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HIGH-TEMPERATURE, GAS-FILLED CERAMIC RECTIFIERS, THYRATRONS, AND VOLTAGE-REFERENCE TUBES

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Technology Utilization Division
OFFICE OF TECHNOLOGY UTILIZATION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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FINAL REPORT

Development of

HIGH-TEMPERATURE, GAS-FILLED, CERAMIC RECTIFIERS, THYRATRONS, AND VOLTAGE-REFERENCE TUBES

by

E. A. Baum and N. D. Jones

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

December 15, 1964 through January 26, 1966

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Development of

HIGH-TEMPERATURE GAS-FILLED CERAMIC RECTIFIERS, THYRATRONS, AND VOLTAGE-REFERENCE TUBES

by E. A. Baum and N. D. Jones

SUMMARY

The work effort on this contract was directed toward establishing the technology for operating gas thyratrons, diodes and voltage regulator tubes in a high-temperature, high-vacuum environment. The major problem areas requiring solution were:

1) Cathode design
2) Electron emission from grid and anode
3) Electrode sputtering and gas clean-up
4) Ceramic-metal seals

The basic approach on this program was based on the results of investigations conducted during Phase I of the overall high-temperature gas tube program (Contract NAS3-2548). The designs of the thyratron and diode tubes utilize a high purity alumina ceramic envelope. The ceramic seals were fabricated by using high-temperature metallizing and palladium-cobalt brazing alloy. These seals were operated for over 1200 hours at 800°C. Both the grid and anode were fabricated from graphite to minimize gas clean-up due to sputtering and to minimize grid and anode emission. The cathode is a barium-oxide type emitter, approximately 70 cm^2 in area, and designed such that the heater is external to the tube. Gas fill is 100 microns of xenon.

Endurance tests were conducted under varying conditions of voltage, current and frequency in the temperature range of 750 to 800°C. One tube was operated at 15 amperes average current, 150 volts, 60 cycles for over 1200 hours at 800°C. Tests out to 375 hours were conducted at 2000 volts peak inverse voltage, 2.5 amperes average, and 3200 cycles per second.

The results of recovery time measurements indicate that during the first 100 hours of operation, some gas clean-up occurs. However, after

this time no further reduction in recovery time is apparent. This indicates that an equilibrium condition exists where the amount of gas being evolved from the sputtered surfaces is equivalent to the amount subject to clean-up. Tests conducted under phase-retard conditions are required before a complete evaluation of gas clean-up can be made.

Investigations were made and endurance tests run on neon-filled regulator tubes at temperatures to 800°C. The normal running voltage for this design was 125 volts, with less than a 4-percent variation over the range of 25 to 75 milliamperes. The regulation, $\Delta V/\Delta I$, was found to be 0.08 volts per milliampere over this same current range. It was also found that the regulation was less at 800°C than at lower temperatures. Endurance tests out to 1500 hours at a nominal 50-milliampere current indicate that the primary mode of failure is due to a gas clean-up mechanism. Prior to failure the running voltage gradually increased until the discharge extinguished.

INTRODUCTION

This final report on Contract NAS3-6469 covers the period of 15 December 1964 through 26 January 1966. The work effort on the contract was directed toward establishing the validity of the technology and design concepts established on Contract NAS3-2548 for the development of high-temperature ceramic rectifiers, thyratrons, and voltage-regulator tubes.

The performance objectives of the program were as follows:

1) Thyratron and rectifier tubes having a continuous rating of 2000 volts, 15 amperes, 2000 PIV, 3200 cycles, operating at 400°C to 800°C in a vacuum environment.

2) Voltage-regulator tubes having a rating of 120 volts DC, 50 milliamperes, and 3-percent accuracy over a current range of 25 to 75 milliamperes, operating at 400°C to 800°C in vacuum.

The thyratrons and rectifiers fabricated during this program were given a series of electrical and endurance tests under varying voltage and load conditions. These performance tests were conducted over a frequency range of 60 to 3200 cycles per second and at tube temperatures up to 800°C in a vacuum environment. The electrical tests performed during this contract were limited to separate high-voltage and high-current operation due to limitations of the test equipment. Tubes also successfully passed 35 g mechanical shock tests.

Voltage-regulator tubes were given a series of tests at temperatures from 250°C to 800°C ambient in vacuum. Endurance tests were conducted at 800°C ambient in vacuum at 50 milliamperes direct current.

THYRATRON AND RECTIFIER TUBES

TECHNICAL APPROACH

This program is a continuation of the work performed on Contract NAS3-2548. The work effort of Contract NAS3-2548, in the area of high-temperature xenon-filled rectifiers and thyratron tubes, consisted of a study of the basic problems associated with tube designs capable of operating under environmental conditions of high temperature and high vacuum. The major areas of interest confronting development of rectifier and thyratron tubes for high-temperature (to 800°C) operation are:

1) Cathode design
2) Electron emission from grid and anode
3) Electrode sputtering and gas clean-up
4) Ceramic-metal seals

Hot-cathode gas rectifiers and thyratrons are generally capable of high-current, high-voltage operation. The thyratron differs from the gas diode only in the starting mechanism. In a thyratron, once the discharge has been started by the grid pulse, tube current is controlled by the impedance of the external circuit. After the grid has fired, it is surrounded by a positive ion sheath which shields it from the plasma. Any change in grid potential only changes the sheath thickness without influencing the main discharge characteristics. The tube regains control only after the anode voltage has been driven negative for a sufficient time to allow the residual ionization to decay to a point where the field due to the grid potential can extend into the cathode region. Deionization time or recovery time of a given tube structure determines the operating frequency. Recovery time in general, depends on the gas pressure, tube current, electrode distance, and grid potential. To produce short recovery times in inverter and high frequency rectifier applications, electrode distances and grid structure dimensions are minimized to shorten the ion diffusion times.

Cathodes and Electron Emission from Anode and Grid

In a hot-cathode discharge operating in the space-charge-limited condition, a double sheath forms in front of the cathode, i.e., a negative sheath

is adjacent to the cathode and a positive ion sheath is between the negative sheath and the neutral plasma. If the circuit impedance is lowered, thereby increasing the current so that cathode operation is temperature-limited, a single positive-ion sheath forms in front of the cathode and causes an increase in cathode potential drop. Any additional increase in current may result in ion bombardment of the cathode surface, resulting in excessive cathode sputtering and stripping of the oxide-coated cathode surface. This is caused by ions accelerated through the cathode potential drop.

Dispenser-type cathodes have an advantage over the typical oxide-coated cathode used in commercial gas tubes in that the emission characteristics are not permanently changed by ion bombardment, since the emissive material is replenished from the bulk cathode. The main disadvantages associated with a dispenser cathode are the relatively high evaporation rate and the higher heater power required to obtain the operating temperature. Evaporants, principally barium and/or barium oxide, lower the work function of the other tube electrodes, causing electron emission from the anode and grid. At operating temperatures above 400°C, emission from the anode and grid can become appreciable, resulting in the inability of the tube to hold off inverse voltage and, in the case of the thyratron, causing loss of grid control. All factors considered, the oxide cathode was selected for use in gas tubes for the NAS3-6469 program.

Based on data in the literature[1, 2] and investigations on the NAS3-2548 program, graphite was selected as the electrode material for both grid and anode because barium on graphite is a comparatively poor electron emitter. Also, the rate of barium evaporation from graphite is comparately high. Both factors tend to minimize electron emission from a graphite surface subjected to barium evaporation.

1. J. A. Champion, The Suppression of Screen Grid Emission by Carbon; British Journal of Applied Physics, 7, 395 (1956).
2. G. A. Esperson and J. W. Rodgers, Studies on Grid Emission; IRE Transactions on Electron Devices, ED-3, No. 2 (April 1956).

Electrode Sputtering and Gas Clean-Up

The term "gas clean-up" denotes the loss of gas in a gas discharge device. In inert gas-filled tubes, gas clean-up is usually due to material sputtered from the anode by ion bombardment. This problem can be experimentally evaluated most readily by operating the tube for long periods under high inverse voltage conditions. Graphite is also a good choice for the electrode materials in that the sputtering rate is low compared to metals, and any sputtered layer would not be expected to permanently trap gas at a wall temperature of 800°C.

Ceramic-Metal Seals

During the NAS3-2548 program, several metal-ceramic seal samples fabricated from 3/4-inch diameter alumina were tested at 800°C in a vacuum environment for up to 3750 hours. Test diodes were also successfully fabricated using 2-inch diameter alumina bodies. Several metal-ceramic sealing techniques were employed, and test results were very encouraging. Based on experience from the NAS3-2548 program, the seal system first chosen for the subject program (NAS3-6469) was a 94-percent alumina body with "high temperature" molybdenum-manganese metallizing and a subsequent braze of palladium-cobalt alloy. This system, however, was not reliable because of alloying between the palladium-cobalt braze material and the metallizing. A high-temperature metallizing technique was subsequently applied, resulting in a highly reliable high-temperature seal.

DESIGN

Thyratrons fabricated for this program were of two designs, "Design I" shown in Figure 1 and "Design II" shown in Figure 2. Both designs have the same envelope outside diameter, and the graphite grids and anodes are identical; the mechanical supports for these two electrodes are also very similar in both designs. Figure 3 presents an external view of a Design II tube, and Figure 4 depicts the internal structure and component parts. Note that Design II is more compact than Design I even though the Design II cathode is more than twice as large as its Design I counterpart (see "Cathode Design" which follows). Eight early tubes were generally of Design I configuration and twelve subsequent tubes were fabricated using Design II.

Cathode Design

The early tubes utilized a 30 cm^2 barium-oxide type cathode which was readily available because of its recent use in a commercial tube. While this

cathode operated satisfactorily in short-term tests, experience indicates that the associated emission density of 0.5 average amperes per cm^2 is high where long life and reliability are important. Therefore, a cathode design embodying ten large fins as the major emitting surface was designed and fabricated. This design is shown isometrically in Figure 5, and the cathode shield and heater parts are shown in Figures 6 and 7. Two versions of this cathode were used, one with an emitting area of 73 cm^2 and the other 62 cm^2. The latter version had narrower fins to accommodate cathode shielding (see "Cathode Shield Design", which follows). All tubes operated on long-term endurance tests were of the finned versions; no difference in performance between 73 cm^2 and 62 cm^2 versions was noted (or expected) in 1000 hours time.

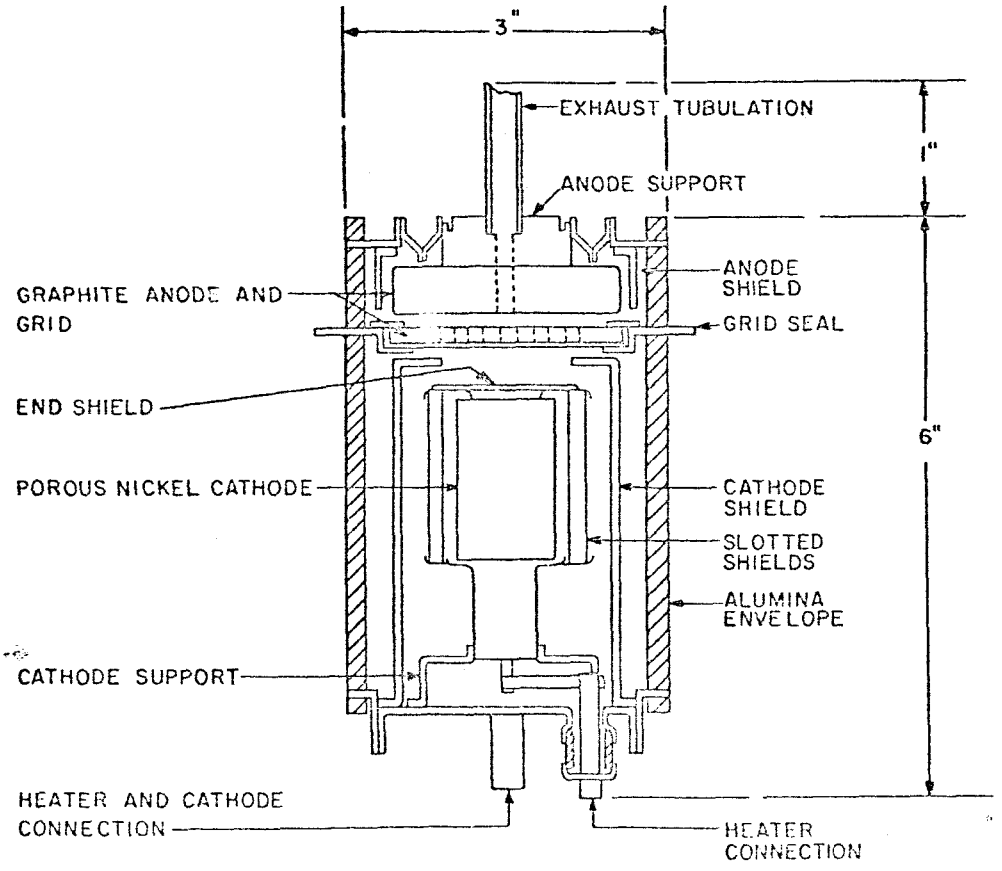


Figure 1 - Design I Thyratron

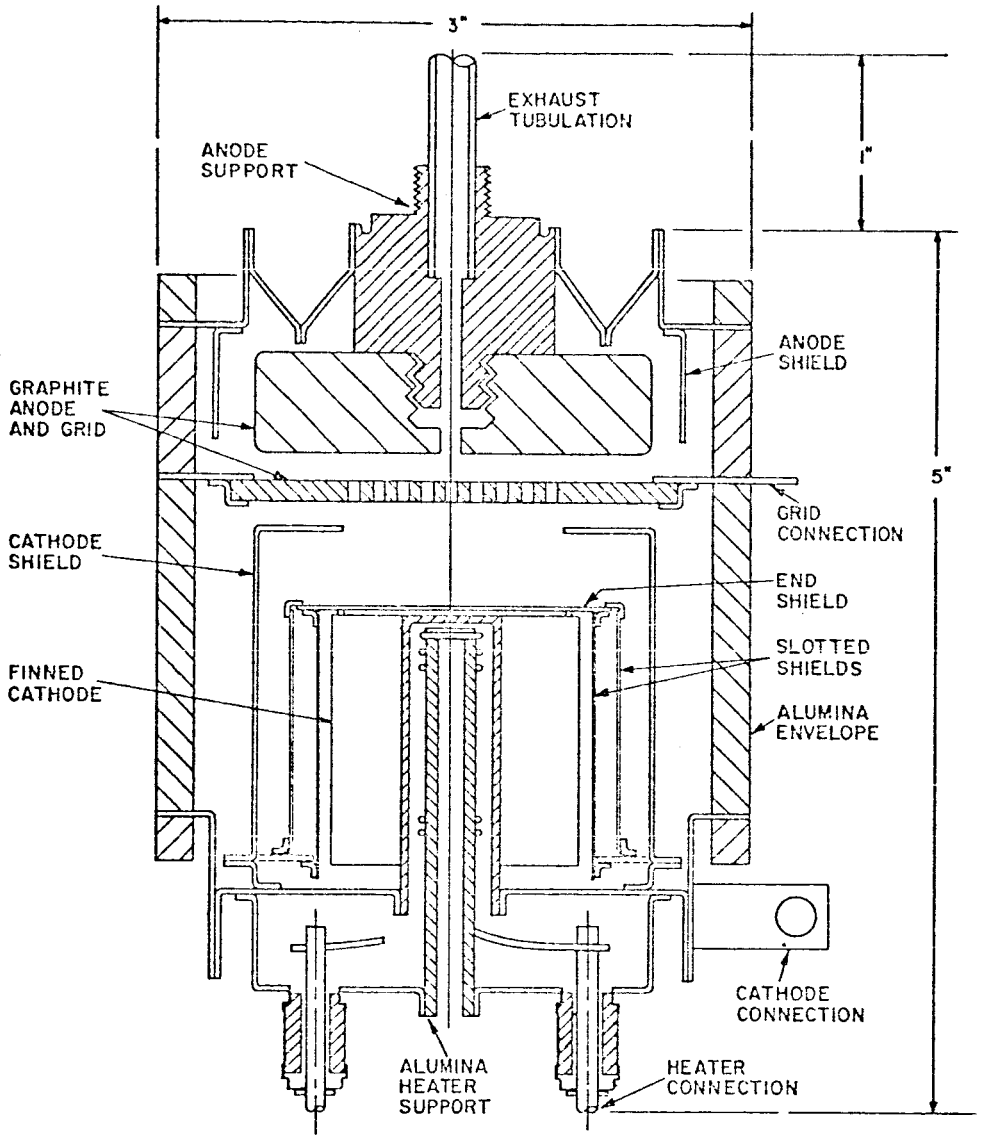


Figure 2 - Design II Thyratron

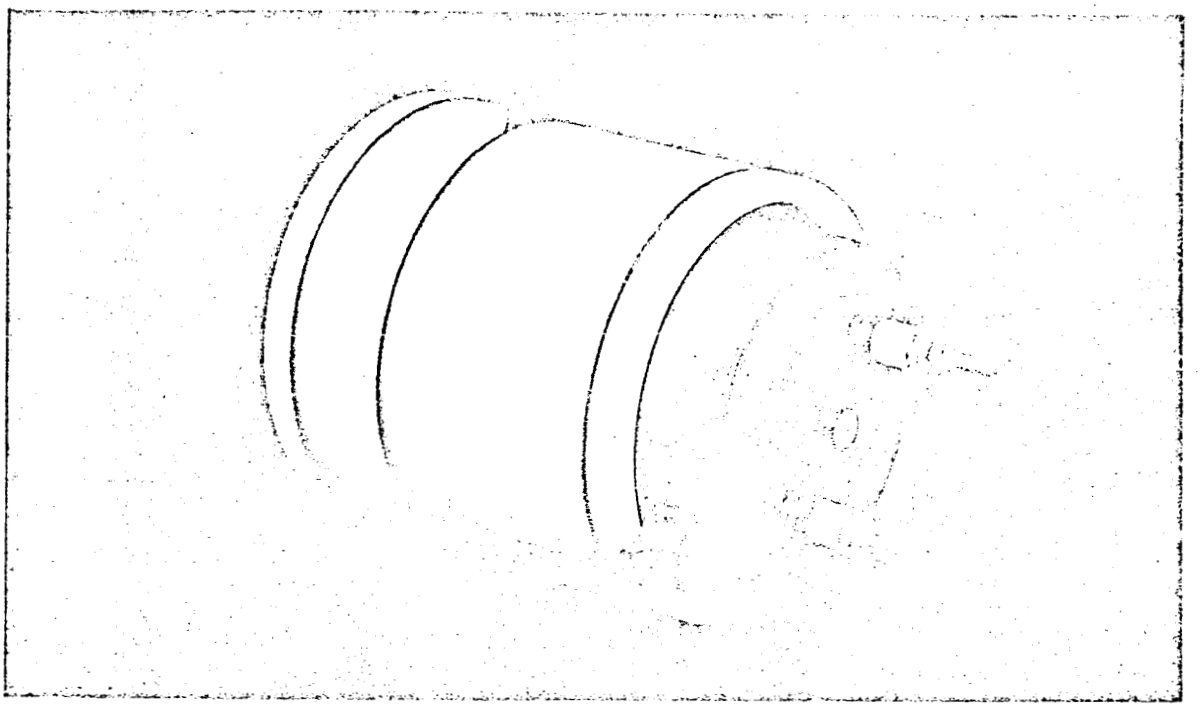


Figure 3 - External View of Design II Thyratron

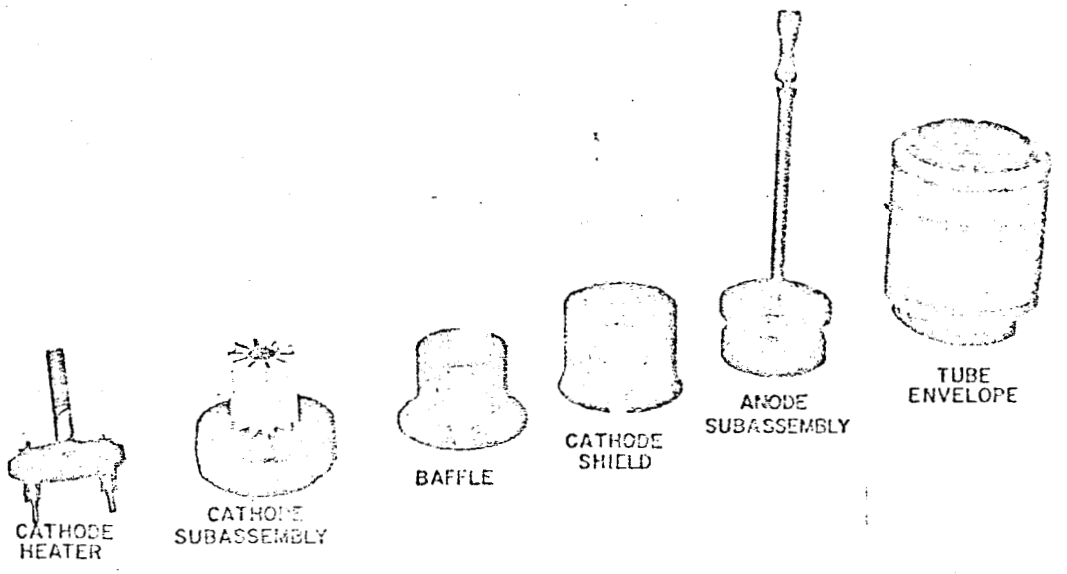


Figure 4 - Internal Structure of Design II Thyratron

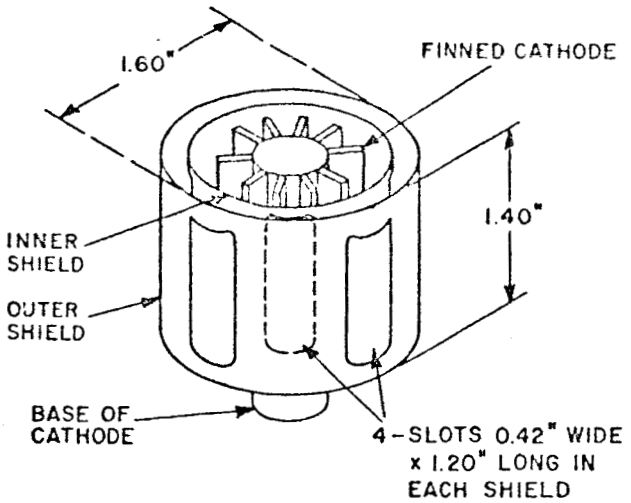


Figure 5 - Cathode and Shield Structure of Design II Thyratron

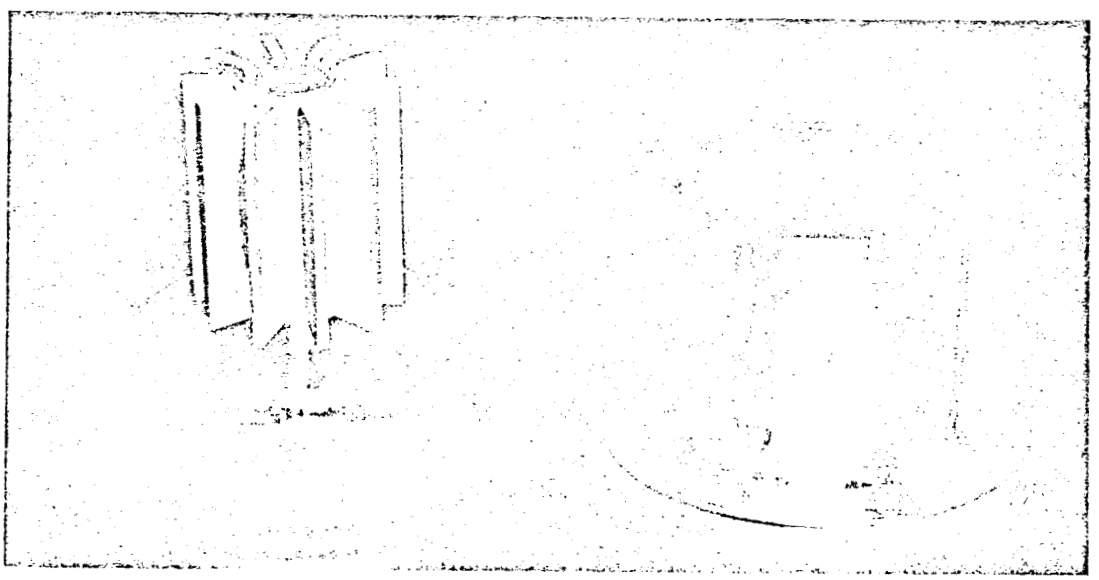


Figure 6 - Cathode and Slotted Shield for Design II Thyratron

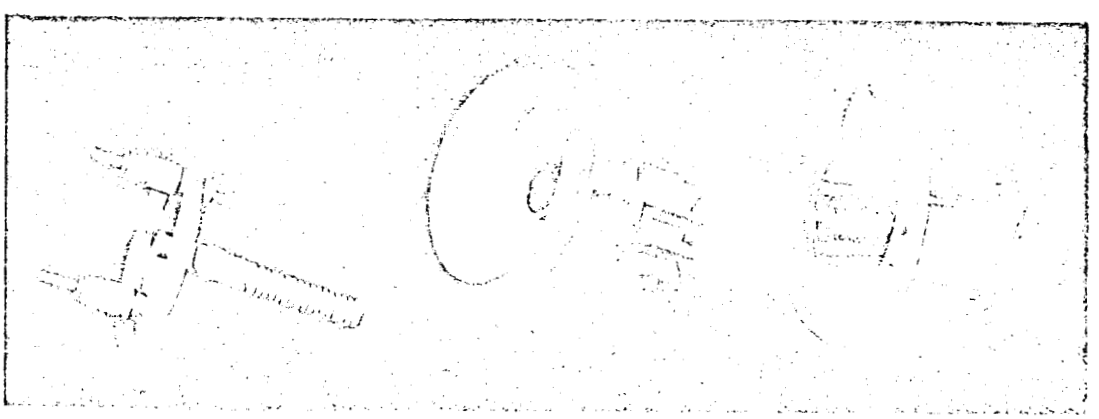


Figure 7 - Cathode and Heater Parts for Design II Thyratron

This cathode design also embodies another feature worth noting. The center cylinder is a vacuum-tight member which serves as part of the vacuum envelope, so the heater is "external" to the gas tube. This eliminates the problem of heater voltage causing ionization of tube gas, with resultant loss of grid control. Also, this design adapts readily to being heated by waste heat in a system, e.g. heat could be fed into a "stud" to fit in the cathode.

The heater assembly shown in Figure 7 has a tungsten wire helix wound on an alumina support. The heater leads are connected to ceramic pin seals brazed into a header which can be removed and replaced as a unit, without disturbing the gas tube vacuum seals.

It should be noted that in addition to the barium-oxide cathode, other cathode systems were considered for the thyratron such as barium-tungstate and thoriated-tungsten. The tungstate cathode is a comparatively new device, and was evaluated on Contract NAS3-2548. The possible use of the thoriated-tungsten system is also discussed in the Final Report[3] for Contract NAS3-2548. The main disadvantage with the latter approach is the high cathode temperature required to obtain the necessary emission density. Since one of the aims of the program was to minimize heater power requirements, this approach gave way to the barium-oxide system.

Briefly, the barium-oxide system has these principal advantages: 1) parts are readily and quickly fabricated as compared to the other systems, 2) overall, it is less critical of processing methods and of the inevitable minute amounts of contaminants in completed tubes, and 3) it is at least as efficient, thermally, as the tungstate system and much more efficient than the thoriated system. Principal disadvantage is an inability to withstand severe ion bombardment or arcing which occasionally occurs in gas-filled tubes. However, barium-oxide cathodes can be shielded and are made large enough to offset the losses in area due to bombardment.

Cathode Shield Design

As is the usual practice in thyratrons, the cathode was well shielded to minimize ion bombardment of the barium-oxide coating and to reduce evaporation of cathode materials on grid and anode. All tubes were designed with a

3. E. A. Baum, Development of High-Temperature Ceramic Rectifiers, Thyratrons, and Voltage Regulator Tubes; Report No. NASA CR-54303; prepared by General Electric Company for NASA under Contract NAS3-2548.

cup-shaped cathode shield and an end shield (a disc) as shown in Figures 1 and 2. In addition, two slotted shields (see Figures 5, 6, and 7) were added to nine of the thyratrons fabricated for test. Tubes with slotted shields are called "tightly baffled", while tubes without slotted shields are called "open" tubes. Early tubes contained shields with slots as small as 0.260 inch in width, but baffling appeared to be too "tight", as indicated by hard starting characteristics, so the slot width was increased to 0.420 inch.

Tube Envelope Design

The extension of operating temperatures to the 800°C range required state-of-the-art advances in ceramic-to-metal sealing techniques. Considering that there is little experience in operating vacuum-tight metal-ceramic envelopes in the 800°C temperature range, some difficulty was experienced in the initial envelope.

Despite indications from the preliminary work performed on metal-ceramic seals under Contract NAS3-2548, the sealing system first tried for these tubes resulted in very poor seals. The system employed initially involved 94-percent alumina ceramics, molybdenum-based metallizing palladium-cobalt brazing alloy, and molybdenum or kovar metal members. This system failed completely because it was impossible to achieve a rapid brazing cycle with the large parts involved, as compared to the smaller parts used in the NAS3-2548 program, where this system was successful. Metallographic examination of these poor seals showed that the palladium-cobalt brazing alloy dissolved the metallizing from the ceramic, apparently at such a time-dependent rate that it presented no problem with the smaller parts brazed in a faster schedule.

As an expedient to produce usable tubes for test, the brazing alloy and metallizing system were changed to one which experience indicated to be reliable, i.e. copper-gold brazing alloy and a "low-temperature" molybdenum-based metallizing. The first tubes tested used this seal system.

A second problem became evident when tubes were put on test: the interelectrode resistance of these early tubes at 800°C was much lower than normal thyratron circuits allow for. It was found that this is primarily due to low bulk resistance of the 94-percent alumina ceramics at high temperature. Curves showing measurements of bulk resistance versus temperature are given in Figure 8. Early tubes also showed some visual evidence of evaporation from the copper-gold brazing alloy, as expected. Although this is not a short-term problem, it would contribute to lower reliability and shorter tube life. Another factor weighing against the copper-gold low-

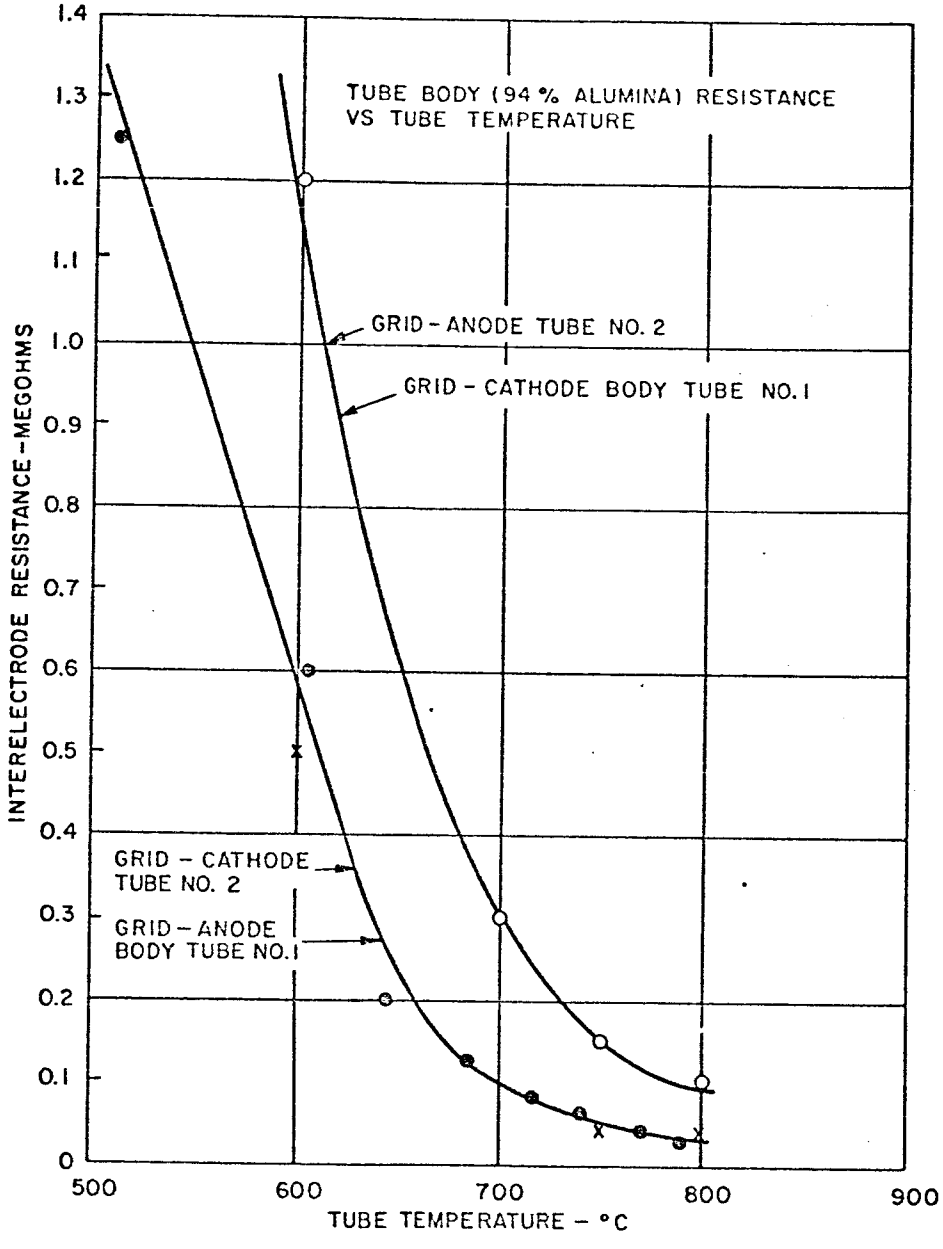


Figure 8 - Bulk Resistance Changes of the Design I Tube Body

temperature molybdenum metallizing seal system is the general axiom that brazed seals do not operate long and reliably near their melting points, due primarily to the time-temperature dependence of metallurgical changes in the alloys involved.

These factors dictated a second change in the sealing system. Except for the factor of low bulk resistance, it might have appeared practical to use a high-temperature active-alloy seal system (i.e., titanium based) which has proved reliable on other high-temperature tube programs.[4] However, the bulk resistance problem indicated the need for a change in ceramic material.

To accomplish all these objectives, it was decided to convert to a sealing system recently developed in the Materials Technology Unit of the G.E. Tube Department. This system employs a much higher purity alumina body for ceramic parts -- a Lucalox* type alumina which requires higher temperature processing and more costly fabrication techniques. The alumina body is designated as type A976, with a purity of 99+ percent and bulk resistivity of at least 20 times that of the 94-percent alumina at 800°C, based on tube performance. This sealing system involves a tungsten-based metallizing technique, and the use of palladium-cobalt brazing alloy for a subsequent braze at approximately 1300°C. The A976/tungsten/palladium-cobalt sealing system was used for tube Nos. 9 through 20, including all tubes operated on long-term endurance tests. It should be noted that none of these twelve tubes suffered a failure attributable to metal-ceramic seal failure.

A third problem area became evident during early experiments: molybdenum metal members were dissolved by molten palladium-cobalt unless temperature and brazing time were very carefully controlled. The kovar/palladium-cobalt system is much less critical in this respect, so kovar was substituted for molybdenum for all metal-ceramic seals.

*Registered trade-name of General Electric Company

4. Final Technical Summary Report, Vapor-Filled Thermionic Converter Materials and Joining Problems - Plasma Research Pertinent to Thermionic Converter Operation; Reporting period 15 Nov. 1961 - 15 Dec. 1962; prepared by General Electric Co. Power Tube Department for BuShips under Contract NObs-86220.

Parenthetically, it should be noted that one molybdenum member was retained in the tube envelope, i.e. the anode support (see Figure 2). The kovar tubulation is brazed into the molybdenum anode support using a copper-rich platinum-copper alloy. Two tube envelope failures occurred at this braze during this program, one after an endurance run of 1100 hours (tube No. 13). This is a weak point in the structure which should be corrected.

TESTS

Endurance Tests

As in any program directed to the development of hardware, the crucial item is reliability of performance in a realistic application test, i.e. "Endurance Tests" as defined here. The most realistic and definitive test for a thyratron tube is a test at maximum tube rating. Equipment could not be made available, however, to make a full-scale application test; therefore, with the cognizance of NASA, the major endurance tests were run partly at full rated current but at low voltage, and partly at full rated voltage and lower currents. While this is a compromise between the desirable and the practical, it does allow a good measurement of tube capability.

Thyratron endurance tests were conducted in vacuum chambers at pressures of approximately 10^{-6} torr. Average temperature of the tube envelope was approximately 750°C for all endurance tests. The testing arrangements were of two different types. One type consisted of an oven in the vacuum chamber, with radiation shields for heat insulation, as shown in Figures 9 and 10. The second type, shown in Figure 11, included a small vacuum chamber with an external oven in air. The insulation was of quartz felt and glass wool. An overall view of a typical endurance test station is included as Figure 12.

Thyratron endurance tests conducted during this program are summarized in Table I.

Rated Current Tests

These tests were conducted primarily at 60-cycle line voltage with approximately 150 peak inverse volts applied to the tube. The tube was operating essentially as a rectifier in this case (because anode voltage was applied to the grid through a high-impedance circuit which limited grid current). Tubes were operated at rated average current of 15 amperes, and a peak current of approximately 47 amperes.

As equipment could be freed from other tests, tubes were also operated at 3200 cycles and approximately 150 peak inverse volts, at 15 average

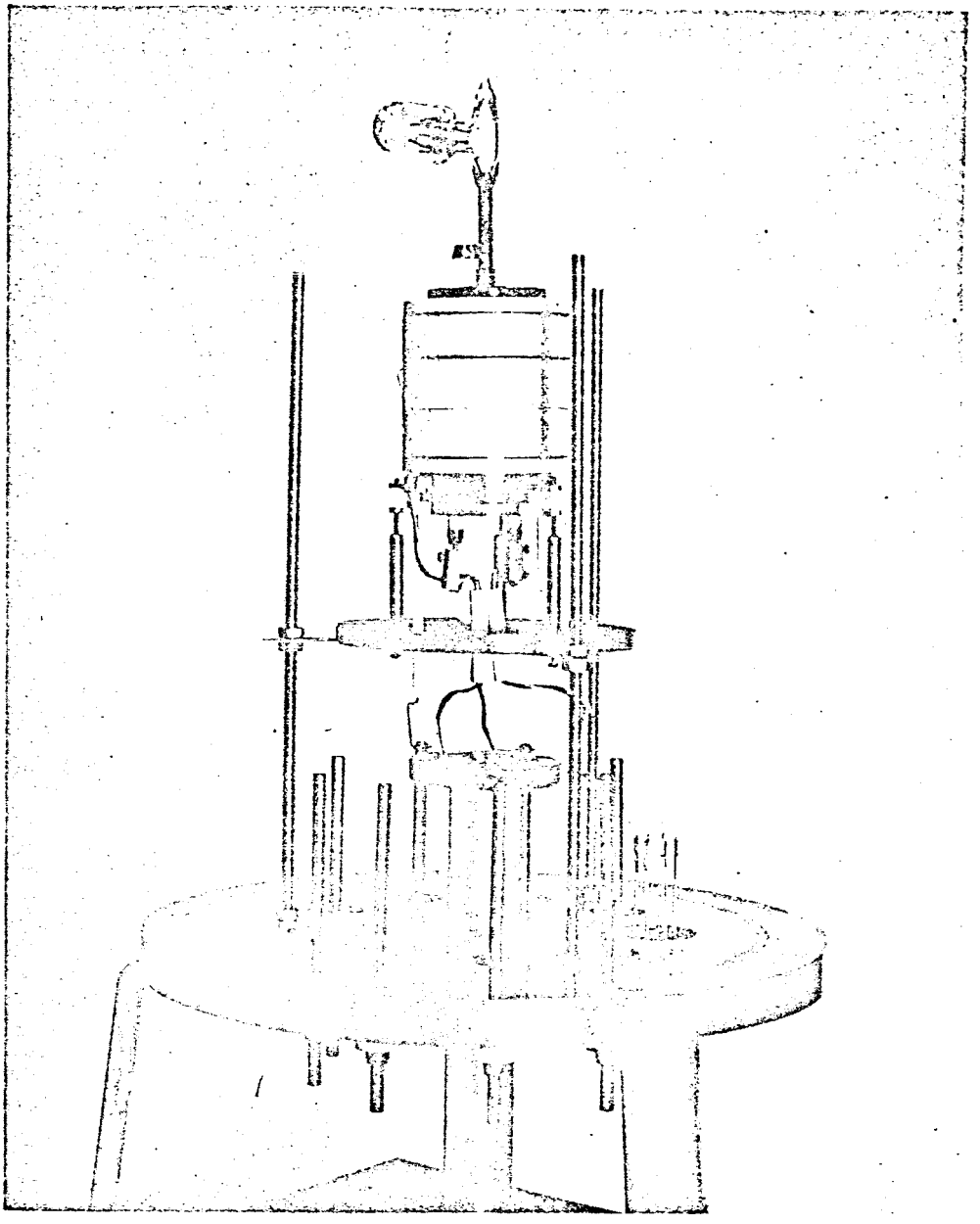


Figure 9 - Thyratron Equipped with Vacuum Gage Being Set Up for Endurance Test

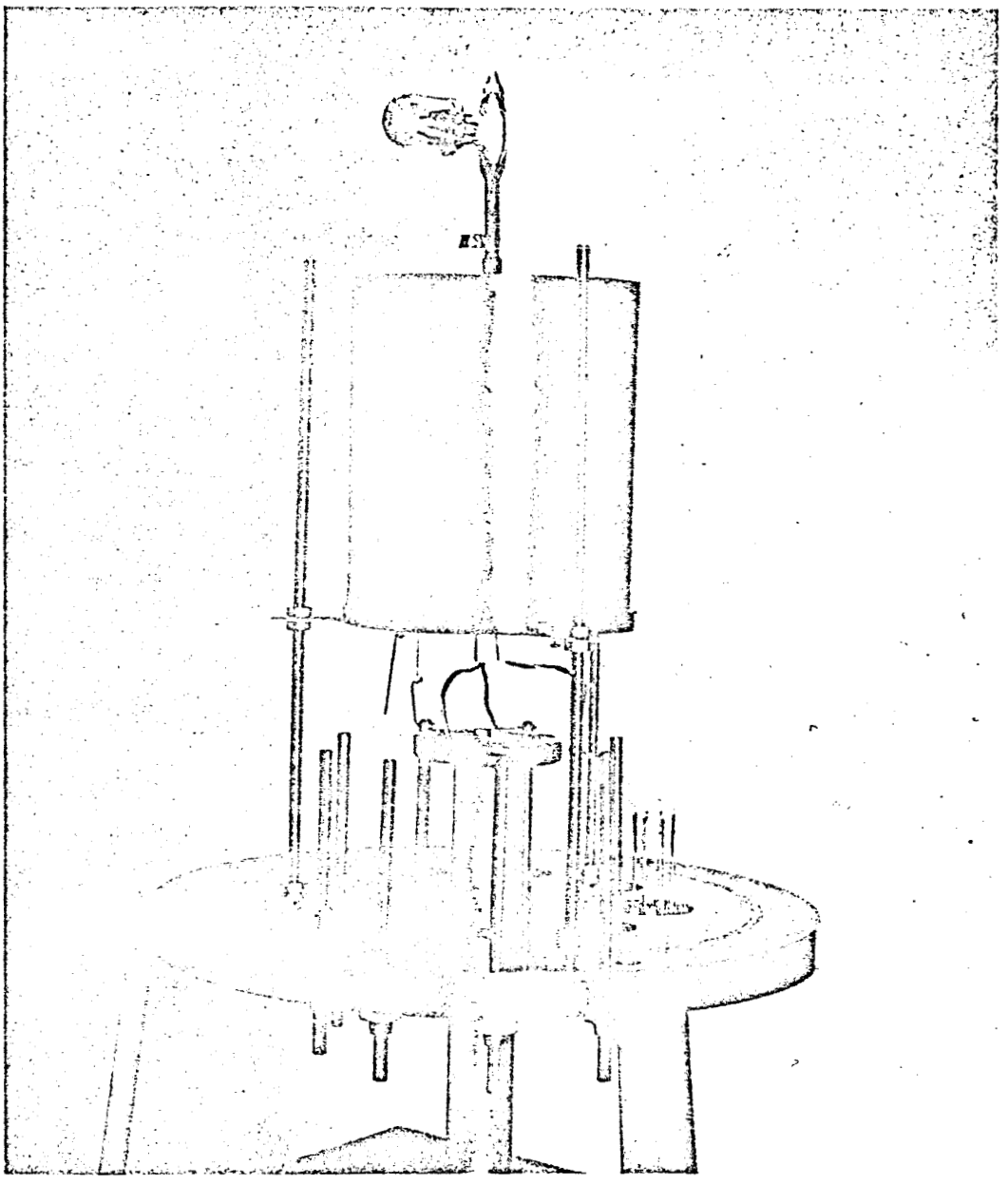


Figure 10 - Thyratron Installed in a Vacuum Type Oven

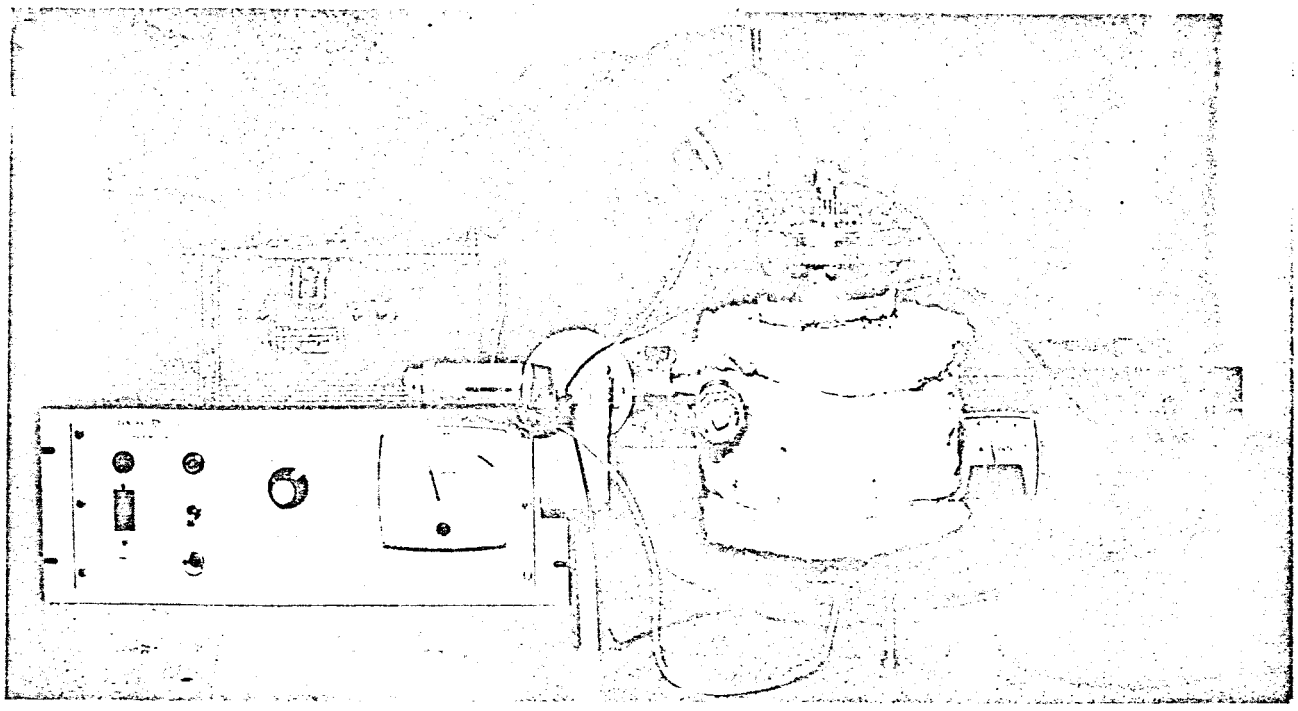


Figure 11 - Endurance Test Station with External Type Oven

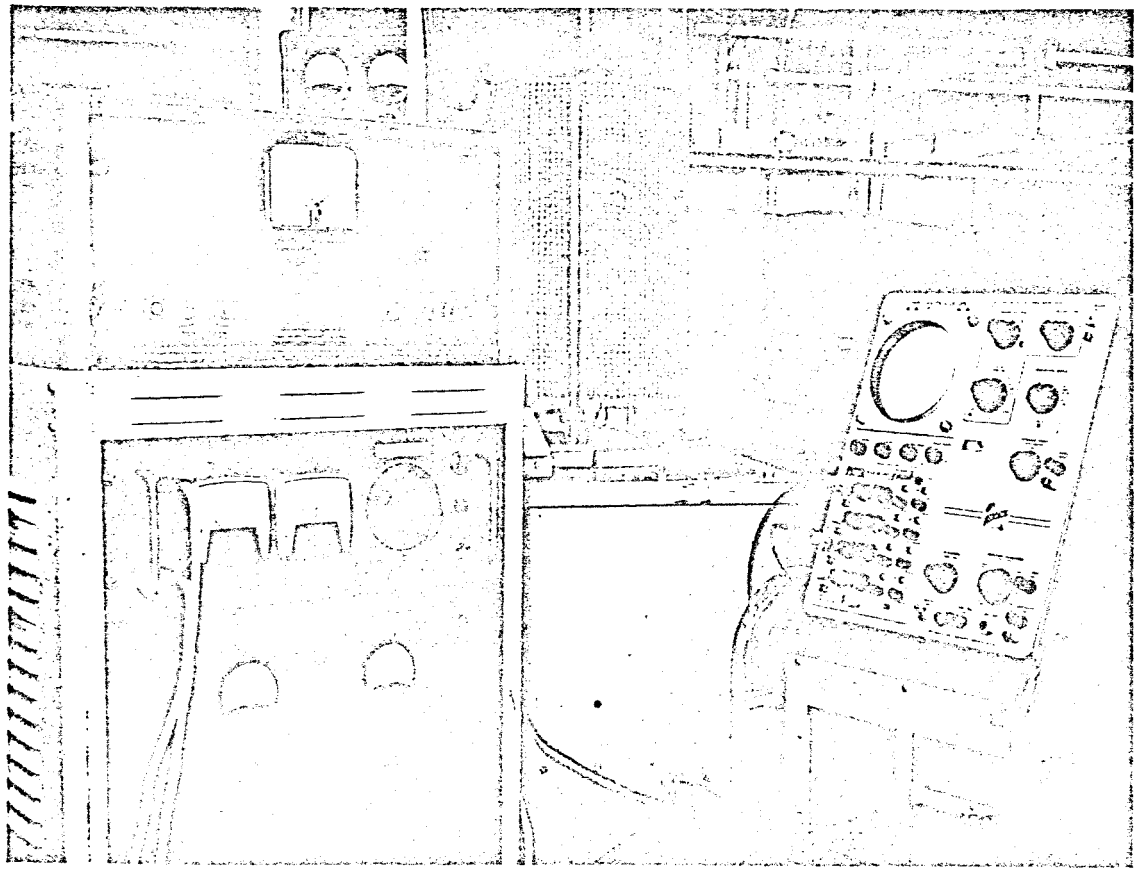


Figure 12 - Overall View of Typical Endurance Test Station

Table I - Summary of Endurance Tests at 750°C

Tube No.	Cathode Shield Type	Hours on Test: High Current	Hours on Test: High Voltage	Hours on Test: Total	Comments	Mode of Failure
9	Tight	3	350	353	Variable starting voltage. (see Figure 21)	Impossible to start.
12	Tight	350	200	650	Includes 100 hours standby at temperature. High electrical leakage.	Impossible to start. (see "Electron Emission from Grid and Anode")
13	Open	1094	8	1102	High-voltage 3200-cycle tests at 0, 500, 750 and 950 hours.	Leak at tubulation braze.
14	Open	125	300	425	Very high grid emission.	Ceramic envelope crack. (see "Electron Emission from Grid and Anode")
15	Tight	620	300	920	Electrical leakage became worse with time.	Very high grid-anode electrical leakage.
16	Tight	825	375	1300	Includes 100 hours standby at temperature. Recovery time data. Pulse emission data.	Burned hole in envelope near anode.
19	Open	75	100	175	Recovery time data. Pulse emission data.	Ceramic envelope crack (not at seal).

amperes, for comparatively short times. In these tests the tubes were controlled by varying grid bias so that grid control characteristics could be measured. From the standpoint of tube endurance, these tests are indistinguishable from 60-cycle full-current tests, with the exception of 3200-cycle operation. No problems were experienced with 3200-cycle operation at rated current.

Such testing permits evaluation of two of the critical parameters of tube operation, i.e. maintenance of cathode emission level and maintenance of vacuum integrity of the tube envelope at operating temperature. The other critical parameters -- i.e., maintenance of gas pressure and back emission from grid and anode -- can only be evaluated under high-voltage operating conditions.

The barium-oxide cathode was chosen in preference to a dispenser type cathode because of its higher efficiency. The approach was to use an anode and grid material having a high rate of evaporation (of barium) from its surface at operating temperature in order to minimize electron emission at operating temperature. This approach, however, requires extensive processing of the electrode parts to prevent poisoning of the cathode, since the high-temperature of the tube parts would increase the amount of extraneous gases passing to the cathode. Small amounts of chemically active materials arriving at the cathode can cause a decrease in emission characteristics. Oxygen, carbon dioxide, and halogen compounds are particularly notorious in this respect.

The gaseous discharge which occurs in thyratron operation results in ions which are electrostatically driven to the cathode, so that maintaining a discharge may serve both to contaminate the coating and to physically damage the coating due to ion bombardment. Physical damage occurs at ion energies above 20 volts.

Barium-oxide cathodes are subject to deterioration with time due to several factors. First, the rate of production of free barium gradually declines with time. Second, some of the chemical compounds produced serve to increase the electrical resistance of the coating. Both of these phenomena are accelerated by drawing current through the coating. Because of the resistance of the coating, the cathode temperature increases with increased current.

Following this line of reasoning, the full-current tests conducted are considered adequate for evaluating cathode emission effectiveness. Emission effectiveness is measured by measuring tube voltage drop at maximum tube current as the tube operates on endurance test. The changes in tube drop versus time for the five tubes which were operated for more than 100 hours at full current are plotted in Figure 13.

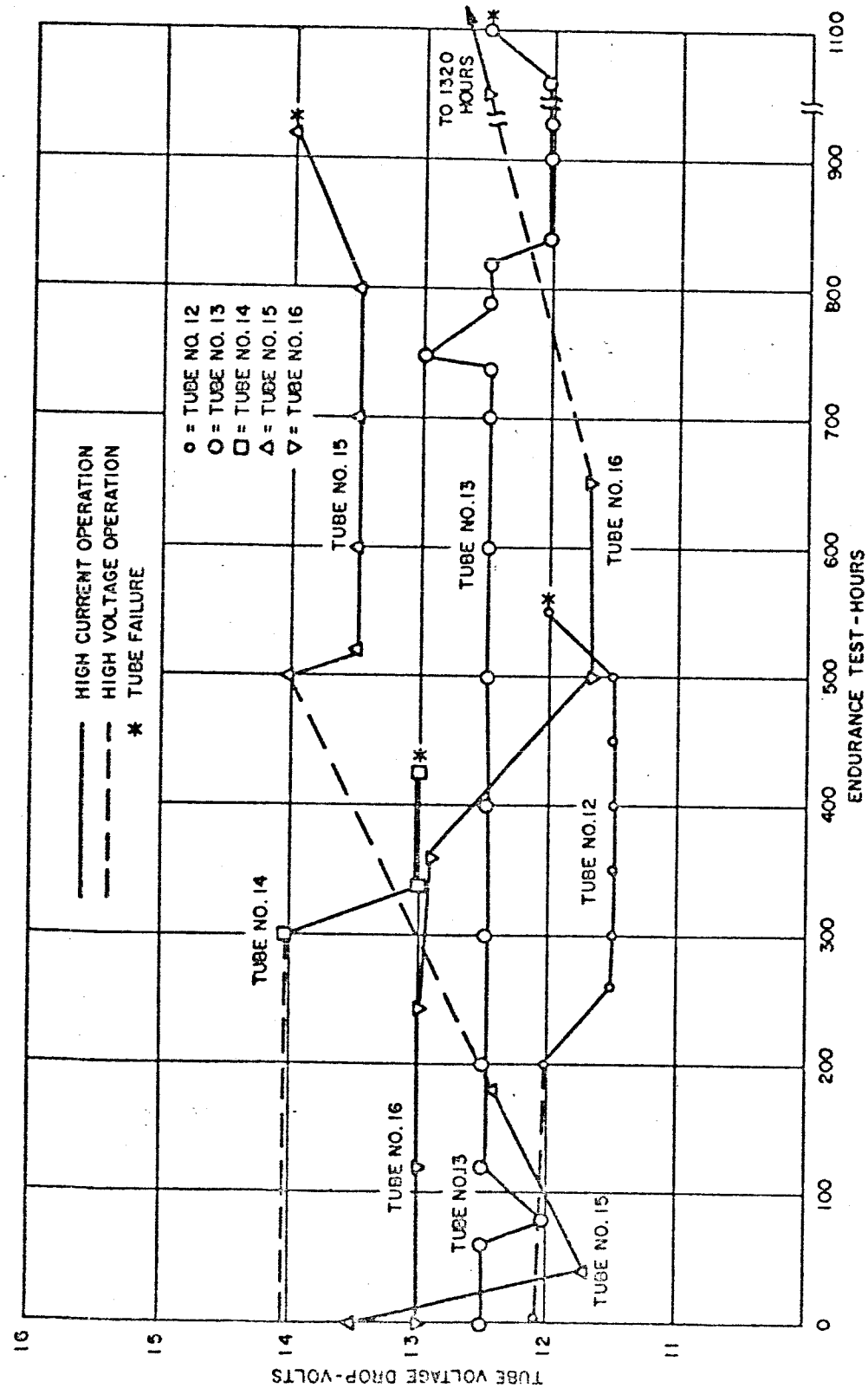


Figure 13 - Tube Voltage Drop During Endurance Tests

The voltage drop V_D of a gaseous discharge tube can be expressed as:

$$V_D = V_i + V_p + V_R + V_f$$

where:

V_i = Ionization potential of the gas (12.14 volts for xenon)

V_p = Plasma drop (perhaps one volt for these tubes)

V_R = IR drop due to cathode coating resistance (coating resistance is about 0.07 ohms to 0.10 ohms for acceptable performance for these tubes)

V_f = Excess voltage drop which exists only if the electron sheath at the cathode is depleted and a finite electric field appears at the cathode emitting surface. This occurs when current demanded of the tube exceeds reasonable overload ratings, or when cathode emission deteriorates.

V_i and V_p are constant in a gas tube at normal gas pressure. V_R and V_f cannot be measured separately, although the values of each can be deduced from data taken. The sum of $V_R + V_f$ is also a direct indicator of cathode emission, since resistance increases as the cathode deteriorates and V_f increases when cathode emission decreases. Thus a voltage drop increase with life is a measure of coating resistance increase and of decreasing cathode emission capability. For a xenon tube, a drop of approximately 15 volts represents the upper limit of good thyratron operation.

Since the changes in tube drop shown in Figure 13 do not signify any cathode deterioration, the cathodes in these tubes would appear to be adequate for at least 1000 hours life.

Maintenace of Vacuum Integrity

The tests at rated current were probably the principal and most significant tests of physical deterioration of the tube envelope. Approximately 75 to 80 percent of the power dissipated in the tube is anode and grid dissipation; therefore, the full-current tests duplicate the thermal conditions of a full-power test. Since the physical processes leading to deterioration of metal-ceramic seals, brazes, and welds are all very much affected by temperature, the duplication of actual operating temperature is important. Temperature cycling also tends to accelerate deterioration. Each tube on full-current test was turned off for several minutes, approximately one time per day, until the anode temperature decreased to near wall temperature, and then the tube was started again.

As an indication of the need to test the tube envelope under the most realistic conditions, it should be noted that the first eight tubes experienced envelope failures. These tubes were fabricated using gold-copper seals similar to those used previously for short-term tests at high temperatures. The history of tubes that were not endurance tested is summarized in Table II. As noted previously, the envelope design improvements implemented in tube Nos. 9 through 20 markedly improved the durability of the tube envelope.

High-Voltage Tests

These tests were conducted primarily at 1700 to 2000 peak inverse volts and 3200 cycles with occasional operational checks at 400, 1000, and 2000 cycles. The average current was approximately 3 amperes and the peak current about 9 amperes. Tubes were controlled by varying grid bias. Anode voltage, grid voltage, and cathode current were monitored by oscilloscope to enable daily monitoring of operating characteristics. Typical oscilloscope traces of high-voltage operation are shown in Figure 14. Critical parameters of tube operation evaluated in high voltage tests include gas clean-up, electron emission from grid and anode, and electrical interlectrode leakage.

The clean-up rate in gas diodes and thyratrons depends upon the degree of ionization at current cessation and on the rate of application of inverse voltage. When these conditions result in large numbers of high-energy positive ions bombarding the anode, or other surfaces at anode potential, the bombarding ions "sputter" atoms from the bombarded surfaces and deposit them on adjacent tube surfaces. When sputtered as described, most metals are very efficient at trapping gas molecules within the metal lattice.

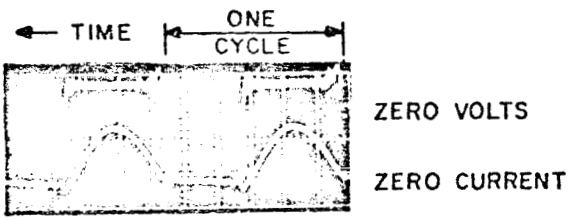
Since the degree of ionization at current cessation depends upon the rate of change of current just prior to the application of inverse voltage, the commutation factor, CF, is customarily used to describe susceptibility to gas clean-up for industrial thyratron or diode applications. The commutation factor is expressed as:

$$CF = \left|\frac{dV}{dt}\right|_o \times \frac{di}{dt}_o$$

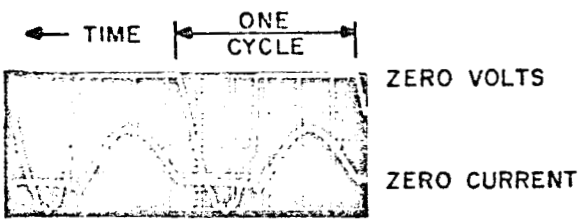
The dV/dt term defines the rate of rise of inverse voltage at current cessation (commutation), and di/dt defines the rate of decrease of current just prior to commutation. Thus, gas clean-up depends upon frequency, wave shape, and peak inverse voltage applied to the tube. The commutation factor for a 3200-cycle sine wave, 2000-PIV, 15-ampere operation was graphically derived from the oscilloscope traces shown in Figure 14 and was

Table II - Summary of Tubes Not Endurance Tested

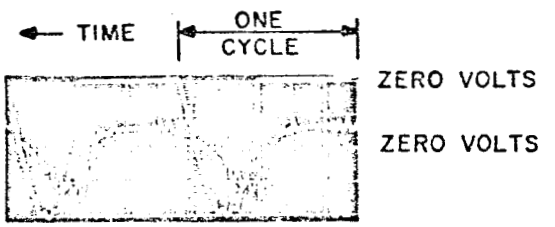
Tube No.	Cathode Shield Type	Hours on Test: High Current	Hours on Test: High Voltage	Hours on Test: Total	Comments	Mode of Failure
1	Open	1	0	1	Electrical leakage noted (30 cm^2 cathodes Nos. 1-7).	Leak at tubulation braze.
2	Open	25	55	80	Tube characteristics OK except for high electrical leakage.	Metal-ceramic seal leak (grid seal).
3	Open	2	0	2	Little data obtained.	Envelope leak. Possible metal crack.
4	Open	16	14	30	Good check on tube characteristics (see "Grid Characteristics").	Leak at heater connection (metal-to-metal braze).
5	Open	24	8	32	"Hollow Anode" tube (see "High-Voltage Tests"). Operation OK.	Same as No. 4
6	Tight	30	40	70	Same as No. 4	Same as No. 2
7	Open	8	8	16	Same as No. 5	Same as No. 2
8	Tight	1	1	2	72 cm^2 cathode	Leak through crack in molybdenum flange.
10	Tight	50	0	50	30 cm^2 cathode	Impossible to fire.
11	Tight	1	0	1	63 cm^2 cathode	Glass vacuum gage leaked. Rerun. Gage leaked again.
17	Tight	1	0	1	63 cm^2 cathode	Tube still OK
18	Tight	1	0	1	63 cm^2 cathode	Tube still OK
20	Open	1	0	1	63 cm^2 cathode	Glass vacuum gage broken making "pinchoff".



UPPER TRACE: ANODE VOLTS - 20 VOLTS / DIVISION
LOWER TRACE: TUBE CURRENT - 5 AMPERES / DIVISION



UPPER TRACE: ANODE VOLTS - 400 VOLTS / DIVISION
LOWER TRACE: TUBE CURRENT - 5 AMPERES / DIVISION



UPPER TRACE: ANODE VOLTS - 400 VOLTS / DIVISION
LOWER TRACE: GRID VOLTS - 10 VOLTS / DIVISION

Figure 14 - Oscilloscope Traces of High-Voltage Operation of Tube No. 6

approximately 100 volt-amperes/microsecond^2. The most severe industrial thyratron 60-cycle applications are at about 200 volt-amperes/microsecond^2 per cycle. Thus, for the commutation factor of 100, at 3200 cycles, sputtering would be approximately 3200/(2 x 60), or about 26 times worse than the most severe industrial thyratron applications.

The tests conducted under this phase of the program, at approximately 20 percent of full-rated current, are about 20 percent as severe as a test at full-rated current and voltage. To compensate for this slow rate of clean-up, compared to operation at full ratings, it was considered desirable to accurately measure gas pressure in the tubes. To accomplish this, three attempts were made to monitor gas pressure in thyratrons on endurance test using a glass thermocouple vacuum gage sealed onto the exhaust tubulation. In Figure 9, tube No. 14 is shown set up for endurance test with a thermocouple gage sealed to the tubulation. Unfortunately, in all three thyratrons so equipped, the vacuum gage failed early in life. Two failures were caused by discharges to the thermocouple elements which resulted in a comparatively heavy current that burned the delicate elements out. An attempt made to isolate the thermocouple element also resulted in burn out of the gage elements. In the other case the glass envelope failed.

Lacking the direct measurement of gas pressure by vacuum gage, other indicators of gas pressure were investigated. One crude indicator of low gas pressure is tube voltage drop, which will be somewhat higher at very low gas pressures than at normal gas pressures. This effect was not noted in any of the five tubes run on high-voltage endurance tests. A better indicator is deionization time, measured as the time required for the grid to regain control and cut off the tube after anode voltage goes negative. These "recovery time" tests are described in a later section.

Recovery time tests on tube Nos. 16 and 19 indicate faster deionization time after high-voltage operation for over 100 hours, which points to some gas clean-up. This is not too surprising, since there was definite visual evidence that metal had been sputtered on the walls of all tubes tested for even a few hours at high voltage. Since the principal target of the ions which produce sputtering is the anode, the source for the sputtered metal is apparently the nickel anode shield. It is planned to replace the shield with a graphite member in future designs.

In summary, the gas clean-up problem for high-temperature gas tubes has not been completely resolved by these tests, but indications are that gas clean-up is not a catastrophic failing of this tube design. The credit for

moderate success should be attributed partly to the graphite electrodes. Graphite has the lowest sputtering rate of materials useful for electrodes (see Figure 15). Also the molecular structure of the sputtered graphite should not trap gas effectively because of the amorphous structure of the sputtered layer. In the past, the use of metal electrodes in similar gas tubes at high frequency and voltage has been notably unsuccessful.

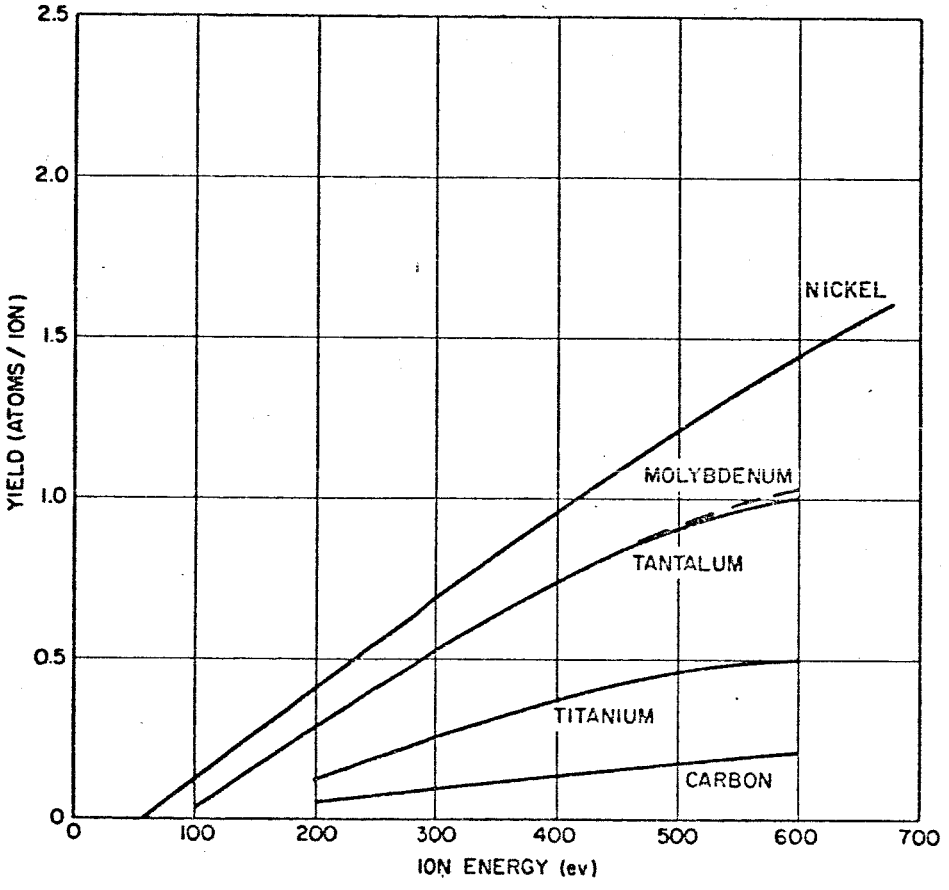


Figure 15 - Sputtering Yields in Xenon[5]

5. Data for this figure extracted from General Mills Inc. Report No. 2309, Sputtering Yield Data in the 100-600 ev Energy Range, July 15, 1962.

Problems related to sputtering can also be reduced by providing a minimum practical spacing between the grid and anode, thereby minimizing deionization time after commutation.

Another method employed to minimize gas clean-up is the use of a "hollow anode". The modifications made in the Design I thyratron to accommodate a hollow anode are shown in Figures 16 and 17. The advantage of the hollow anode configuration is that most of the material sputtered from the anode arrives at another part of the anode surface where it is subject to re-sputtering, which then releases gas trapped by the initial sputtering action. Tube Nos. 5 and 7 were of the hollow anode variety, and early performance was similar to the other thyratrons. The possible shortcoming of this structure is that the distance between the grid and anode is larger than the other designs, meaning longer deionization time and therefore some limit on performance at higher frequencies. However, both tube Nos. 5 and 7 operated properly at 3200 cycles, indicating that the limit is beyond this frequency. The hollow anode trial was a backup effort, in case of gas clean-up problems with the Design II tube on endurance tests.

ELECTRICAL INTERELECTRODE LEAKAGE

It should be noted as an adjunct to the sputtering situation discussed above that two endurance-test tubes (Nos. 12 and 15) developed objectionable grid-anode electrical leakage. This is believed to be due to sputtering from the nickel shield. As discussed previously, this problem can be alleviated by converting to a graphite anode shield.

Another factor causing increased electrical leakage is that cathode evaporants migrate throughout the tube interior at 800°C and coat ceramic envelope surfaces. This phenomena probably accounts for grid-cathode electrical leakage being consistently higher than grid-anode leakage, despite the longer grid-to-cathode alumina insulator.

ELECTRON EMISSION FROM GRID AND ANODE

All endurance tests were monitored for evidence of electron emission from grid and anode. The onset of appreciable electron emission from the grid results in loss of grid control of forward voltage, while anode emission results in breakdown of the tube in the inverse direction ("arcback"). Endurance test tubes were checked daily for such control failure.

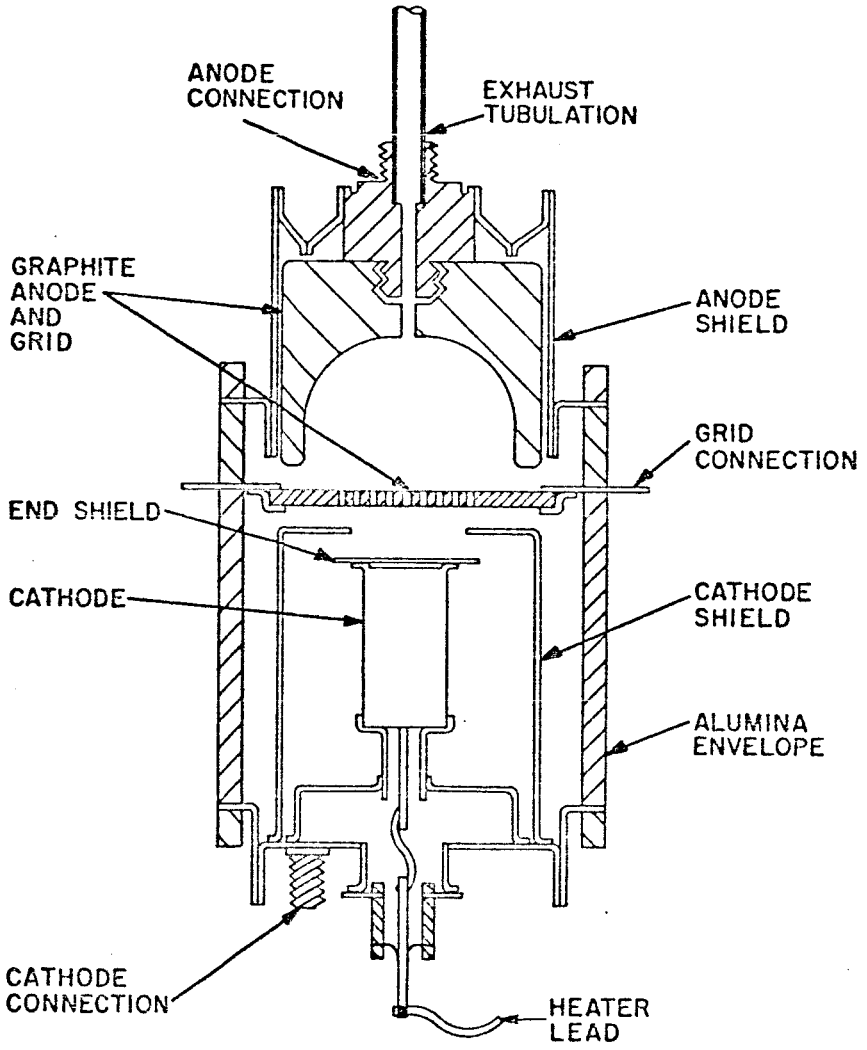


Figure 16 - Hollow Anode Tube Structure

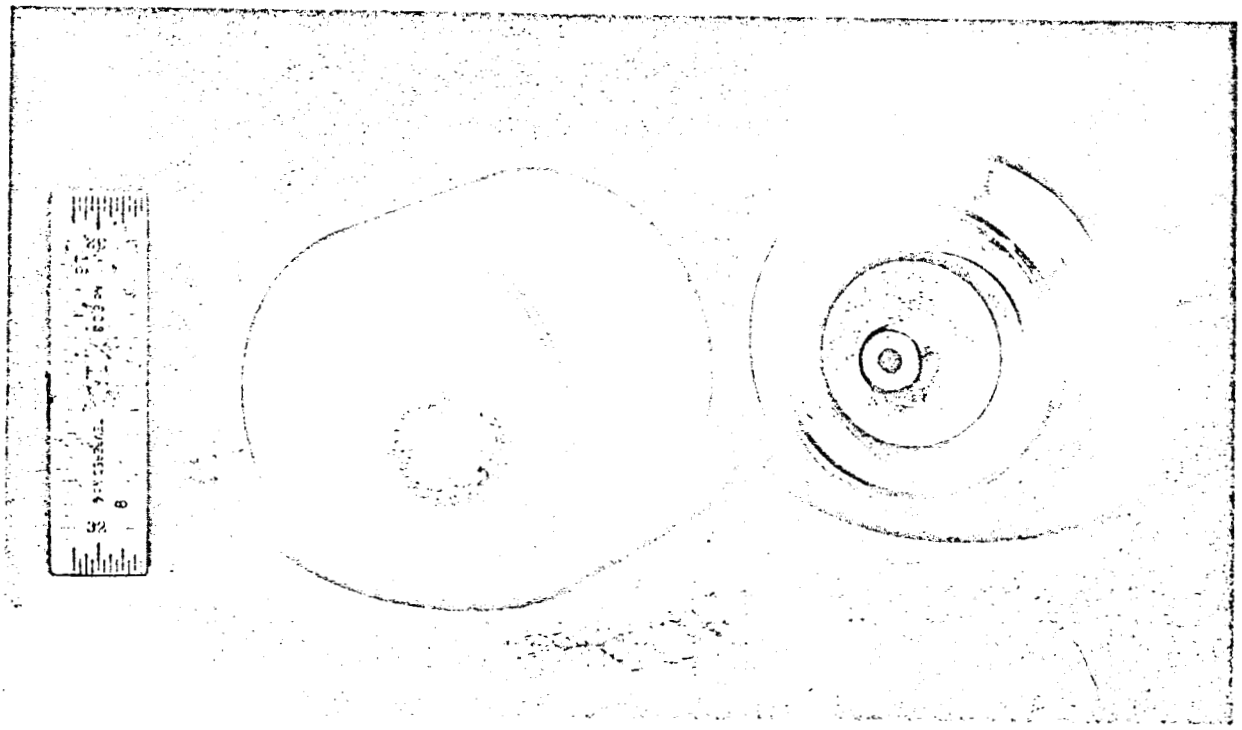


Figure 17 - Hollow Anode Parts

As discussed in the final report[6] for Contract NAS3-2548, the use of any barium system cathode in combination with a high operating temperature creates a critical problem area with regard to grid and anode emission. Also, as discussed, graphite has desirable electron-emission characteristics, and electron emission declines going from an electrode temperature of 750 to 900°C. This has been borne out in endurance tests since full-current operation (anode temperature estimated as greater than 900°C) resulted in less anode emission than noted in low-current high-voltage tests where the anode temperature was lower.

Anode emission is usually the more objectionable phenomenon in thyratrons and the only problem of this sort in rectifiers where there is no grid. Anode emission can result in a gaseous arc or "spark" discharge in the inverse direction, by which a large portion of the circuit energy can be suddenly dissipated in the tube, sometimes destroying it. This discharge can be indirectly initiated by a very small electron current (microamperes) emitted from the anode, and results in a high-voltage "glow" type discharge in which high-energy ions bombarding the anode generate electrons at the anode surface and maintain the glow discharge; such conditions can lead to localized heating at the anode and result in destructive arc or "spark" discharges.

Since interelectrode electrical leakage makes measurement of anode-emission currents impossible under operating conditions, the incidence of anode emission is deduced from the voltage waveform monitored on an oscilloscope.

Two tubes failed due to apparent arcing to the anode structure, involving the nickel anode shield rather than the graphite anode. In both cases, the ceramic envelope cracked due to heat shock transmitted to the ceramic envelope through the metal anode support members. Tube No. 12 failed, while being treated for failure to fire properly, by increasing cathode temperature by approximately 200°C; this may have increased anode emission. Tube No. 14 failed during the night while not being monitored but, when opened for evaluation, had a melted area on the nickel anode shield adjacent to the crack in the ceramic envelope, indicating an arc as described above. This offers additional incentive for redesigning the anode shield structure.

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6. E. A. Baum, Development of High-Temperature Ceramic Rectifiers, Thyratrons, and Voltage Regulator Tubes; Report No. NASA CR-54303, pp 19-33; prepared by General Electric Company for NASA under Contract NAS3-2548.

Grid emission was perhaps even worse than anticipated. Apparently, every metal member in the grid-cathode section of the gas tube can become a good electron emitter under conditions realized by operating the tube at temperatures approaching 800°C. A rather eratic grid control characteristic resulted. However, the occurrence of grid emission without loss of grid control indicates that the graphite grid is a comparatively poor electron emitter. This offers another reason for replacing metal members with graphite where feasible; the grid emission situation should improve greatly.

The usual range of grid emission current was 0.01 to 0.1 ampere. However, in one exceptional case (tube No. 14) several amperes of grid current could be obtained for a short time. This was apparently a matter of unintentionally arriving at very well optimized conditions of coverage by cathode evaporant and of grid temperature.

GRID CHARACTERISTICS

As mentioned previously, graphite electrodes were used in an attempt to maintain high work function surfaces on the grid and anode under operating conditions. The grids were designed to have a positive control characteristic. This is a so-called "tight" structure. A positive voltage is required on the grid to initiate the discharge, and the grid voltage is essentially independent of anode voltage. Typical grid characteristics are shown in Figures 18, 19 and 20. The grid characteristics are also independent of frequency up to 3200 cycles, indicating that the deionization time is less than 150 microseconds.

A positive grid characteristic is one means of minimizing problems due to grid emission, since the tube can be controlled without having the grid voltage appreciably negative with respect to the cathode. In this case, no grid-cathode discharge can be established. This eliminates at least one-half of the loss-of-control problem resulting from grid emission, because the grid-to-anode discharge is less likely to occur due to a lower incidence of cathode evaporants in the anode-grid region.

RECTIFIER OPERATION

Since rectifier performance can be almost duplicated using a thyratron structure, an evaluation of such performance was made by means of the xenon thyratron structure shown in Figure 2. This is accomplished by operating the thyratron in a rectifier circuit with the cathode and anode connected as a rectifier, and with the grid connected to the anode by a resistor to limit

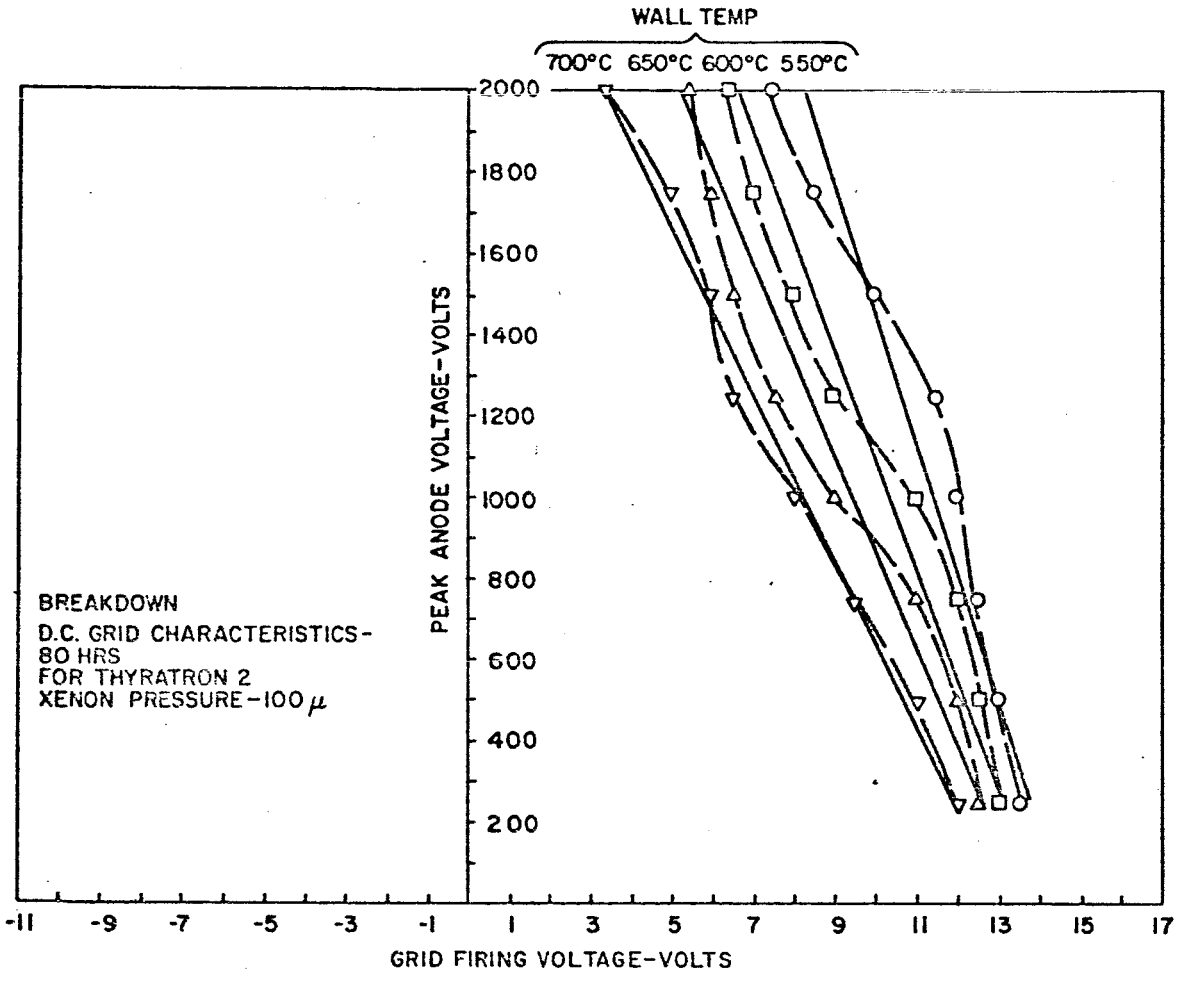

Figure 18 - DC Grid Characteristics of Tube No. 2

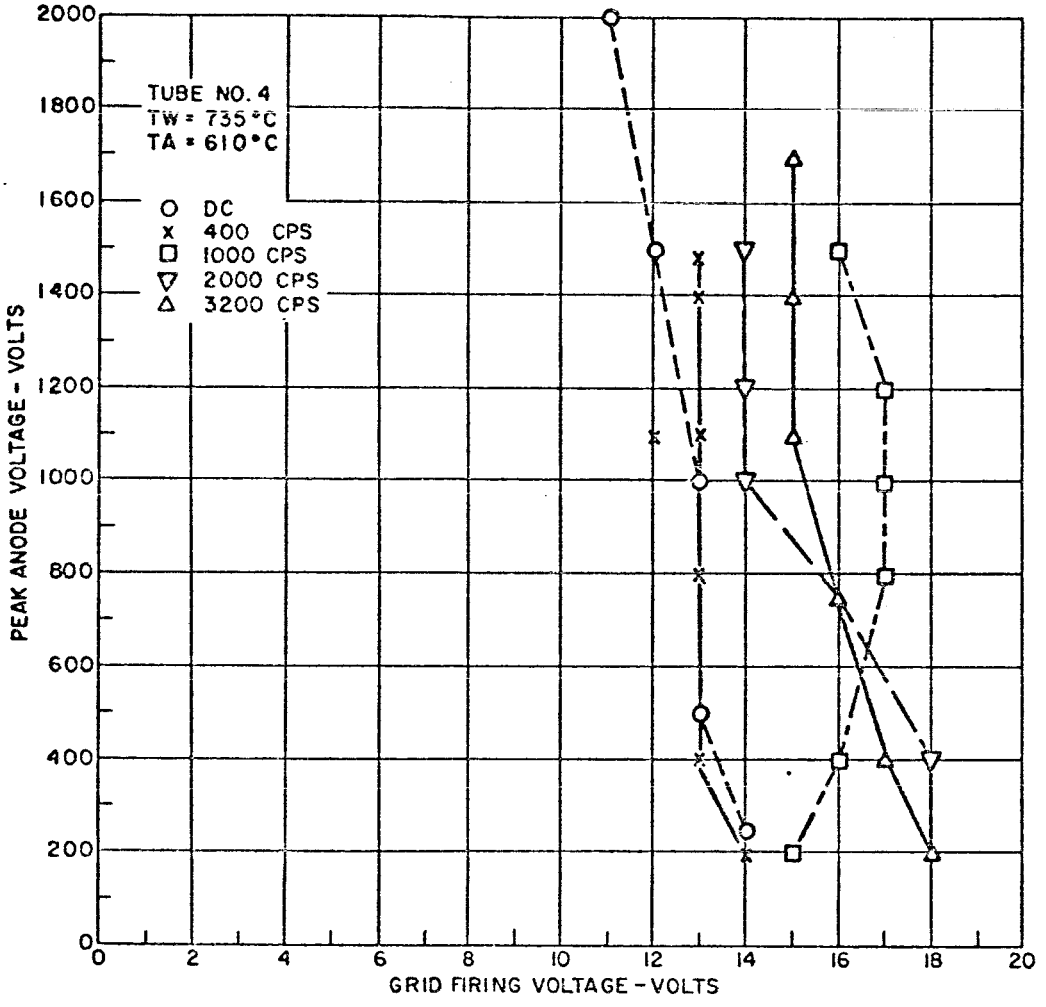

Figure 19 - Grid Characteristics of Tube No. 4

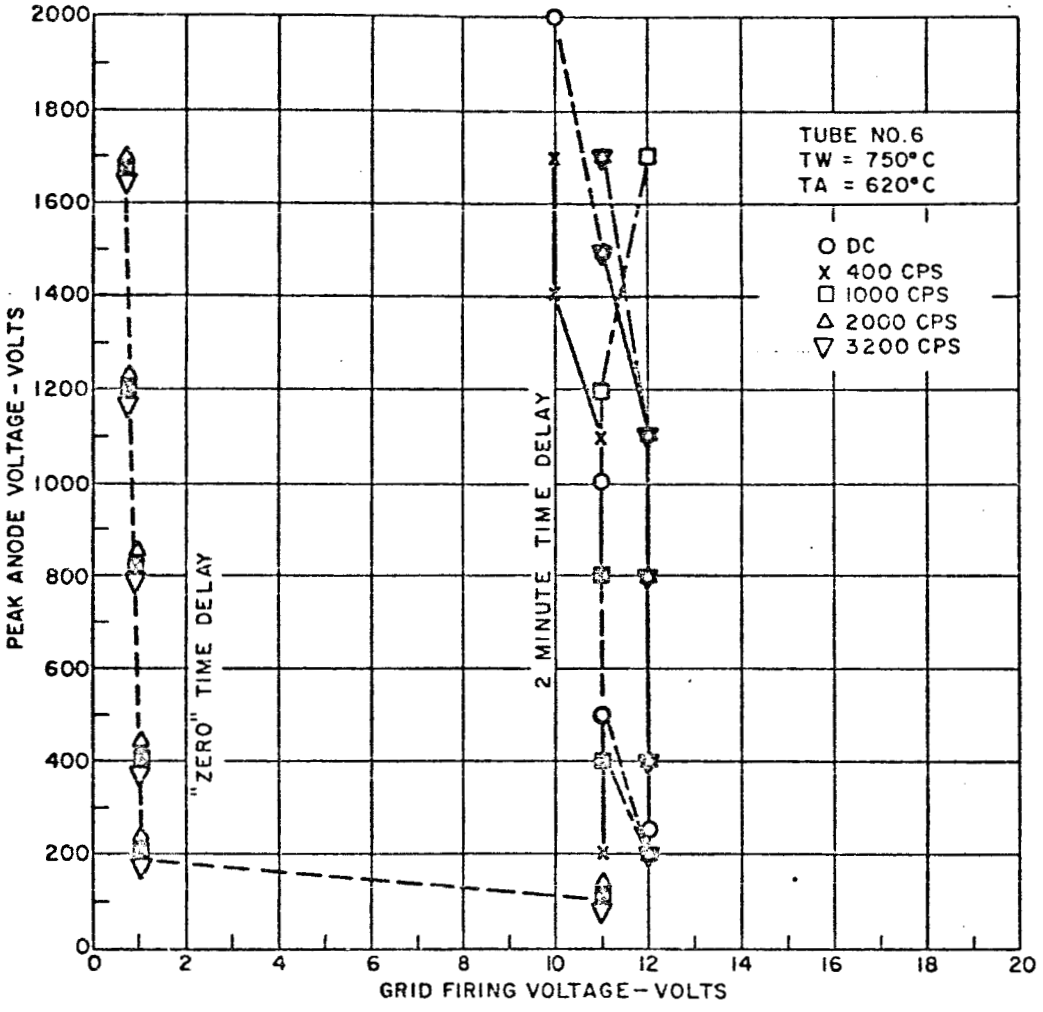

Figure 20 - Grid Characteristics of Tube No. 6

grid current to about 0. 1 ampere and thus avoid overheating the grid structure. Tube No. 13 was operated in this mode for over 1000 hours. Since rectifier operation can be duplicated very closely in this manner, it was not considered necessary to undertake making the required design changes, and fabricating and testing more tubes to further verify rectifier performance.

Compared to a rectifier of similar design, a thyratron operated in the rectifier mode would have 1 to 2 volts higher forward voltage drop, which means a slightly higher anode wattage to dissipate and slightly lower efficiency. If these minor points are not considered objectionable, it may well be more practical, for reasons of economy, to use thyratrons as rectifiers rather than making two tubes for such applications in eventual space power programs.

CATHODE SHIELDING FACTOR

A tightly baffled thyratron has, in effect, two grids. In addition to the grid so designated, the shielding around the cathode can be considered a grid at cathode potential. This means that changes in the shielding structure should be reflected in grid characteristics. One would have expected that tube No. 2 and tube No. 4 (of open shield structure) would be alike in grid characteristics, and that tube No. 6 (tightly baffled) would require a much higher positive grid voltage; however, the grid characteristics of tube No. 6 differed little from tube No. 2 or No. 4 (see Figures 18, 19 and 20). Tube No. 5 and tube No. 7, also of open structure, were similar in grid characteristics.

In general, among endurance tested tubes, the most prevalent and most stable grid characteristic conditions were similar to those exhibited by tube No. 6, both for "open" tubes and for tightly baffled tubes. The lack of variation between the two structures suggests that the grid-cathode discharge is initiated from a surface outside of the area of the cathode and slotted shields.

Tube No. 8 was tightly baffled, similar to tube No. 6, but was difficult to fire at all. This was partially negated by the early failure of tube No. 8 due to an envelope leak. Tube No. 9, which had tight baffling, exhibited some anomalous grid characteristic behavior, varying considerably with tube life, as plotted in Figure 21. Possible reasons for such anomalous behavior are discussed below.

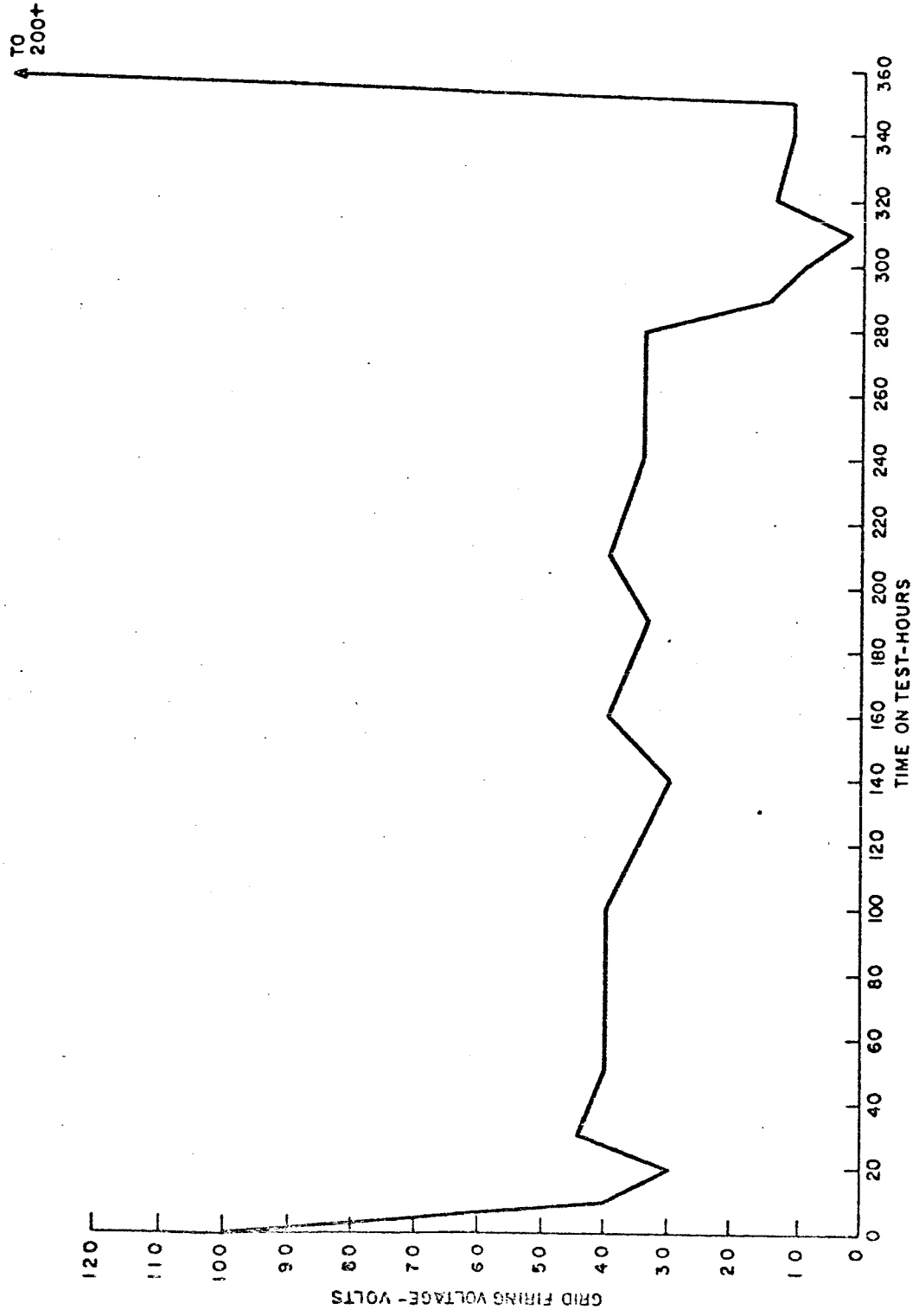

Figure 21 - Starting Voltage vs. Life for Tube No. 9

TEMPERATURE EFFECTS

A temperature anomaly first observed in tube No. 6 was subsequently found to be typical behavior for all the tubes. Figure 20 shows the grid characteristics immediately after cessation of the discharge and again two minutes later. The latter characteristic was normal for a cold starting tube. As the curve shows, when the tube was firing continuously (i.e., every half cycle), the required grid voltage was less than 5 volts. If the measurements were made about two minutes after the tube had been turned off, the tube would control at about 10 to 15 volts positive on the grid; approximately ten volts difference was typical. This effect was independent of anode voltage above 200 volts and of frequency from 60 to 3200 cycles, and only slightly dependent on wall temperature from 550 to 750°C. The shift in firing voltage is apparently a step-function, and usually occurs 10 to 60 seconds after tube current is cut off. It was somewhat more prevalent at a tube current of 10 to 15 amperes than at 2 to 5 amperes.

When the tube is conducting, the discharge heats the anode, grid, and cathode-shield structure. It is considered improbable that the anomalous behavior described above is due to anode or grid temperature changes. This effect is more reasonably initiated from the cathode-shield structure because: (1) it operates in the temperature range of appreciable electron emission for barium on nickel, (2) the grid voltage required to fire the tube is too low to initiate a discharge, and (3) the cathode shield is of small enough mass to change temperature rapidly in the area near the center hole in the cathode shield (see Figure 4).

The hypothesis for this anomaly is that the discharge is initiated in a region where electric field from the anode penetrates the grid. If cathode evaporants condense out on the shield surface directly under the grid, this surface could act in a manner similar to a cathode. The temperature, and therefore the emission from this shield, would be sufficiently high immediately after the tube is cut off to maintain a discharge. With the tube off for a time, the shield would cool, and not be able to furnish enough emission to start a discharge, thus preventing breakdown from occurring. If this is the case, it is suggested that when the tube is conducting, the positive grid voltage required to fire drops to a value necessary to start a discharge from the cathode shield. As the current builds up, the discharge extends to the main cathode.

Other interesting observations also fit this hypothetical picture. When some tubes were operated for relatively long periods of time at high voltage

and at 3200 cycles, the grid voltage required to fire displayed a tendency to increase. In some cases, the grid firing voltage increases to as high as 200 volts. The grid control voltage could be reduced by raising the cathode temperature 200°C for a few minutes. It is believed that this action replenished cathode evaporants on the shield structure.

Moreover, some observations were made under phase-retard conditions, in which tube firing is prevented until late in the positive half cycle. Under these conditions, the initial ion energies during the ionization time (breakdown) can attain relatively high values since a high anode voltage is available when the tube fires. These energetic ions bombard the cathode-shield structure causing sputtering from the surface. When tubes were operated under phase-retard conditions, hard starting developed in a matter of a few hours. This effect might also be the result of gas clean-up.

Another deviation appeared occasionally in tubes afflicted by hard-starting, illustrating the tightness of the grid structure. Tubes requiring 50 to 100 positive grid volts to start would sometimes establish a cathode-to-grid discharge without firing the tube, at a current of 0.1 or more amperes and 15 to 25 volts drop. Since the tube should inevitably fire with such a current directed to the area of the grid slots, it is thought that the source of electron current emission is not near the cathode proper, the current is being emitted from the outside of the cathode shield, probably near the alumina envelope. This phenomenon illustrates again that any metal surface can become an electron emitter at those temperatures where barium cathode evaporants can occur.

RECOVERY TIME TESTS

These tests were made with d-c anode voltage applied and with the tube conducting. A pulse of negative voltage (100 volts) was applied to the anode by the simple RC circuit shown in Figure 22. The capacitor will discharge into the plate supply and charge to the plate supply voltage at a logarithmic time rate, as shown graphically in Figure 23. If the tube is not deionized by the time the capacitor voltage reaches 12 volts positive, the tube will continue conducting, or if deionization is accomplished, the tube will cut off, and the minimum recovery time can be determined from the RC time constant and from the relationship:

$$V_T = (V_s + V_c)\left(1 - \exp - \frac{T_R}{RC}\right)$$

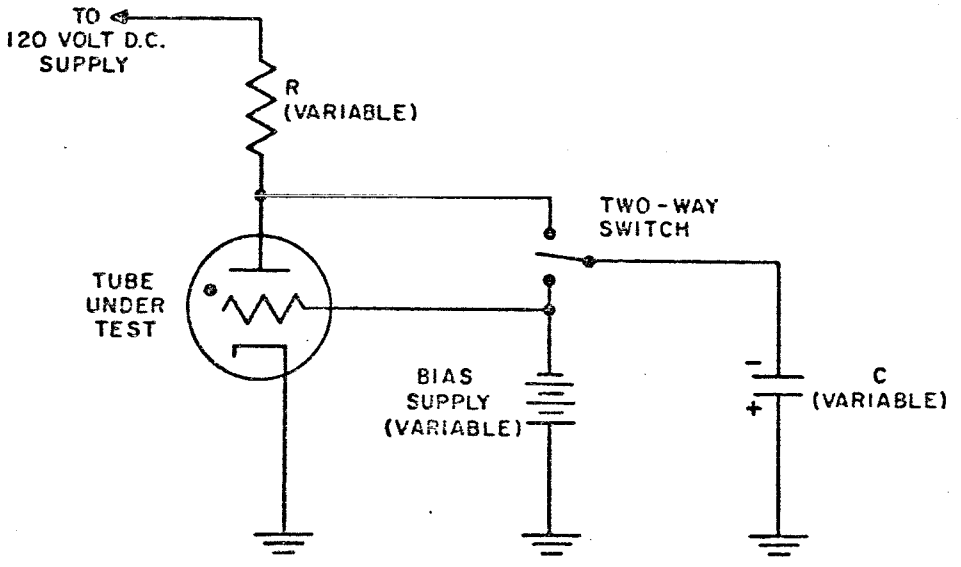

Figure 22 - Recovery Time Test Circuit

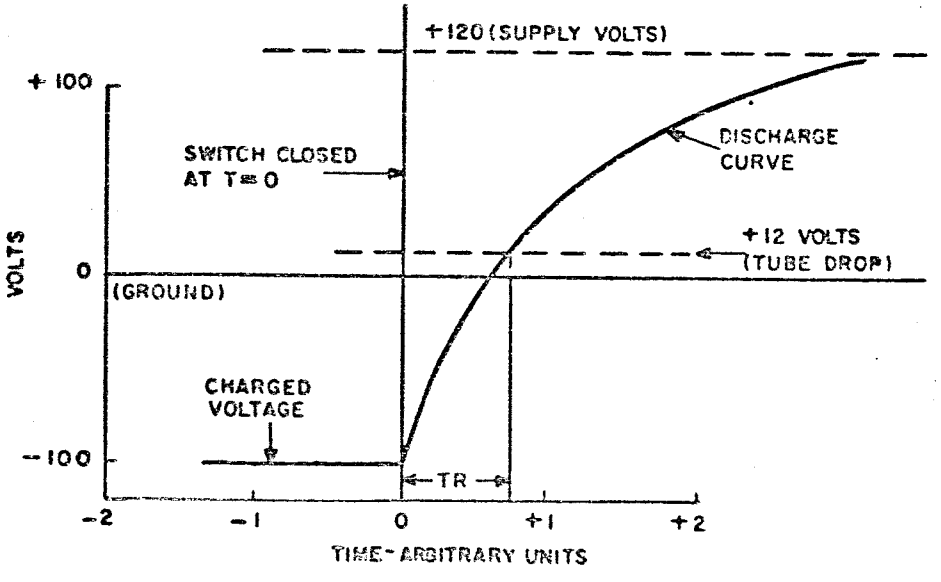

Figure 23 - Recovery Time Voltage Discharge Curve

$$\text{or:} \quad \frac{V_s + V_c - V_T}{V_s + V_c} = \exp -\frac{T_R}{RC} = \frac{1}{\exp \frac{T_R}{RC}}$$

Solving for T_R:

$$T_R = \left[RC \ln^{-1} \left(\frac{V_s + V_c}{V_s + V_c - V_T} \right) \right] = RC \left[\ln^{-1} \left(\frac{220}{108} \right) \right] = .71\ RC$$

where:

T_R = recovery time

R = load resistance, ohms

C = capacitance, in microfarads

V_T = voltage at time T_R = 112 volts

V_s = supply voltage = 120 volts

V_c = capacitor voltage = 100 volts

The recovery time is a function of tube current and gas density, because the degree of ionization is a function of current and the diffusion rate of ions is influenced by gas density. Figure 24 includes a series of curves illustrating recovery time as a function of average tube current for tube Nos. 16 and 19. The initial data were taken after a few hours of operation. The lower curve, for tube No. 19, was taken after 150 hours of high-voltage operation at 3200 cycles per second. The curves for tube No. 16 were taken after 650 hours of low-voltage operation at 60 cycles and no high-voltage operation. Successive curves were also taken after 250 hours and 375 hours of high-voltage operation at 3200 cycles per second. Total on-time of this tube was 1050 hours.

A reduction in recovery time occurred in both tubes initially, even though tube No. 16 was not operated at high voltage during the first 650 hours. Successive curves on tube No. 16 show little or no decrease out to 375 hours of high-voltage 3200-cycle operation. This indicates that gas clean-up early in life is not due to the high inverse voltage but rather to

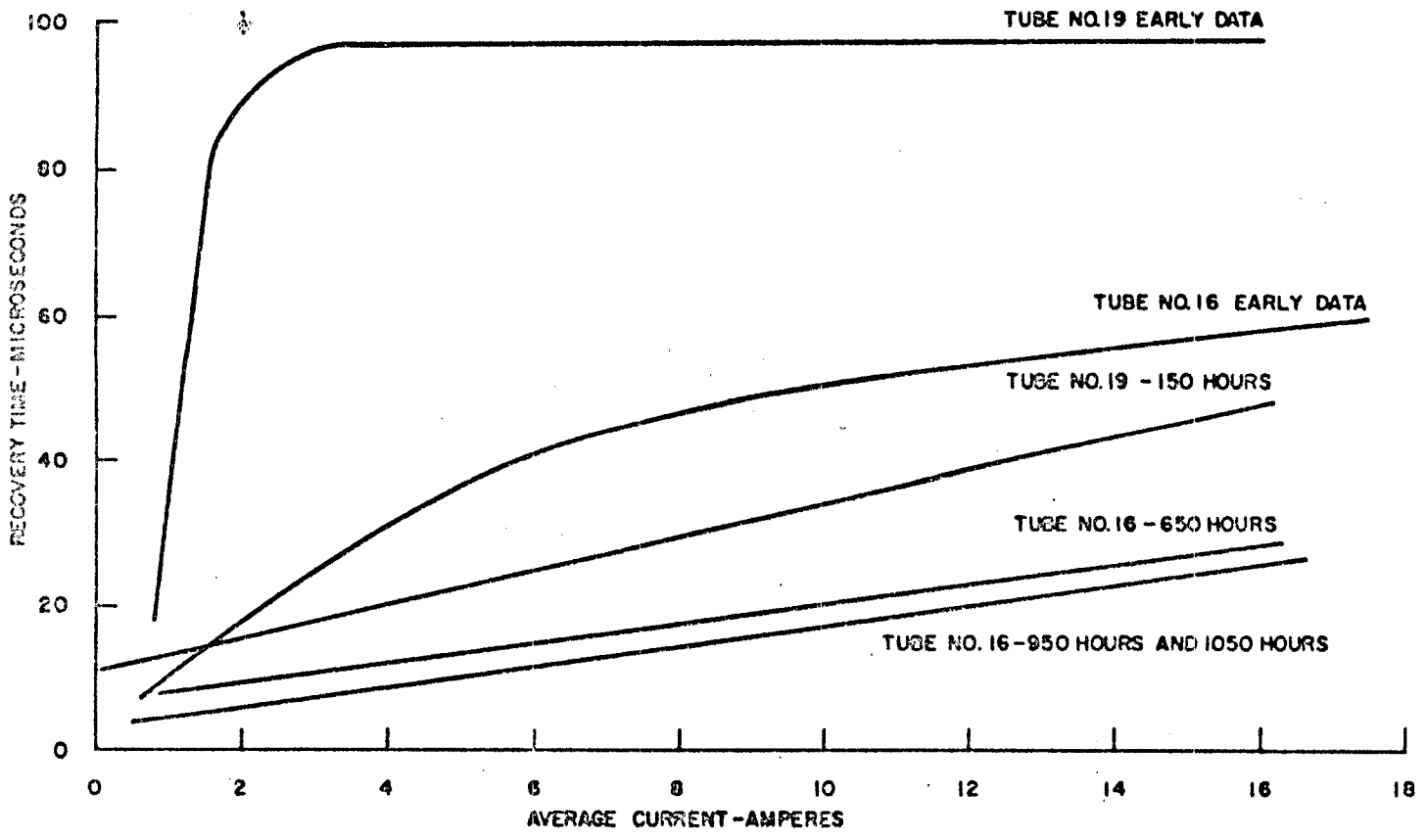

Figure 24 - Recovery Time vs. Average Current for Tube Nos. 16 and 19

another mechanism such as sorption of the fill gas by the thoroughly outgassed graphite grid and anode. Figure 25 is a plot of recovery time versus grid potential for a constant 15-ampere average current for tube Nos. 15, 16, and 19. The initial xenon pressure in all three tubes was 100 microns. The data on tube No. 15 was taken after 600 hours of low-voltage operation.

PULSED EMISSION TESTS

Pulsed emission tests were made by applying 1/2 cycle of 60-cycle line voltage once per second to the tube under test. These tests were made to evaluate the electron emission capability of the cathode at various peak currents, but at low average current. This provides an emission test of cathode capability at higher currents than are feasible when the tube is operated continuously, since at high average current the electrodes would quickly become overheated, or the cathode could be damaged by ion bombardment resulting from excessive tube drop. Peak emission tests given an indication of the general condition of the barium -- oxide cathode. Cathodes tend to activate when emitting large currents, as shown in Figure 26. The tube drop at a steady 15 average amperes is much lower than the pulse test data curve. This effect is due to heating of the cathode at high average currents.

More typical peak emission data is shown in Figure 27 for tube No. 16. Two curves are plotted, at 10 and 60 hours of life, illustrating some cathode activation as indicated by a decrease in the cathode coating resistance "R" (the slope of the curve). Again, typical steady-state operation is better than "peak" data, as shown.

CURRENT OVERLOAD CAPACITY

The basis for estimating the maximum current that can be safely drawn from these cathodes is found in pulse-emission studies of oxide cathodes,[7,8] which show that current capability is an exponential function of pulse length

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7. W. E. Danforth, and W. E. Ramsey, Decay of Thermionic Emission of Barium-Strontium Oxide Cathodes During Space-Charge-Limited Operation, Physics Review, 73, 1244-1245, 1947.
8. R. M. Matheson and L. S. Nergaard, The Decay and Recovery of Pulsed Emission of Barium Oxide-Coated Cathodes, Journal of Applied Physics, 23, 869-875, 1952.

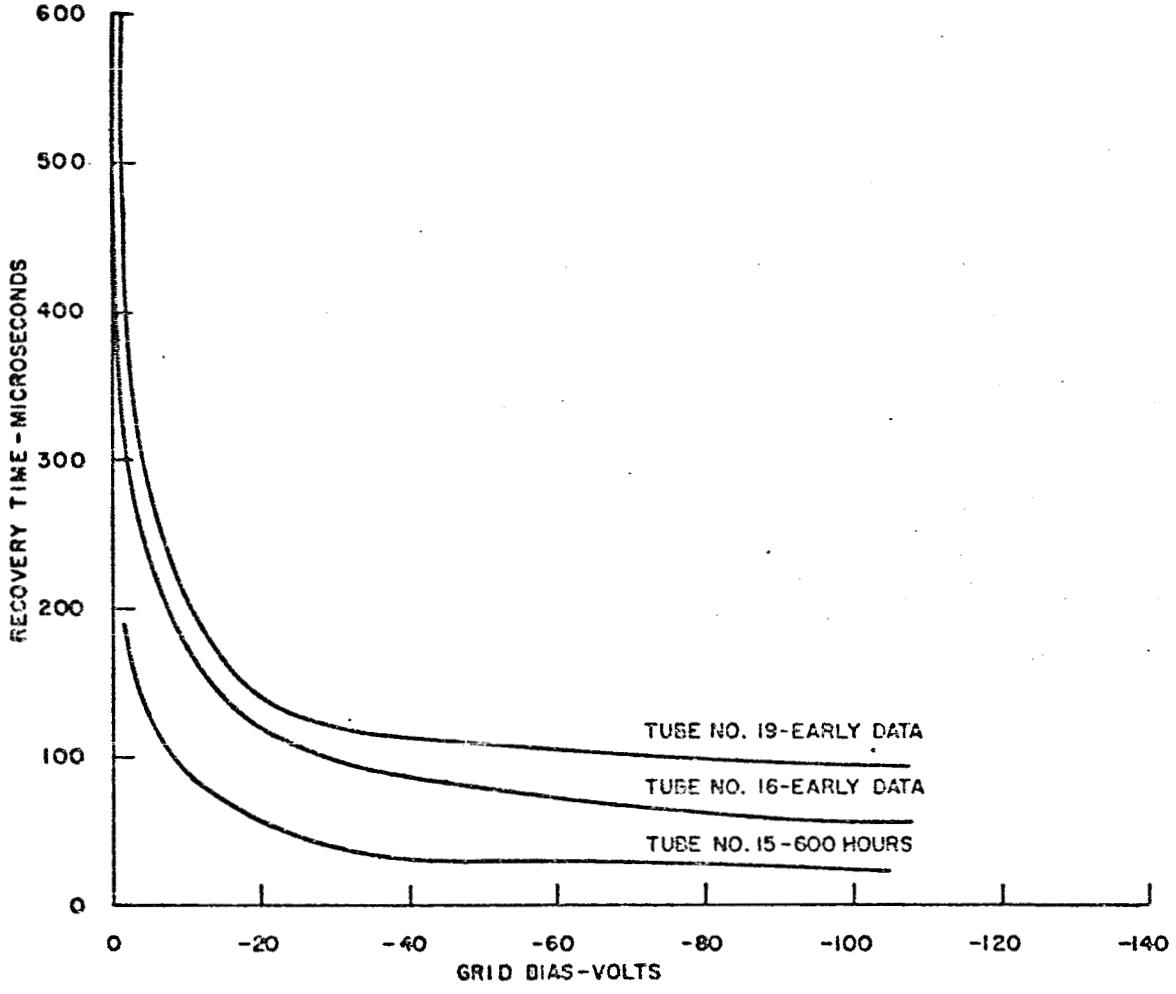

Figure 25 - Recovery Time vs. Grid Bias for Tube Nos. 15, 16, and 19

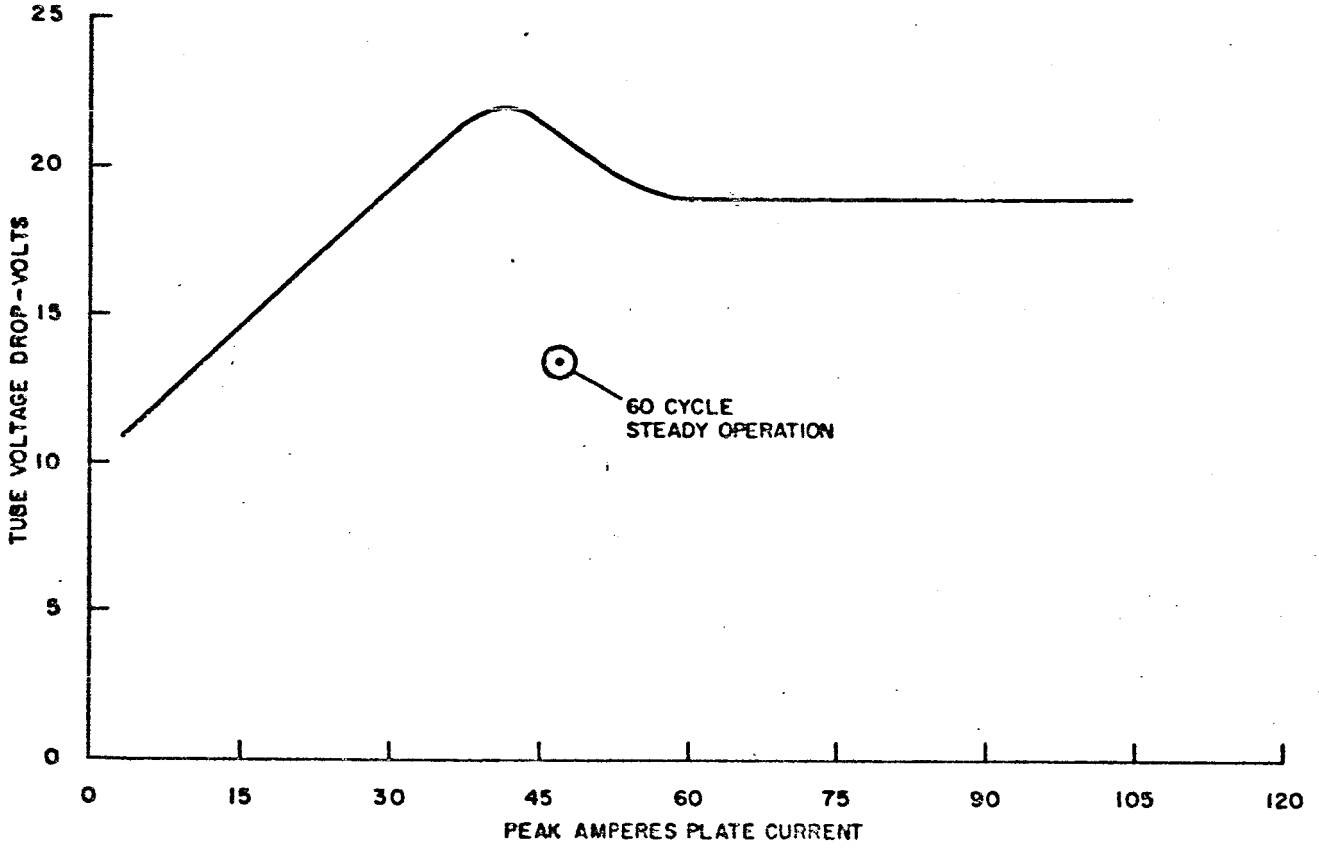

Figure 26 - Peak Emission Test of Tube No. 19 at 150 Hours of Life

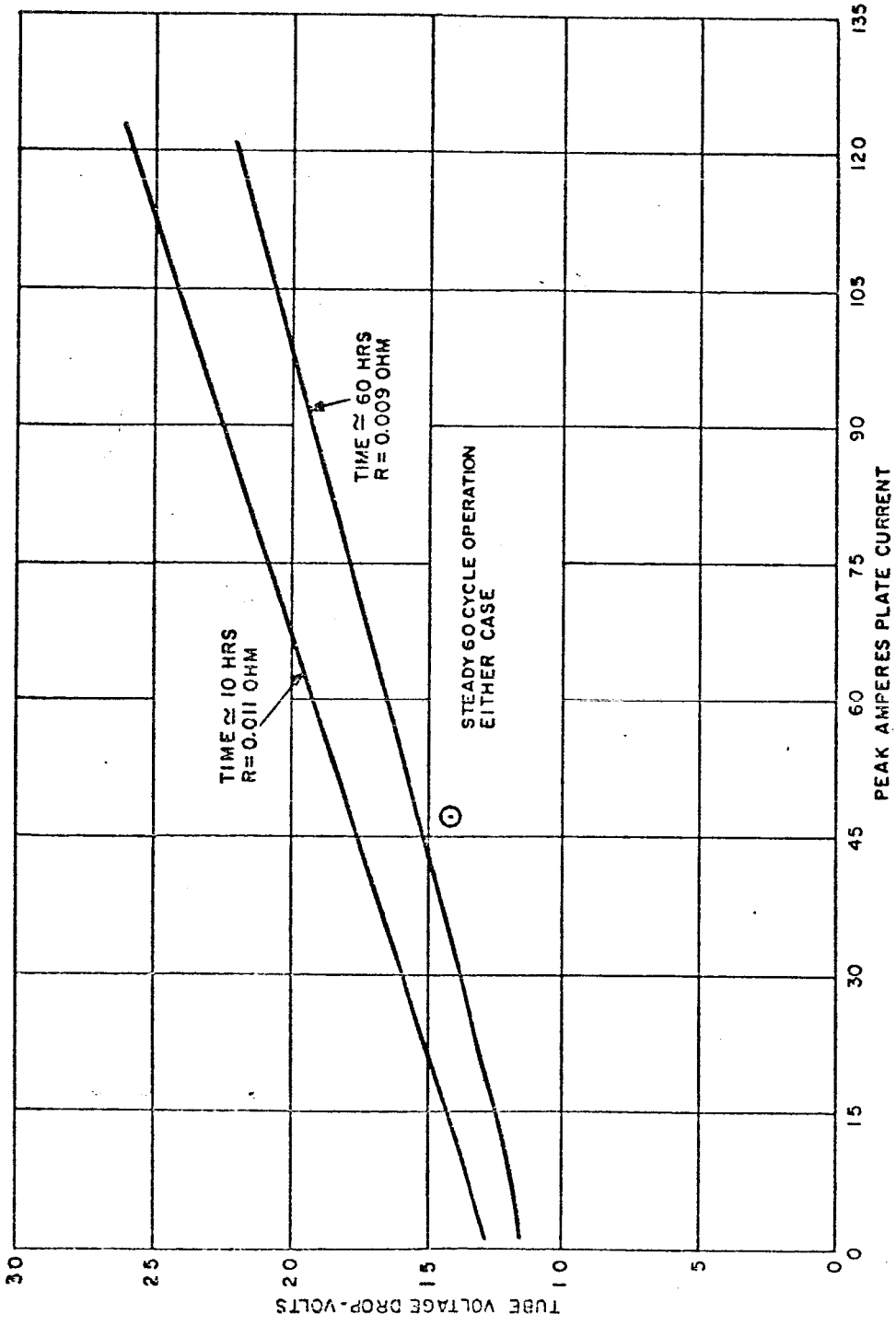

Figure 27 - Peak Emission Tests of Tube No. 16

(time). Since an exponential function is a straight line on a semi-log graph, a graphical extrapolation can be readily made from existing data to the desired operating frequencies as represented by the length of a single half-wave pulse in microseconds. This is plotted in Figure 28. The two data points are: (1) 150 amperes at 60 cycles (see "Pulsed Emission Tests") and (2) data obtained using a 10-microsecond pulse of voltage to draw current from a 30 cm^2 "Design I" cathode, where 10 amperes or more per cm^2 was obtained. According to this extrapolation, maximum peak current for a single half-cycle pulse would range from 300 amperes at 400 cycles to 475 amperes at 3200 cycles. Overloads lasting 2 to 3 cycles should be limited to perhaps 200 and 320 peak amperes, respectively.

CATHODE HEATER CHARACTERISTICS

Barium-oxide cathodes are very sensitive to temperature. At excessively high temperatures, barium evaporation and chemical deterioration are accelerated, and at excessively low temperatures, emission capability falls rapidly, leading to ion bombardment or "sparking" damage to the coating in gas tubes. Therefore, the temperature characteristic of the cathode versus heater voltage was checked before the Design I or Design II tubes were operated. This characteristic is shown in Figure 29 for Design II cathodes, at various tube wall temperatures. Figure 30 illustrates heater current and wattage versus heater voltage at 500 and 750°C.

Note that "start-up" conditions will generate some systems problems here. For example, the heater input wattage for an ideal 830°C cathode temperature, at 500°C wall temperature, is more than twice that required for a 750°C wall.

ELECTRODE MATERIALS

The principal advantages of graphite as a material for grid and anode were discussed above, i.e., 1) a high re-evaporation rate of cathode evaporants, and 2) a low sputtering yield in a noble gas discharge. Some note should also be taken of problems incurred by using graphite electrodes.

One obvious lack is mechanical strength, compared to metals. This is usually a minor problem, circumvented by designing heavier sections and better support. Also, fabrication techniques are limited because neither welding nor brazing is feasible.

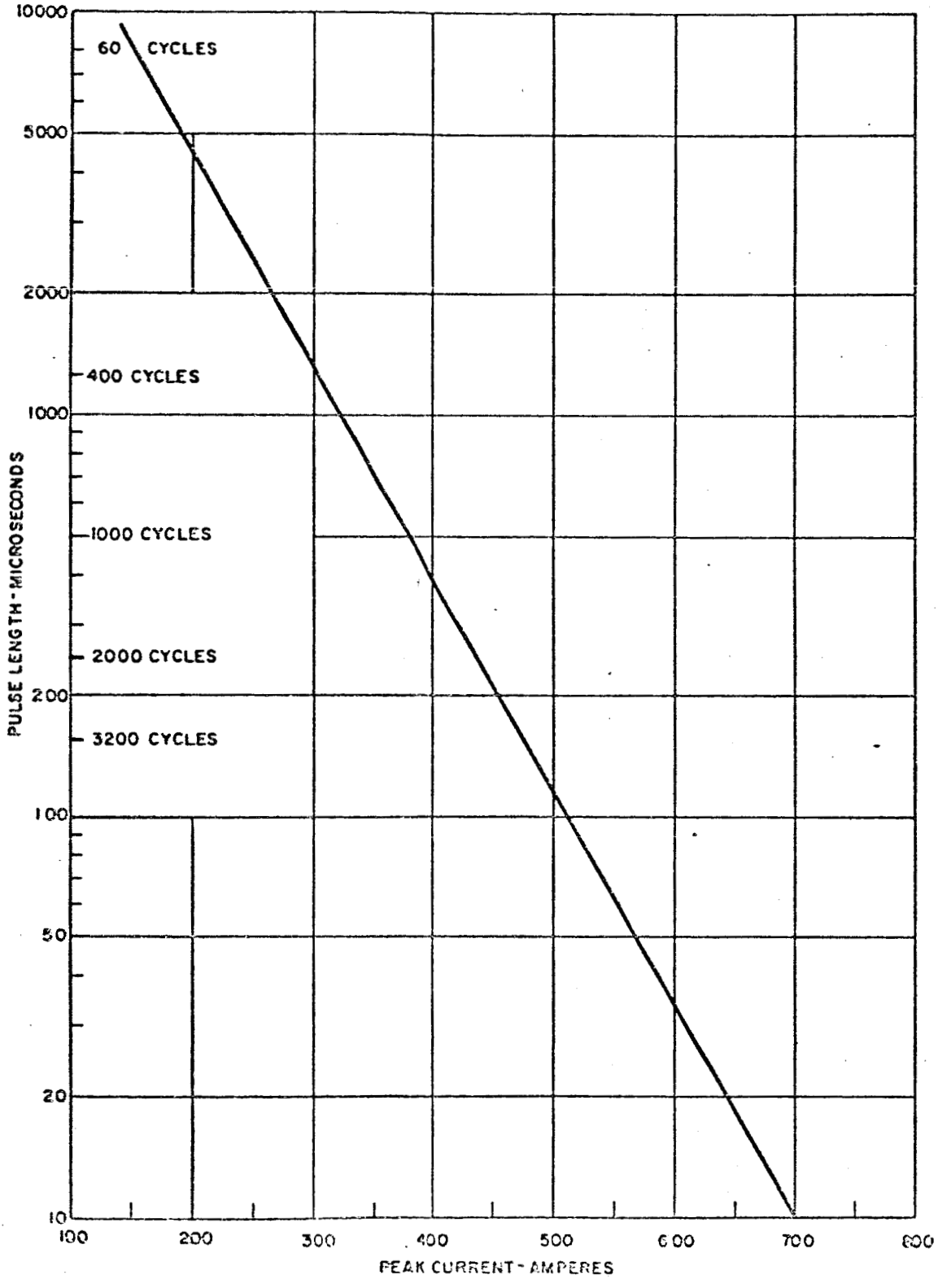

Figure 28 - Single-Pulse Current Capability of Thyratrons with 63-CM^2 Cathodes

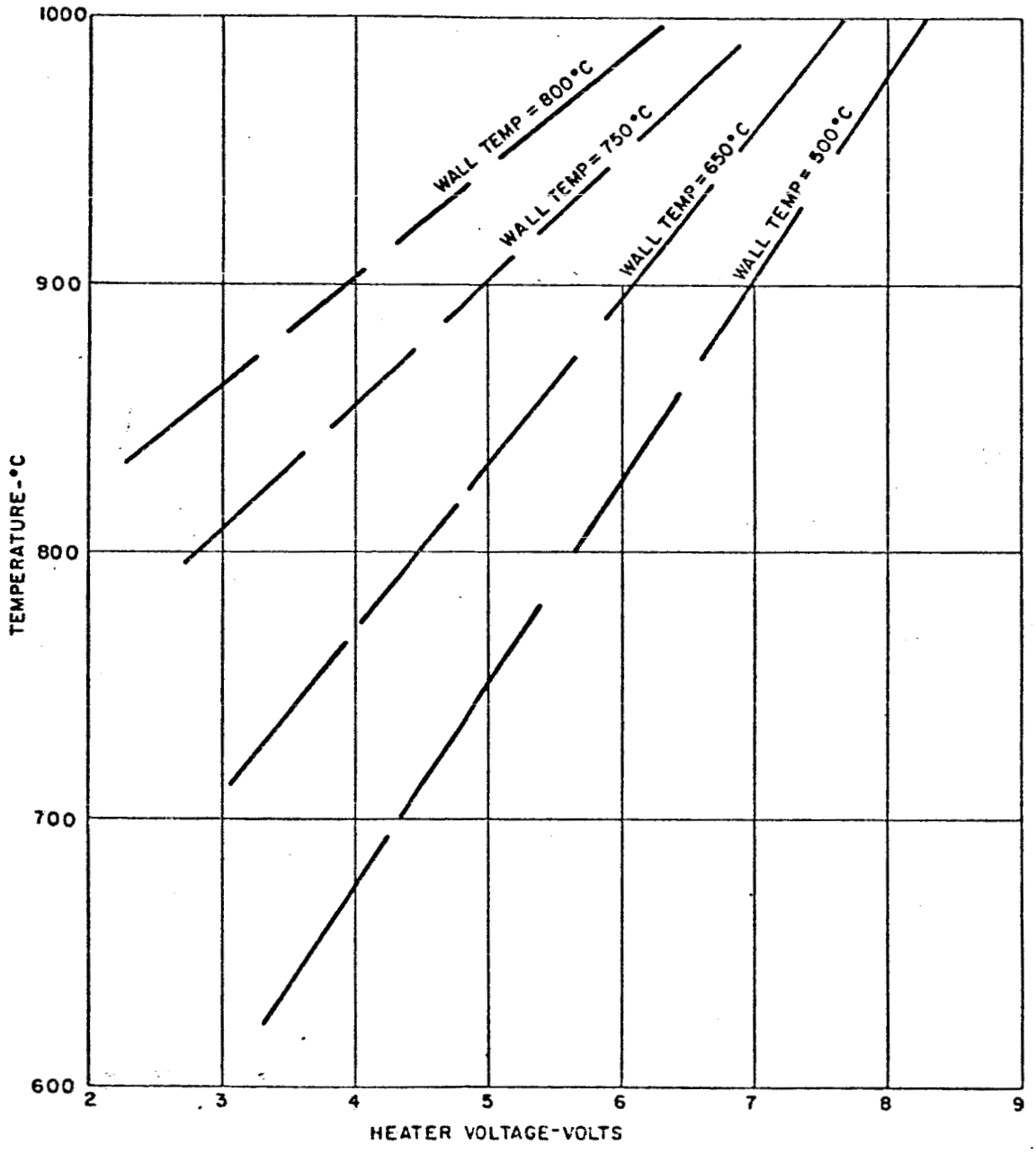

Figure 29 - Cathode Temperature vs. Heater Volts for Design II Cathodes

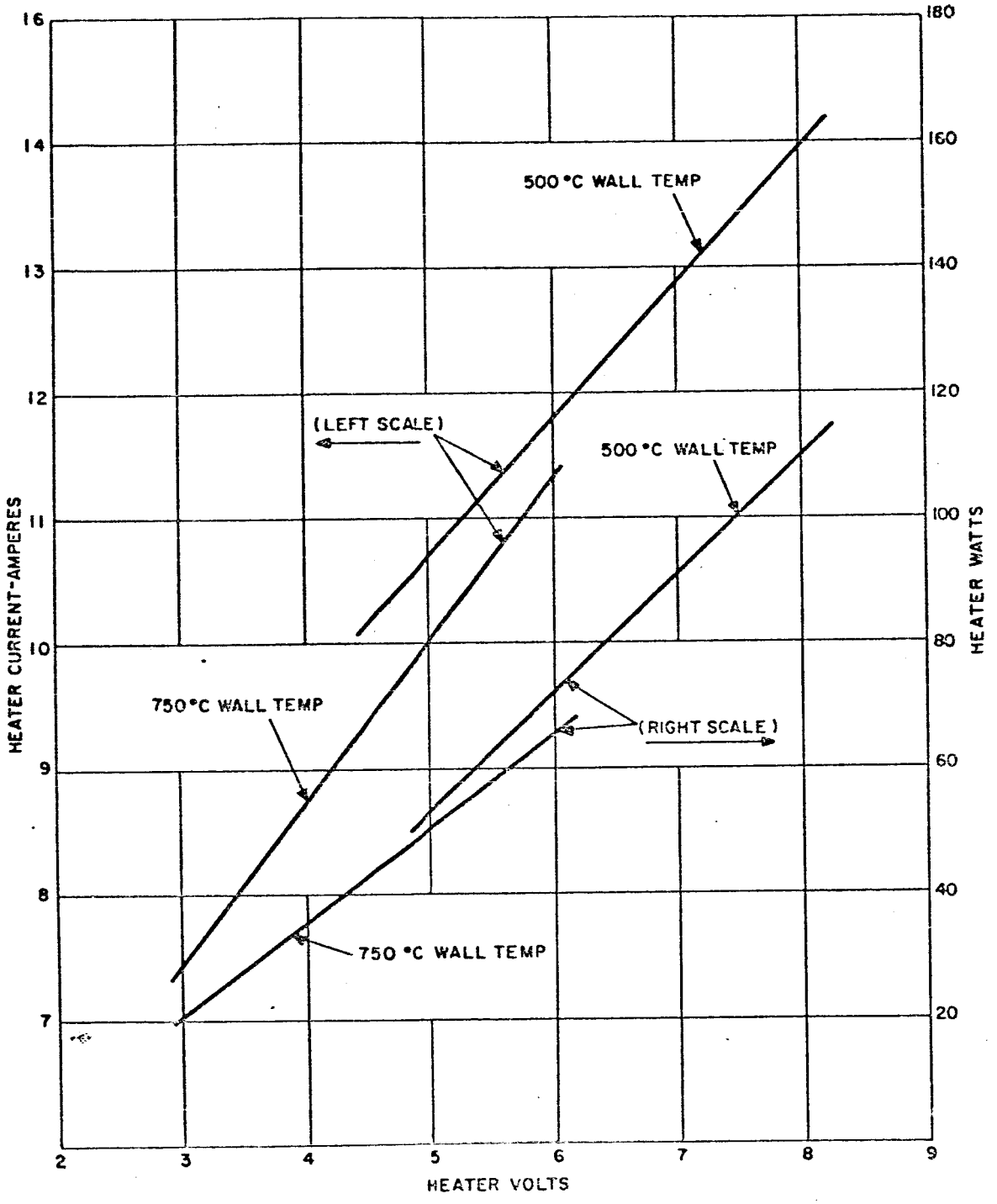

Figure 30 - Heater Current and Wattage Characteristics at 500°C and 750°C Ambient for Design II Cathodes

It would appear that at least two mechanisms at work in gas tubes result in selective transport of graphite electrode material. The sputtering of the anode material by positive ion bombardment at commutation has already been discussed. This results in line-of-sight deposits of "soot", principally on the grid and anode, as can be seen in Figure 31 which depicts tube No. 9 after endurance tests. The accumulation of a very heavy layer of "soot" could result in flaking of the coating and thereby cause erratic shorting problems. There are other graphite-transport mechanisms in evidence such as extensive graphite deposits near the cathode, principally inside the cathode shield. Figure 32 depicts the interior of the shields from tube Nos. 9 and 13 after endurance tests. A hypothesis to explain selective graphite deposits in areas near the cathode is as follows:

The residual oxygen and carbon monoxide in the tube can generate an oxygen cycle due to dissociation of CO by electrons of 11.11-volt energy, which are available in a xenon discharge:

$$CO + e\ (11.11\ ev) \rightarrow C + O^-$$

The negative oxygen ion will drift to the anode or grid during the time of the main discharge, which means that the oxygen would preferentially recombine with graphite at the grid or anode to form more CO and thereby continue an "oxygen cycle". The neutral C atom would tend to randomly deposit out on surfaces near the main plasma. However, the ionization potential of C is 11.26 volts, so some carbon may become C+ before depositing, making the cathode structure a preferential deposit site. Since ionization would be most probable near the cathode sheath, where 11 - 12 ev electrons are most dense, the graphite would deposit in the cathode region. This may explain why the soot deposits in the shield of tube No. 9 (see Figure 32), and on other tightly baffled tubes, conforms to the image of the slots in the slotted cathode shield. Open tubes, such as tube No. 13 (Figure 32), have no such graphite pattern, and more soot exists on the cathode proper.

Pyrolitic Infiltrated Graphite

Approximately half of the tubes that were endurance tested had porous-graphite anode and grid parts infiltrated with pyrolitic graphite, and the remaining tubes utilized plain vacuum-fired porous graphite. Based on the short-term tests conducted under Contract NAS3-2548, it appeared that the infiltrated material produced less "sooting" and less tendency to damage cathode emission capability (due to contaminants evolved from the graphite).

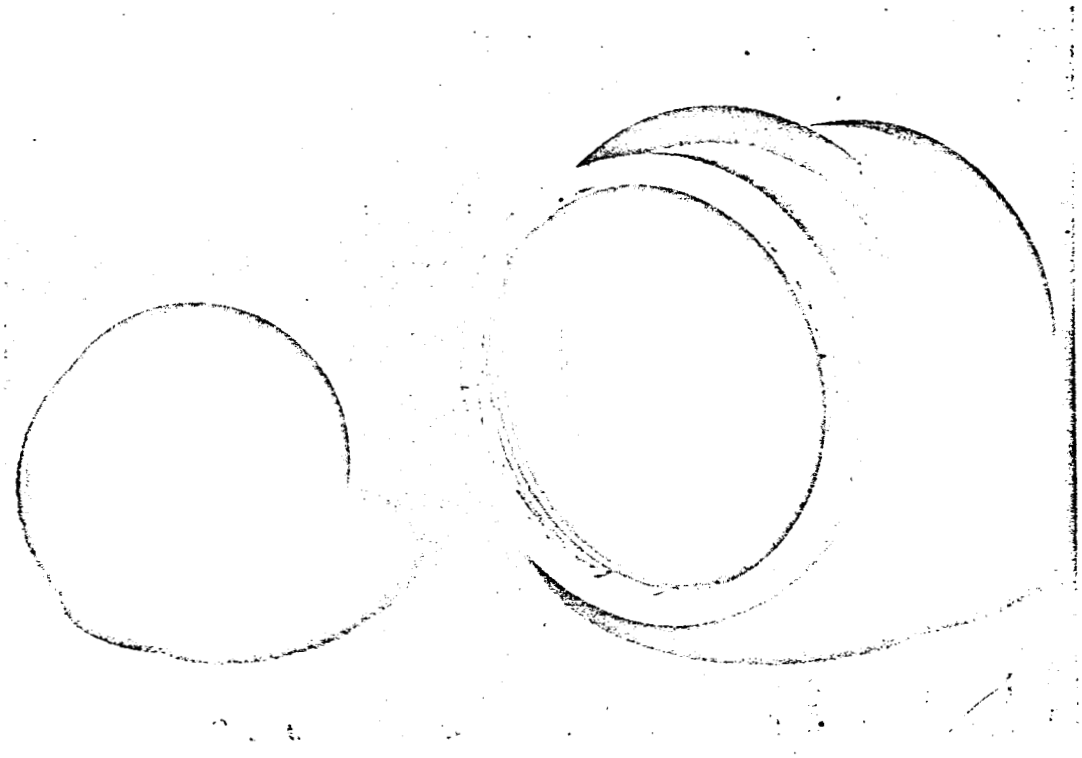

Figure 31 - Anode and Grid of Tube No. 9 after Endurance Tests

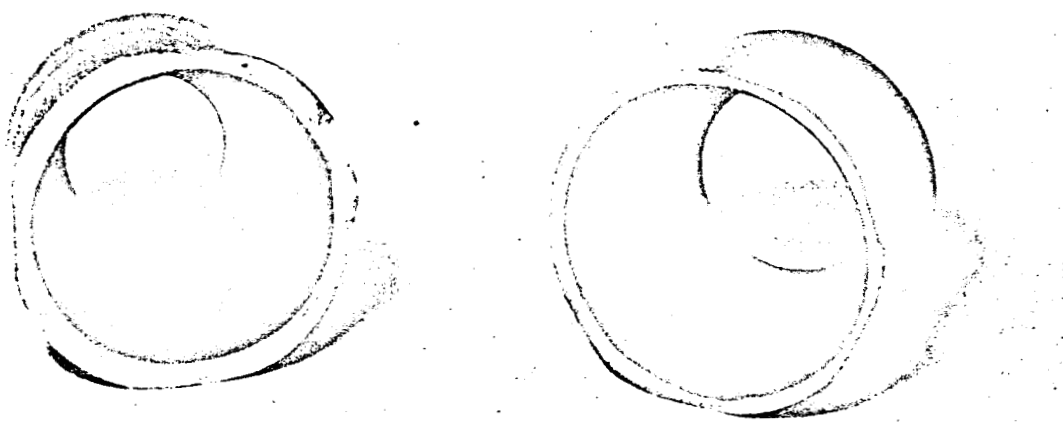

Figure 32 - Cathode Shields of Tube Nos. 9 and 13 after Endurance Tests

However, the endurance tests conducted in this program showed few significant differences between plain and infiltrated material.

SHOCK TESTS

As outlined in the contract requirements, two Design II tubes were shock tested at 35g with a half-sine pulse of 8 milliseconds duration. Shocks were applied three times in each direction, in three mutually perpendicular axes, for a total of 18 shocks. The shock mount fixture and tubes are shown in Figure 33.

Tube Nos. 15 and 20 were shock tested. Tube No. 15 is exactaly as shown in Figure 2, and tube No. 20 differs only in cathode shielding (the slotted shields are not used, and the end shield is welded to the cathode fins by means of small channel-shaped pieces, i.e. tube No. 20 is of "open" shield structure).

In addition to an electrical heater test before and after shock, the tubes were X-rayed in two mutually perpendicular planes before and after shock testing. These X-ray photos are shown in Figures 34 and 35. No evidence of change resulting from shock is apparent on any of the elements.

DISCUSSION

There are a number of areas requiring further effort to improve reliability of high-temperature gas thyratrons for applications in the 10,000-hour life range. Recommendations for further work are outlined below.

To produce a more meaningful evaluation of tube life, longer endurance tests should be performed. It is also important that tests be conducted at full tube voltage and current ratings, to evaluate gas clean-up more fully. In this vein, a more accurate measure of gas clean-up rate can be obtained with a gas pressure gage; a Pirani gage element attached to the cathode shield, but well shielded from the main plasma, would be a good choice.

As discussed in this report, it appears that more extensive use of graphite would be advantageous, both in regard to sputtering problems and to reduce unwanted electron emission. To accomplish this, some redesign is required. A sketch of the proposed design is shown as Figure 36. In this design, all surfaces subject to positive ion bombardment are essentially covered by graphite members. This also means that surfaces which may contribute to electron emission are covered by graphite, which should improve the problem.

The anode shield in the proposed redesign is connected to the grid to shield the insulating ceramic from the principal source of sputtered material, the graphite anode. Additional shielding adjacent to the insulating ceramic can be provided, if necessary. Note that the envelope design must also be changed at both the cathode and anode ends, to allow the larger graphite pieces to be assembled into the tube.

The weak point of the Design II envelope is the braze between the tubulation and molybdenum anode support, where two tube failures occurred. The proposed redesign of Figure 36 utilizes a kover-to-kovar weld to replace the tubulation braze, and provides for a braze to the molybdenum anode support as a mechanical/thermal connection. A threaded stud is also brazed on external to the envelope to provide an external mechanical/thermal anode connection.

It is possible that some improvement in the "sooting" problem can be accomplished by employing schemes which reduce the level of oxygen in the tube, based on the "oxygen cycle" postulated for this phenomenon. One probable source of oxygen is the porous graphite, which adsorbs gas proportional to the surface area of the structure. Solid pyrolitic graphite, being a dense non-porous structure, would produce less gas and should be better in this respect than the porous graphite infiltrated with pyrolitic graphite used in this program. To effectively take advantage of this property, all graphite parts should be of solid pyrolitic graphite. Moreover, the anode should have the "AB" crystal (the high thermal conducting direction) parallel to the tube axis to take advantage of the thermal properties of pyrolitic graphite. A second possible approach is to provide a "getter" which will chemically pump oxygen and other gases.

Experience in related programs (Contract NAS3-6005 and internal company-funded work) indicates that the sooting problem and electrical interelectrode leakage problem can be improved by using a gas fill which combines readily with oxygen (xenon is inert). For example, a thyratron using the vapor from the metal thallium as a gas fill had less indication of these problems; these limited tests also indicate that thallium is compatible with present tube materials. Also, the metal vapor is not subject to clean-up problems because the vapor is supplied from a pellet of metal held in a reservoir at the lowest temperature in the tube (600 to 700°C for thallium).

In any subsequent program, early tubes should be used to evaluate structures designed to minimize unwanted electron emission and tube control characteristics where critical surfaces are essentially all graphite. This means eliminating slotted shields around the cathode in the early tubes to maximize the incidence of cathode evaporants at critical surfaces.

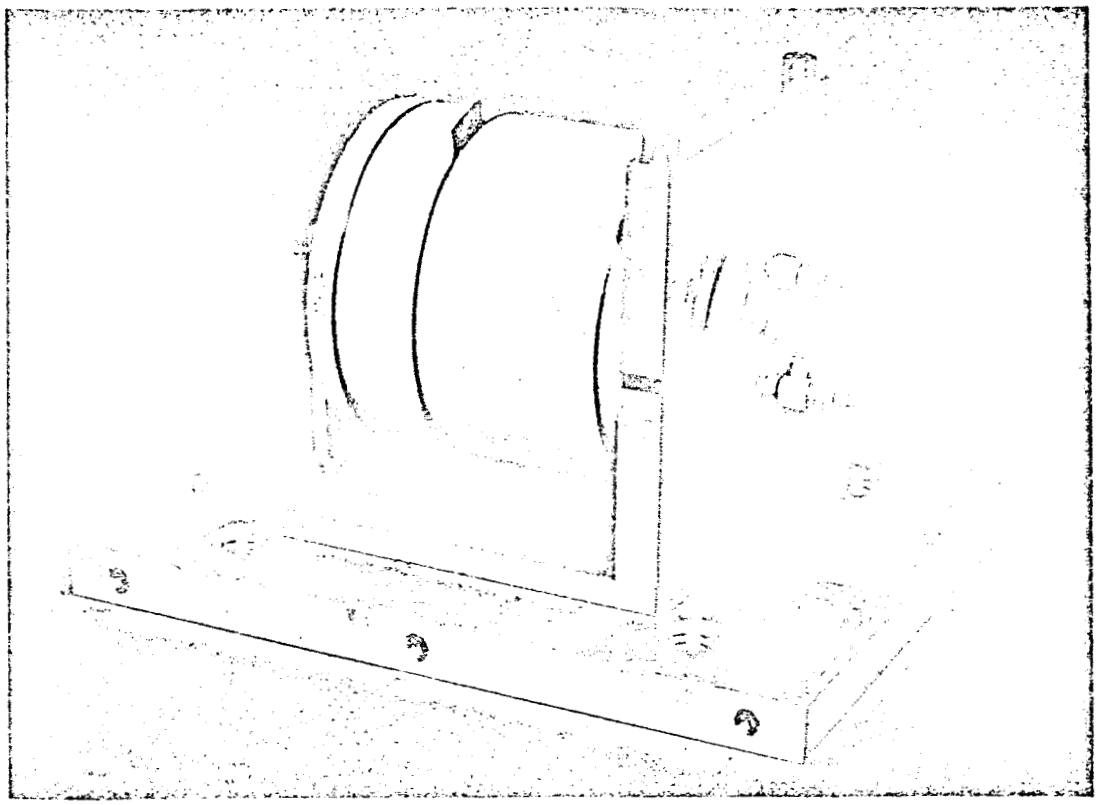

Figure 33 - Thyratron in Shock Test Fixture

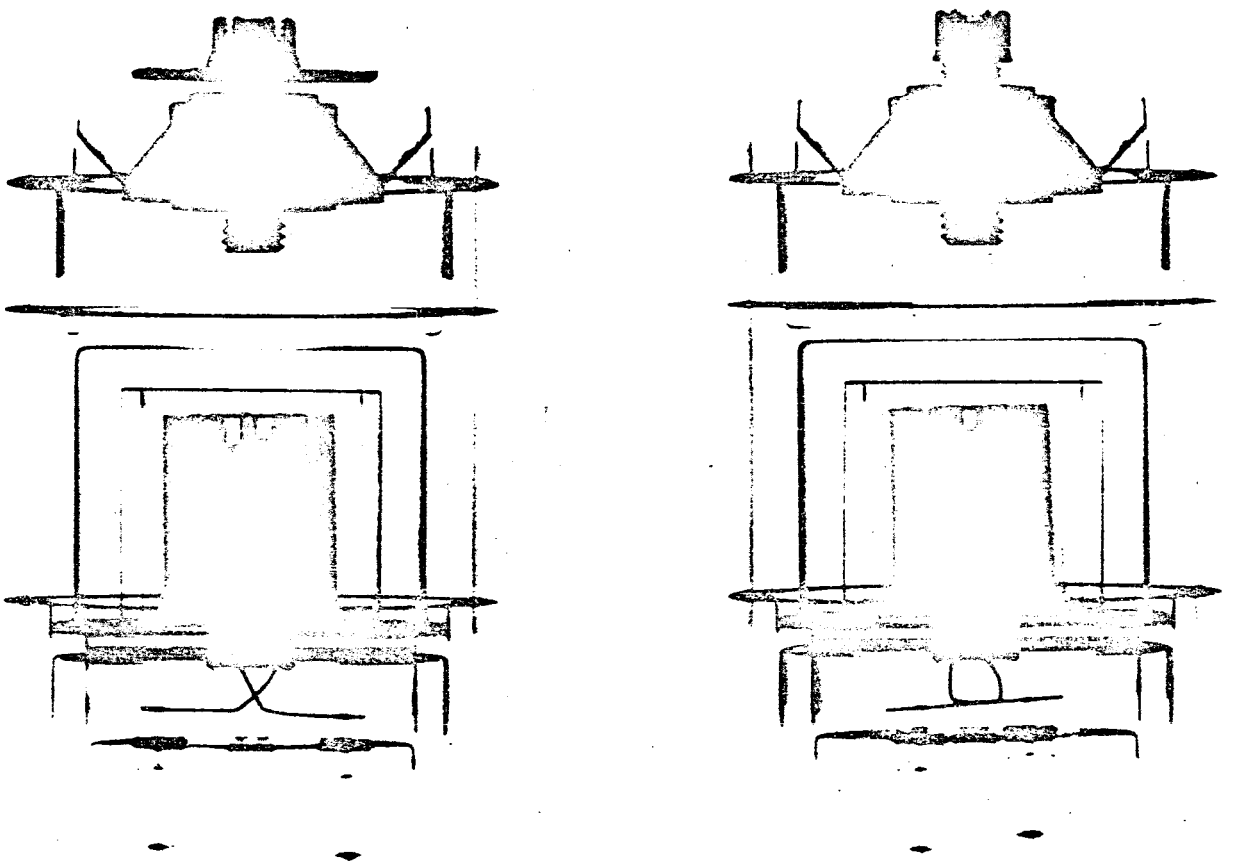

Figure 34(a) - X-Rays of Tube No. 15 Before Shock Test

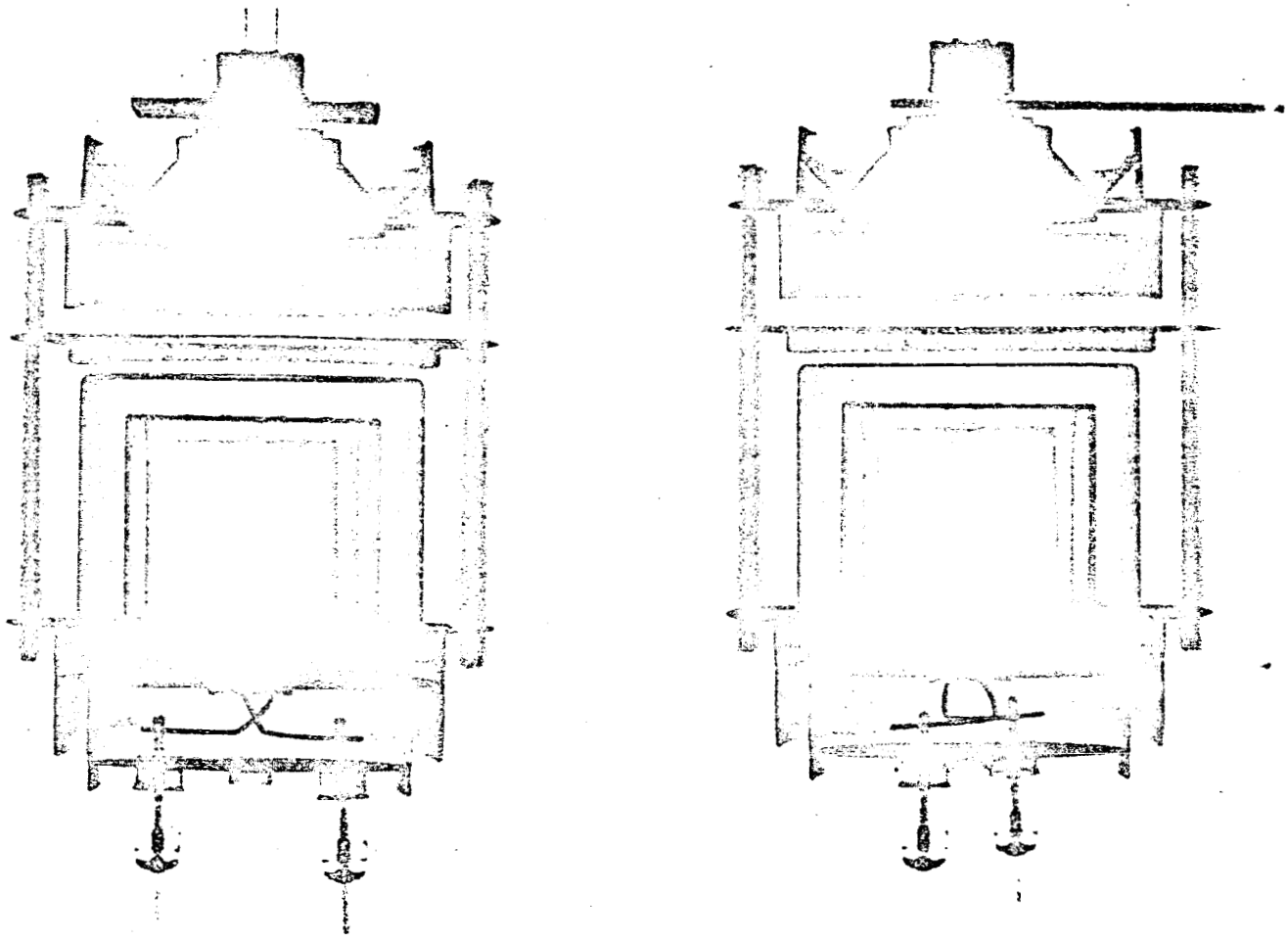

Figure 34(b) - X-Rays of Tube No. 15 After Shock Test

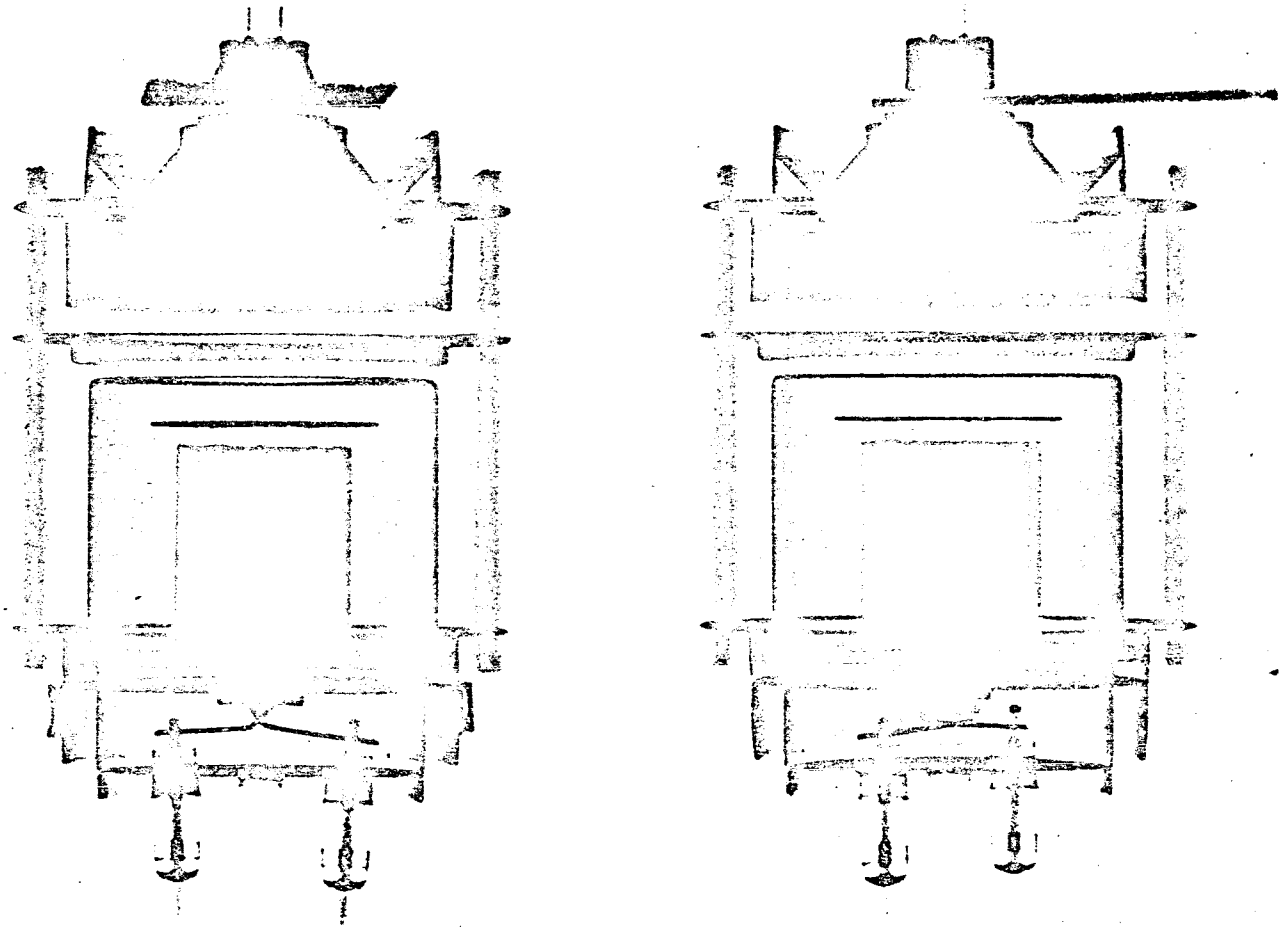

Figure 35(a) - X-Rays of Tube No. 20 Before Shock Test

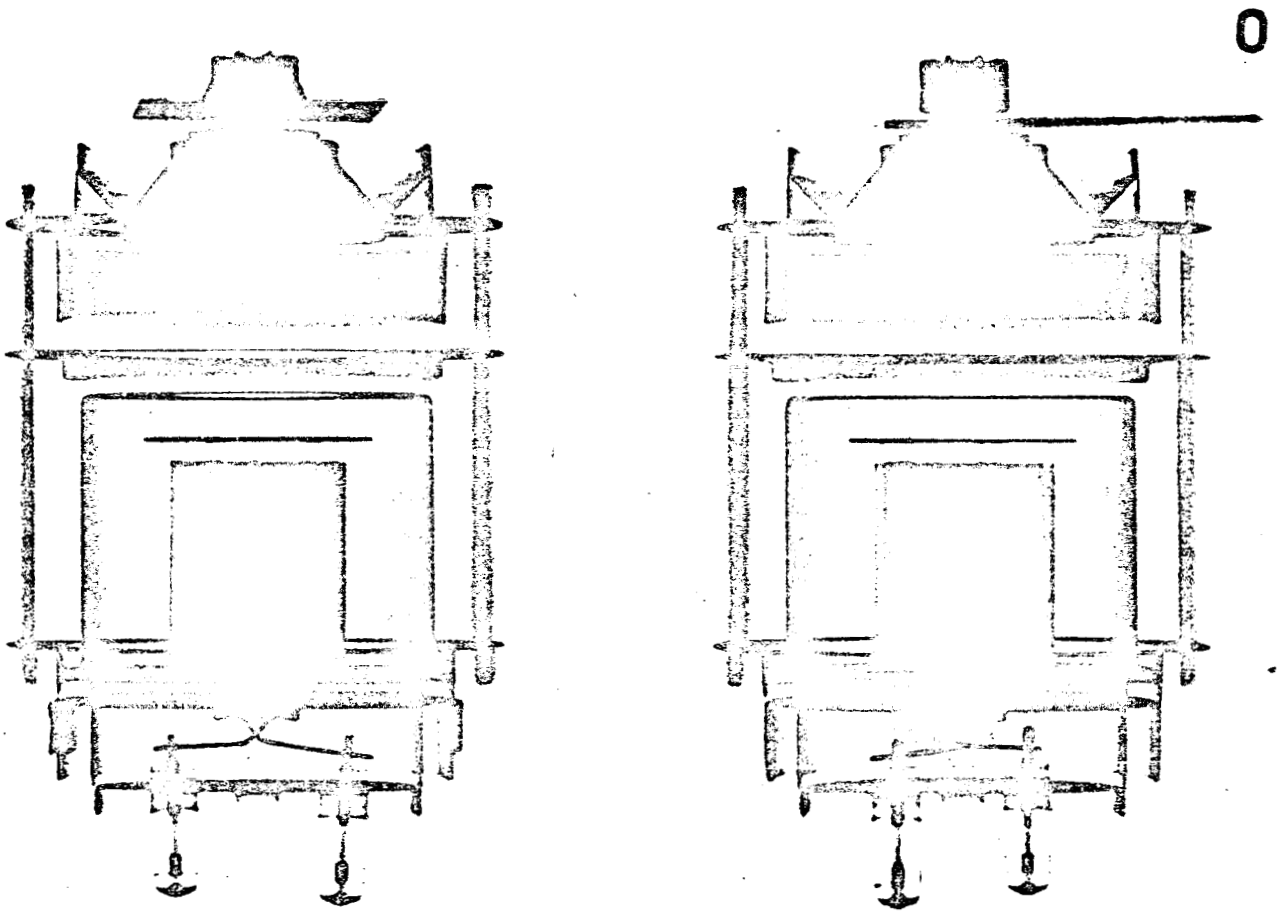

Figure 35(b) - X-Rays of Tube No. 20 After Shock Test

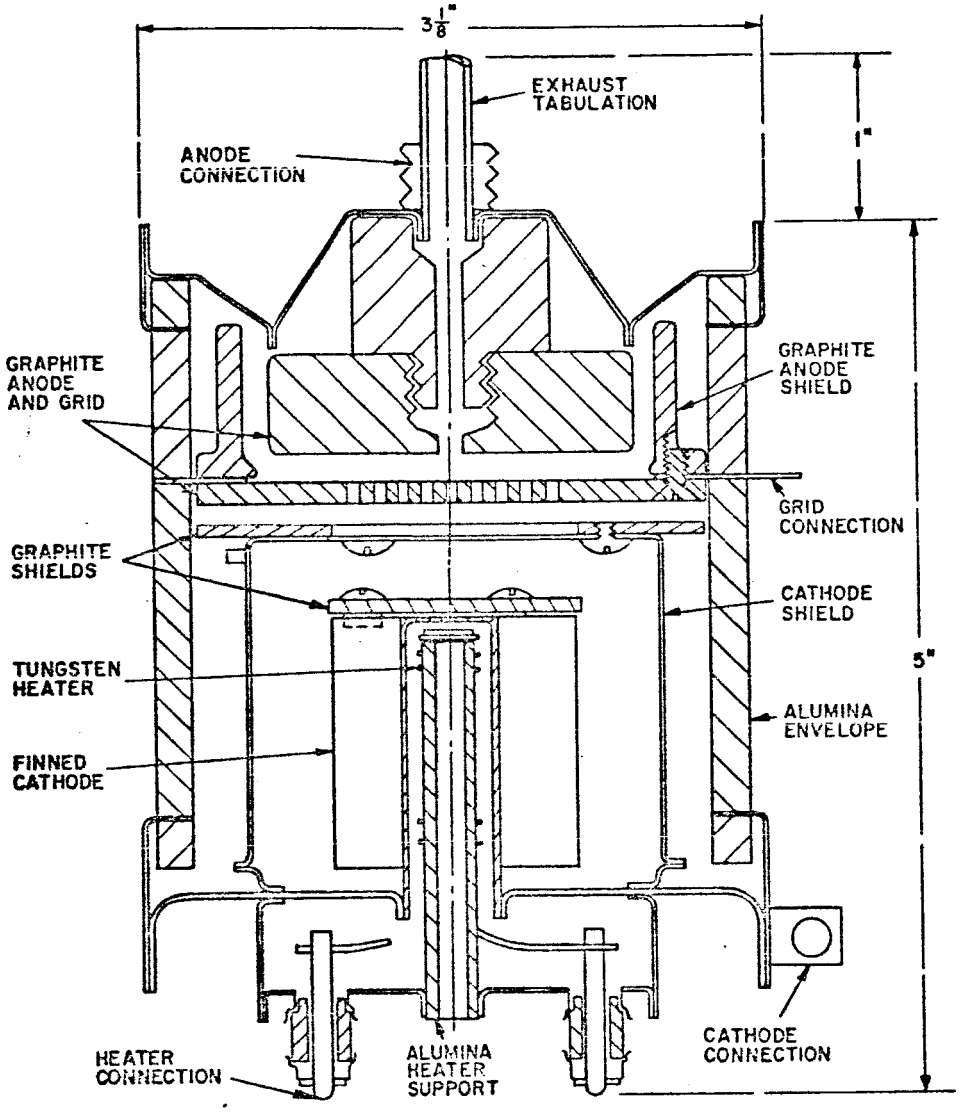

Figure 36 - Improved Thyratron Design

CONCLUSIONS

This program has demonstrated the feasibility of operating thyratrons and rectifiers at tube envelope temperatures approaching 800°C with peak voltage ratings of 2000 volts, forward or inverse, at 400 to 3200 cycles per second and a current rating of 15 average amperes. The "Design II" thyratron envelope has performed well in that no envelope failures occurred at metal-ceramic seals or at metal-to-metal welds during endurance tests. The finned-design barium-oxide cathode also performed well at full rated current and therefore should be adequate for further tests. Operation at 2000 peak volts has not presented serious gas clean-up problems. The use of graphite, which produced good results in the electrodes of the present design should be pursued more extensively in future shield designs.

VOLTAGE REGULATOR AND REFERENCE TUBES

GENERAL

Voltage-regulator and voltage-reference tubes constitute two principal applications of the cold-cathode glow discharge phenomenon. The region of operation for a voltage-regulator device is in the normal glow portion of the volt-ampere characteristic. In this region, the tube voltage is practically independent of tube current over a fairly large range, and the current density is constant. If the current is increased sufficiently until the cathode is completely covered by the glow, then any further increase in current requires an increase in current density, resulting in an increase in tube drop.

The criterion for a reference tube operating at high temperature is that the discharge voltage be stable with temperature. Generally the discharge shows a small negative temperature coefficient over the temperature range of 25 to 100°C. Typically, however, the tubes tested on this program have shown negative temperature coefficients up to 250°C.

TUBE DESIGN

Figure 37 shows a cross-sectional view of the regulator tube design tested on this program, and Figure 38 is a photograph of the completed tube. The electrode geometry is coaxial, with a minimum anode-to-cathode spacing of 0.015 inch. This provides the breakdown gap for starting. The cathode is a molybdenum cup formed from 0.010-inch sheet stock. The inside diameter of the cup is 0.470 inch, and the height is 0.355 inch. This provides a total cathode area of 4 cm^2 and a maximum current capacity of approximately 80 to 100 milliamperes for the normal glow region.

The anode is a kovar tubing brazed to a nickel support and extends to within 0.015 inch of the bottom of the molybdenum cathode. Both the anode and cathode supports are welded to nickel seal flanges. The seal flanges are brazed to the alumina ceramic body by utilizing a titanium, nickel-rich active alloy seal which is effected at 1280°C in vacuum. The use of this active alloy seal allowed the regulator tube to be fabricated with a single braze cycle. The palladium cobalt seal using high purity alumina is not required because of the low applied voltage in this case.

Tube processing consisted of vacuum firing to 900°C for one hour. Typical tube pressure during exhaust was 2×10^{-7} torr, and after bakeout

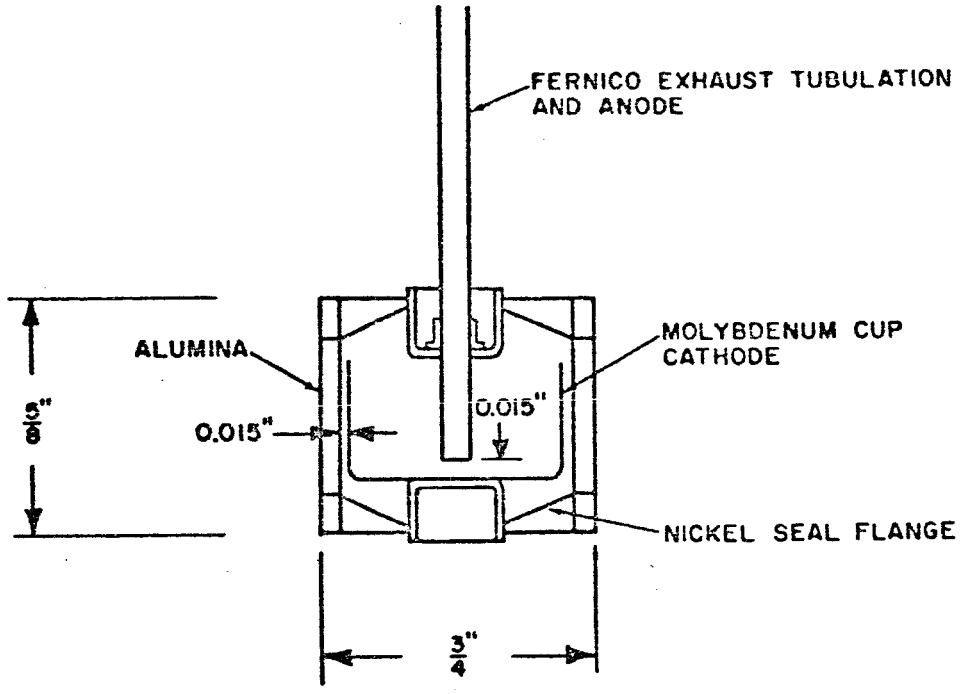

Figure 37 - Cross-Sectional View of High-Temperature Regulator Tube

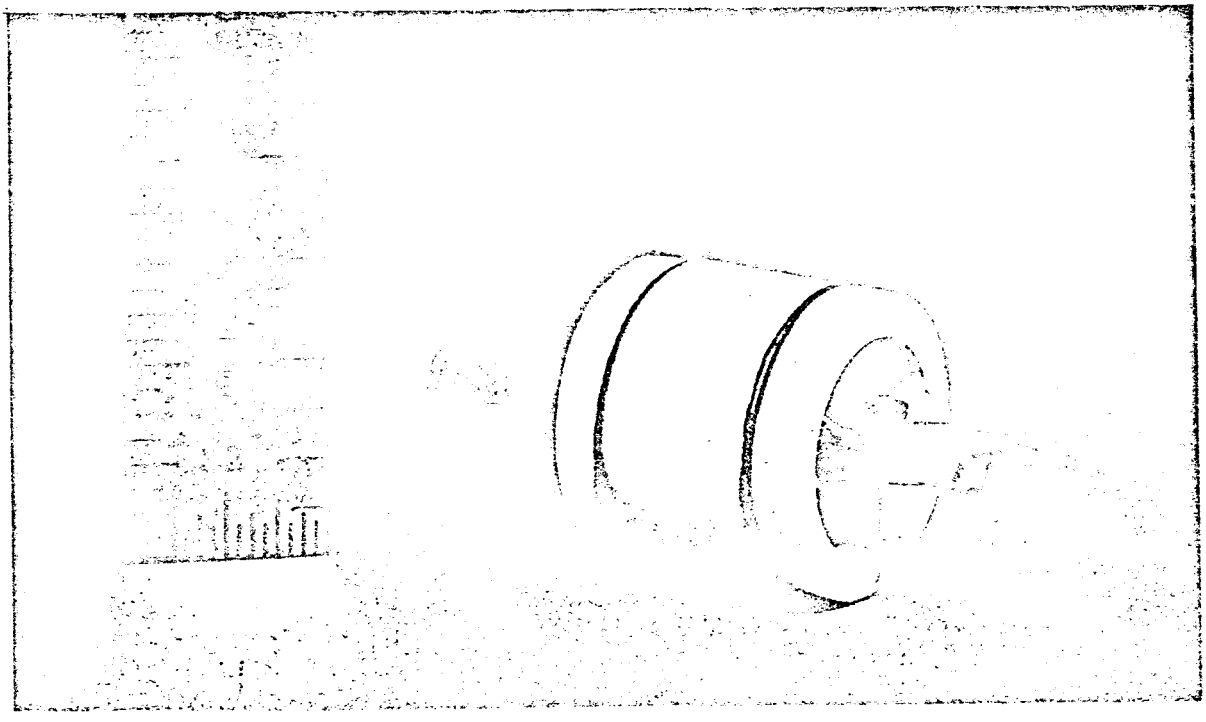

Figure 38 - Completed Regulator Tube

the pressure would drop to 10^{-8} torr. Gas loading was done at room temperature, with typical loadings of 60 torr.

A total of 11 voltage regulator tubes were made during the program. The first five tubes failed during initial tests due to vacuum leaks that developed in the final pinch-off. The pinch-off on the exhaust tubulation was made by pinching the 0.010-inch wall kovar and welding. The leaks were traced to pinch-weld seals made on the tubulation near the tube where the temperature of the tubulation was approximately equal to the bakeout temperature. It was found that leak-tight pinch-offs could be made consistently in regions where the tubulation temperature did not exceed approximately 500°C.

EXPERIMENTAL RESULTS

Figure 39 shows a series of typical volt-ampere characteristics taken at 800°C. These curves represent the initial volt-ampere characteristics. Considering the portion of the curve from 25 to 75 milliamperes a straight line, the slope varies from 0.06 volts/ma to 0.08 volts/ma. This is less than a 4-percent voltage variation over the 50-milliampere range. The initial running voltage, at 50 milliamperes, was in the range of 125 volts, ±2 percent.

Tube Nos. 6 and 7 were the first two voltage-regulator tubes on endurance test, accumulating a total of 358 hours and 403 hours, respectively. This includes 128 hours on both tubes at temperatures below 450°C. The next two tubes placed on endurance test were loaded to a 16-torr pressure at room temperature. These tubes failed after 92 hours at 800°C for tube No. 8 and 63 hours for tube No. 9. Failure of both tubes was due to gas clean-up. Tube Nos. 10 and 11 were loaded to 60-torr neon at room temperature. Tube No. 10 initially showed oscillations in the volt-ampere characteristic of approximately 13 volts and a normal running voltage, at 50 milliamperes, of 127.5 volts. The slope, $\frac{\Delta V}{\Delta I}$, over the range of 25 to 75 milliamperes, was 0.08 volt/ma. During the first 700 hours of operation, two distinct modes of operation were apparent. The volt ampere-curve at approximately 150 hours, at 50 milliamperes, is shown in Figure 40. Upon increasing the tube current, a voltage jump of 7 volts would occur in the range of 35 to 45 milliamperes. It is unlikely that the step variation in voltage of this tube was due to the glow extending over patches of varying work function on the molybdenum cathode. Typical variations of this kind are no more than about 1 volt. Since this tube initially had a high running voltage

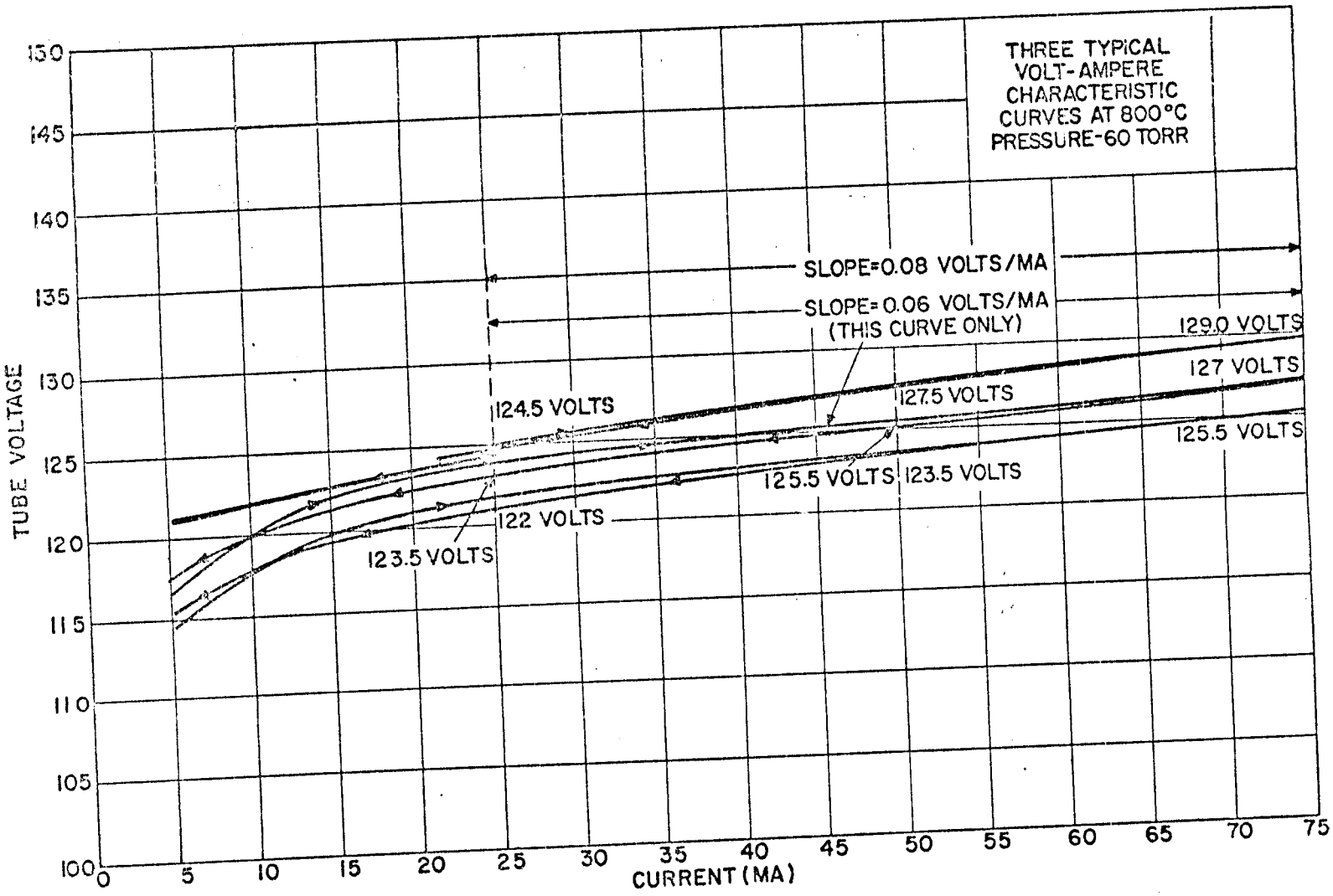

Figure 39 - Typical Voltage-Regulator Tube Volt-Ampere Characteristic at 800°C

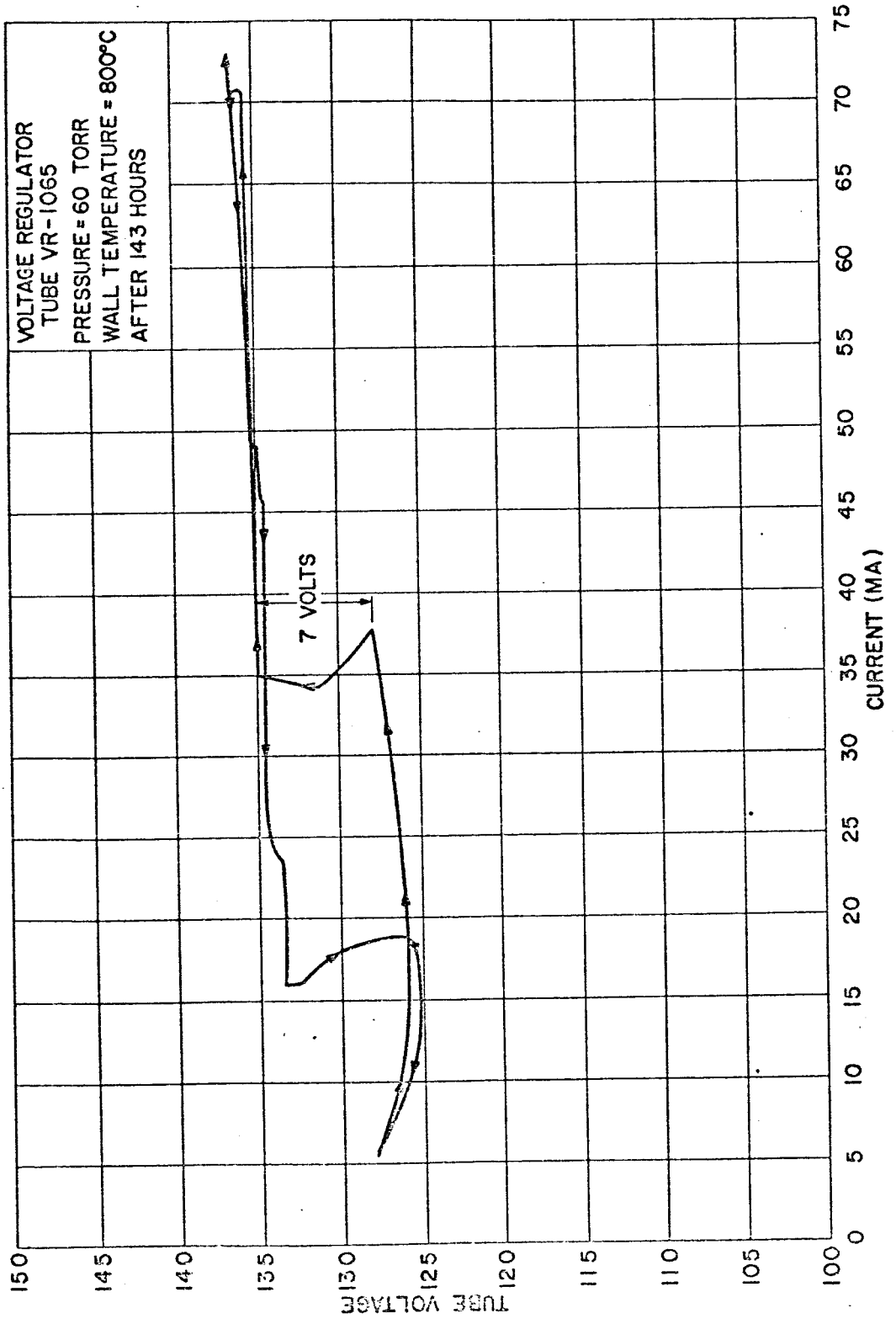

Figure 40 - Volt-Ampere Characteristics for Tube No. 10 After 150 Hours

and showed large amplitude oscillations, it is more likely that these effects were due either to poor processing of the molybdenum cathode, which resulted in large variations in the emission characteristics, or to gas impurities which were eventually cleaned-up. This irregularity persisted to approximately 750 hours, when the characteristic curve changed to that shown in Curve A of Figure 41. After 1510 hours, the characteristic changed to that shown in Curve B of Figure 41. During the last 60 hours of operation before failure, the running voltage gradually increased above 150 volts. At this point, the discharge extinguished, and the tube could not be restarted. Examination of the tube after failure showed the structure to be leak tight.

Figure 42 shows the initial volt-ampere characteristic for tube No. 11 at 800°C. The slope of this curve is 0.08 volts/ma. This tube was also loaded to 60 torr at room temperature. The total number of hours accumulated at 800°C was 780 hours. Figure 43 shows three volt-ampere characteristic curves taken during the final 190 hours of operation. The curves were taken at intervals of 593, 743, and 768 hours. Although the slope of the curve did not vary significantly, 0.02 volt/ma to 0.05 volt/ma, the running voltage increased from 124.5 volts, at 50 ma, to 136 volts. This was the typical mode of failure for all tubes and is indicative of a gas clean-up mechanism. None of the endurance tubes showed failure due to a vacuum leak.

The curves shown in Figure 44 represent the volt-ampere characteristic at wall temperatures of 270 and 800°C. A thermocouple was attached to the cathode flange for measuring the cathode temperature. With the tube mounted in the oven and no heat applied, the wall temperature reached 316°C and the cathode 424°C for a tube current of 50 ma. The regulation, $\frac{\Delta V}{\Delta I}$, over the range of 25 to 75 ma is 0.13 volt/ma. When the wall temperature was raised to 800°C for the same current, the cathode temperature increased to 835°C and the regulation, over the same current range, was 0.08 volt/ma. This was characteristic of all the tubes tested, i.e., the regulation was better at the higher temperature.

ENDURANCE TESTS

Investigations were made and endurance tests performed on neon-filled regulator tubes at an ambient temperature of 800°C. The tubes were mounted in the test station as shown in Figure 45, with two tubes per station. The tube wall temperature was maintained by a tungsten radiation heater placed around the tube. A complete test station is shown in Figure 46. An 8 liter/second ion pump, mounted on the test chamber, held the chamber

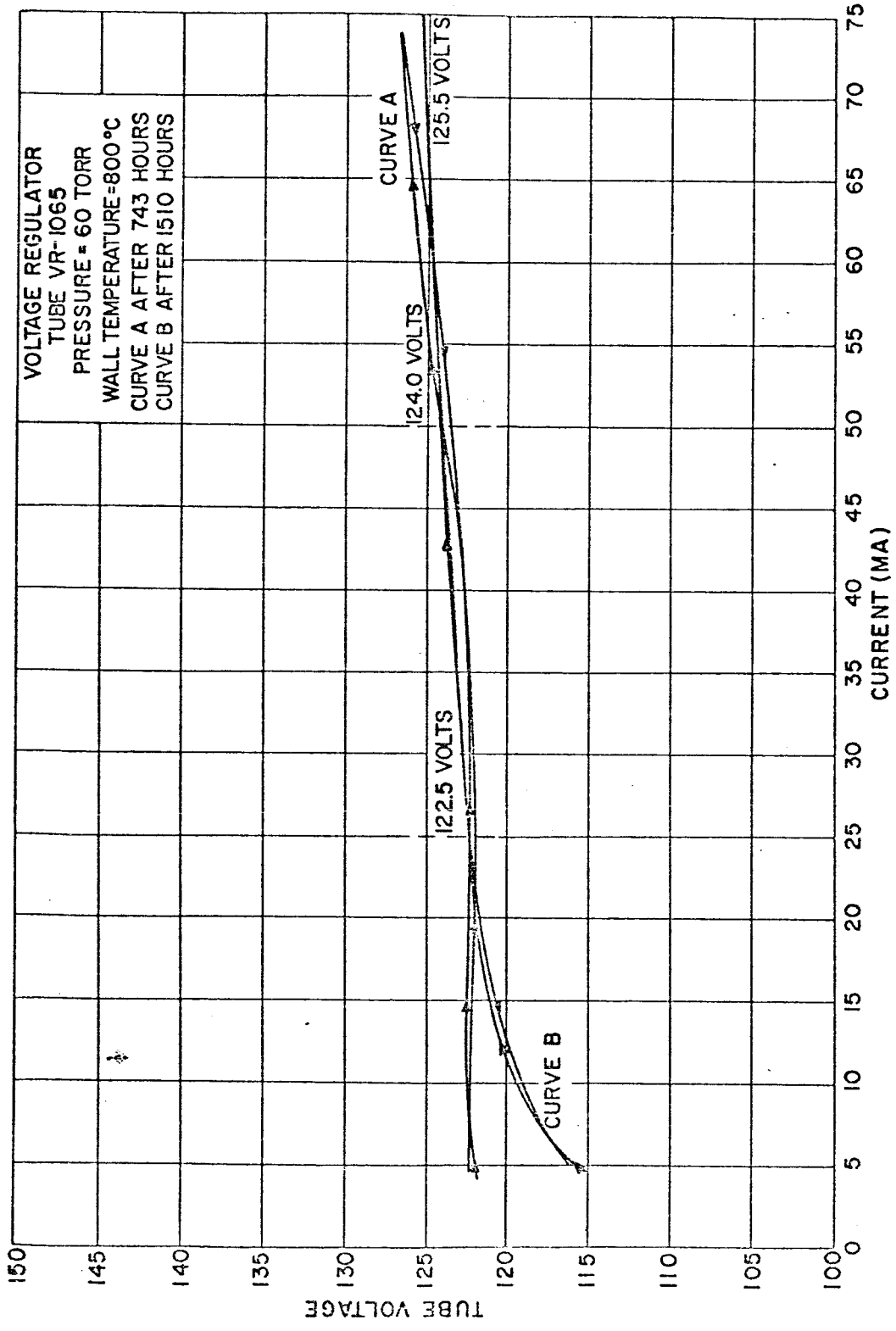

Figure 41 (a) - Volt-Ampere Characteristics for Tube No. 10 After 750 Hours

(b) - Volt-Ampere Characteristics for Tube No. 10 After 1510 Hours

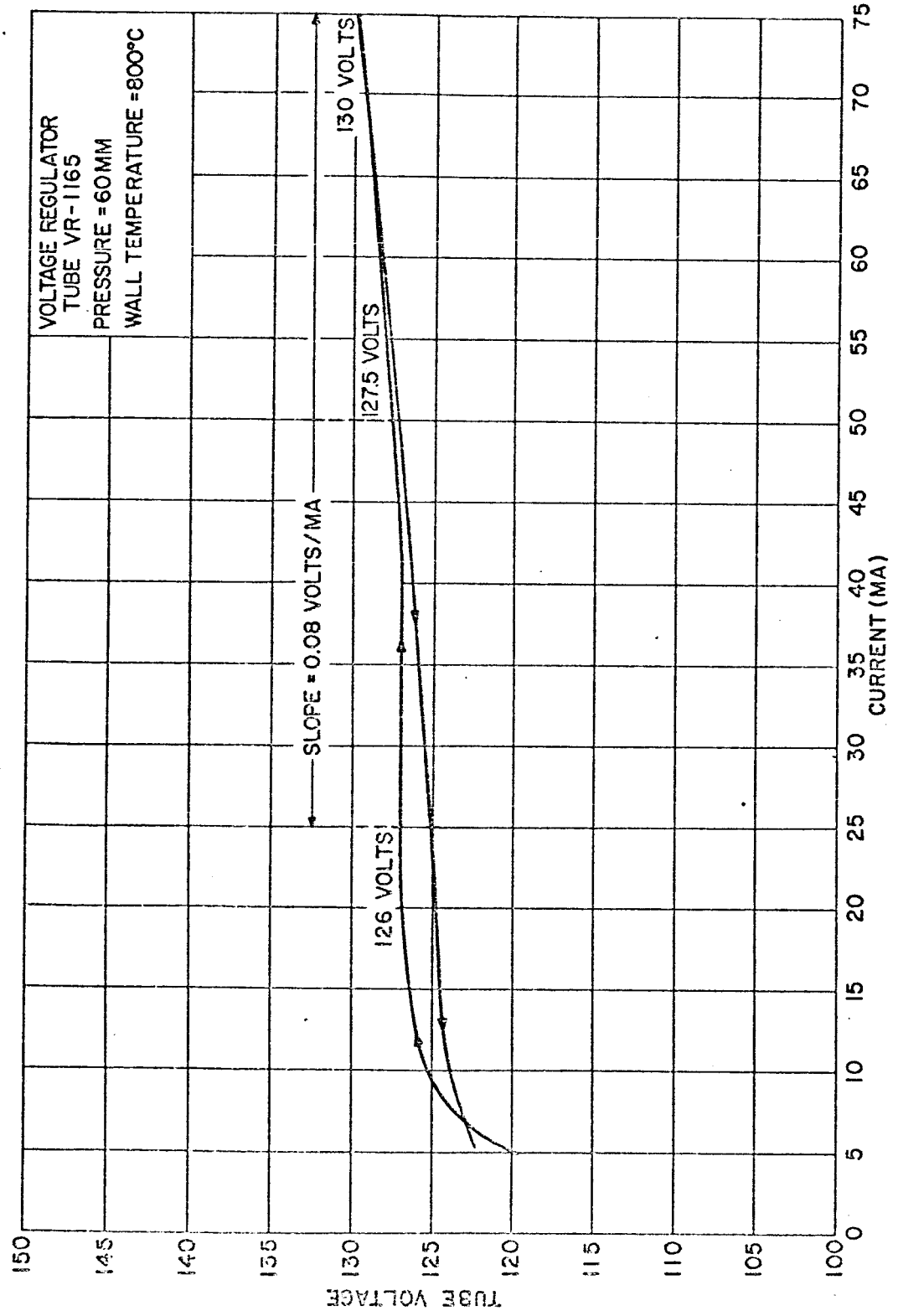

Figure 42 - Initial Volt-Ampere Characteristics for Tube No. 11 at 800°C

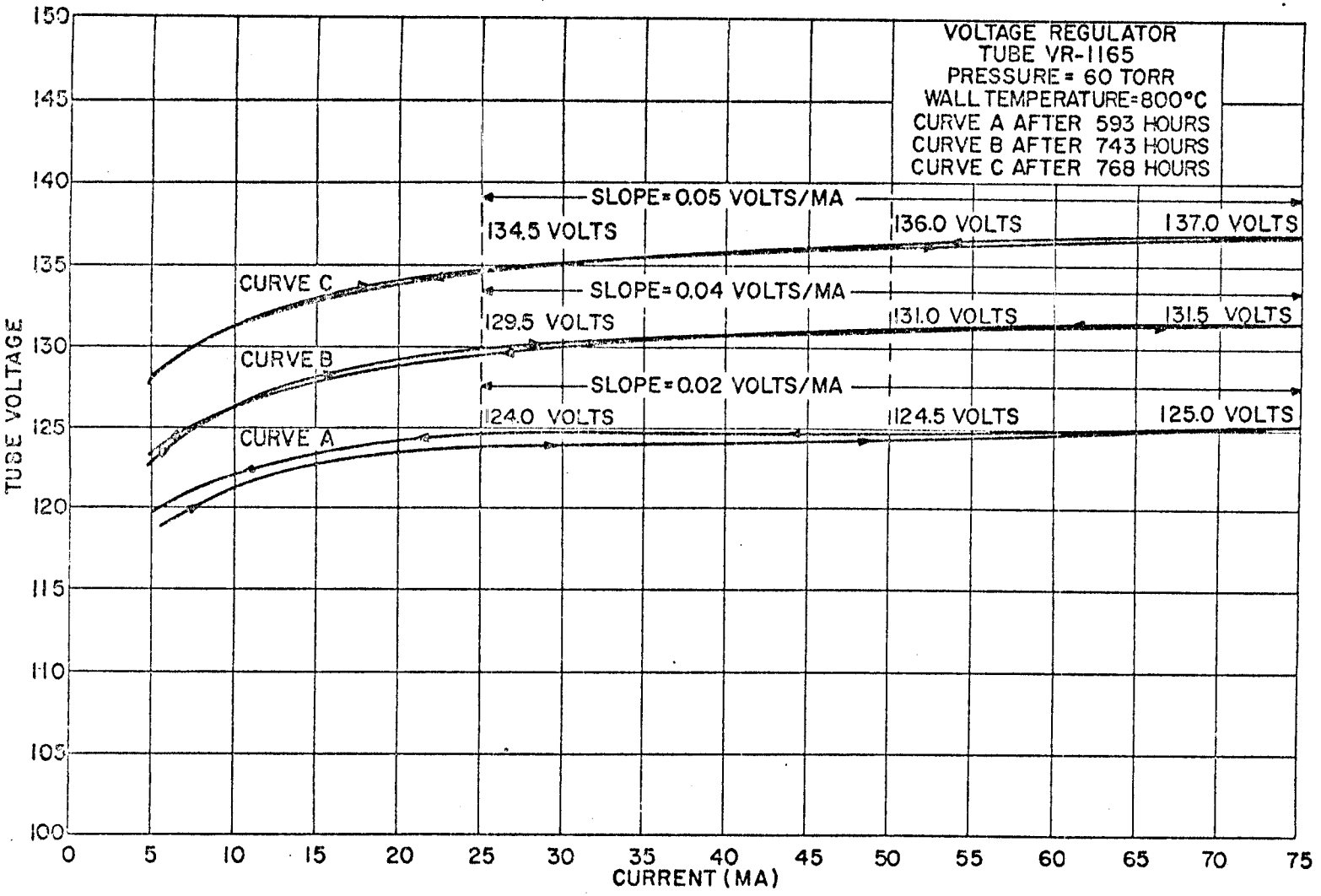

Figure 43 - Volt-Ampere Characteristics for Tube No. 11 During Final 190 Hours

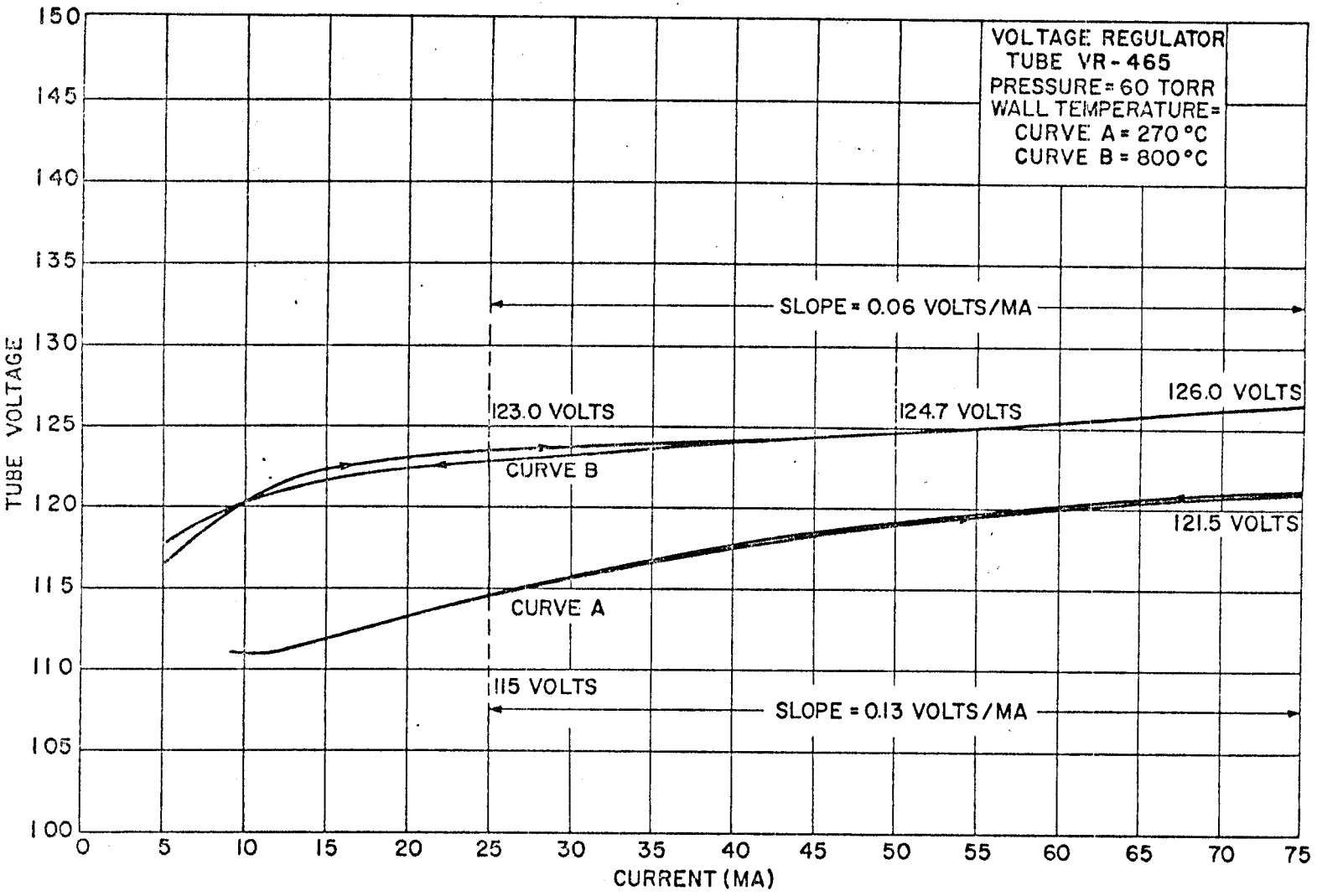

Figure 44 - Volt-Ampere Characteristics for Tube No. 4 at 270°C and 800°C Wall Temperature

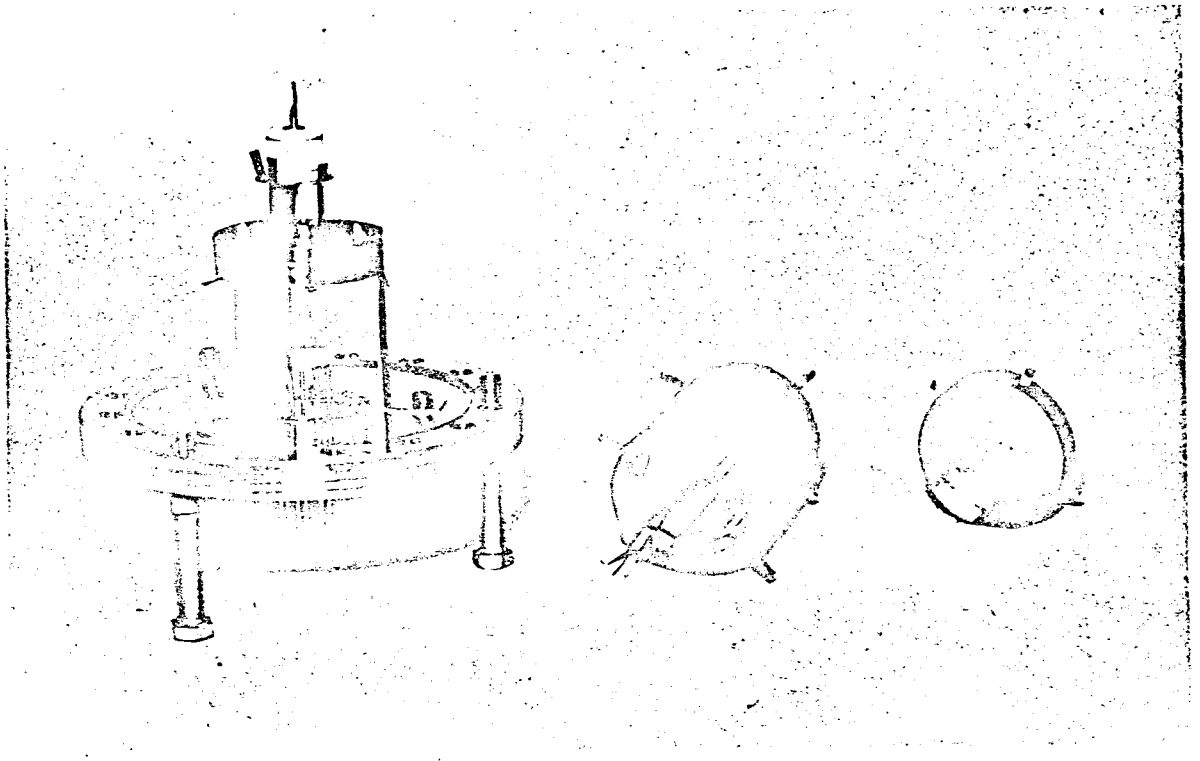

Figure 45 - Two-Tube Test Station

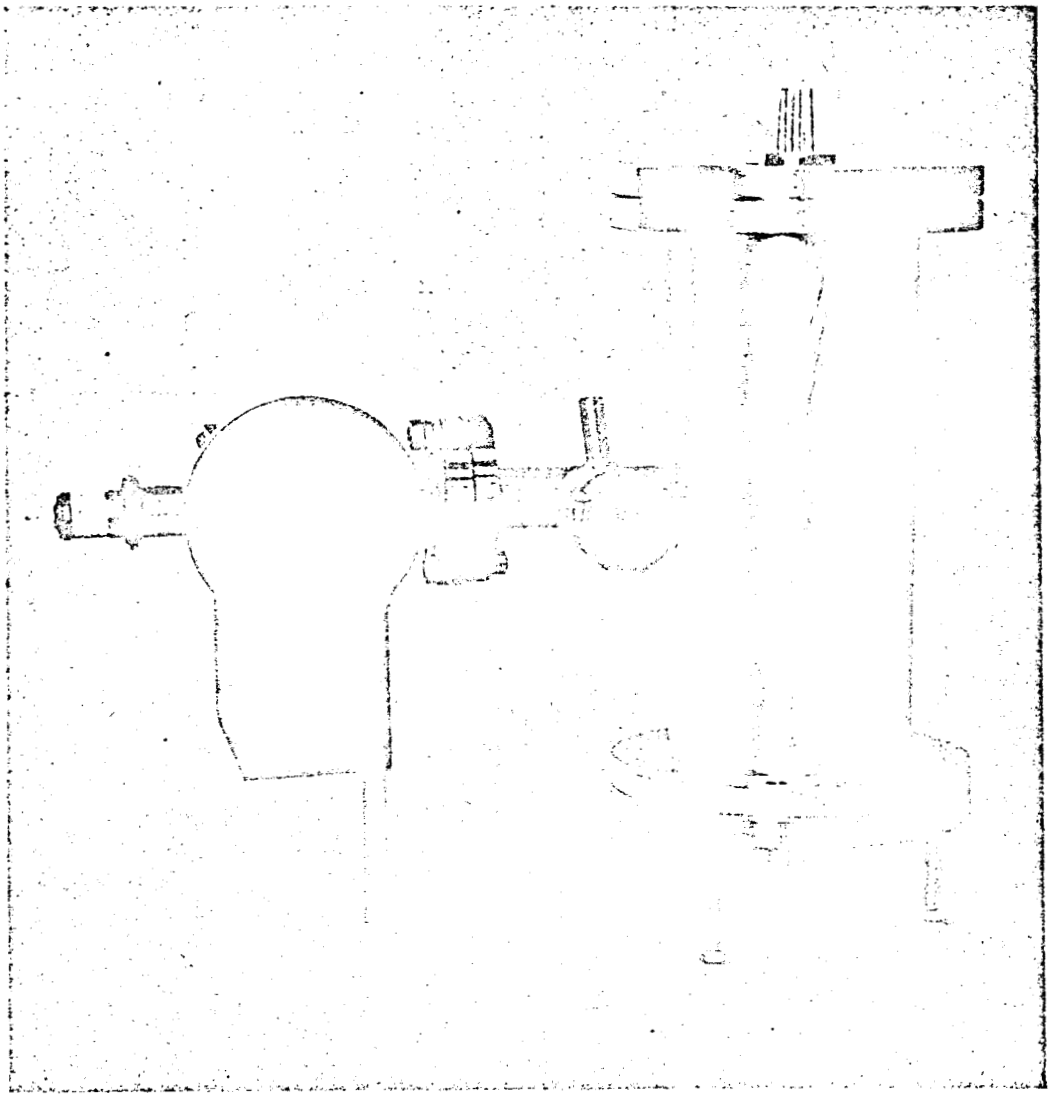

Figure 46 - High-Temperature Regulator Tube Test Station

pressure during the endurance runs at less than 10^{-7} torr. A photograph of the exhaust and processing station, recording equipment, and a single endurance test station is shown in Figure 47. The tube temperature, voltage, and current could be monitored continuously, and an x-y plotter was used for periodic checks on the volt-ampere characteristic.

DISCUSSION

The results of extended operating tests at 800°C on the ceramic voltage-regulator tube shows the present seal configuration to be a reliable structure for 800°C operation. The results indicate that the regulation of the designed tube can be held within the limits of 0.06 to 0.09 volt/ma for an operating temperature of 800°C, with a 60-torr fill pressure. At lower temperatures, the regulation increases to as high as 0.15 volt/ma. The nominal running voltage with neon as the fill gas (at 60 torr) and a molybdenum cathode is 125 volts, ±2 percent at 50 ma. The voltage variation was found to be within ±2 percent from the nominal running voltage, at 50 ma, for the current range of 25 to 75 milliamperes.

The regulation was seen to improve over the desired current range at the higher tube temperature. Data obtained indicates that at low temperatures a larger temperature difference exists between the wall and the cathode for the present structure. If the operating voltage depends on the gas density in the cathode fall region of the discharge, then at higher gas temperature (tube temperature) the relative change in gas density in the cathode region, due to increased current, would be less than the change associated with lower tube temperatures. In this case, the regulation may be improved by providing a structure in which the cathode can be maintained at a nearly constant temperature which approaches the environmental temperature. A structure of this kind is shown in Figure 48.

The endurance tests indicate that the primary mode of failure can be attributed to a gas clean-up mechanism. Prior to failure in every case, the running voltage gradually increased until the discharge extinguished. This generally occurred over a period up to 150 hours. When an ion strikes the cathode surface, its energy is sufficient to extract an electron thereby neutralizing the ion and releasing a second electron giving rise to secondary emission. If the energy is great enough an atom of cathode material can also be released, the sputtering rate being inversely proportional to the pressure. Once the pressure is reduced to the range where the abnormal glow sets in, the sputtering increases due to the higher tube drop.

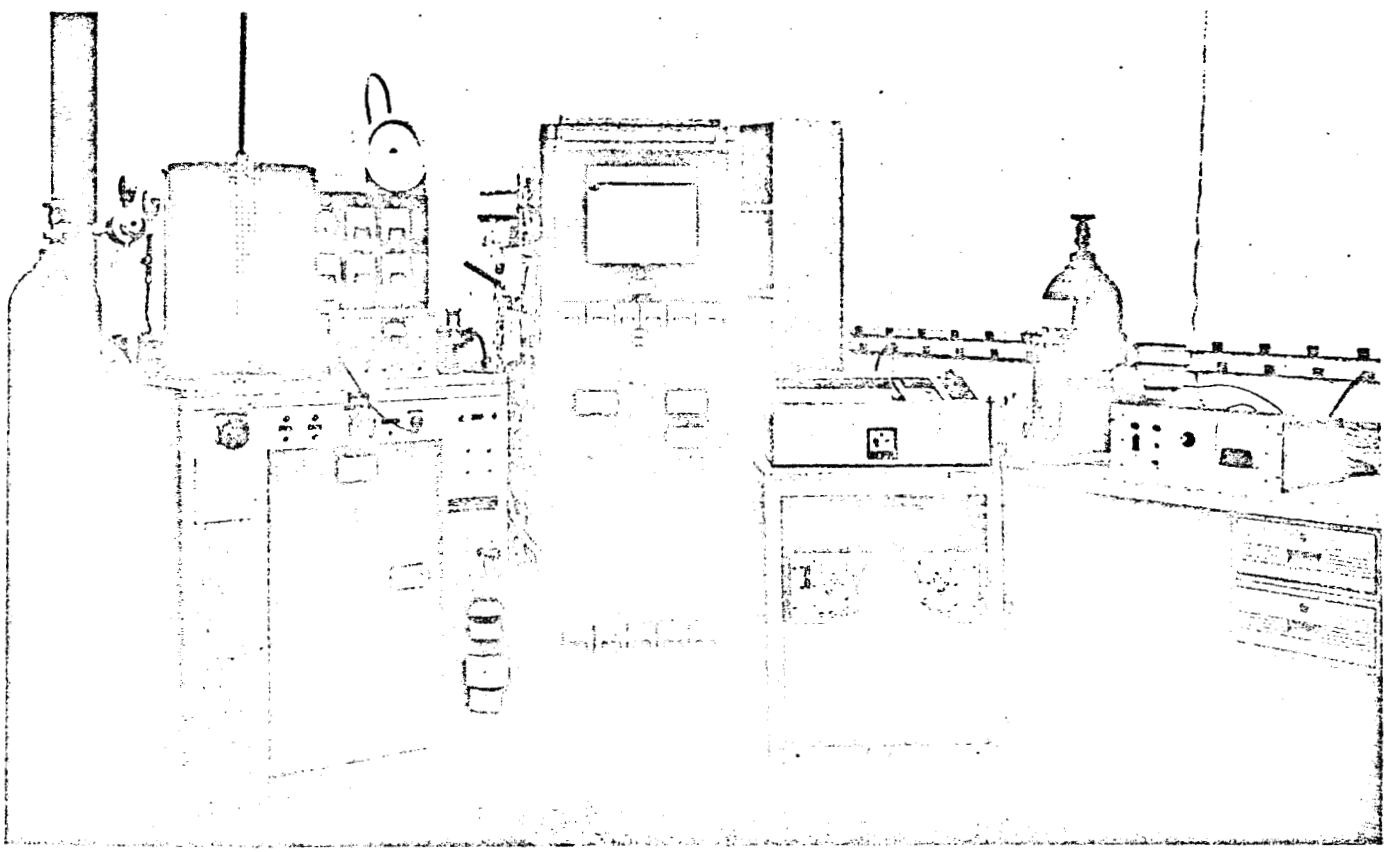

Figure 47 - Overall View of Exhaust Processing Station for Regulator Tubes

CONCLUSIONS

The nominal running voltage of the voltage-regulator tube designed on this program, using neon as the fill gas at 60 torr pressure and a molybdenum cathode, was 125 volts ±2 percent over the current range of 25 to 75 milliamperes.

The endurance tests conducted showed the seal structure to be reliable for extended operation at 800°C. The mode of failure indicates a gas clean-up mechanism, resulting in a gradual increase in the running voltage. The regulation of the cylindrical tube geometry was improved at 800°C operating temperature as compared with that at 300°C. Design changes as suggested in the previous section would be expected to improve the regulation as a result of improved heat flow from the cathode.

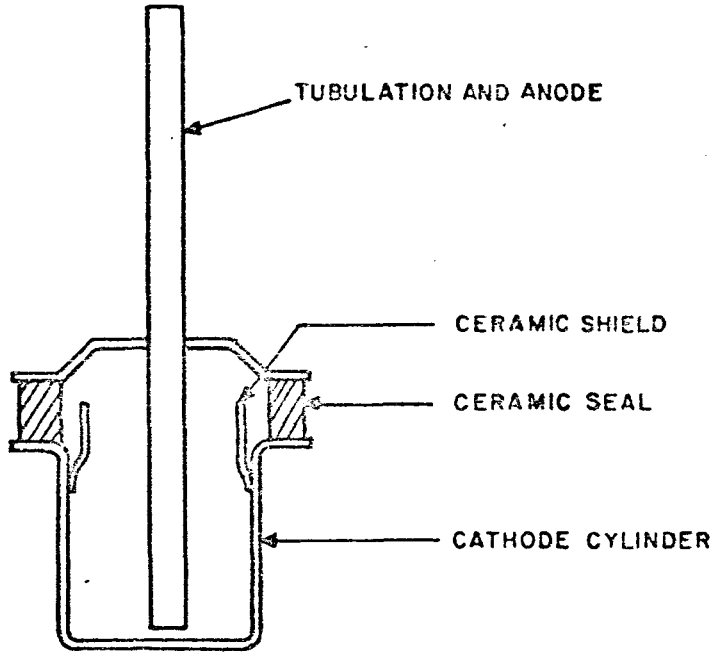

Figure 48 - Proposed High-Temperature Voltage Regulator Tube

Development of

HIGH-TEMPERATURE GAS-FILLED CERAMIC RECTIFIERS, THYRATRONS, AND VOLTAGE-REFERENCE TUBES

by E. A. Baum and N. D. Jones

ABSTRACT

This report covers the work performed on the development of rectifiers, thyratrons and voltage-regulator tubes for operation at up to 800°C in vacuum. Performance and endurance tests were conducted at currents to 15 amperes average, 2000 peak inverse volts and at frequencies to 3200 cycles per second. Endurance tests were run on tubes operating in vacuum at pressures of less than 10^{-6} torr and temperatures of 750°C to 800°C. The designs of the rectifier and thyratron tubes is based on the use of graphite electrodes for reduction of grid and anode emission and to minimize gas clean-up.

Voltage-regulator tubes were tested at 800°C in vacuum. The normal running voltage for 60 torr neon pressure was 125 volts, with approximately a 4 percent voltage variation over the range of 25 to 75 milliamperes. Tubes were also endurance tested at 50 milliamperes with the longest operating time being 1510 hours at 800°C.