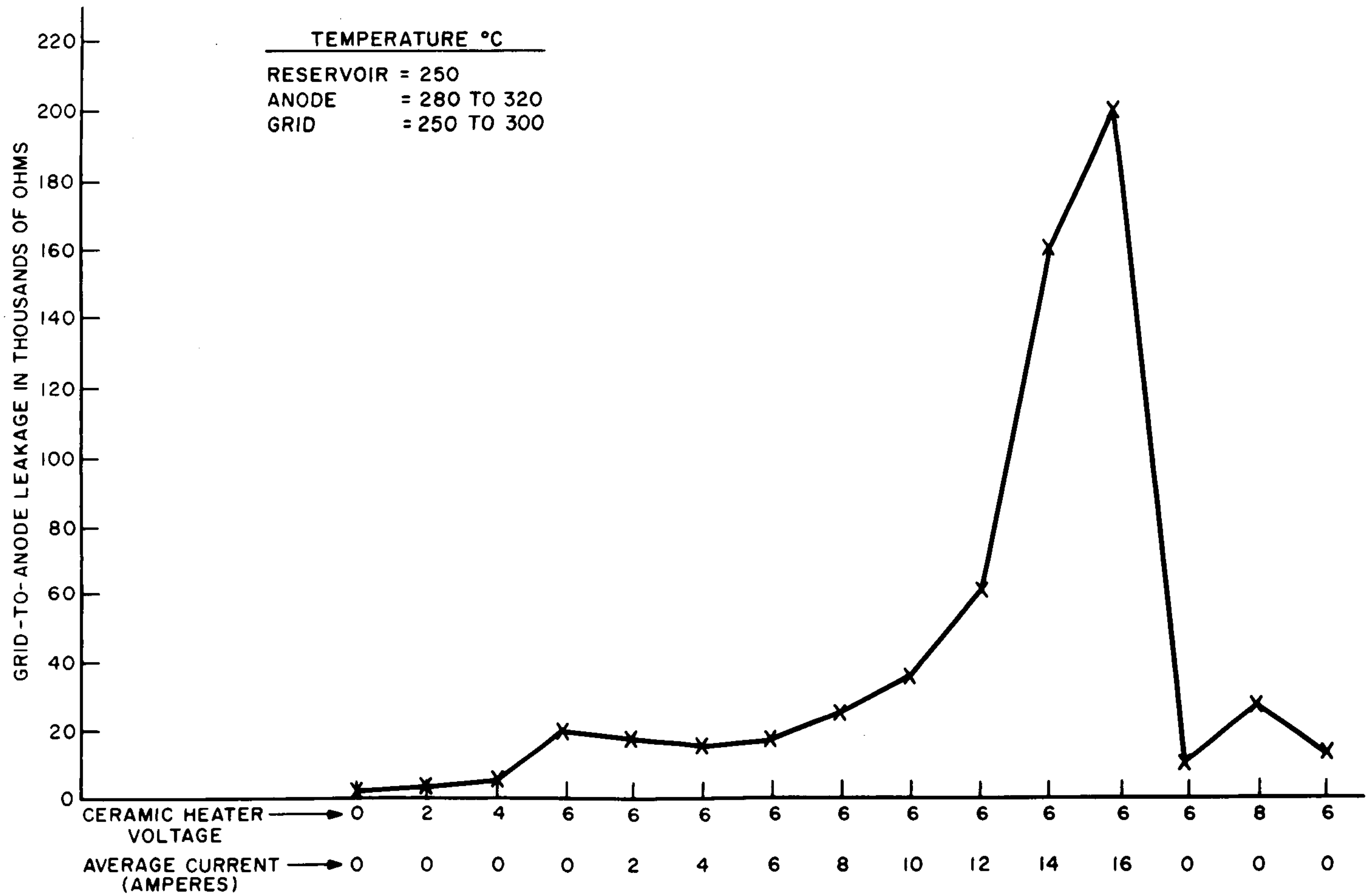

Figure 34 - Grid-to-Anode Leakage Versus Ceramic Heater Voltage and Average Current, Type Z-7009, Tube No. 21

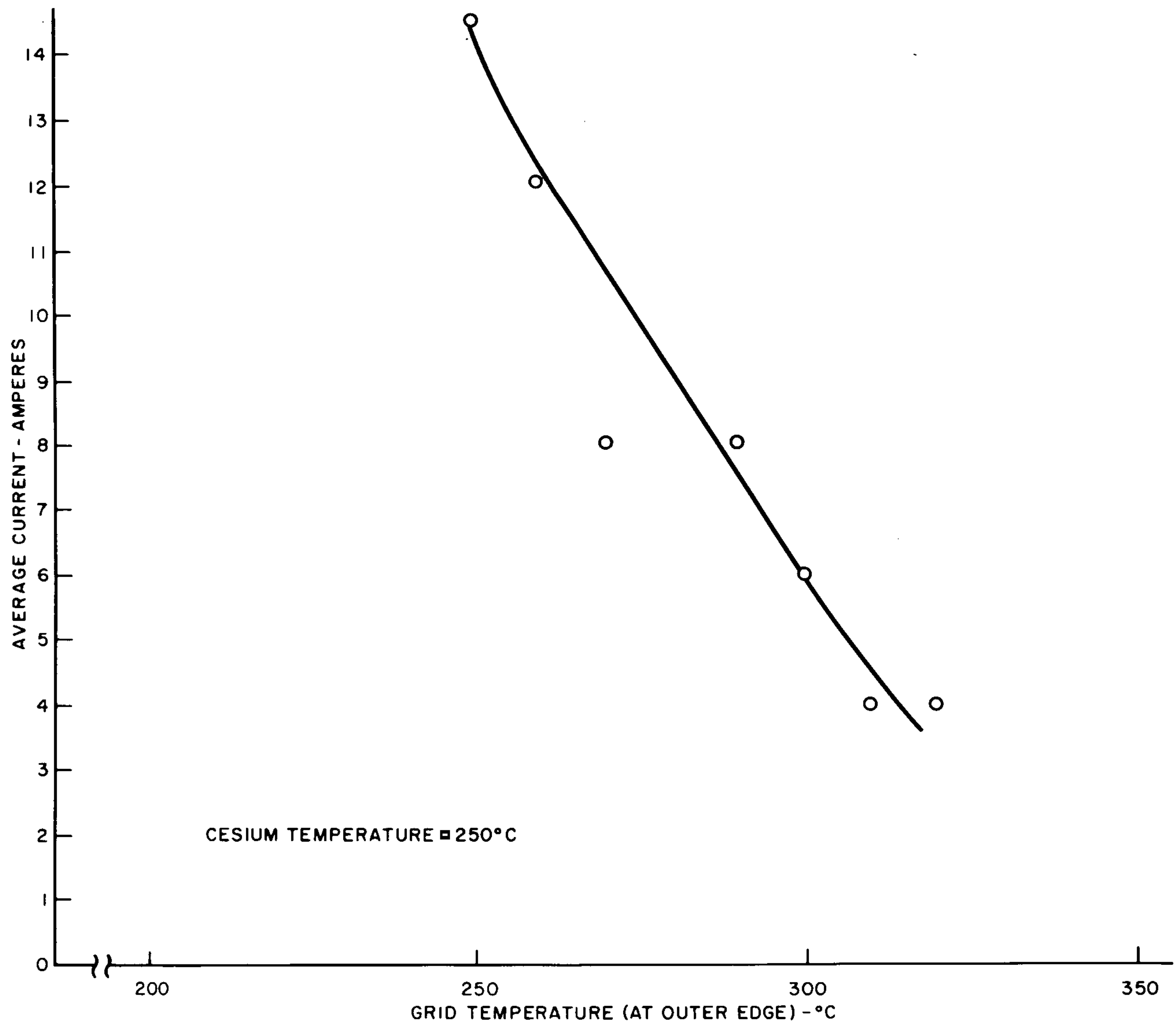

Figure 35 - Maximum Average Current with Grid Control Versus Grid Temperature, Type Z-7009, Tube No. 21

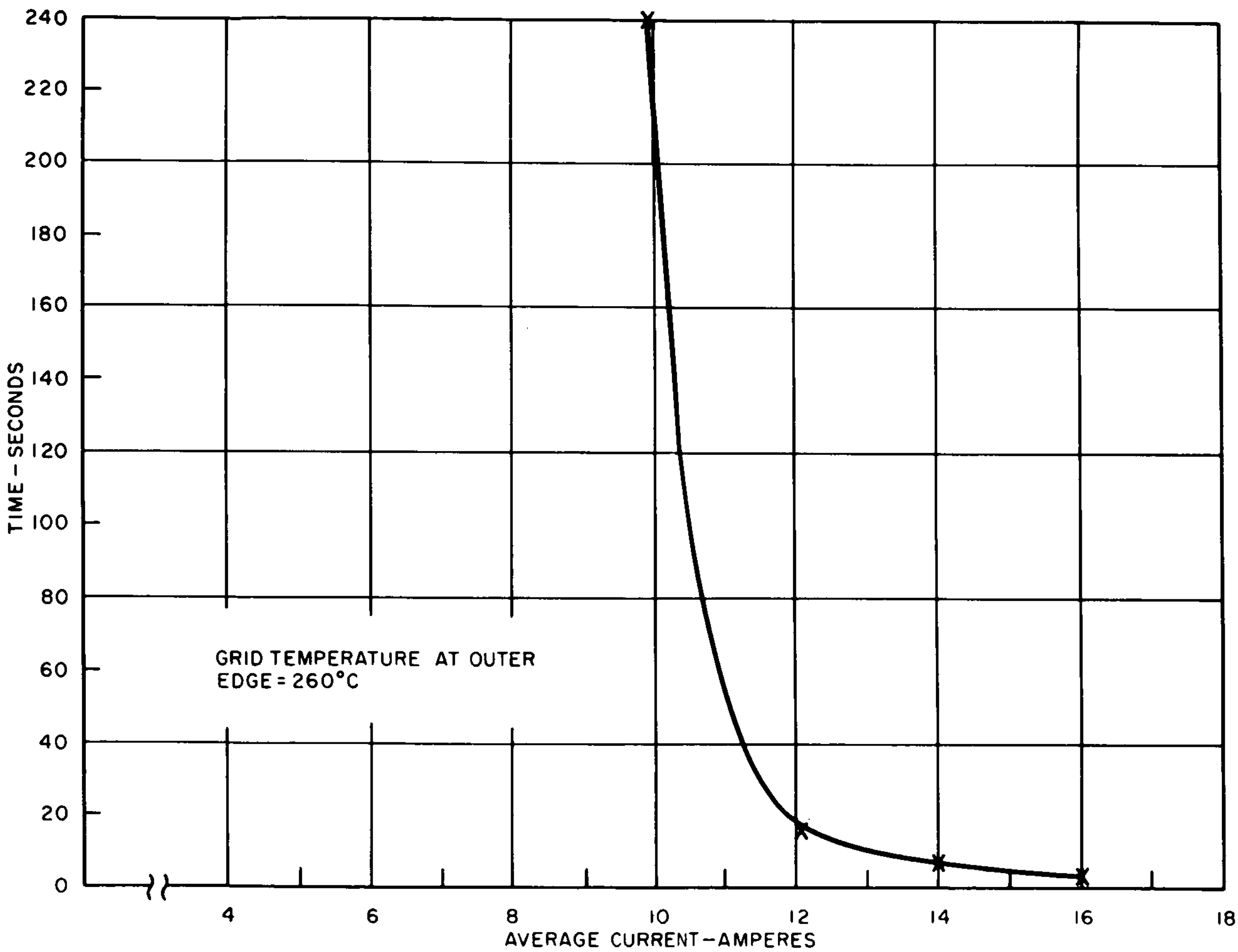

Figure 36 - Maximum Operating Time with Grid Control Versus Average Current, Type Z-7009, Tube No. 21

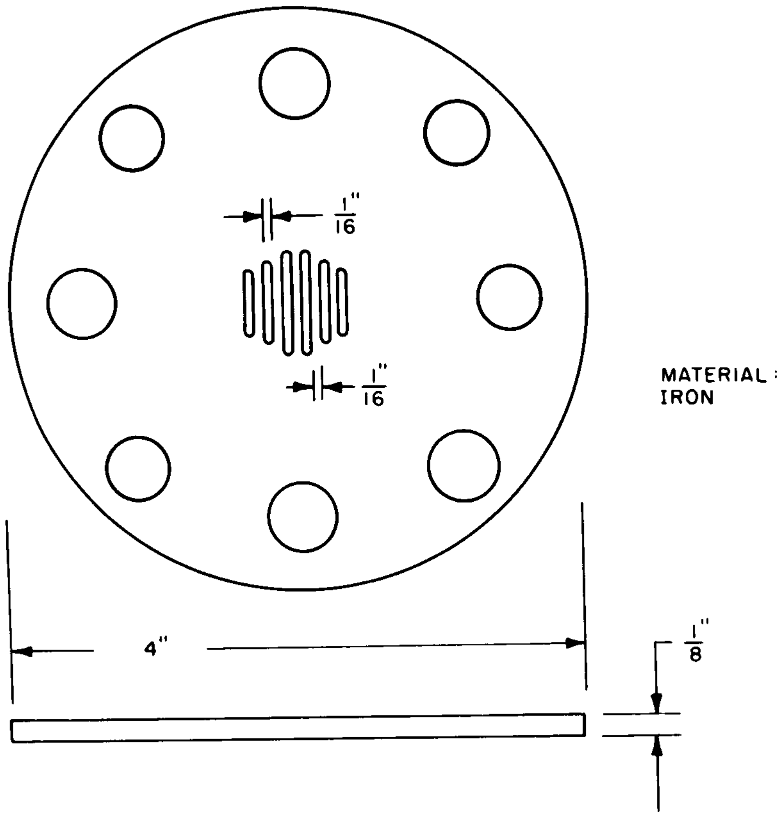

Figure 37 - Control Grid Design for Type Z-7009,
Tube Nos. 20 and 21

(5) The longest bar is considered in the following expression in order to develop the worst case of temperature rise.

Thus, we have

$$T = \frac{PL}{KA} = \frac{2.5(0.95)}{0.67\ (0.005)} = \frac{2.4}{0.033} = 72^{\circ}C$$

where: T = temperature rise in degrees centigrade between end of bar and its midpoint

P = one-half the power entering the grid bar = 5/2 = 2.5 watts

L = one-half the length of the longest bar = 3/8 inch = 0.95 centimeter

K = coefficient of thermal conductivity for iron = $0.67 \frac{\text{watts}}{(\text{cm})(^{\circ}\text{C})}$

A = cross section area of bar = $(1/16)(1/8) = \frac{1}{128}$

= 0.0078 square inch

= 0.05 square centimeter

Based on the aforementioned assumptions, the center of the bar could run 72°C hotter than the ends of the bar. This temperature rise should be added to the temperature rise occurring between the outer edge and the portion of the grid containing the slots. The development employed in calculating the latter temperature rise will now be discussed:

(1) The following expression is given[3] for the case of radial heat conduction in a tube having an inner radius r_i, and outer radius r_o, and a length L.

$$Q = \frac{t_i - t_o}{\left[(1/2\pi\ KL) \ln \frac{r_o}{r_i}\right]}$$

If: r_i, r_o, and L are in centimeters,

t_i = temperature at inner radius in degrees C,

t_o = temperature at outer radius in degrees C, and

3. Eckert, E.R.G., Drake, R.M., Jr., Heat and Mass Transfer, 1st Edition, New York: McGraw-Hill Company, (1959), p 37

K = coefficient of thermal conductivity in watts per centimeter per degree C,

then: Q, the heat flow is expressed in terms of watts.

(2) This formula may be converted to

$$P = \frac{T}{(1/2\,\pi\, K_{th}) \ln \frac{r_o}{r_i}}$$

where: P is directly substituted for Q since, in our example, P is the power input (to the grid) in watts,

th is directly substituted for L to denote thickness of the grid,

T is substituted for $(t_i - t_o)$ to denote temperature change, for which

$$T = \frac{P}{2\,\pi\, K_{th}} \ln \frac{r_o}{r_i}$$

(3) Heat flows from the innermost part of the grid radially to the outer edge, with the innermost part of the grid being defined as a circular opening which will barely contain the slotted portion of the grid. For the grids discussed, the circular opening has a diameter of 3/4 inch.

(4) The amount of heat flow is equal to the power arriving at the grid from the cathode, plus the grid dissipation resulting from the discharge. This is the aforementioned 10 watts plus 1/2 cathode power = 10 + 40 = 50 watts.

(5) The values are now known for calculating T, the temperature rise:

P = 50 watts

$$K = 0.67 \frac{\text{watts}}{(\text{cm})(^{\circ}\text{C})}$$

th = thickness of grid = 1/8 inch = 0.32 cm

r_o = outer radius of disc = 2 inches = 5.08 cm

r_i = inner radius of disc = 3/8 inch = 0.95 cm

Substituting, we obtain

$$T = \frac{50}{2\pi(0.67)\,0.32} \ln \frac{5.08}{0.95}$$

$$= \frac{50}{1.34} \ln 5.3$$

$$= 3.74\,(1.67) = 62^{\circ}C$$

The total temperature rise from the outer edge to the center of the grid thus becomes $72^{\circ}C + 62^{\circ}C = 134^{\circ}C$.

Three modifications were made in a redesign of the grid (Figure 38) for Type Z-7009, Tube No. 22, to reduce the temperature gradient at the grid:

(1) The material was changed from iron to copper. With the higher conductivity of copper (K = 3.88), a gain of 3.88/0.67 = 5.8 should be realized.

(2) The thickness of the grid was changed from 1/8 to 1/4 inch, resulting in another gain of 2.

(3) The width of the grid bars was changed from 1/16 to 3/32 inch, producing an additional gain of 1.5 at the grid bars.

The overall gain (or reduction factor for temperature gradient) at the grid bars becomes 5.8 (2) 1.5 = 18, and the overall gain for the solid outer portion of the grid becomes 5.8 (2) $\approx$ 11. For the proposed copper grid, and the same power assumptions made for the iron grid, the temperature rise at the grid bar = 72/18 = $4^{\circ}C$, and for the outer portion = 62/11 $\approx$ $6^{\circ}C$. Thus, the hot-spot temperature of the copper grid should be only about $10^{\circ}C$ higher than the temperature at the outer edge.

Test results for Type Z-7009, Tube No. 22, confirmed the above estimates, and grid control at 15 amperes average was demonstrated for temperatures (measured at the outer edge of the grid) to $360^{\circ}C$ maximum, or roughly 100 degrees higher than the corresponding maximum temperature for the iron grid. Figure 39 illustrates the comparison as a function of average current. With these measurements, and the knowledge of the relative conductivities of the grids, it may be estimated that the critical hot-spot temperature at which grid control is lost is about $375^{\circ}C$. While Tube Nos. 21 and 22 were compared initially under similar conditions, and with reservoir temperatures of about $250^{\circ}C$, subsequent testing of No. 22 over a long

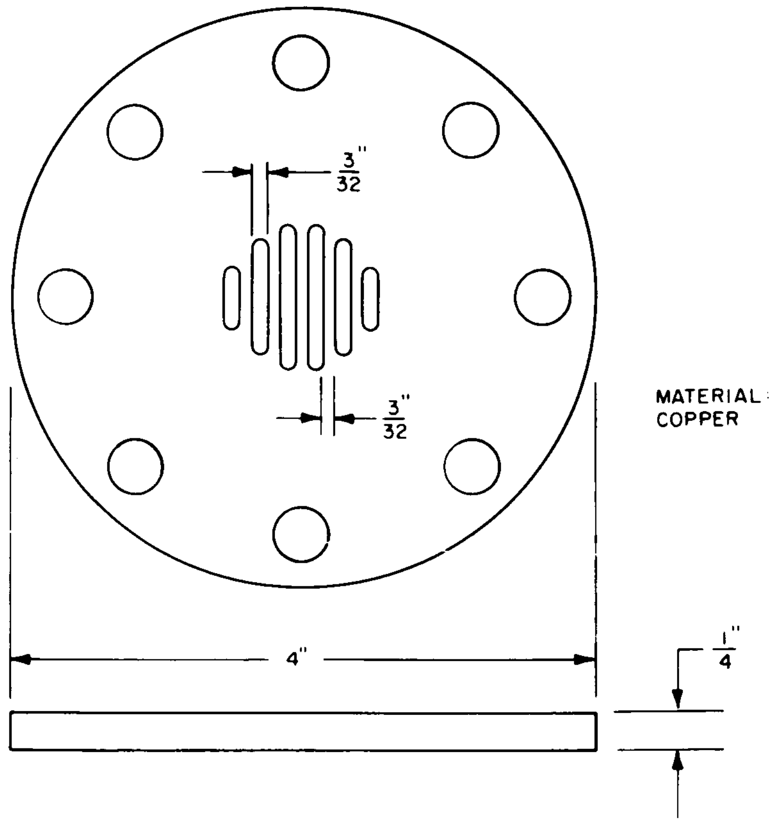

Figure 38 - Control Grid Design for Type Z-7009, Tube No. 22

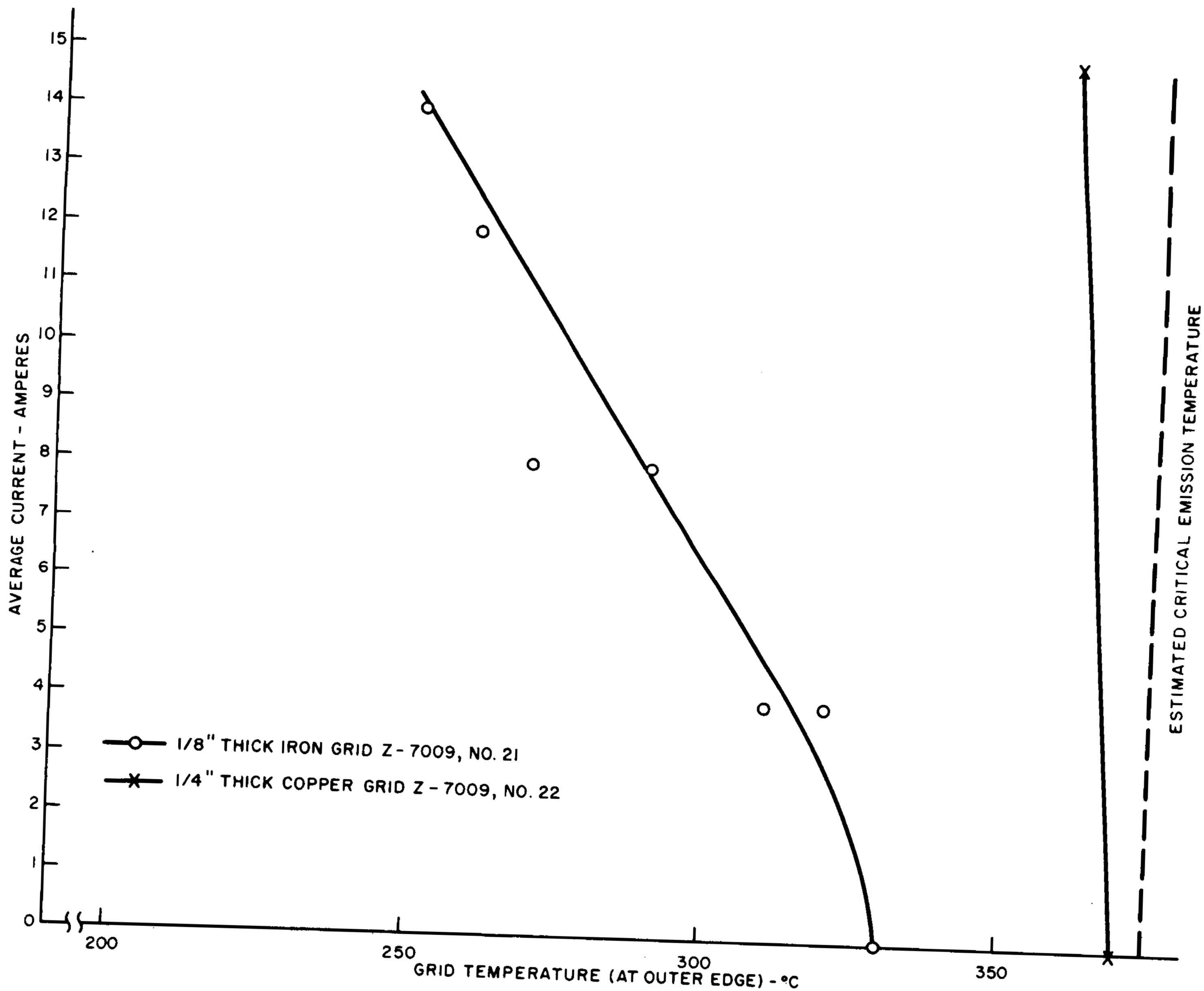

Figure 39 - Maximum Average Current with Grid Control Versus Grid Temperature

period of time, and with other reservoir temperatures, indicated that the grid temperature should be limited to 300°C maximum. This point will be discussed further in the section which follows (see "Endurance Run").

The grid characteristic and maximum controllable voltage for Tube No. 22 are given in Figures 40 and 41, respectively.

High-frequency performance was appraised by connecting the tube and load to a variable-frequency power supply and determining at what frequency grid control deteriorated. Anode voltage was set at 110 volts RMS since, with available equipment, it was impossible to have high voltage and high current simultaneously.

It was determined that up to a certain frequency, grid control was not altered from the 60-cycle case. Above this frequency, there was a rapid rise in the negative grid-supply voltage needed to maintain grid control. This reflected the need, at high frequency, for collecting ions at the grid or permitting the grid to contribute to the deionization of the tube. The increase in grid-supply voltage over that needed for the 60-cycle case was termed excess bias-supply voltage, and the latter was plotted as a function of frequency (Figure 42) for various average currents. The effect of cesium temperature on high-frequency performance is given in Figure 43. In this testing, a full half-cycle was available for deionization and recovery. The maximum frequency attainable by cesium tubes in an inverter circuit would be considerably reduced, since in such a circuit only a fraction of the half-cycle would be available for recovery.

ENDURANCE RUN

The purpose of the endurance run was to subject one of the Type Z-7009 thyratrons to a 1000-hour test at rated load and voltage while operating at an environmental temperature of 300°C.

A simulation circuit was planned in which the thyratron would be connected to the 110-volt a-c shop line for one half-cycle and to a low-current, high-voltage transformer on the subsequent half-cycle. Thus, the tube could conduct 15 amperes average from the low-voltage shop line on even half-cycles and be subjected to the low-power, high-voltage circuit on odd half-cycles. With variac control, the inverse voltage applied to the tube could be varied between 0 and 750 volts. The necessary switching functions would be accomplished by two industrial thyratrons as shown in Figure 44.

The endurance run was initiated before the simulation circuit was available. Thus, approximately 500 hours of operation were logged with a

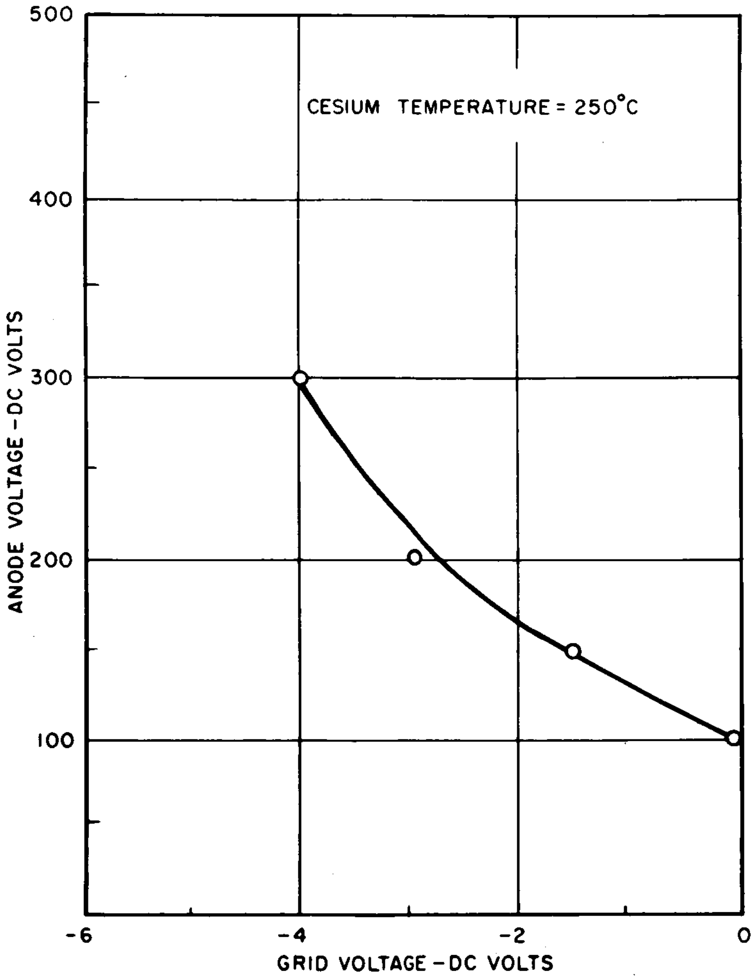

Figure 40 - Grid Characteristic, Type Z-7009, Tube No. 22

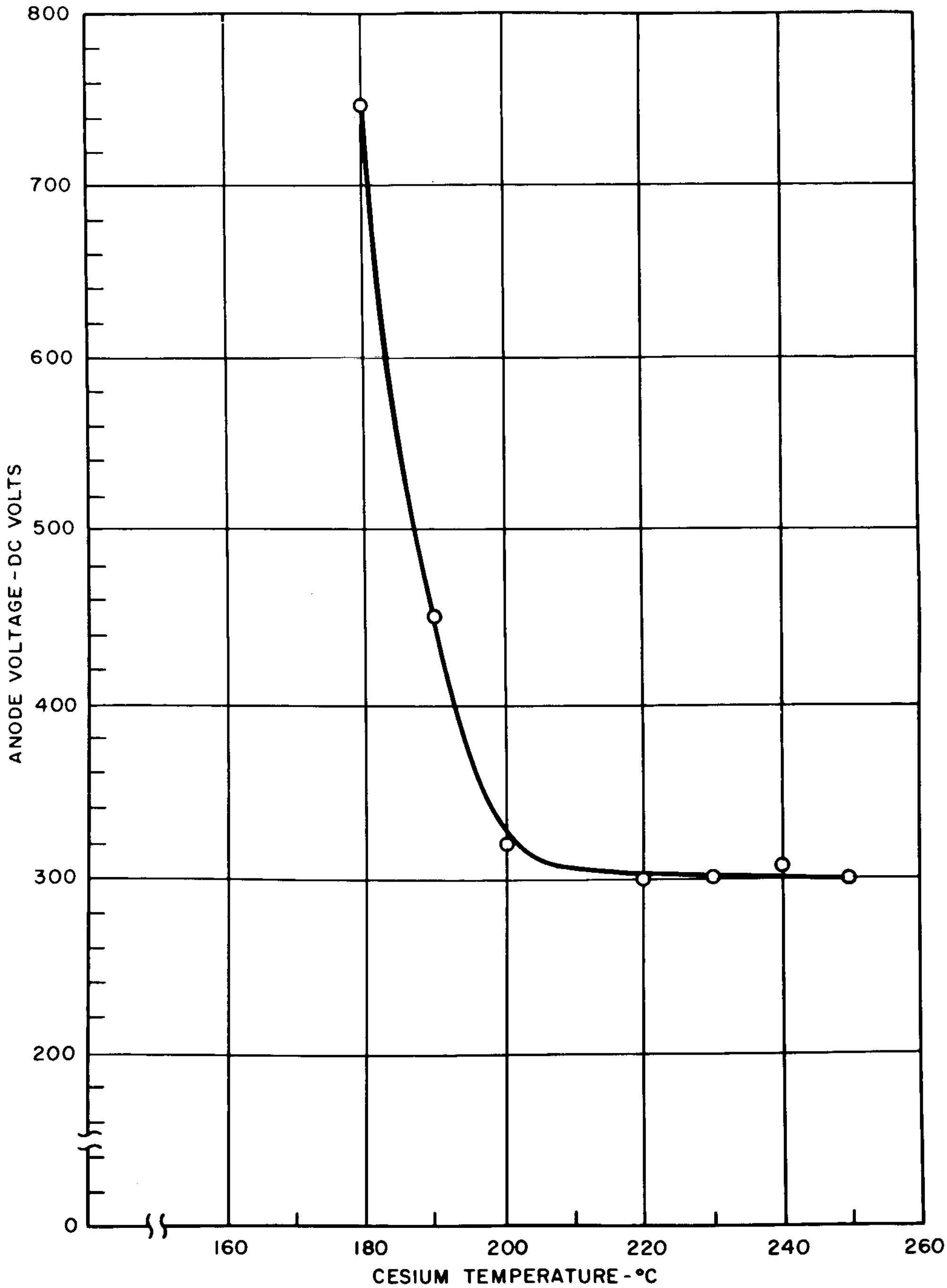

Figure 41 - Maximum Controllable D-C Voltage Versus Cesium Temperature, Type Z-7009, Tube No. 22

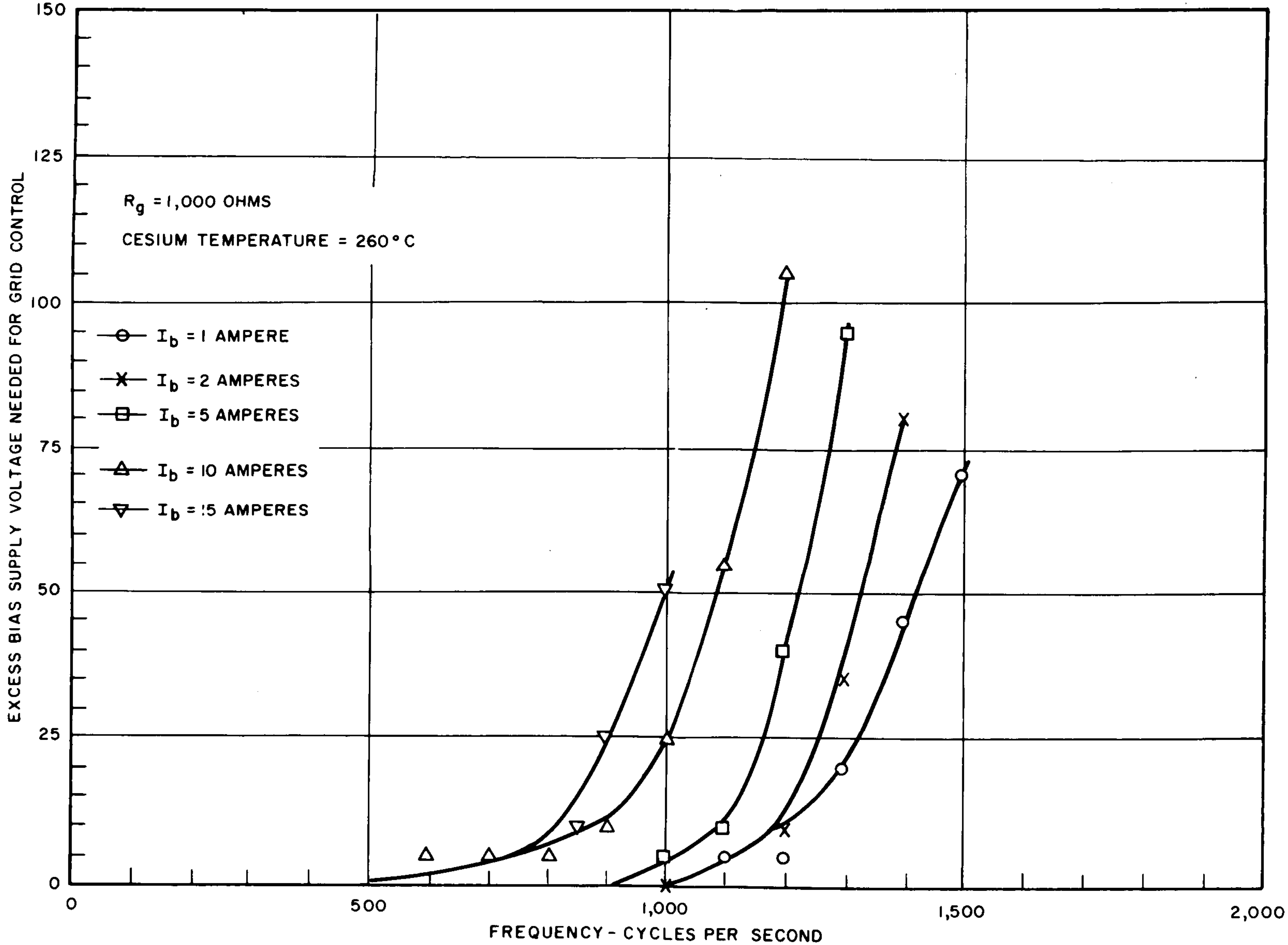

Figure 42 - High-Frequency Performance, Type Z-7009, Tube No. 22

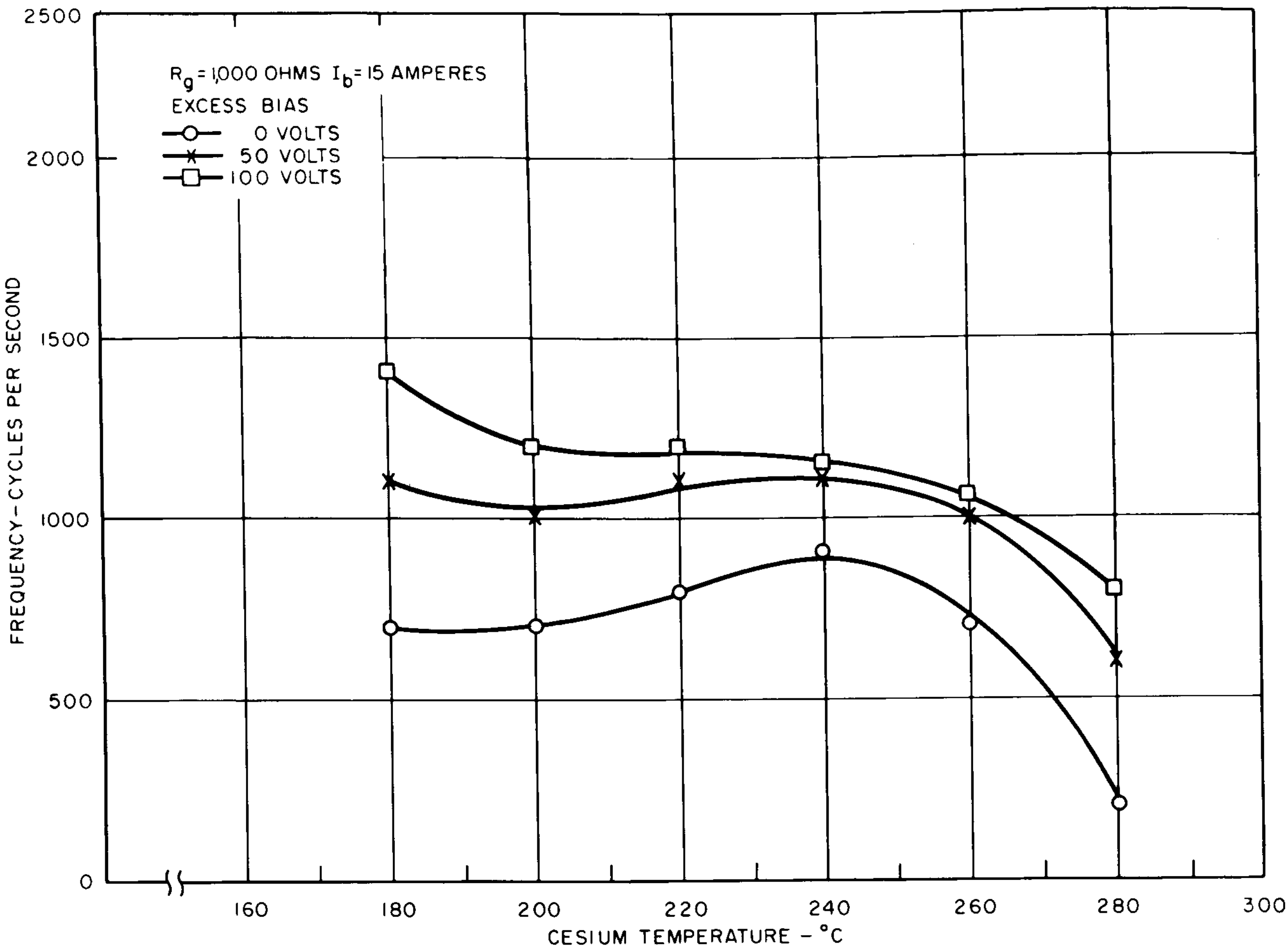

Figure 43 - Maximum Frequency Versus Cesium Temperature
Type Z-7009, Tube No. 22

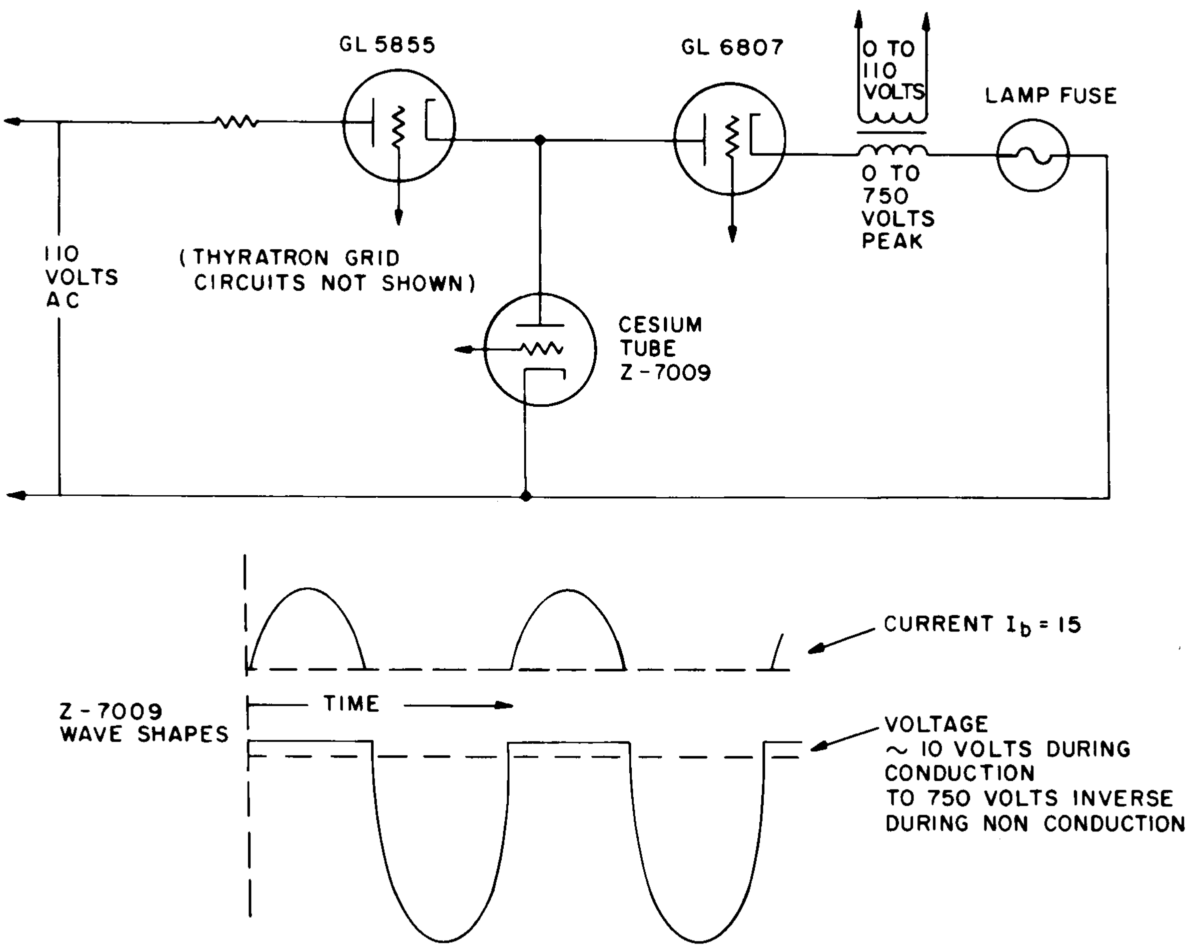

Figure 44 - Schematic of High Inverse Voltage Simulation Circuit

110-volt a-c supply only, wherein the inverse voltage was limited to 150 volts. From 500 hours on, the tube was subjected to higher inverse voltages.

The tube selected for the endurance run was Type Z-7009, Tube No. 22. As mentioned previously, this tube performed initially with a grid temperature as high as 350°C. Subsequent experience, however, disclosed the fact that freedom from grid emission could not be assured unless the heat-sink temperature for the grid was limited to 300°C. The cause of the apparent reduction in the grid emission ceiling of 50 degrees is not fully understood, but the following factors have a bearing on the matter.

(1) Early testing was conducted at a reservoir temperature of approximately 250°C. It was subsequently determined that grid emission reached a maximum when the reservoir temperature was reduced to the range of 220°C to 230°C. Maximum permissible grid temperature as a function of reservoir temperature is shown in Figure 45. Loss of grid control was used as the criterion of maximum permissible grid temperature. Tube conduction was 15 amperes average.

(2) A slight change in the work function of cesium on the copper (grid) substrate may have occurred.

(3) The early test possibly was not conducted over a period of sufficient duration to allow all of the surroundings -- such as the tube support stand and bell jar -- to reach equilibrium temperature.

Throughout the endurance run, anode temperature was maintained at 300°C or higher, and the grid was held at 290°C to 300°C. Periodic tests were taken to ascertain the status of the following tube parameters: tube drop at 100 amperes peak, tube drop at 15 amperes average (with d-c supply), starting voltage for zero bias at grid, and the necessary negative bias to hold off 300 volts applied to the anode. Plots of these characteristics are shown in Figures 46, 47, 48 and 49.

At 500 hours, when the aforementioned simulation circuit was completed, reservoir and anode temperature conditions were varied in order to obtain the maximum inverse-voltage capability of the tube. Refer to Figures 50 and 51. The curves in these figures are based on short-term data where the operating time for each point was of only a few seconds duration, the time required to set up the condition and make observations on an oscilloscope.

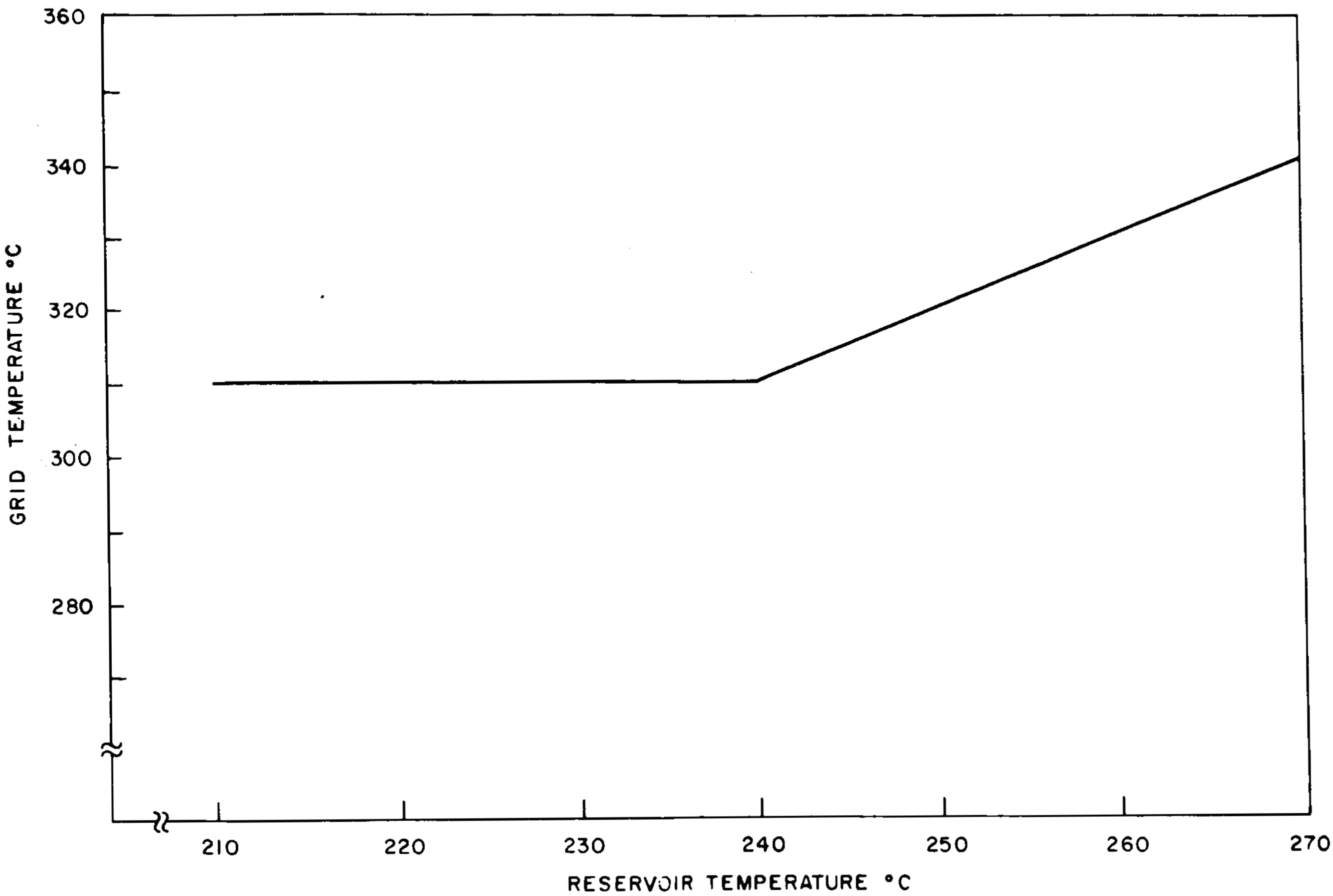

Figure 45 - Maximum Permissible Grid Temperature Versus Reservoir Temperature, Type Z-7009, Tube No. 22

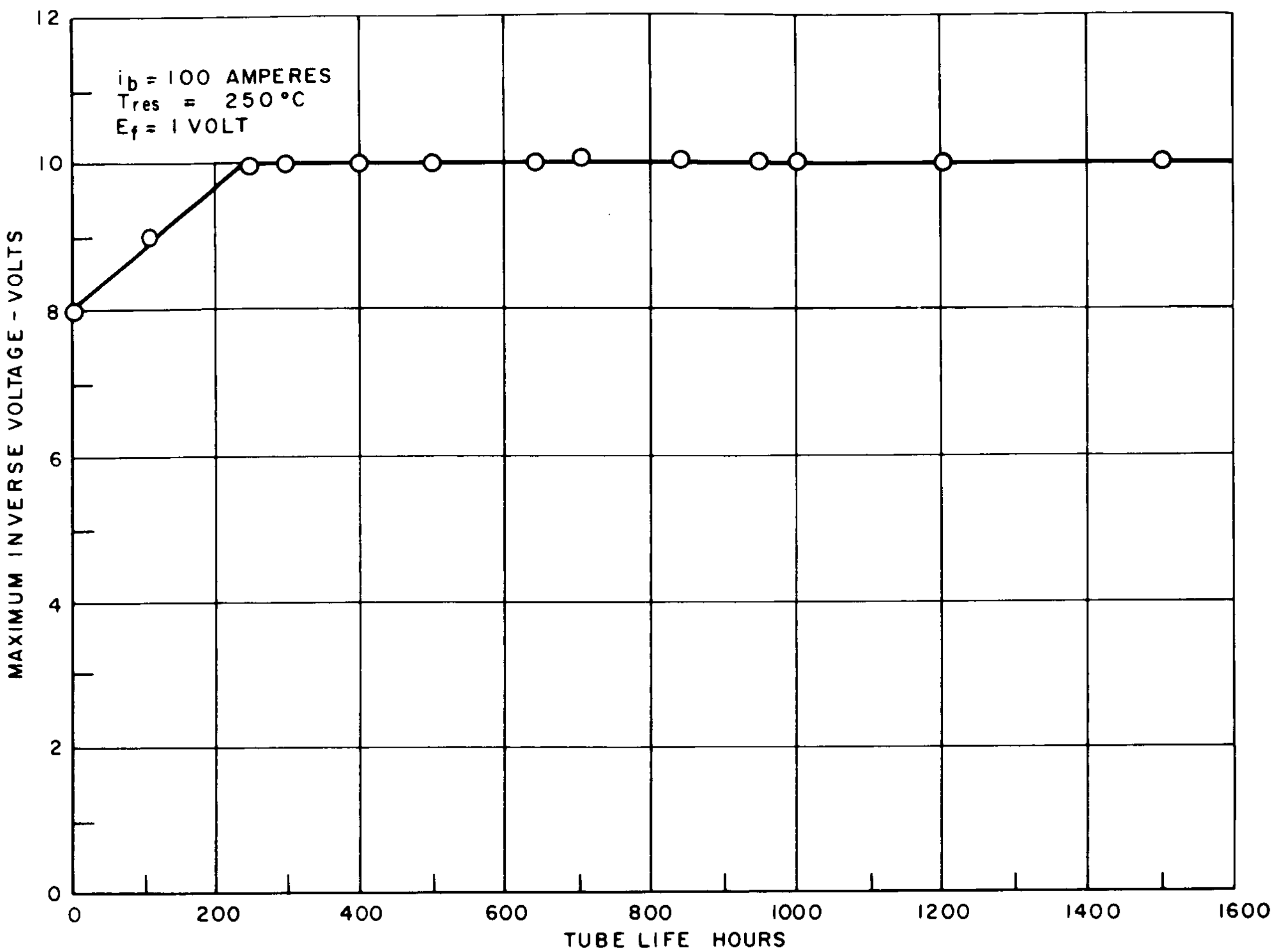

Figure 46 - Peak Tube Drop Versus Life, Type Z-7009, Tube No. 22

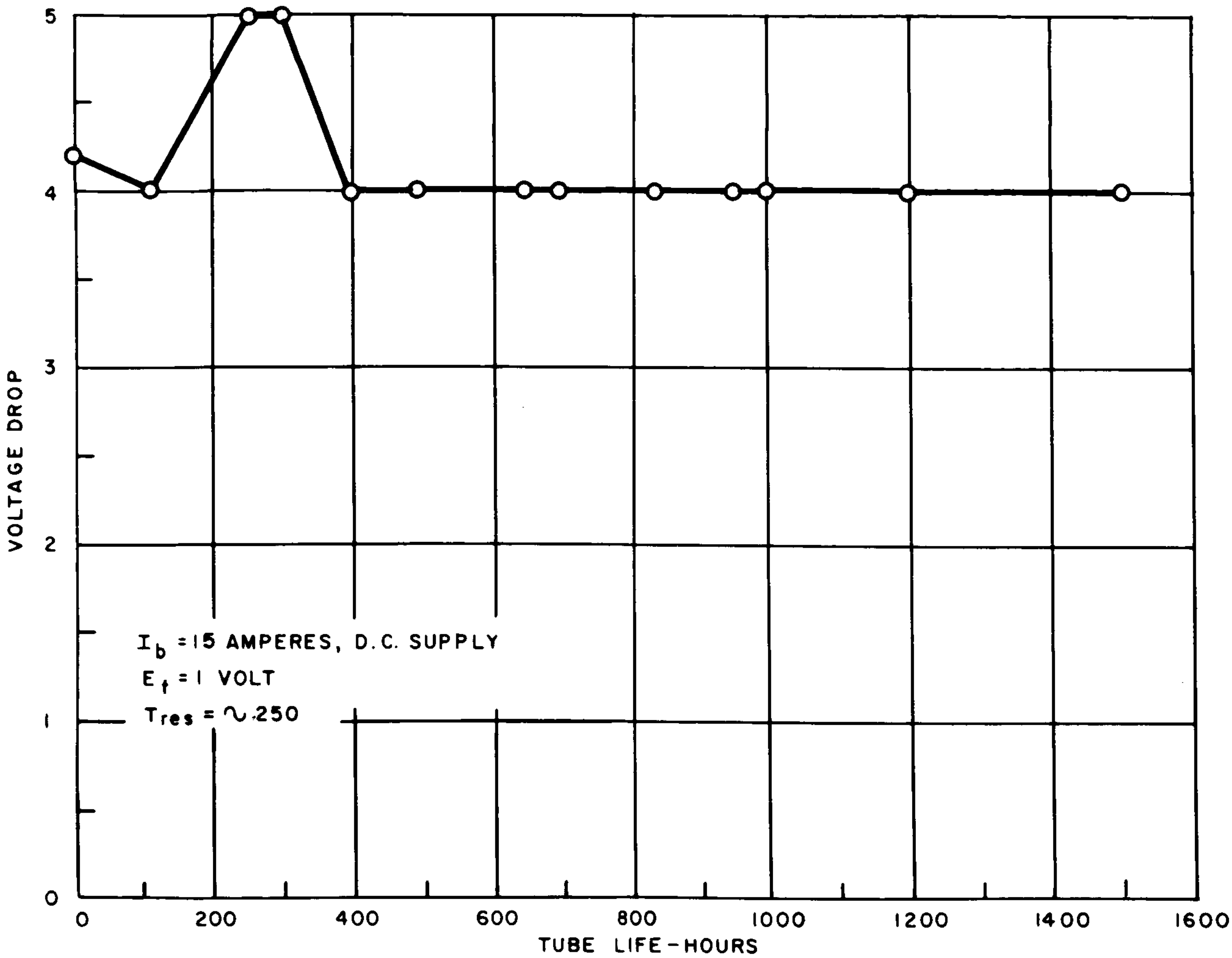

Figure 47 - D-C Tube Drop Versus Life, Type Z-7009, Tube No. 22

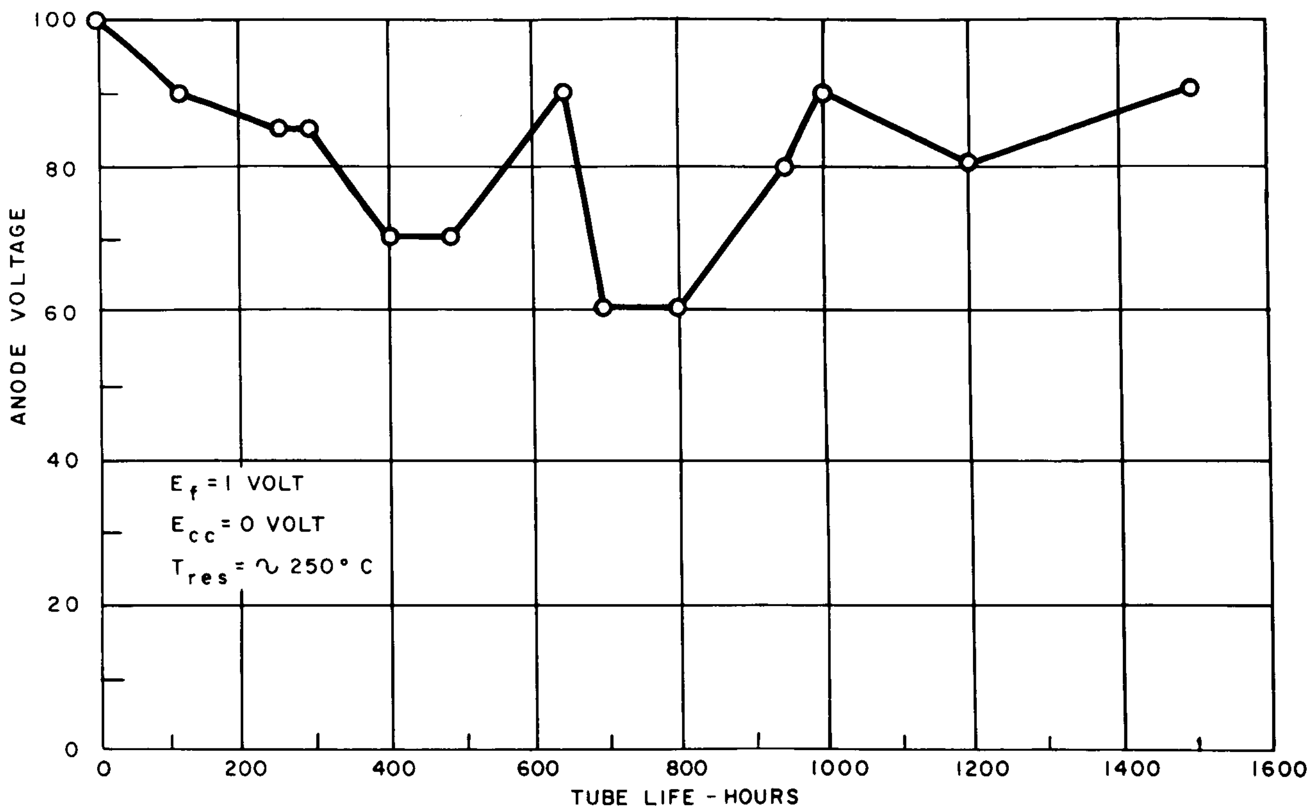

Figure 48 - Starting Voltage Versus Life, Type Z-7009, Tube No. 22

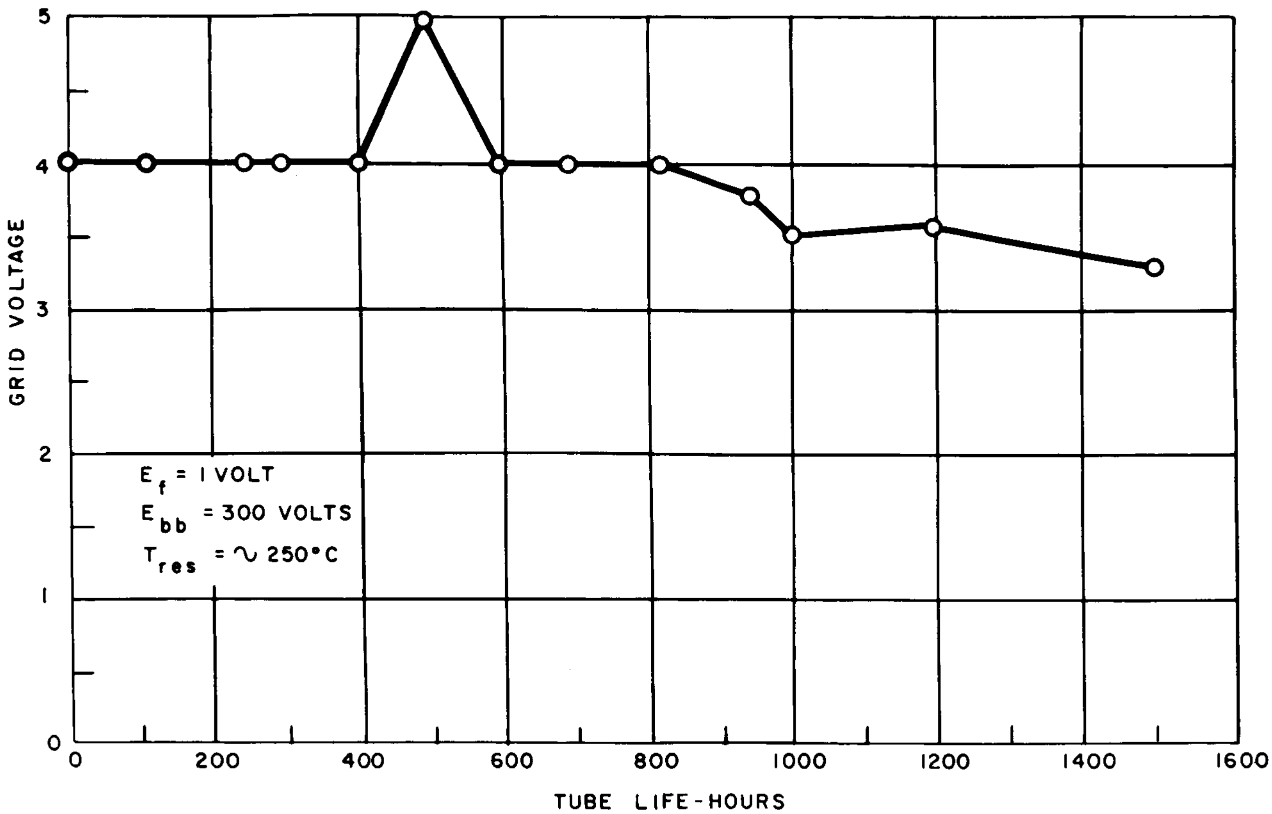

Figure 49 - Grid Characteristic Versus Life, Type Z-7009, Tube No. 22

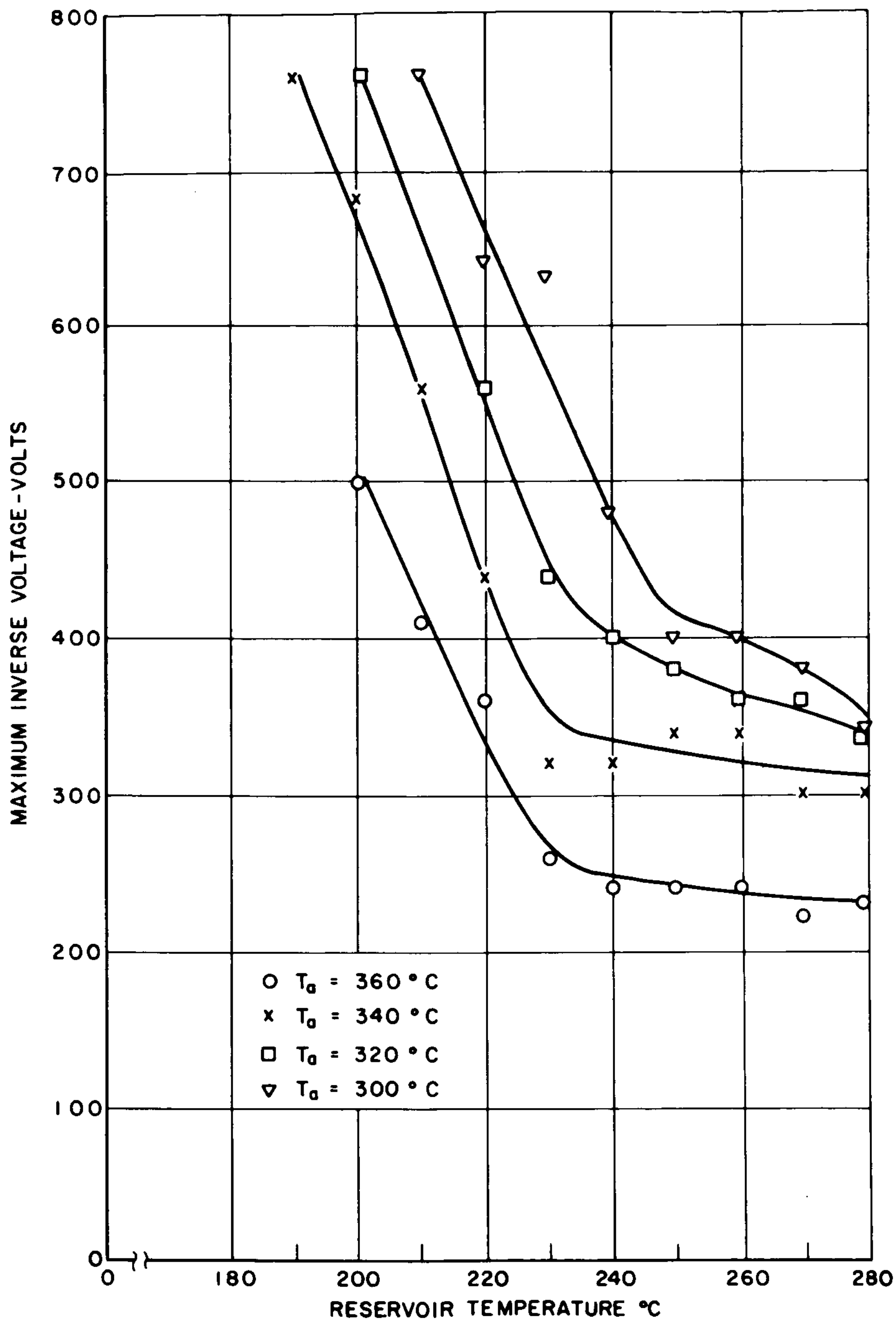

Figure 50 - Short-Term Maximum Inverse Voltage Versus Reservoir Temperature, Type Z-7009, Tube No. 22

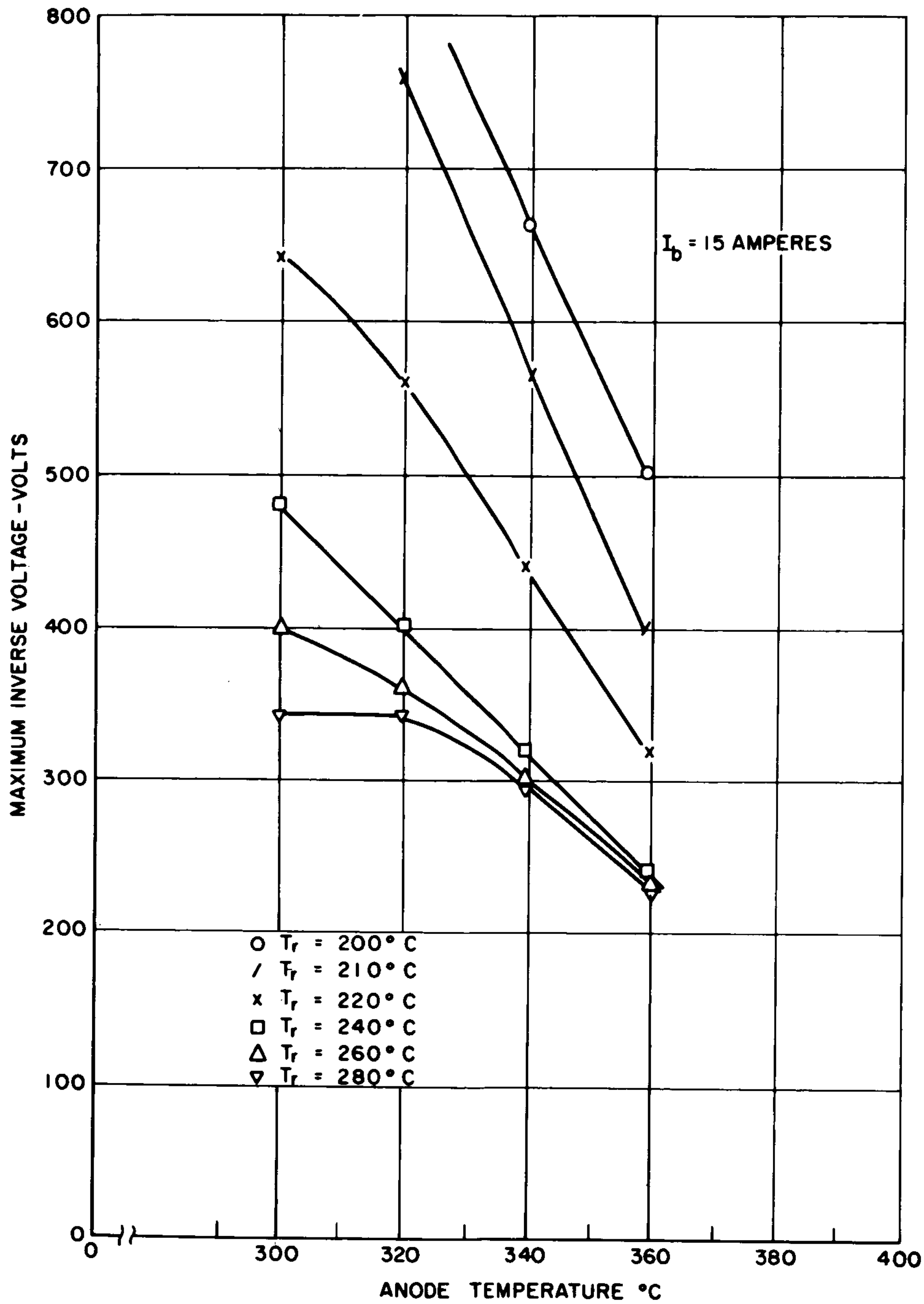

Figure 51 - Short-Term Maximum Inverse Voltage Versus Anode Temperature, Type Z-7009, Tube No. 22

It was assumed that over long operating periods some degradation in maximum inverse voltage might be observed as a result of a statistical increase in triggering agents such as cosmic rays, variation or surges in applied line voltage, and temperature fluctuations at the tube. Accordingly, additional data were taken for longer term points, where each point represents successful operation without arc-back for a period of approximately 24 hours. Comparisons of short-term and long-term results for two different anode temperatures are given in Figures 52 and 53. Approximately 1000 hours were used in obtaining the long-term data.

Although the objective requirement for the endurance run was 1000 hours, freedom from failure permitted an accumulation of 1500 operating hours, at which point the run was arbitrarily terminated.

CONCLUSIONS

Several materials show promise of being suitable for use as vapor-fills in high-temperature thyratrons and diodes.

(1) Cesium iodide does not dissociate adequately for use as a vapor-fill in high-temperature tubes.

(2) Thallium may be used as a vapor fill for tubes operating in the $600^{\circ}C$ range.

(3) Cesium and rubidium may be used as vapor fill materials for tubes operating generally in the $300^{\circ}C$ range.

(4) The ability of cesium to remarkably reduce the work function of a surface on which it resides leads to extremely simple cathode design and a cathode that is not subject to depletion by evaporation.

(5) Evaluation of three cesium thyratrons (Z-7009) has indicated

a) Emission capabilities are sufficient for meeting the 15-ampere average objective.

b) Heat rejection for the grid and anode in the $250^{\circ}C$ to $300^{\circ}C$ centigrade range is satisfactory.

c) Anode voltage capabilities are 300 volts forward and 500 volts inverse over a reservoir range of $190^{\circ}C$ to $220^{\circ}C$.

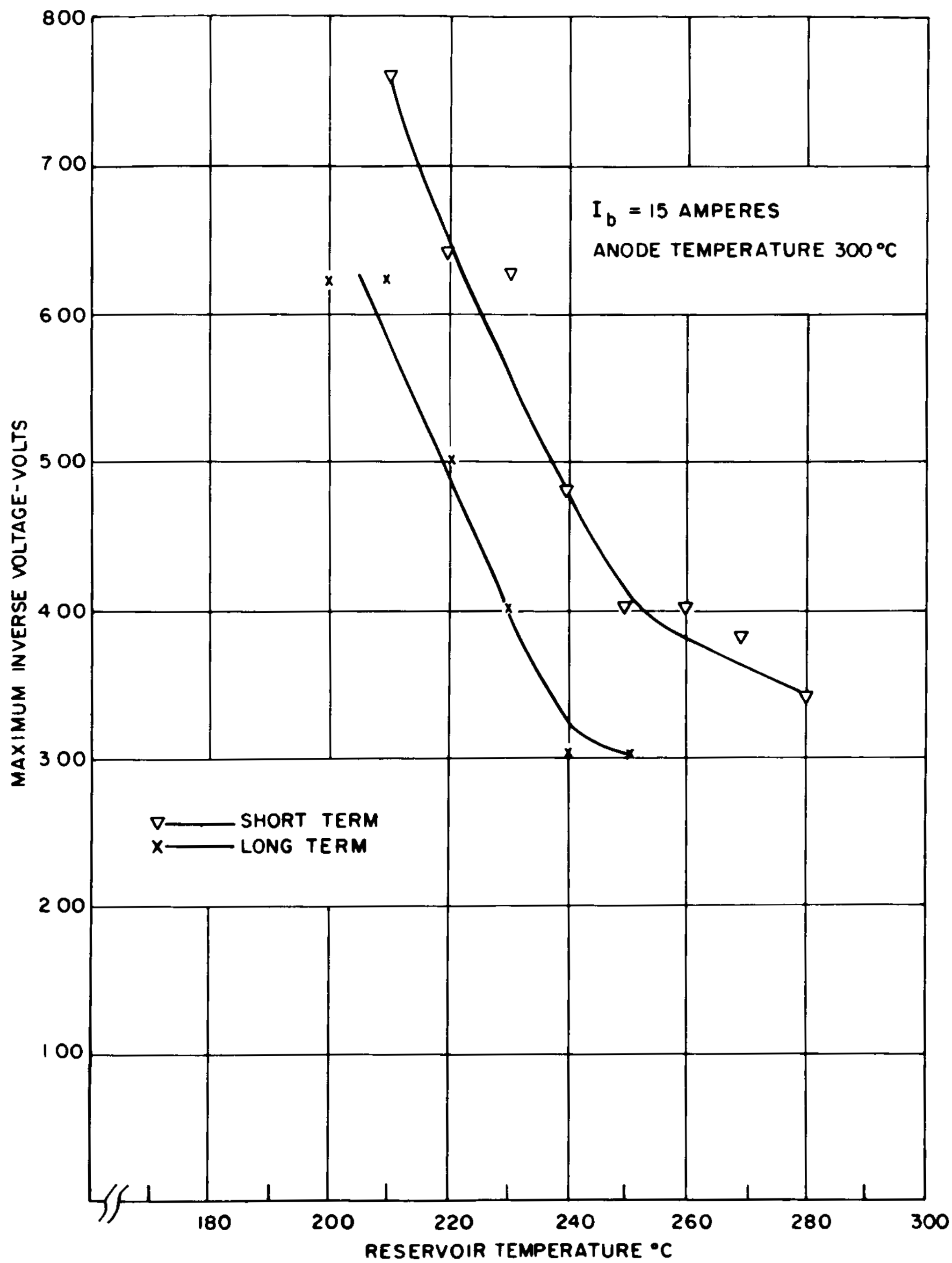

Figure 52 - Maximum Inverse Voltage Versus Reservoir Temperature for Anode Temperature of 300°C Type Z-7009, Tube No. 22

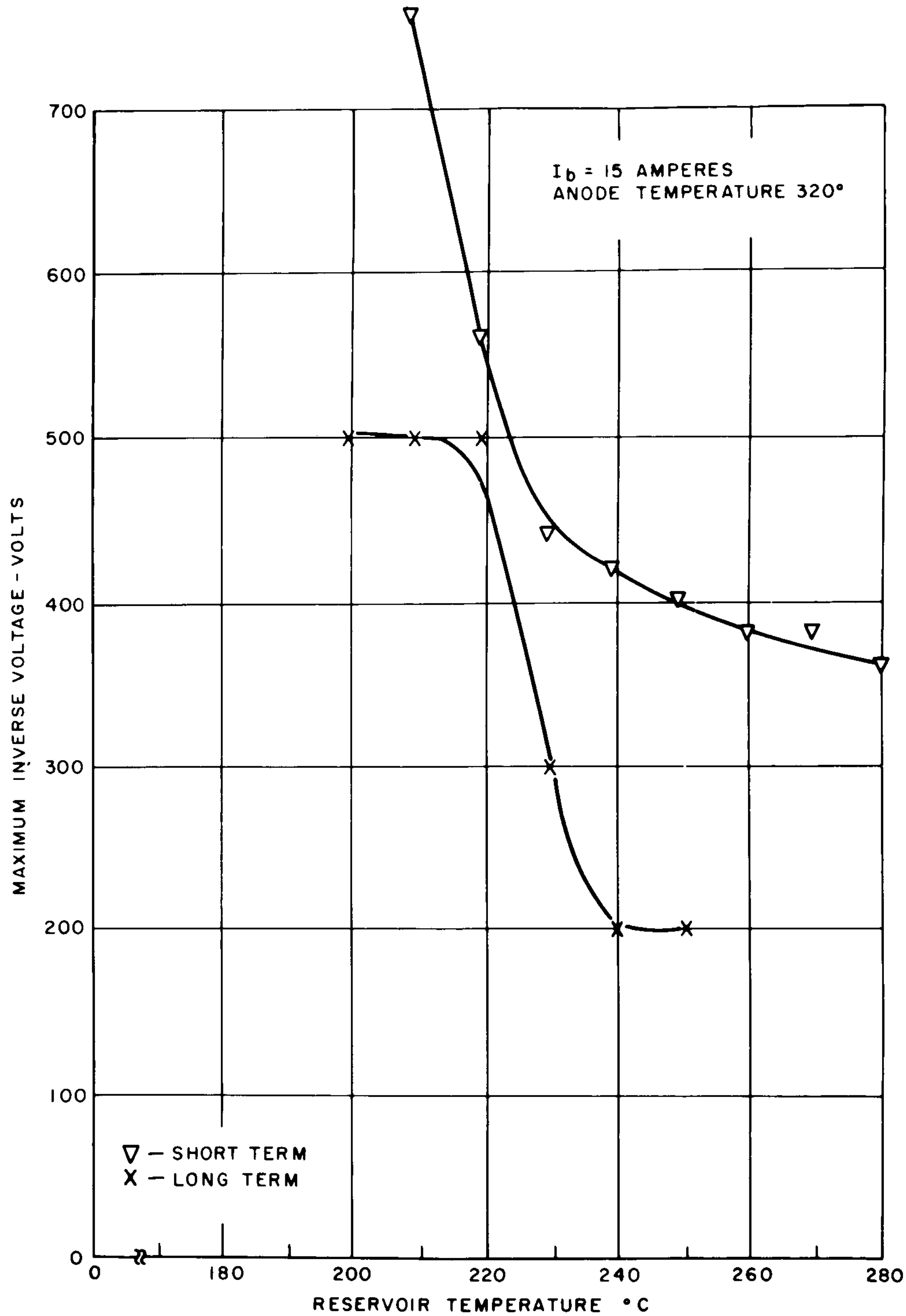

Figure 53 - Maximum Inverse Voltage Versus Reservoir Temperature for Anode Temperature of 320°C, Type Z-7009, Tube No. 22

(6) Operation of a cesium thyratron for 1500 hours of endurance testing has shown no deleterious trends.

(7) Further design modifications would be needed to enable the Type Z-7009 thyratron to reach the objective inverse voltage rating of 750 volts inverse, and to produce a recovery time of 100 microseconds.

Appendix A
FILL MATERIALS FOR 600°C OPERATION

CESIUM IODIDE

As the first pair of tubes were studied on test, it was apparent that the conduction characteristics in forward and inverse directions were essentially the same. Further, the tubes were similar to low-impedance resistors at elevated temperatures and high-impedance (about 20 megohms) resistors at room temperature.

When one tube was opened, a generous metallic coating was evident on the ceramic separating the anode and cathode flanges. X-ray spectroscopic analysis of the coating identified titanium, nickel, cesium, and iodine. A titanium-halogen cycle was suspected as the cause of the coating.

A titanium-halogen cycle permits free titanium to combine with free iodine, with the titanium-iodide product migrating throughout the interior of the tube. Subsequent partial dissociation of the salt occurs leaving free titanium (displaced from its original location) and free iodine. Such a cycle repeats until the relocation of free titanium, associated with localized temperature differences within the tube, produces equilibrium.

The first tubes employed tantalum flange seals, high-purity alumina ceramic, and nickel-titanium brazing washers containing a surplus of titanium so that the resulting eutectic melted at 942°C (Figure A-1). Possible ways to counter the halide cycle were considered as follows:

(1) Variation of titanium-nickel ratio.

(2) Nickel plating the titanium-bearing seal area.

(3) Selection of a sealing material not subject to halogen reaction.

By increasing the ratio of nickel to titanium, the resulting seal could be effected at 1280°C, with the resulting braze consisting primarily of $TiNi_3$, plus TiNi, as shown near the right-hand side of Figure A-1. More important, however, is the fact that there would be less free titanium at the seal structure to trigger a titanium-halogen cycle.

Several attempts to fabricate seals with the $TiNi_3$ were unsuccessful;

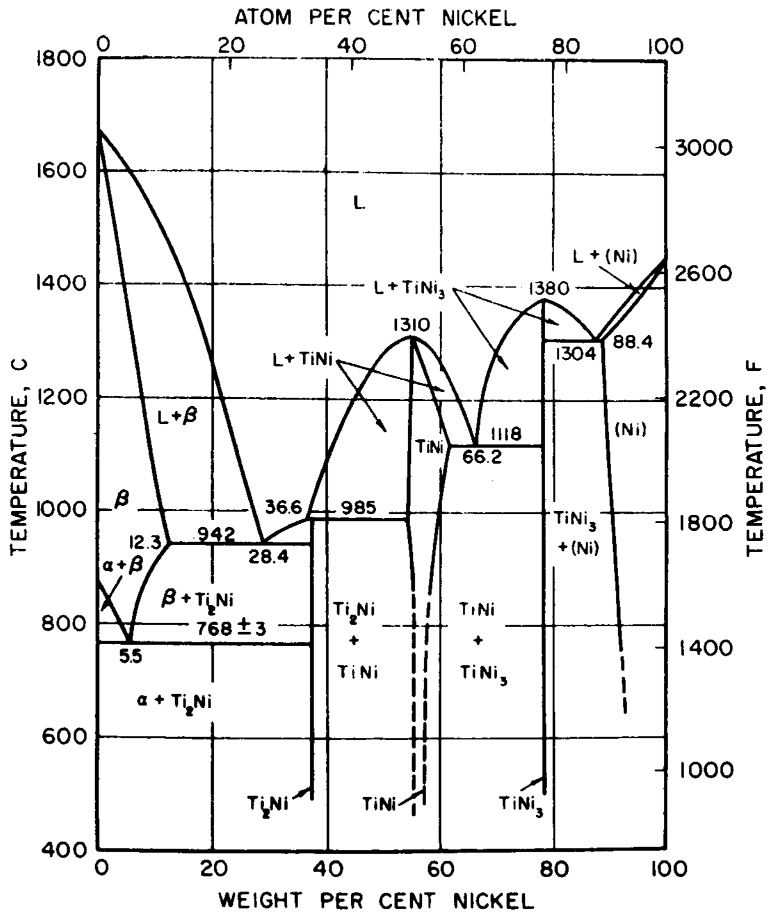

Figure A-1 - Nickel-Titanium Phase Diagram it was concluded that the material was more brittle than the Ti_2Ni alloy and, thus, unsuitable for further study.

Type Z-7009, Tube No. 6, was fabricated with nickel-titanium brazed seals, with the seal area covered by a layer of nickel plating. This approach proved to be inadequate in protecting against the formation of a halogen cycle. Although the cold impedance of the tube was initially 18, 000 ohms, the impedance fell precipitously during test to a fraction of an ohm.

Tube No. 5 utilized a sealing alloy of palladium and cobalt, known as "Palco"*. Since this alloy will not wet tantalum, molybdenum flanges were sealed to the ceramic.

The interelectrode resistance of Tube No. 5, when cold, was greater than 20 megohms and fell to a minimum of 1, 000 ohms when hot (reservoir = 650°C, cathode temperature = 1100°C). Such a leakage path could have been formed by cesium, or the apparent tube impedance could have been caused by emission from the anode and cathode. In any event, the hot (1, 000 ohm) resistance was high enough to permit the tube to be studied as a rectifier. After a number of heat cycles, the cold impedance fell to 1.3 megohms. While this is a significant reduction from the original impedance, the impedance is several orders of magnitude higher than that of comparable tubes made with nickel-titanium brazing alloy.

Some cathode emission was observed in Tube No. 5, although only with a high tube drop of about 50 volts at 5 amperes peak. Thus, either inadequate dissociation of the cesium iodide was occurring, or the presence of negative ions was adversely affecting tube losses.

It was apparent that an outstanding degree of success had not been realized in the alkali-halide filled tubes. Although there had not been enough investigation to conclude positively that alkali-halide tubes were not practical, it became obvious that considerable additional work would be required in any event, and tube design and operation were to become more complex.

Further investigation of alkali-halide fill materials was not scheduled.

*Trade-name of Western Gold and Platinum Company, Belmont, California

THALLIUM

Thallium fill was investigated in Type Z-7009, No. 19, a tube containing a barium system cathode. The tube had wide welding flanges (see Figure 6 in text) to permit disassembly for repair, inspection, or replacement of parts. The cathode was a five-square-centimeter barium-dispenser type, with the thallium reservoir located in a tubulation on top of the anode.

At a cathode temperature of $1100^{\circ}C$, the tube could be operated continuously at an average current of 2 amperes with a voltage drop of about 8 volts. At higher cathode temperatures, 50 to 60 amperes peak could be drawn from the cathode with reasonably low voltage drops (Figure A-2). In the interest of minimizing cathode evaporation, $1100^{\circ}C$ was chosen as the operating temperature.

With the reservoir running at a higher temperature than the tube wall, the tube wall established the thallium vapor pressure within the tube (Figure A-3). Thus, the tube drop was high when the wall temperature was below $580^{\circ}C$, corresponding to the low-equilibrium thallium vapor pressure of 4 microns.

There was evidence of some reaction between thallium and barium, at wall temperatures of $650^{\circ}C$ or higher, corresponding to 30 microns of vapor pressure; at this temperature the tube drop increased when high current densities were drawn from the cathode. At low current densities and at $650^{\circ}C$, the tube drop remained low, but the tube drop became high at any current density, if the thallium pressure was increased sufficiently (Figure A-4).

These curves suggest that a certain amount of unalloyed or uncovered free barium is needed at the cathode surface in order to emit a given current or rate of electron flow. Whether or not sufficient free barium exists, depends upon the balance between the arrival rate of thallium molecules (which is proportional to vapor pressure) and the diffusion rate of free barium (which is dependent on cathode temperature).

Maximum inverse voltage as a function of anode temperature, which is given in Figure A-5, was obtained in a half-wave rectifier circuit having a load resistance of 25,000 ohms.

A life test was started with the following operating conditions:

(1) Cathode heater power, 170 watts (corresponding to a cathode temperature of $1100^{\circ}C$.

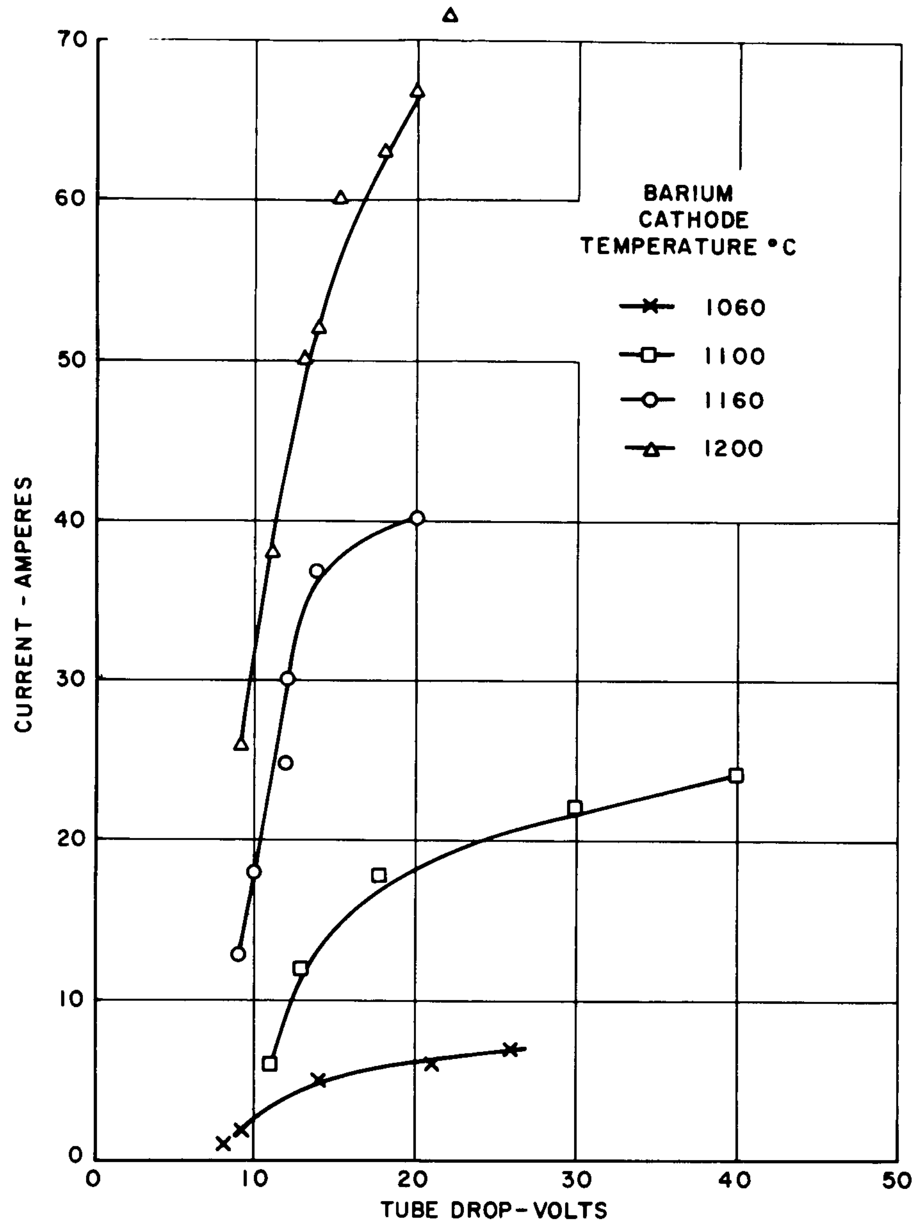

Figure A-2 - Current Versus Voltage, Type Z-7009, Tube No. 19

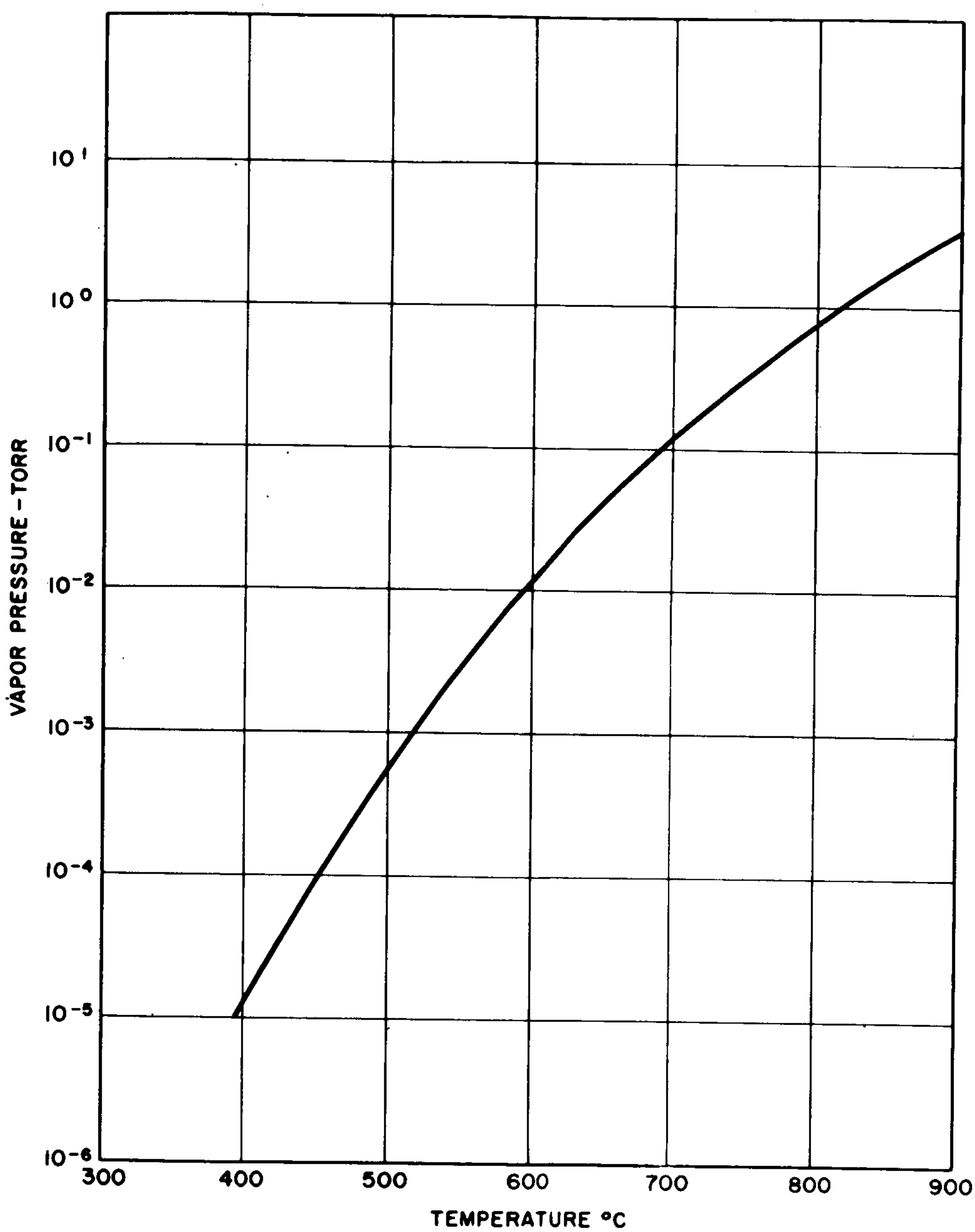

Figure A-3 - Vapor Pressure Curve for Thallium

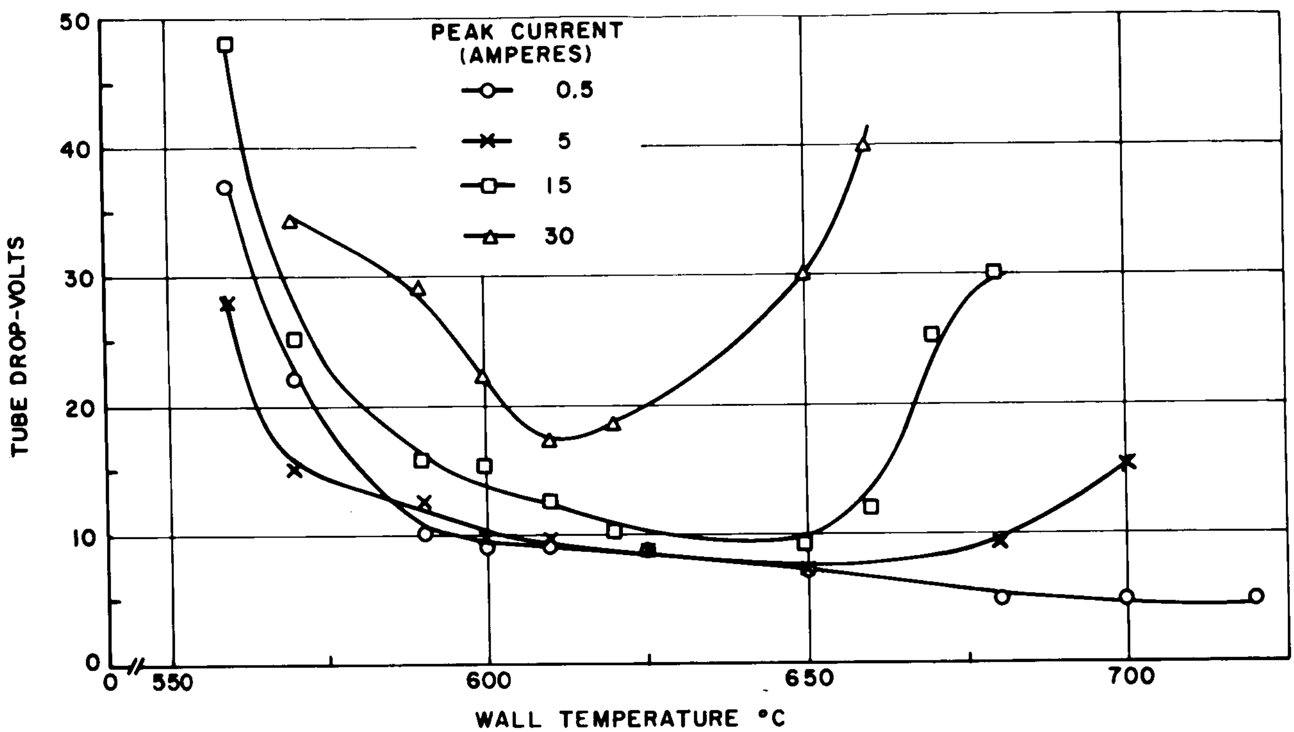

Figure A-4 - Tube Drop Versus Wall Temperature, Type Z-7009, Tube No. 19

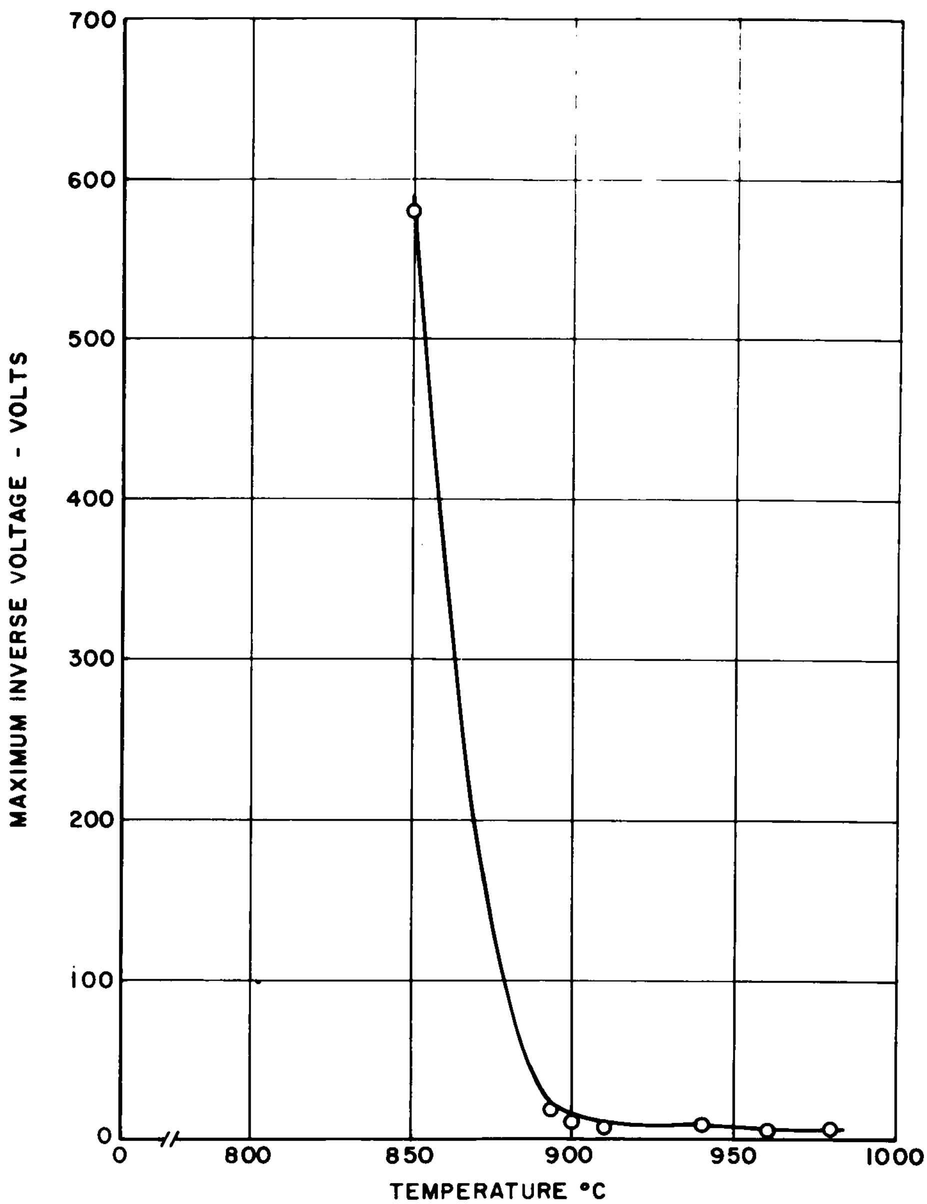

Figure A-5 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 19

(2) Wall temperature, 600°C to 630°C.

(3) Thallium vapor pressure, 8 to 20 microns.

(4) Average current, 2 amperes.

(5) Peak current, 6 amperes.

Cathode emission was checked during life testing by measuring the tube drop at various peak currents, yielding the curves shown in Figure A-6. The cathode seemed to improve during life, as indicated by the fact that initially the tube drop for 20 amperes peak exceeded 25 volts, whereas at the end of the test, the tube drop was less than 25 volts for a peak current three times as high.

After 500 hours of operation, the life test was discontinued, and the following tests were conducted:

(1) Inverse emission versus anode temperature.

(2) Effect of thallium pressure on cathode emission.

(3) High-frequency operation.

Inverse anode emission had increased, thus indicating that the maximum anode temperature should not exceed 800°C.

When thallium vapor pressure was increased by elevating the wall temperature to 750°C, cathode emission was reduced, though not to the same extent indicated by the curves of Figure A-4. Emission reduction was temporary as end-of-life emission (Figure A-6) was regained when the tube-wall temperature was reduced.

When connected to a variable-frequency power supply, the tube was successfully operated as a half-wave rectifier at frequencies to 6,000 cycles per second. Inverse voltage was set at 150 volts and average current at 2 amperes. No attempt was made to check the upper limit of thallium pressure during this test. Finally, the tube was operated for 2 hours at an average current of 2 amperes, with the supply frequency set at 3,000 cycles per second.

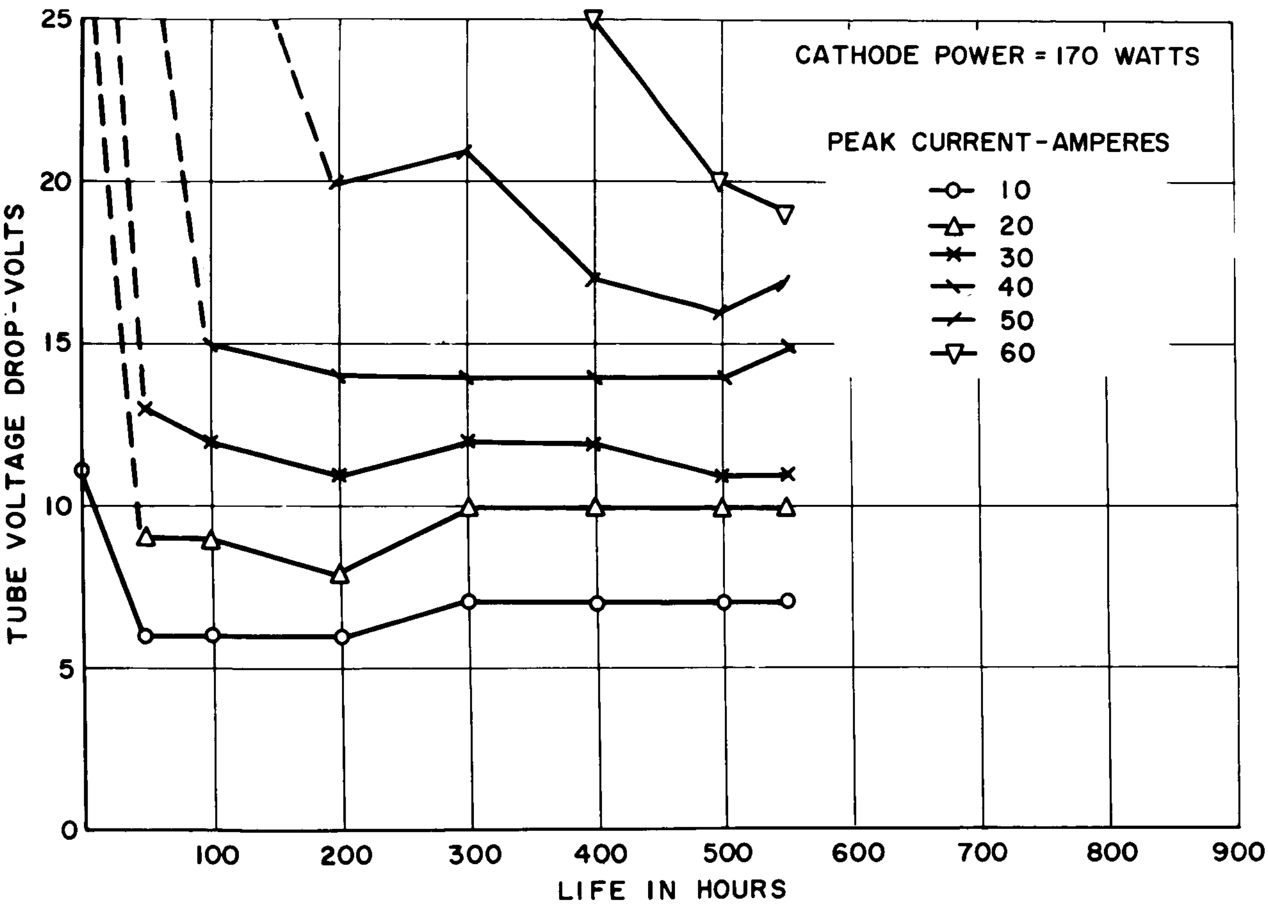

Figure A-6 - Tube Drop Versus Life in Hours, Type Z-7009, Tube No. 19

Appendix B

COATED ANODES

Two tubes -- Type Z-7009, Nos. 7 and 8 -- were constructed, in which the molybdenum anodes were coated with zirconium carbide and hafnium, respectively, by a plasma jet spraying process.

The inverse voltage characteristic (Figure B-1) of the ZrC coated anode (Tube No. 7) showed no improvement over the case for bare molybdenum. Hafnium (Tube No. 8) showed some improvement over bare molybdenum, although not a significant amount (Figure B-2). A degradation in the inverse-voltage capability, as a result of thermal emission, occurred at an anode temperature of 410°C. This compares with a corresponding anode temperature of 380°C for the case of an uncoated molybdenum anode. Tube No. 8 was studied through a cesium reservoir temperature range of 300°C to 125°C, corresponding to a pressure range of 1200 to 3 microns. At the low end of the range, there was an improvement in the inverse-voltage characteristic, since 560 volts inverse could be sustained at an anode temperature of 620°C. This is of academic interest only, because the cathode emission is restricted to very low current levels when the cesium pressure is low enough to permit this gain.

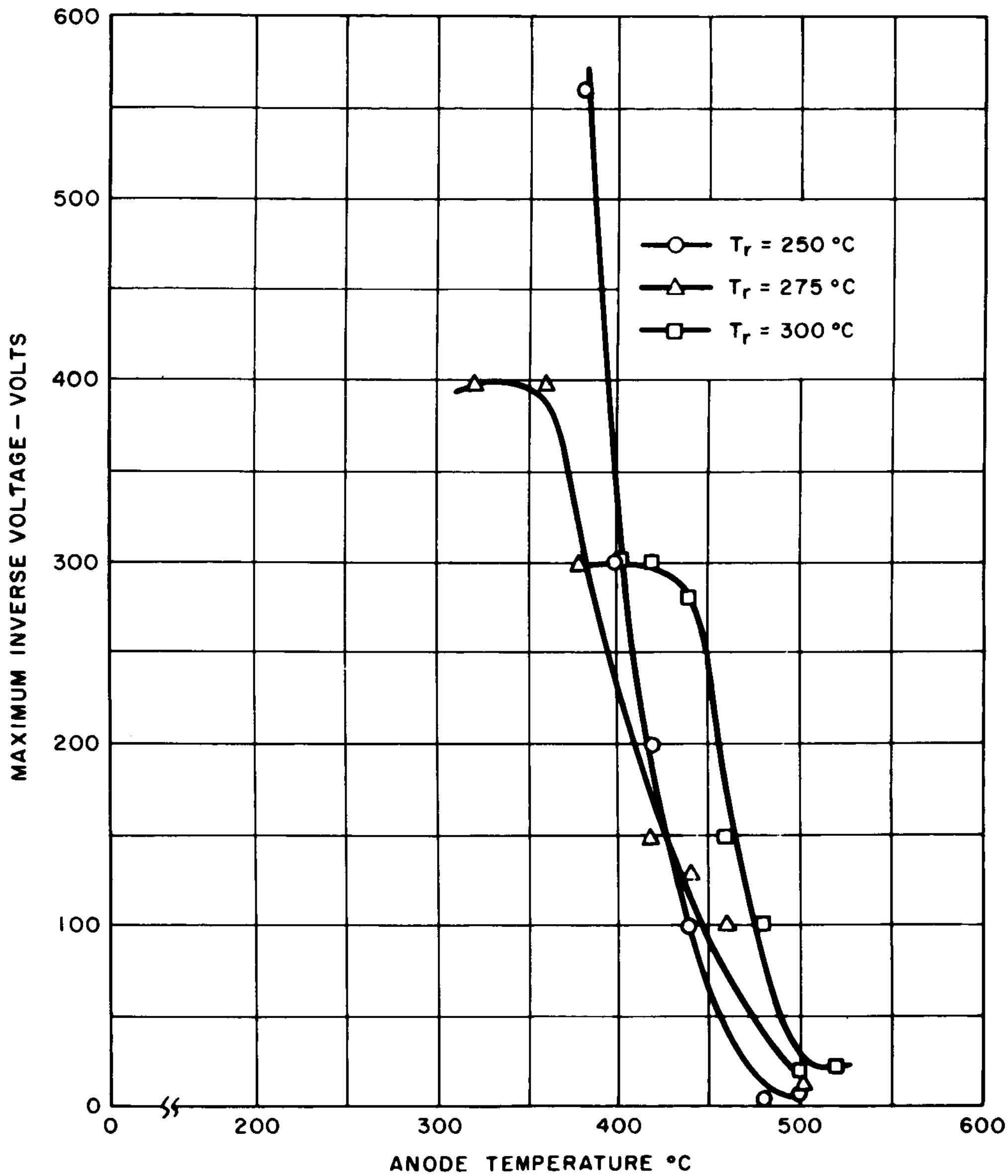

Figure B-1 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 7

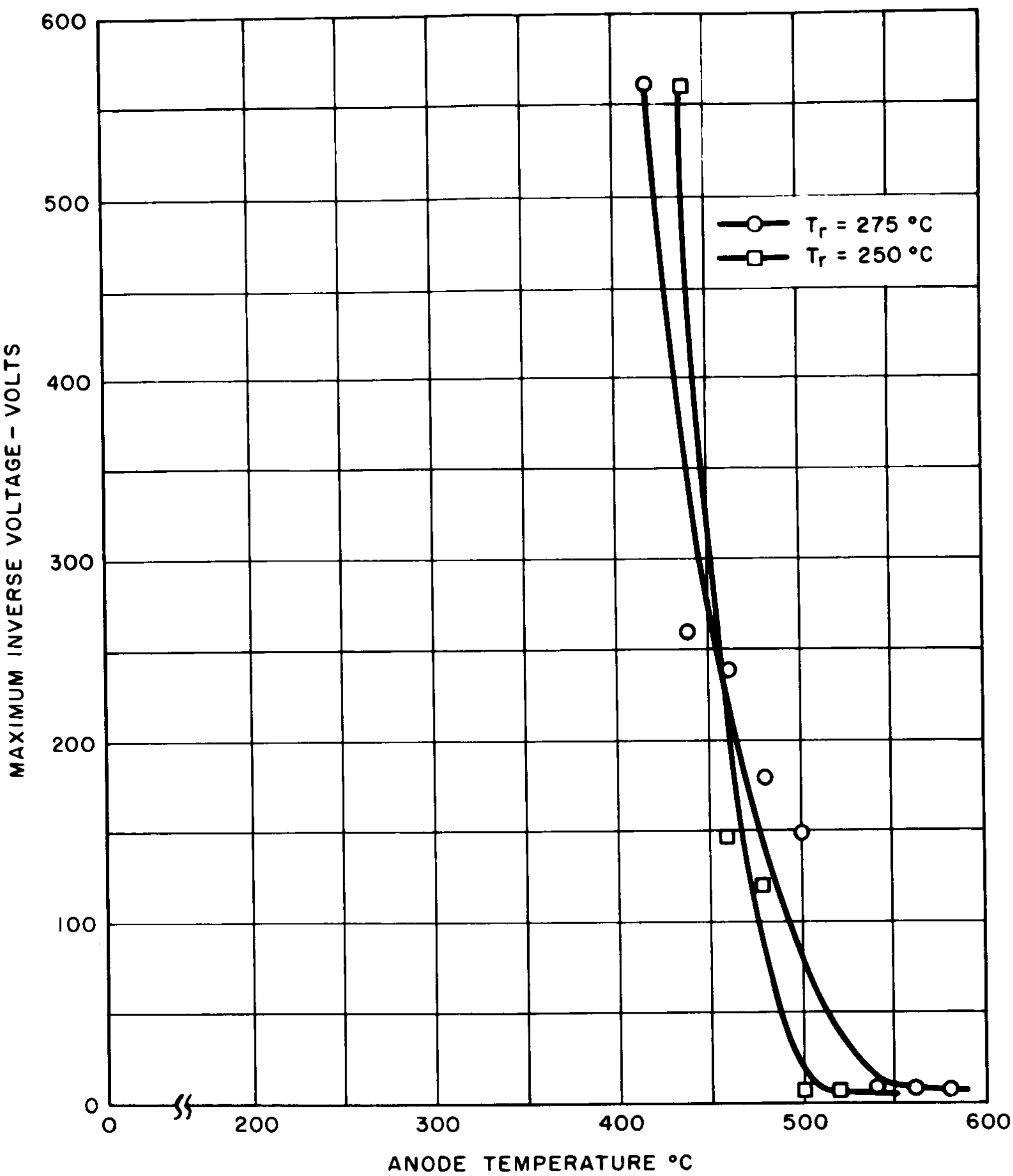

Figure B-2 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 8

Appendix C

RUBIDIUM FILL

Like cesium, the other alkali metals -- rubidium, potassium, sodium and lithium -- and the alkali earths -- barium, strontium, and calcium -- are capable of lowering the work function of a substrate material when deposited on the substrate in the form of a thin layer. Because cesium has the lowest work function and the lowest ionization potential of all the alkali metals, it was deemed that a different alkali metal might produce a less efficient emitter and result in a tube with a lower anode emission at a given temperature. This presented the possibility of coupling a less efficient cathode with an anode that could be raised to a higher temperature before the occurrence of inverse voltage breakdown.

Tube No. 15 was made with a rubidium fill and yielded the emission data shown in Figures C-1 and C-2. A comparison between Figures 11 (see text) and C-2 indicates that the rubidium tube had less efficient cathode emission, but its inverse-voltage characteristic (Figure C-3) was not an improvement over that obtained with a cesium-filled tube.

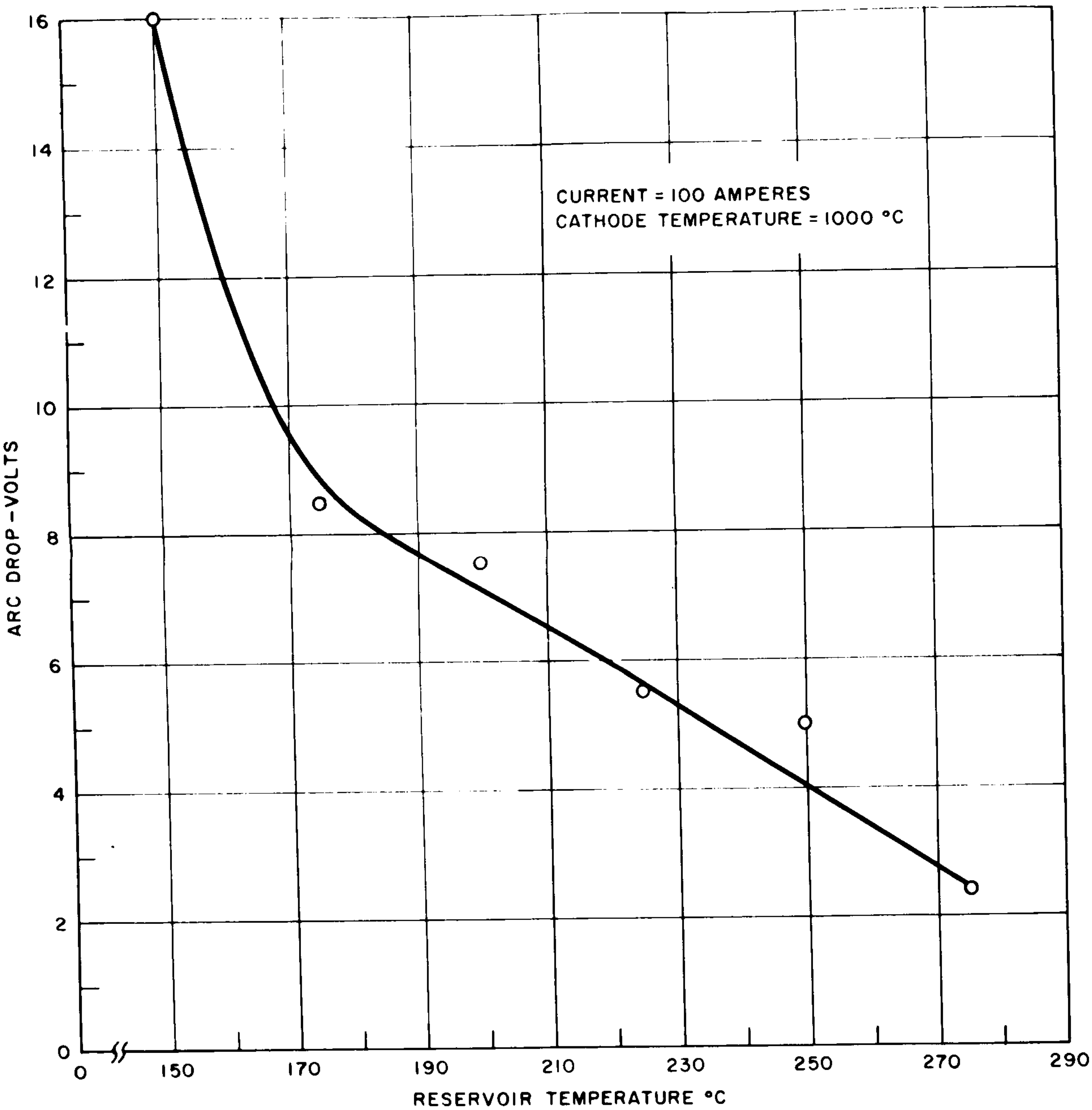

Figure C-1 - Peak Drop Versus Reservoir Temperature, Type Z-7009, Tube No. 15

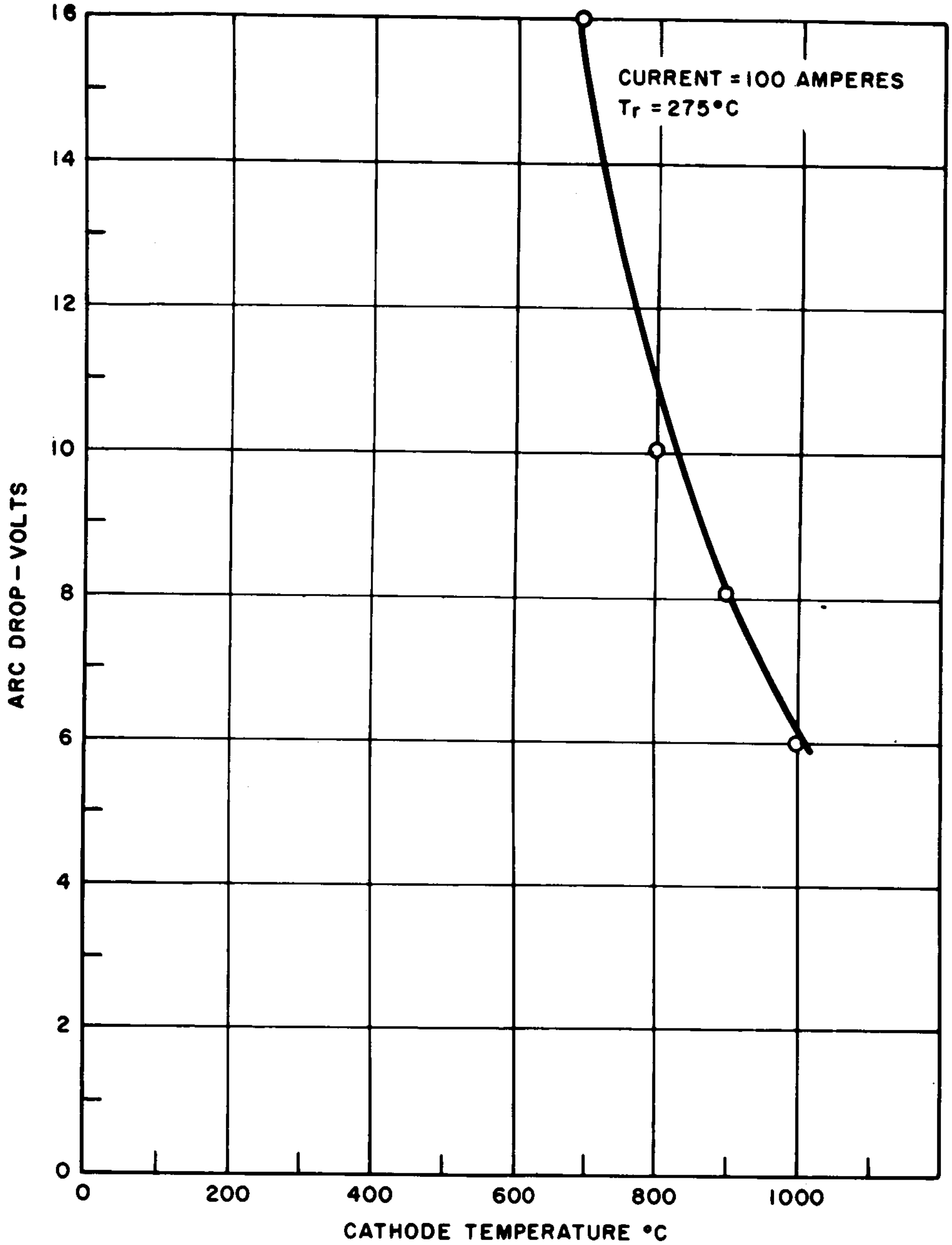

Figure C-2 - Peak Drop Versus Cathode Temperature, Type Z-7009, Tube No. 15

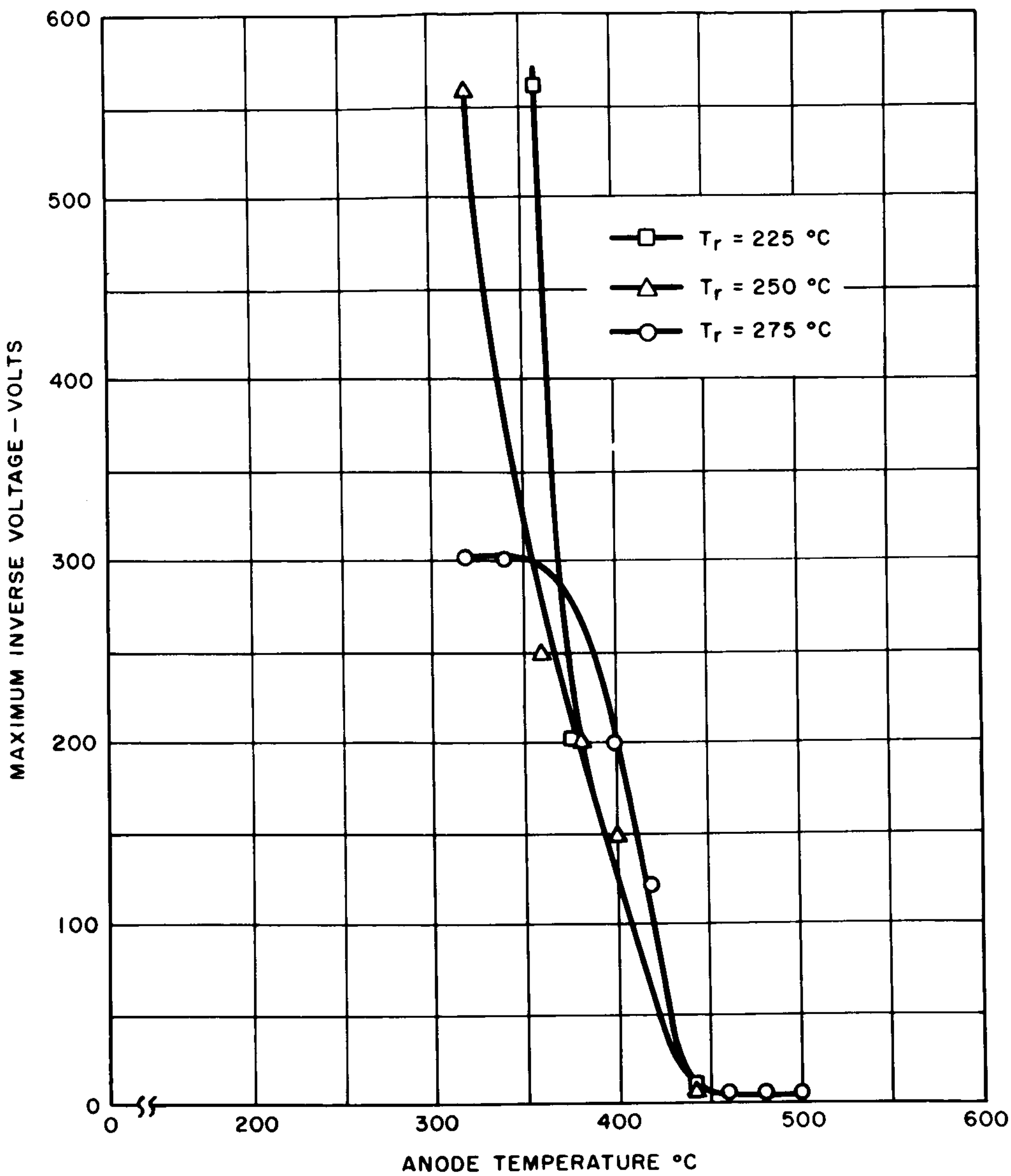

Figure C-3 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 15

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