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# DEVELOPMENT AND ENDURANCE TESTING OF HIGH-TEMPERATURE CERAMIC RECTIFIERS AND THYRATRONS

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16. Abstract

The long-term performance capability of gas-filled ceramic rectifiers and thyratrons was evaluated in a high-temperature, high-vacuum environment. The thyratron design utilized was based on investigations conducted earlier under contracts NAS 3-2548 and NAS 3-6469, respectively. The feasibility of operating these thyratrons at wall temperatures of $650^{\circ}$ to $750^{\circ}$ C at 3200 hertz with 2000 peak forward and inverse volts, and at 15 average amperes, was demonstrated for periods exceeding 10 000 hours.

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## FOREWORD

The research described herein was conducted by the General Electric Company under NASA contract NAS 3-8525. Howard A. Shumaker of the Lewis Research Center Space Power Systems Division was the NASA Project Manager.

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# DEVELOPMENT AND ENDURANCE TESTING OF HIGH-TEMPERATURE CERAMIC RECTIFIERS AND THYRATRONS

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Microwave Tube Operation

## SUMMARY

The purpose of this program was to develop the technology required to enable the design and fabrication of electron tubes capable of withstanding long-term operation in the high-temperature, high-radiation environments characteristic of nuclear space-power systems. In earlier related efforts directed toward this goal, the materials technology and electron physics aspects of such electron tubes had been explored, subsequently leading to the development of a basic thyratron design. The objective of the work described herein was to demonstrate the feasibility of operating such thyratrons for 10,000 hours at a wall temperature of 650 to 750°C, a frequency of 3200 hertz, peak voltages of 2000 forward and inverse volts, and at a current rating of 15 average amperes.

After improvements were made in the working fluid and cathode of the basic tube design, tubes were fabricated for use in conducting endurance tests, in three modes, under high-temperature vacuum conditions. The required circuitry and equipment were also designed and fabricated, and twelve tubes were endurance tested for periods up to 11,000 hours. These tests have demonstrated that the aforementioned operating conditions are feasible for gas-filled ceramic rectifiers and thyratrons. The metal-ceramic tube envelope provided a long useful life during these endurance tests, and thallium vapor was found to be a very useful thyratron working fluid which provides long-term operation by overcoming the gas cleanup phenomenon. Graphite proved to be the most desirable material for electrode and shield structures relative to

minimizing spurious electron emission, gas cleanup and electrical interelectrode leakage. Matrix cathodes, too, provided excellent electron emission performance and long life.

Further improvements in tube design have been identified. These include more extensive use of graphite, the use of a larger cathode area, improved design of cathode support structure and further optimization of the metal-ceramic seal design and processing.

## INTRODUCTION

Further long-term space missions being contemplated will require much higher power levels than presently available hardward can provide. It is also reasonable to expect that achievement of these high power levels will require a nuclear prime power source. Where such power sources are used, the electrical switching and control devices needed for power conditioning functions may be exposed to high-temperature, high-radiation environments. Although available solid-state or electron-tube power conditioning devices may be electrically compatible with such applications, they are completely unsuited to operation in these high-temperature high-radiation environments. The purpose of this work, therefore, was to develop the technology required to enable the design and fabrication of electron tubes capable of withstanding these environmental conditions and providing reliable, long-term operation as space hardware components. The performance objectives specified for tubes were 2000 peak volts, forward and inverse, 15 amperes average current at 3200 hertz, and heat rejection at 800°C. The endurance goal for these tubes was 10,000 hours of operation at rated performance conditions.

Work was initiated several years ago[1] to investigate known problems in the development of such tubes, such as the materials for ceramic-to-metal seals, choice of cathode systems, and back emission from the anode and grid. Later work[2] had the general objective of developing basic design concepts for the electrodes and tube structure. Noble gas-filled diodes and thyratrons were subsequently fabricated and operated at temperatures as high as 700°C for up to 1600 hours to evaluate these design concepts. Based on the results of these earlier efforts, and previous experience with gaseous discharge devices, the major technical areas requiring investigation toward developing the long-term performance capability of these thyratrons were:

(a) vacuum integrity of the envelope,

(b) gas cleanup due to electrode sputtering, surface absorption, or other causes,

(c) electron emission capability of the cathode,

(d) spurious electron emission from other tube structures and electrical interelectrode leakage.

Development of a final design thyratron for evaluation in long-term endurance testing required the fabrication of experimental tubes, followed by short-term performance evaluation, and then redesigning where improvements were indicated. Tube construction and the results of performance and endurance testing are described in this report. Also discussed are tube design modifications which this work indicated to be beneficial in terms of greater reliability and endurance in future thyratron designs.

## TUBE DESIGN

The gas or vapor working fluid of hot-cathode gaseous rectifiers and thyratrons enables an arc-discharge mode of operation, in which relatively large currents are conducted with only a nominal voltage drop across the tube. The thyratron differs from the gas rectifier only in the starting mechanism. The thyratron includes a grid (in addition to the cathode and anode) whose potential controls initiation of the arc discharge, while the rectifier conducts whenever its anode voltage is positive. Once the arc discharge has started, a positive ion sheath surrounds the grid and shields it from the discharge plasma such that changes in grid potential only change the ion sheath thickness without appreciably influencing the main discharge. For either device, the tube current is then controlled by the impedance of the external circuit. The thyratron grid regains control only after the anode has been driven negative for a sufficient time to allow the residual ionization in the grid openings to decay. This time, which is called the deionization time or recovery time, is the factor determining maximum tube operating frequency. Factors governing recovery time are working fluid density, tube current, grid potential and electrode geometry. Recovery time phenomena were previously investigated in depth for metal vapor thyratrons in a related program.[3]

Several aspects of tube design important to high-temperature thyratron operation were established in the previous work described in references 1 and 2. The electrode and shield geometry were designed to obtain very good grid control and very short recovery time at high anode voltages. Graphite was established as a desirable electrode material which contributes negligible contamination to the tube environment at high temperature, is reliably assembled by standard techniques, and is compatible with the working fluids used. Graphite also has other advantages, discussed later in this section. The good performance of ultra-high purity alumina as a high-temperature insulator and envelope material was also demonstrated.

## THYRATRON ENVELOPE

In major respects the envelope design used in this work effort was the same as that established during contract NAS3-6469. The same ceramics and metal-ceramic seals were used but metal parts were changed to utilize graphite more extensively for electrodes and shields in the active area of the thyratron tubes (described in the next subsection). The tube and component subassemblies are shown in Figure 1, and the tube is shown in cross-section in Figure 2. All of the four metal-ceramic seals indicated (ie the anode and cathode seals and two grid seals) utilize ultra-pure alumina ceramic, designated as General Electric ceramic A976, and Fernico V * for the metal pieces. The sealing system involves metallizing the ceramics by a proprietary tungsten-based metallizing technique and the use of palladium-cobalt brazing alloy in a subsequent braze at 1260°C.

All of the five welds indicated on Figure 2 are heliarc type. The material is Fernico except at weld "A" where both materials are tantalum. The Fernico and tantalum are joined at braze "B" by a proprietary brazing alloy derived from Hastalloy X.**

*Alloy of iron, nickel and cobalt

**Haynes-Stellite Company, Kokomo, Indiana

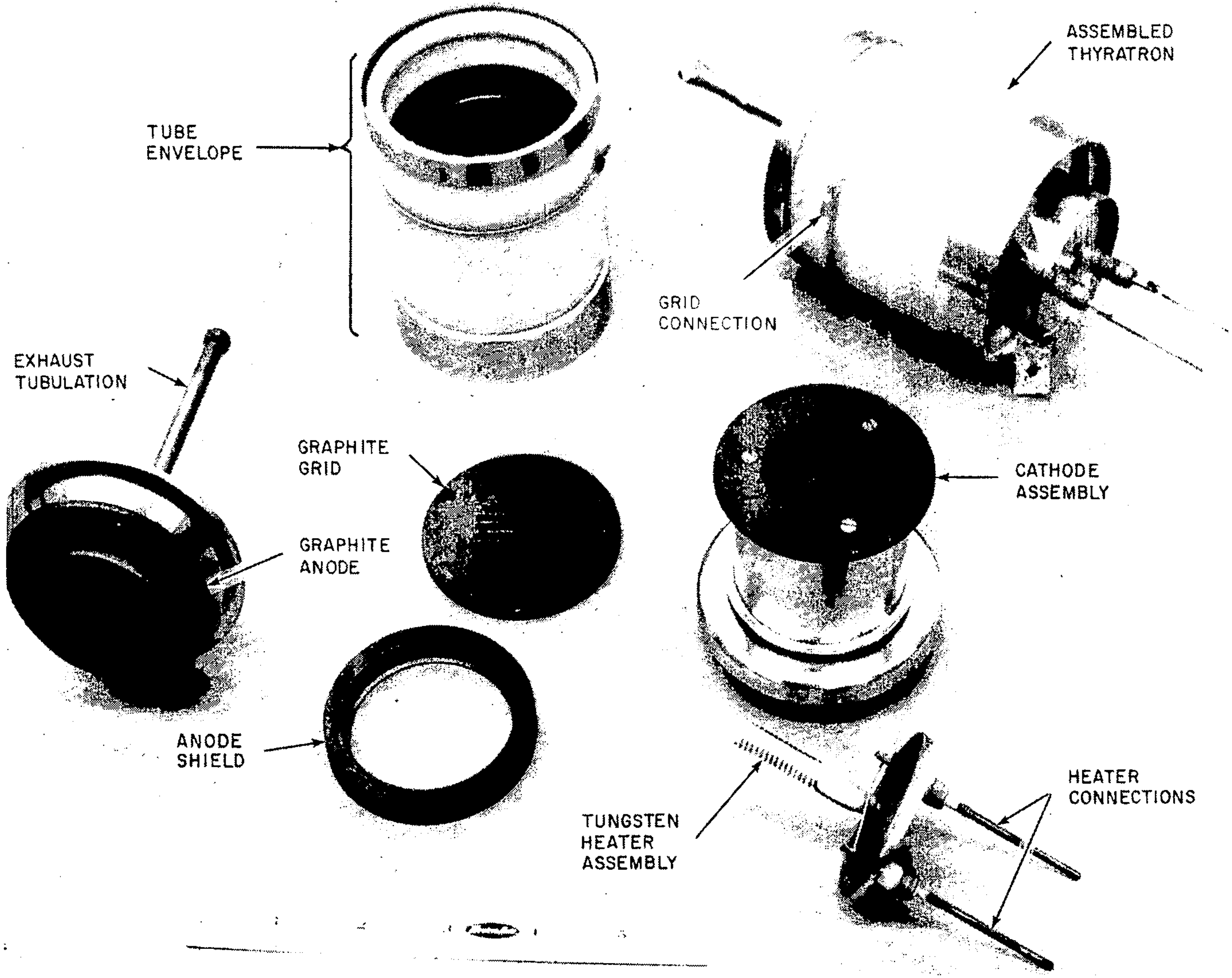



Figure 1 - Thyratron Assembly and Subcomponents

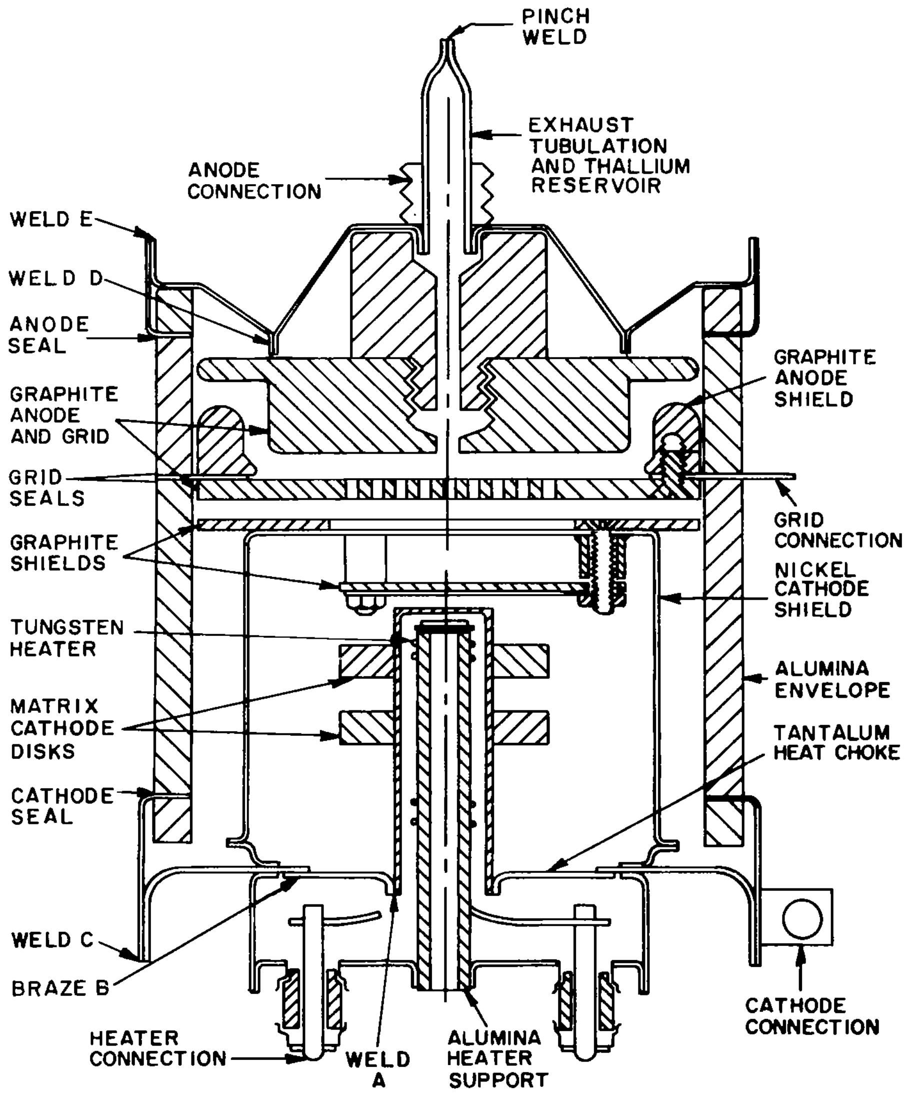



Figure 2 - Final Thyratron Design Developed for Endurance Testing

## CATHODE DESIGN

The tube design incorporated a tungsten matrix cathode, which is a barium system cathode consisting of a porous tungsten sponge, approximately 75 percent dense, and impregnated with barium-calcium-aluminate. The matrix cathode has much better resistance to cathode sputtering than the conventional oxide cathode. This is the configuration shown in Figures 2 and 3, where the matrix cathode proper consists of two washers which are brazed to a tantalum core using nickel-molybdenum eutectic alloy. The core is welded into the tube envelope at weld A in Figure 2. Cathode temperature is controlled by a tungsten heater inside the tantalum core.

The first thyratrons constructed under this contract were fabricated using a barium-oxide coated cathode of the finned configuration shown in Figure 4. The finned structure was fabricated from standard cathode nickel (Driver-Harris Alloy No. 220), and a standard triple carbonate cathode coating was used. These oxide cathodes performed very well in the xenon-thallium thyratrons at full rated current and in emission tests at 100 peak amperes. However, the cathode emission of the first three tubes deteriorated after a few hundred hours of operation in the phase retard test. Examination of the cathodes affirmed that virtually all the oxide coating had been removed by sputtering, leading to the emission deterioration. To alleviate this problem, the tungsten matrix cathode was incorporated in the tube design.

## ELECTRODE SPUTTERING AND GAS CLEANUP

Since grids and anodes fabricated of graphite proved to be very successful in the earlier work of this program, the use of graphie was extended to the shield structure around the cathode and anode, as depicted in Figures 1 and 2, for tubes fabricated during this contract. The efficacy of graphite in this role is attributable to its sputtering rate, which is the lowest among the materials suitable for these tubes.[4] This characteristic is important because material sputtered from the anode by ion bombardment is usually responsible for the gas cleanup phenomenon experienced in inert gas-filled tubes. Gas cleanup occurs when sputtered materials effectively trap gas molecules within the atomic lattice.

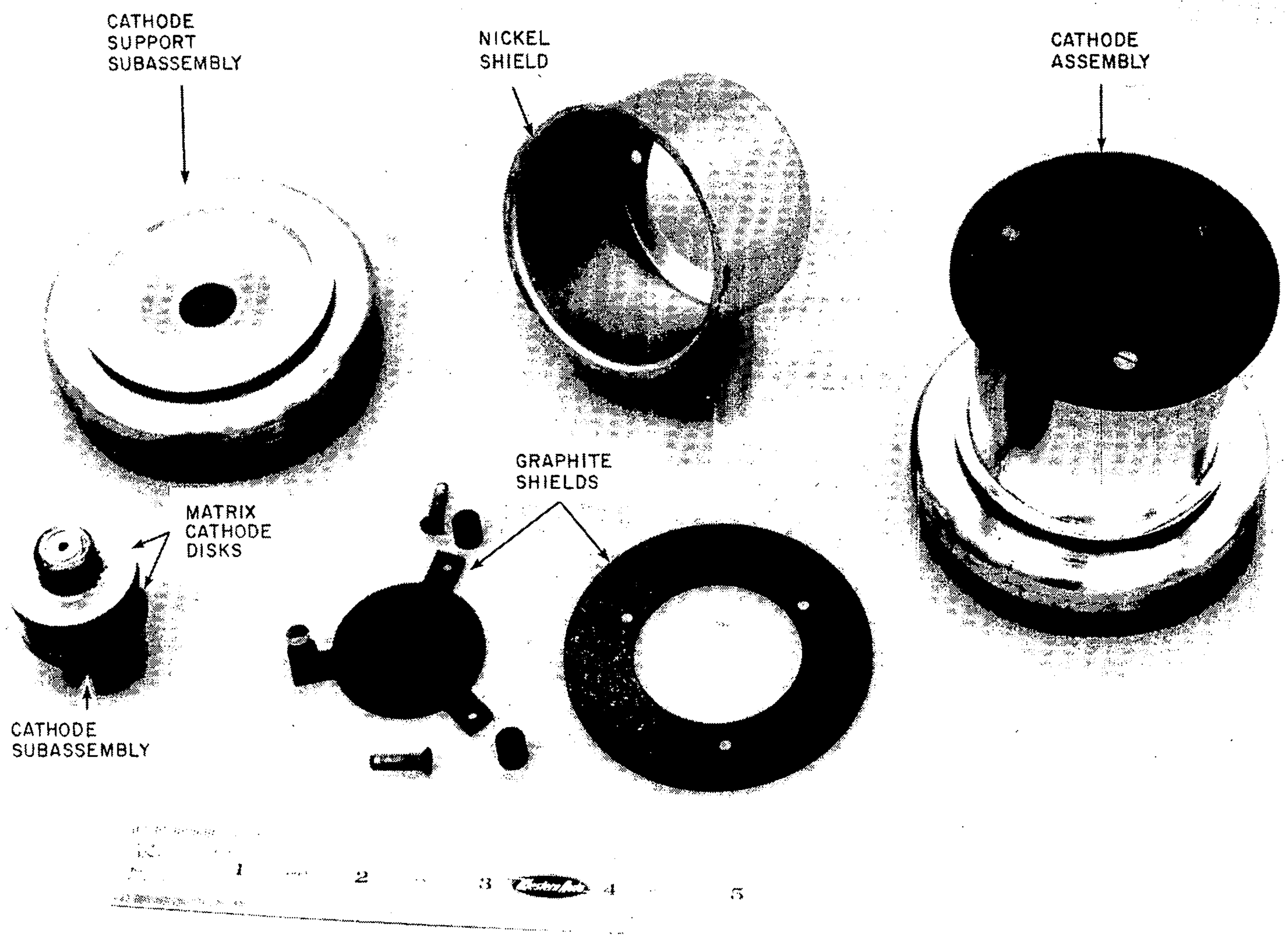



Figure 3 - Cathode Assembly and Subcomponents

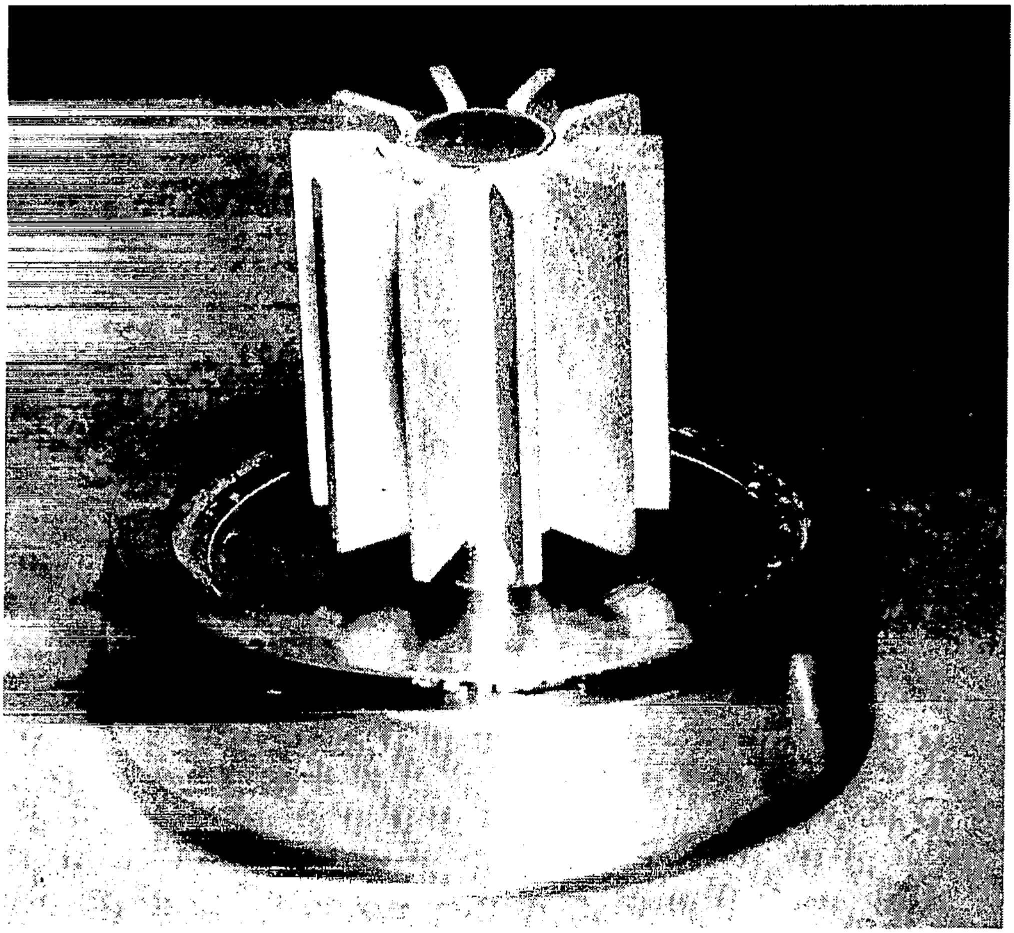


Figure 4 - Finned Cathode Configuration for Coated Cathode Used in Tube 6

## XENON-THALLIUM WORKING FLUID

The thyratrons endurance tested under this contract utilized a xenon-thallium mixture as the working fluid. The thallium is present in the form of vapor only at high temperature -- above 600°C -- with the thallium pressure being controlled by varying the temperature of a small reservoir formed as a one-inch extension on the exhaust tubulation (see Figure 2). This arrangement, which enables a comparatively limitless supply of working fluid stored as liquid thallium, resolved a xenon working fluid cleanup problem experienced early in this program. For good thyratron operation, however, a reservoir temperature of 620 to 680°C must be maintained. This requirement and other aspects of the working fluids are described later in Appendix A.

## ELECTRON EMISSION FROM OTHER TUBE STRUCTURES AND ELECTRICAL INTERELECTRODE LEAKAGE

In gas-discharge devices, unwanted thermionic electron emission from tube parts other than the cathode leads to spurious discharges and loss of control, with either forward or inverse voltage applied. Based on experience with industrial gas-discharge tubes, the total electron current which can be emitted from an electrode without loss of control ranges from $10^{-5}$ to $10^{-4}$ ampere, depending upon electrode geometry, working fluid density, tube current, and voltage. The onset of appreciable grid emission results in loss of grid control of forward voltage -- that is, the grid cannot consistently prevent tube current from flowing when forward anode voltage is applied. Similarly, anode emission results in breakdown of the tube with inverse voltage applied (arc back).

Because the use of barium system cathodes in the presence of high temperatures results in the deposition of cathode evaporants on all tube surfaces, the work functions of these surfaces are lowered. Since thermionic emission is also an exponential function of temperature,[5] this problem becomes particularly critical in high-temperature devices and thus was investigated in depth in the earlier work of this program. This led to the selection of graphite as the most desirable electrode material, since graphite exhibited the highest work function of the materials evaluated in experiments simulating these conditions.

Another general cause of electrical malfunction in thyratrons is interelectrode leakage. This condition results in improper electrical operation of the thyratron circuits, usually due to improper control voltage at the grid. Grid-cathode leakage can reduce the grid control voltage due to excessive grid-circuit current passing through the leakage path and partially shorting the control circuit; grid-anode leakage, too, can cause improper grid control as a result of a fraction of the anode voltage appearing at the grid.

Sputtering or evaporation of metal tube structure material on the respective insulators usually causes electrical leakage, and thyratron insulators are customarily shielded by a geometry which prevents evaporants originating at the active grid and anode surfaces, from having a line-of sight path to the insulators. For this reason the graphite shields shown in Figure 2 were provided in these tubes. However, as described above, high-temperature operation sometimes results in electron emission from all tube surfaces, with consequent sputtering from these surfaces. Thus, the electrical leakage problem is alleviated by the use of graphite for all tube surfaces subjected to electric fields during tube operation, and by using a tube geometry in which the electric fields are minimized at the metal surfaces in the tube structure, as provided in the tube design shown in Figure 2.

## TEST APPARATUS AND TEST CIRCUITS

Endurance tests were conducted in three test modes, designated Full Load tests, High Voltage Phase Retard (HVPR) tests and Accelerated Inverse Voltage (AIV) tests. Two thyratrons were operated in each test mode, each in a separate vacuum chamber. The operating temperature of each tube was controlled by an electrically heated oven capable of maintaining the objective temperature of 800$^{\circ}$C. A separate electrically heated oven was provided to maintain the temperature of the thallium reservoir within a range of 550$^{\circ}$C to 750$^{\circ}$C. Thermocouples were utilized for measuring the reservoir and tube wall temperatures. The test circuitry associated with the three test modes is shown in Figures 5, 6 and 7.

The full load test consisted of operating two thyratrons as half-wave rectifiers at a frequency of 3000 hertz with a sinusoidal peak

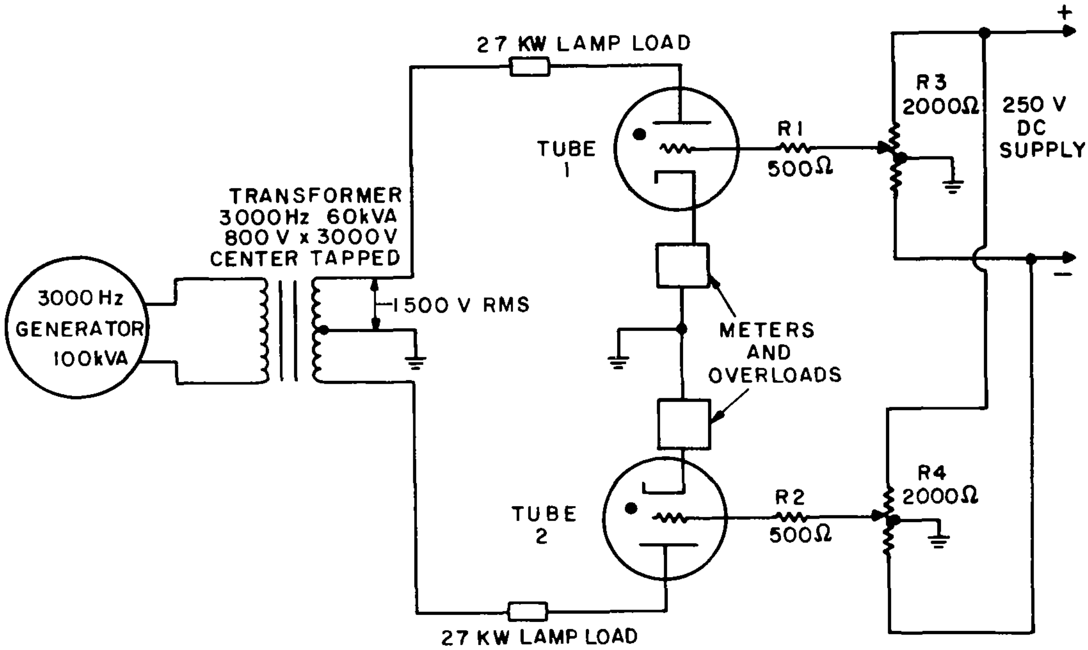



Figure 5 - Full Load Test Circuit

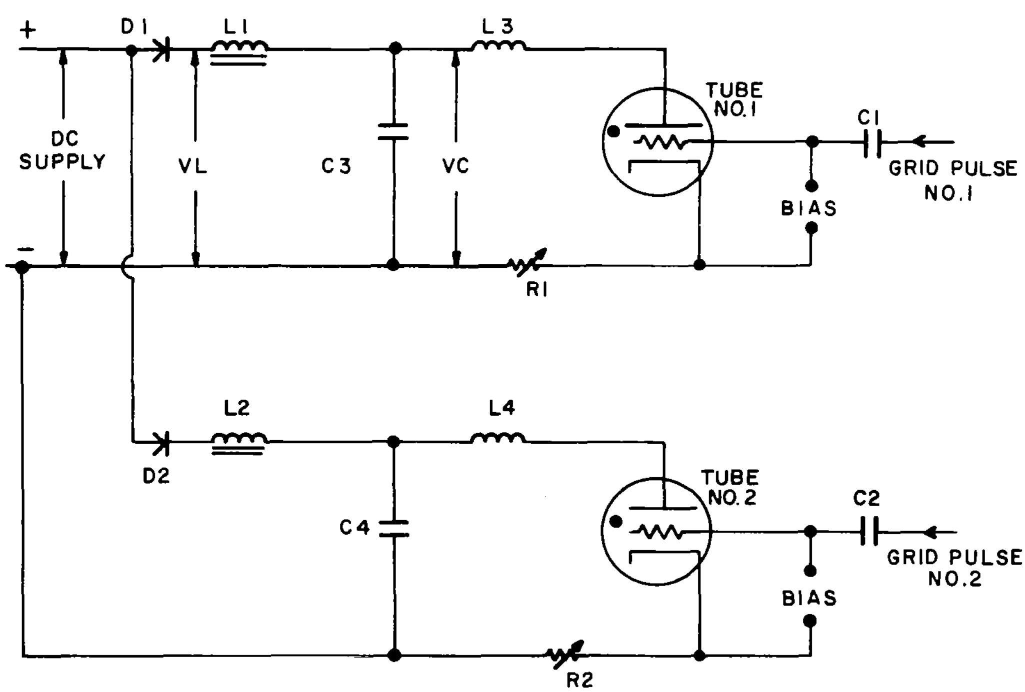



Figure 6 - Accelerated Inverse Voltage Test Circuit

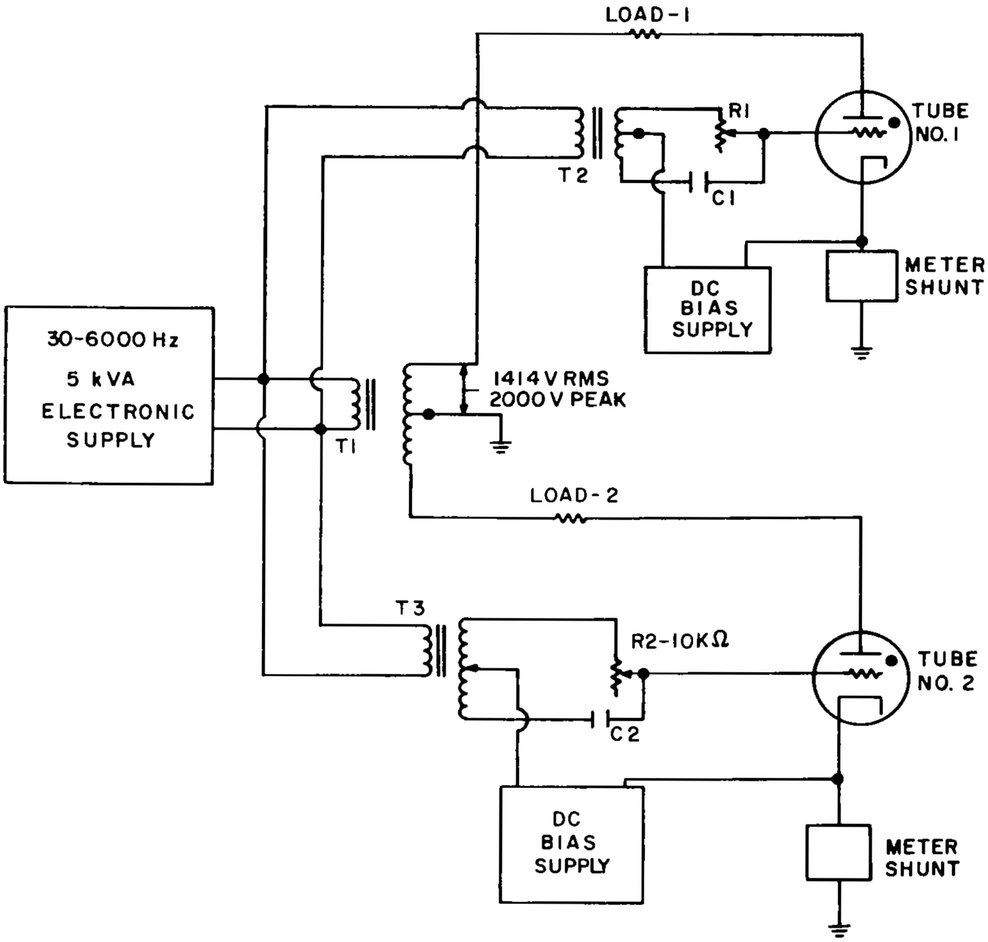



Figure 7 - High Voltage Phase Retard Test Circuit

forward and inverse voltage of 2000 volts, and at anode current of 47 amperes peak, 15 amperes average. The basic circuit used, Figure 5, is essentially two half-wave rectifier circuits with a common ground operated off a single supply transformer with grounded centertap. The 3000-hertz input power was supplied by a 100 kVA motor-generator, with the dc power output being dissipated in a pair of load banks to be described later in this section. The grids were connected to a dc supply voltage adjustable within the range of $\pm 125$ volts, as shown in Figure 5. The grids were biased positive with respect to the cathode for rectifier operation and negative for checking grid control approximately every 100 hours, ie for checking whether the grid bias would control tube current.

The specifications for the AIV tests required a current pulse at the rated peak current of 47 amperes, with an inverse voltage of 2000 volts applied immediately following the current pulse, such that the rise of inverse voltage would be the maximum possible. The principal object of this procedure was the evaluation of gas cleanup due to anode sputtering under worse-case conditions -- ie, where the tube is switched with maximum rates of change of tube current and inverse voltage.

The basic AIV circuit, Figure 6, is a simple charging-line pulse circuit which applies the voltage shown in Figure 8 to the tube being tested. The tube current pulse of 8 microseconds duration for tube 1 occurs when tube 1 is fired to discharge capacitor C3 at a rate determined by $\sqrt{L3C3}$; then C3 is recharged from the dc supply at a rate determined by $\sqrt{L1C3}$. The two circuits were identical and both grid firing pulses (phased $180^{\circ}$ apart) were supplied by a conventional multivibrator-derived pulse circuit with frequency variable from 100 to 4000 hertz. The grid pulse was a 10 microseconds duration with a peak open circuit voltage of 200 volts and a peak grid current of approximately 0.5 ampere. The grid voltage waveform also reflects anode voltage because there is always appreciable electrical leakage grid-to-anode (generally more than $10^5$ ohms resistance) which must be balanced out by grid circuit impedance and grid bias voltage.

The purpose of the HVPR testing was to measure tube performance when the grid was triggered at the time when anode voltage was a full 2000 volts peak forward, followed by the application of 2000 volts peak, inverse, at a 3200 hertz frequency. RMS anode current was set to 3

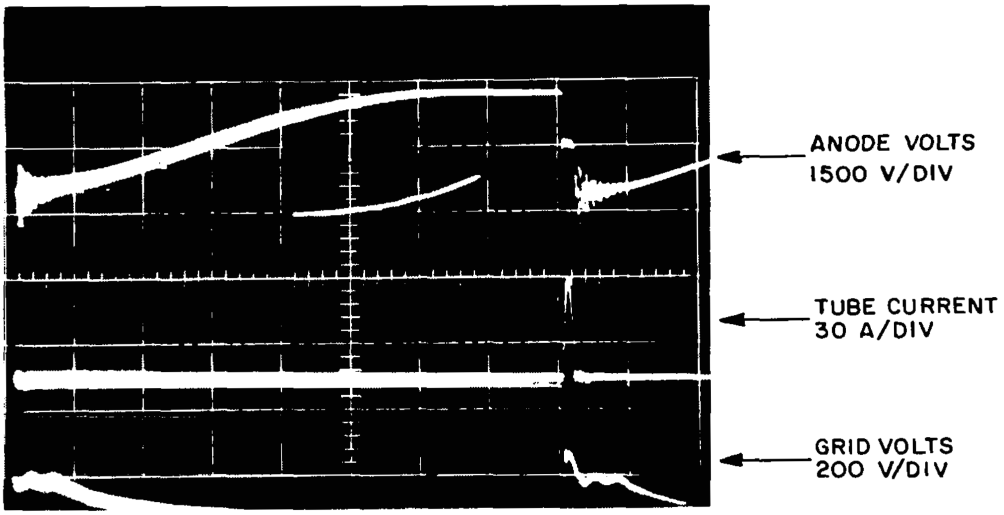



Figure 8 - AIV Voltage and Current Test Waveforms
(Time: 50 $\mu$sec/div.)

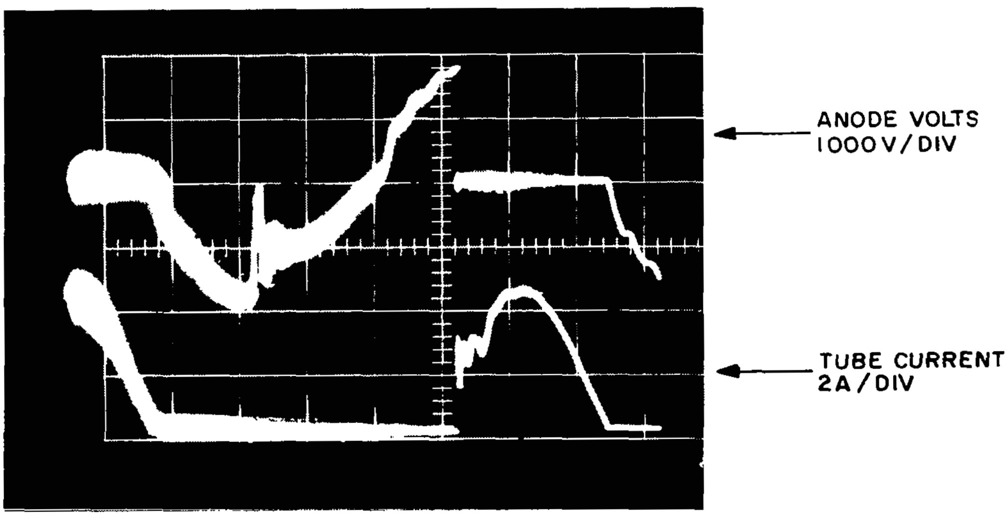



Figure 9 - HVPR Voltage and Current Test Waveforms
(Time: 50 $\mu$sec/div.)

amperes by choice of load impedance. Since the HVPR circuit demands peak current almost instantaneously when the tube is fired, forward tube drop is very high for a few microseconds, imposing conditions of severe ion bombardment of the cathode structure under this mode of operation. This testing was accomplished by utilizing a conventional variable phase control circuit to control the grid firing point with respect to anode voltage, as shown in Figure 7. The 5-kVA variable frequency supply can furnish 2500 peak volts at 3200 hertz, under open circuit conditions. The grid phase control range is from approximately a -30 degree to -180 degree (no conduction) phase angle with respect to anode voltages. During endurance testing, each thyratron was fired at a phase angle of approximately -80 degrees, as shown for one tube in the oscilloscope traces in Figure 9. The circuit disturbance due to the other thyratron firing is seen in the center of the inverse voltage swing, where a circuit resonance of approximately 63 kHz is present.

The test equipment for full load and AIV tests is shown in Figure 10. This photograph shows the high frequency motor-generator and associated controls. The two vacuum chambers and associated intrumentation and controls for the two full-load stations are at the center while the similar AIV test stations are to the right. The cabinet between test stations contains the AIV circuits, oven supplies, and other circuitry. The HVPR test stations and associated circuitry and instrumentation are shown in Figure 11. The right vacuum chamber is a glass bell-jar, while the one at the left is made of metal and equipped with a glass viewing port.

Protective circuitry to detect vacuum failures or tube overcurrent was provided, but more sophisticated circuitry such as a sensor for inverse tube current was omitted as an economy measure. In retrospect, it is apparent that additional protection might have prevented severe damage (due to inverse arcing) to tubes 1 and 2 in full load test (refer to Table I in "Test Results" section). Overvoltage protection also was not provided for the tubes under test until several thousand hours of testing had been accumulated. After failures due to transient overvoltage were experienced, protective spark gaps (GE Cat. No. 503x47) were connected between the anode and cathode terminals outside the vacuum chambers.

All three circuits were equipped with automatic timers to record endurance test hours. The AIV and HVPR tests also had automatic

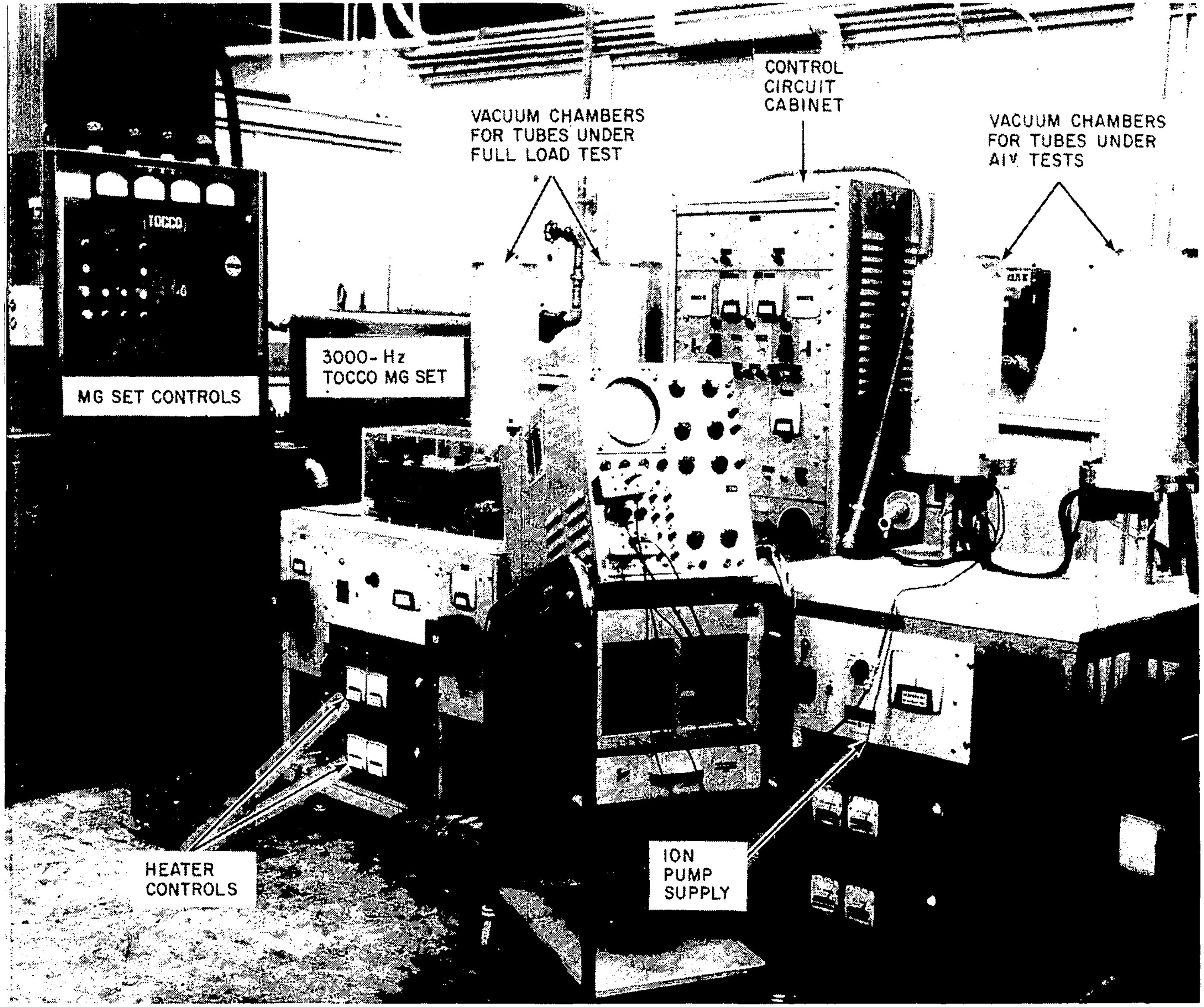



Figure 10 - Full Load and AIV Test Equipment

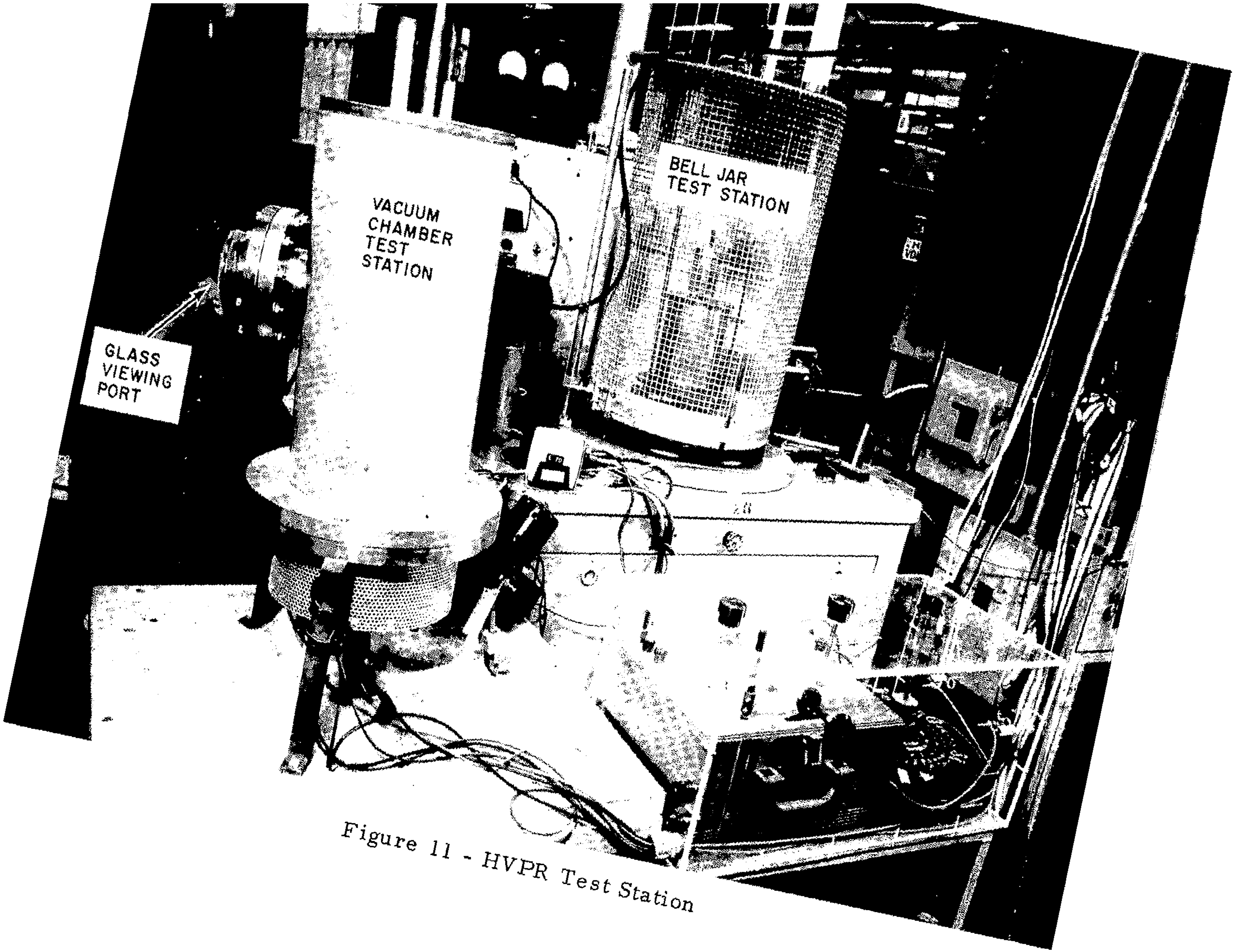



Figure 11 - HVPR Test Station

circuit monitors which recorded circuit outages and recycled the circuit so that minor events would not interrupt testing.

## ELECTRICAL LOAD DEVICES

Both the full load and HVPR tests required substantial dissipation of electrical power as heat. The full load test required 23 kW per tube, and the HVPR test 2.3 kW per tube. The HVPR test utilized 15 300-watt forced-air-cooled resistors for each tube, a conservative design which performed with no difficulty. The 23 kW of electrical power for each tube was dissipated by 36 quartz-envelope infrared lamps connected in a series-parallel array and operated between two water-cooled copper plates. There were 18 1000-watt lamps and 18 500-watt lamps in each load. One tube load is shown in Figure 12. Approximately 98 percent of the power is carried away by the water.

## RECOVERY TIME TESTS

Recovery time tests were made with dc 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 13. The capacitor will discharge into the dc supply and recharge with opposite polarity from the positive 120-volt dc supply voltage at an exponential rate, as shown graphically in Figure 14. If the tube is not deionized by the time the capacitor voltage reaches 10 volts positive, the tube will continue conducting, but if deionization has been accomplished, the tube will switch off and the recovery time can be determined from the RC time constant and from the relationship:

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

Solving for $T_R$, we have:

$$T_R = RC\ell n^{-1}\left[\frac{V_s + V_c}{V_s + V_c - V_T}\right] = RC\ell n^{-1}\,\frac{220}{110} = .69\,RC$$

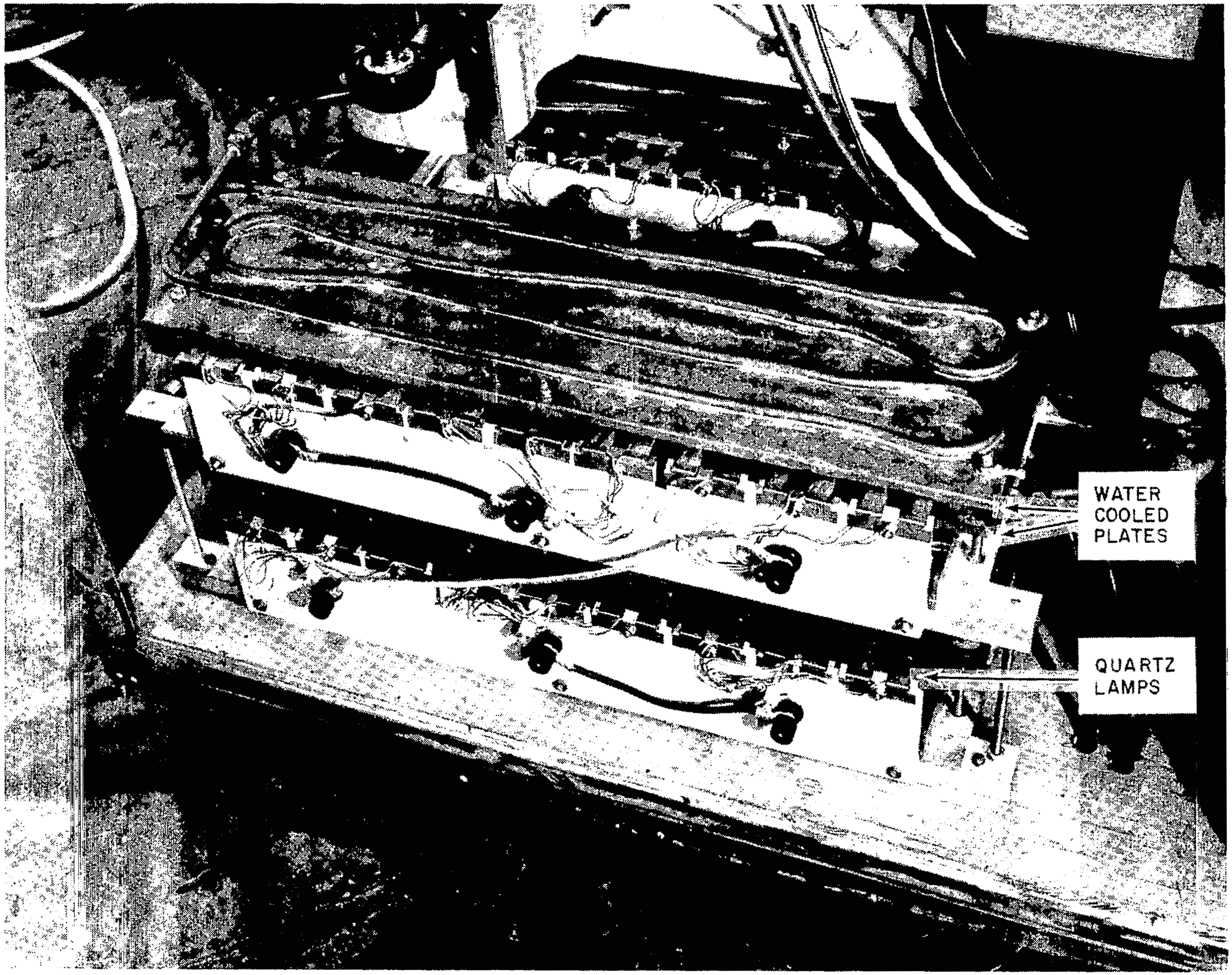



Figure 12 - Lamp Loads

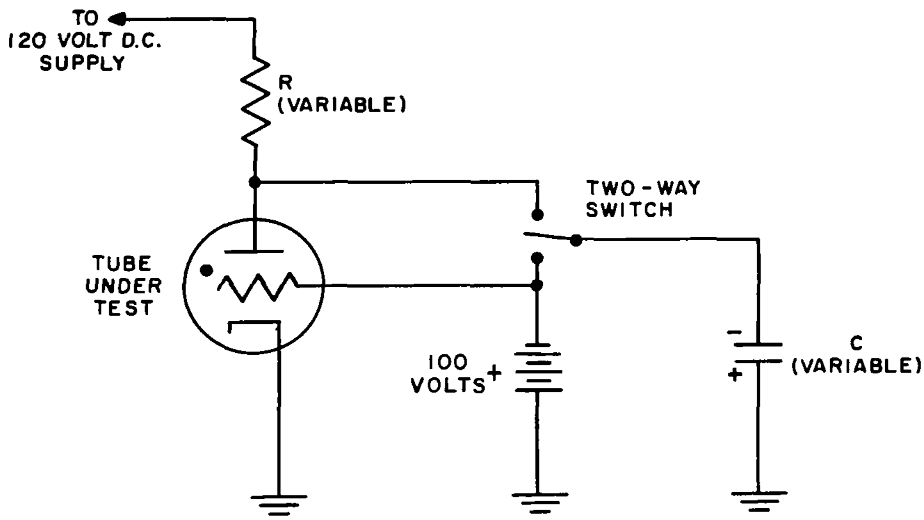



Figure 13 - Recovery Time Test Circuit

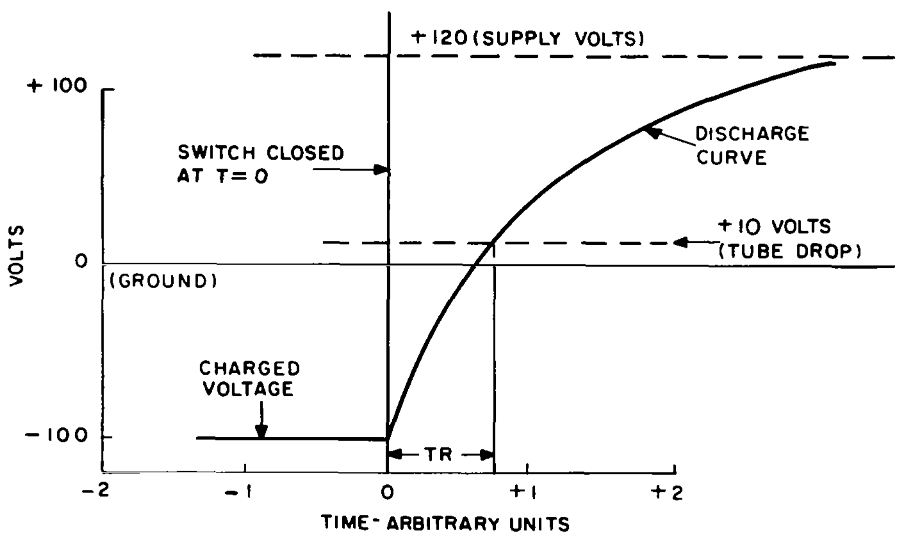



Figure 14 - Recovery Time Voltage Discharge Curve

where

$T_R$ = recovery time, microseconds

$R$ = load resistance, ohms

$C$ = capacitance, microfarads

$V_T$ = voltage at time $T_R$ = 110 volts

$V_s$ = supply voltage = 120 volts

$V_c$ = capacitor voltage = 100 volts

## TEST PROCEDURES

A set of tube performance tests was made before endurance tests started and every 500 test hours thereafter for the first 5000 test hours. The test interval was increased to 1000 hours for times beyond 5000 hours at each test station. In addition, tube performance was monitored almost daily for any major change in tube operation by checking the voltage waveform at each tube, as displayed on an oscilloscope. The grid control characteristics were also checked approximately every 100 hours.

The test data recorded were as follows:

1. Tube voltage drop during peak current conduction was recorded for three conditions: a) on endurance test to detect trends in tube behavior; b) as a 60-hertz, 15 average ampere rectifier representing full load current conditions; and c) at 60 hertz when the tube is fired once per second, which is a pulsed peak emission test, giving good indication of cathode capability.

2. The dc grid voltage necessary to fire, or initiate, conduction of the tube at 60 hertz was measured, and the grid current required for full-current, 60-hertz rectifier operation was measured. Normal grid firing voltage indicates an absence of spurious grid emission or electrical leakage, while normal grid current indicates sufficient working fluid. These two parameters also define the control circuit requirements for

tube applications. Spurious emission from the grid was also monitored by applying 200 negative dc volts to the grid with a 60-hertz anode voltage applied (appreciable grid emission will cause erratic breakdown in the tube).

3. Tube temperature, cathode heater input, tube voltage, test hours, and oven settings were monitored as a check of test equipment operation as well as tube operation on endurance test.

Recovery time tests (described in the previous section) were conducted approximately every 1000 test hours.

A set of typical recorded data, including pulse emission data and recovery time data, is presented in Appendix C.

Before newly processed tubes would operate stably and consistently, a period of 50 to 100 hours of seasoning at 60-hertz full load current was required, which is typical of electron tubes, especially at high voltages. This procedure results in better cathode performance. Then up to 50 hours operation at progressively higher voltages is required to obtain a good high-voltage operating capability.

## TEST RESULTS

Endurance test results for the eleven tubes which were operated 200 hours or longer in the respective test circuits are summarized in Table I. The performance data listed in Table I represent the status of tubes when tests were terminated, ie., 60-hertz tests were conducted after the failure event for tubes 2, 5, 8, 6, and 10, and at the end of the program for tubes 1, 3, 4 and 11. The "Notes" column of Table I indicates the condition of the tube body at completion of endurance tests.

The tube drop (volts) at 100 peak amperes on peak emission test indicates the cathode capability. Tubes which would provide 100 peak amperes at 30 volts would operate at an arc drop of approximately 10 volts under full load, steady-state conditions, while lower peak emission voltages generally provided better performance. Heater power is

## Table I - Results of Performance and Endurance Tests

| Test Condition | Tube No. | Peak Emission Test Volts | Heater Input Watts | Grid Firing Volts | Grid Current(1) Milliamp. | Hours on Test | Reason for Failure | Notes (4) |
|---|---|---|---|---|---|---|---|---|
| Full Load | 1 | -- | --- | -- | -- | 30 | arcback damage | Repaired (4) see tube 1* |
| | 2 | 30 | 243 | 10 | 50 | 9350 | extensive arc damage | |
| | 3* | 13 | 260 | 10 | 15 | 10910 | --- | (3) |
| | 4 | 13 | 264 | 9 | 15 | 1560 | --- | (3) cathode seal leak |
| Accel. Inverse Voltage | 4 | -- | --- | -- | -- | 7470 | --- | moved to full load |
| | 5 | 30 | 214 | 25 | 100 | 6160 | gas depleted | |
| | 1* | 30 | 218 | 19 | 35 | 2135 | --- | (3) (5) |
| High Voltage Phase Retard | 6 | 40+ | 90 | -- | -- | 500 | sputtered cathode(7) | tubulation leak (4) |
| | 7 | -- | --- | -- | -- | 500 | (2) | |
| | 3 | -- | --- | -- | -- | 200 | (2) | Repaired see tube 3* |
| | 8 | -- | --- | -- | -- | 800 | (2) | Repaired see tube 8* |
| | 8* | 16 | 152 | 10 | 35 | 300 | equipment failure | (4) |
| | 9 | 15 | 185 | 7 | 15 | 4870 | " | (6) |
| | 10 | 13 | 209 | 10 | 25 | 7580 | electrical leakage | anode seal leak |
| | 11 | 14 | 226 | 8 | 30 | 6540 | --- | (3) |

*Denotes the repaired version of the tube with the same number

NOTES:

(1) Minimum grid current required to conduct full load current (15 amps average) at 60 Hz.

(2) Removed from test to repair cathode support braze.

(3) Test terminated at end of program.

(4) All tubes had a leak at the cathode support braze except tubes 1, 6, and 8*.

(5) Tube 1 had performed better than these data indicate, but performance deteriorated when the test station vacuum chamber developed a small leak during the last performance tests.

(6) Tube 9 tests were terminated by a catastrophic vacuum system failure and the performance data are from periodic tests prior to that event.

(7) Oxide-coated cathode. All other tubes utilized matrix cathodes.

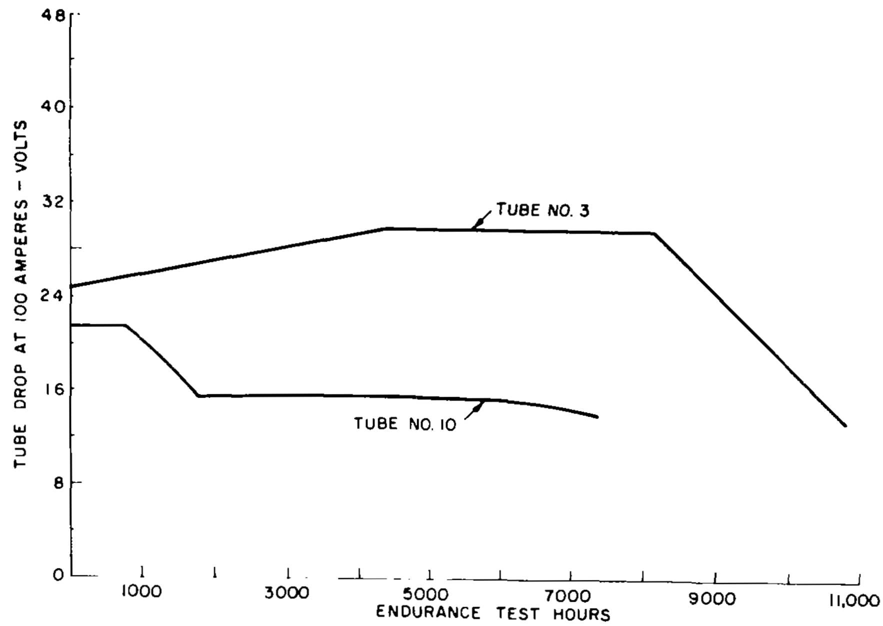
a measure of the cathode temperature required for adequate cathode performance, with 240 watts indicating approximately 1100°C. The variations of these two parameters with life for tubes 3 and 10 are shown in Figure 15.

The need for higher dc grid current to provide full tube current indicates that a low working fluid density exists in the tube (due to more rapid diffusion of ions away from the grid). Representative trends in grid current during endurance tests are shown in Figure 16 for tubes 3 and 5.

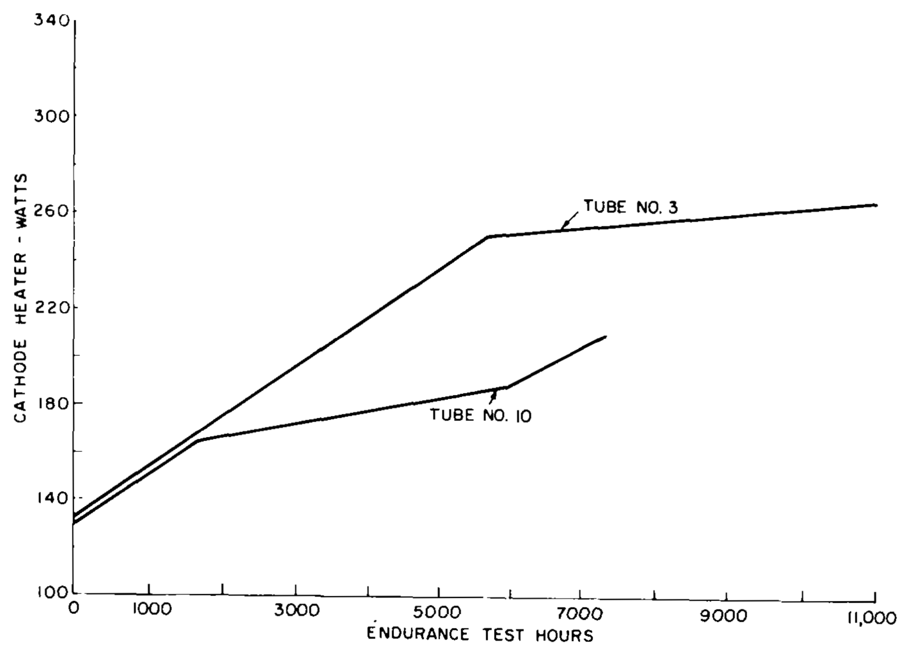
The data in Table II were obtained by x-ray emission after endurance tests were completed. The data for tube 6 were obtained much earlier than data on tubes 4 and 10. The presence of cobalt on the anode insulator indicated that appreciable material had been sputtered from the anode support of tube 6. As a result, the graphite anode and anode-shield design shown in Figure 17 was revised to that shown in Figure 2. The copper deposits in tube 6 resulted from use of copper alloy to braze the cathode shield to the cathode support, a fabrication error. Palladium-cobalt brazing alloy was used for all other tubes.

The ceramic controls of Table II were obtained from tube bodies which had been metallized and brazed but not operated in tubes. The graphite control was the back side of the anode of tube 4.

Metals present in the tubes but not detected were palladium, tungsten, molybdenum and tantalum.




(a) Peak Emission Test Showing Tube Arc Drop in Operating Time




(b) Cathode Power Requirement in Operating Time

Figure 15 - Cathode Performance as a Function of Operating Time on Endurance Test

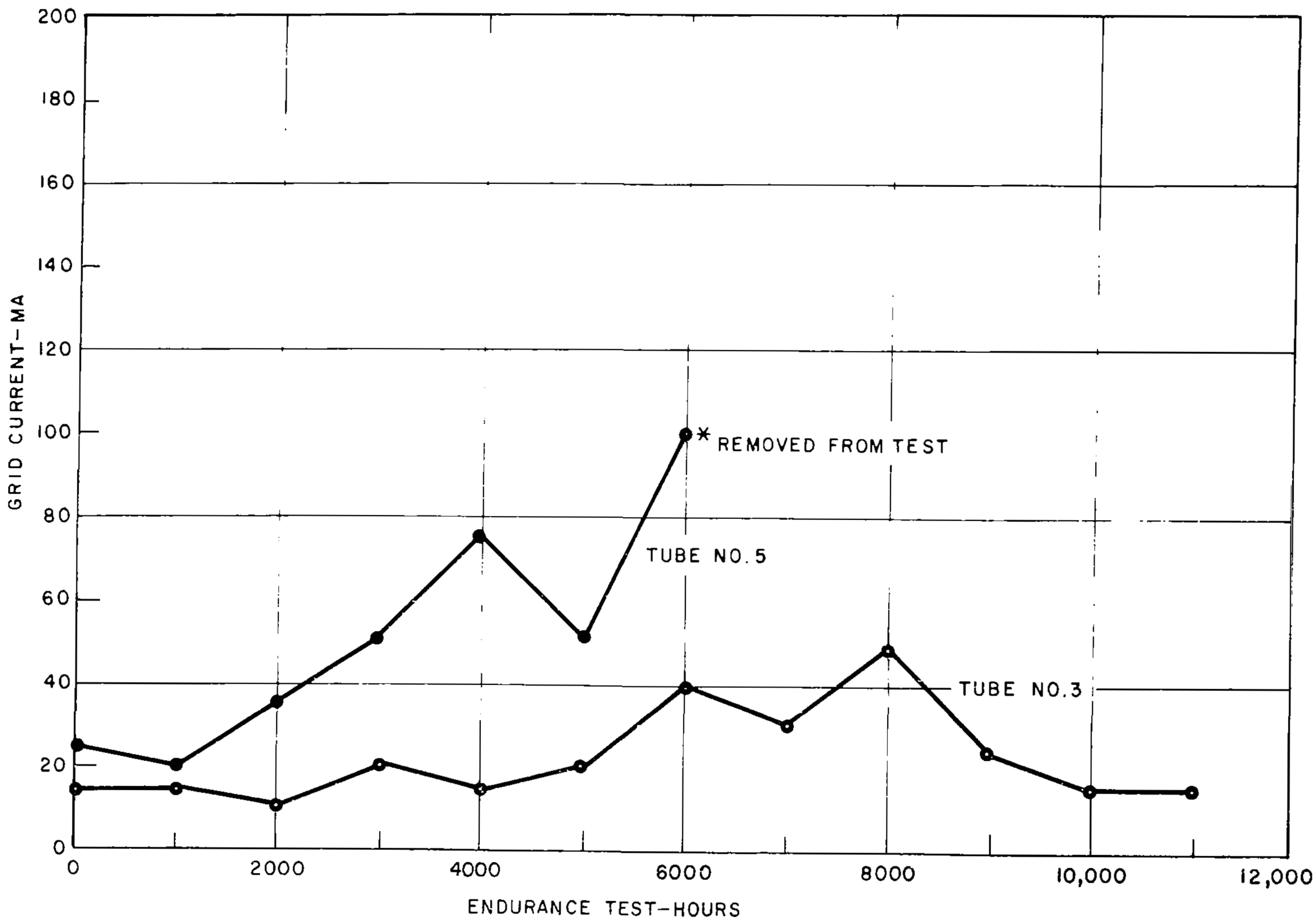



Figure 16 - Grid Current Required for Full-Current 60-Hertz Operation (Tubes 3 and 5)

## Table II - Analysis of Deposits in Endurance Test Tubes

| Element | Tube No. | Anode Insulator | Cathode Insulator | Anode | Grid | | Controls | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Anode Side | Cathode Side | Ceramic | Graphite |
| Thallium | 6 | n.d. | n.d. | -- | -- | -- | n.d. | -- |
| | 4 | n.d. | n.d. | low | n.d. | n.d. | n.d. | n.d. |
| | 10 | n.d. | n.d. | tr. | n.d. | n.d. | | |
| Barium | 6 | tr. | high | -- | -- | -- | n.d. | -- |
| | 4 | tr. | low | high | high+ | low | f.tr. | tr. |
| | 10 | low | high | high+ | high | high | | |
| Calcium | 6 | low | low | -- | -- | -- | low | -- |
| | 4 | tr. | low | low | low | f.tr. | f.tr. | tr. |
| | 10 | low | low | high | tr. | tr. | | |
| Nickel | 6 | high | high | -- | -- | -- | low | -- |
| | 4 | f.tr. | high | f.tr. | tr. | high+ | f.tr. | n.d. |
| | 10 | tr. | high+ | high+ | low | high+ | | |
| Iron | 6 | high+ | high | -- | -- | -- | high | -- |
| | 4 | tr. | tr. | tr. | tr. | tr.+ | tr. | f.tr. |
| | 10 | tr. | tr. | n.d. | f.tr. | tr. | | |
| Others Detected | 6 | high Cu, Co | high+ Cu | -- | -- | -- | high Cu | -- |
| | 4 | tr-K | -- | tr-K | f.tr-K | tr-Cr | tr-K | tr-K |
| | 10 | tr-K | f.tr-K | tr-K | f.tr-K | f.tr-K | | |

Abbreviations:

n.d. = not detected
tr. = trace
f. = faint

Approximate calibration: f.tr. $\simeq 10^{-6}$ g/cm$^2$; high+ $> 10^{-4}$ g/cm$^2$

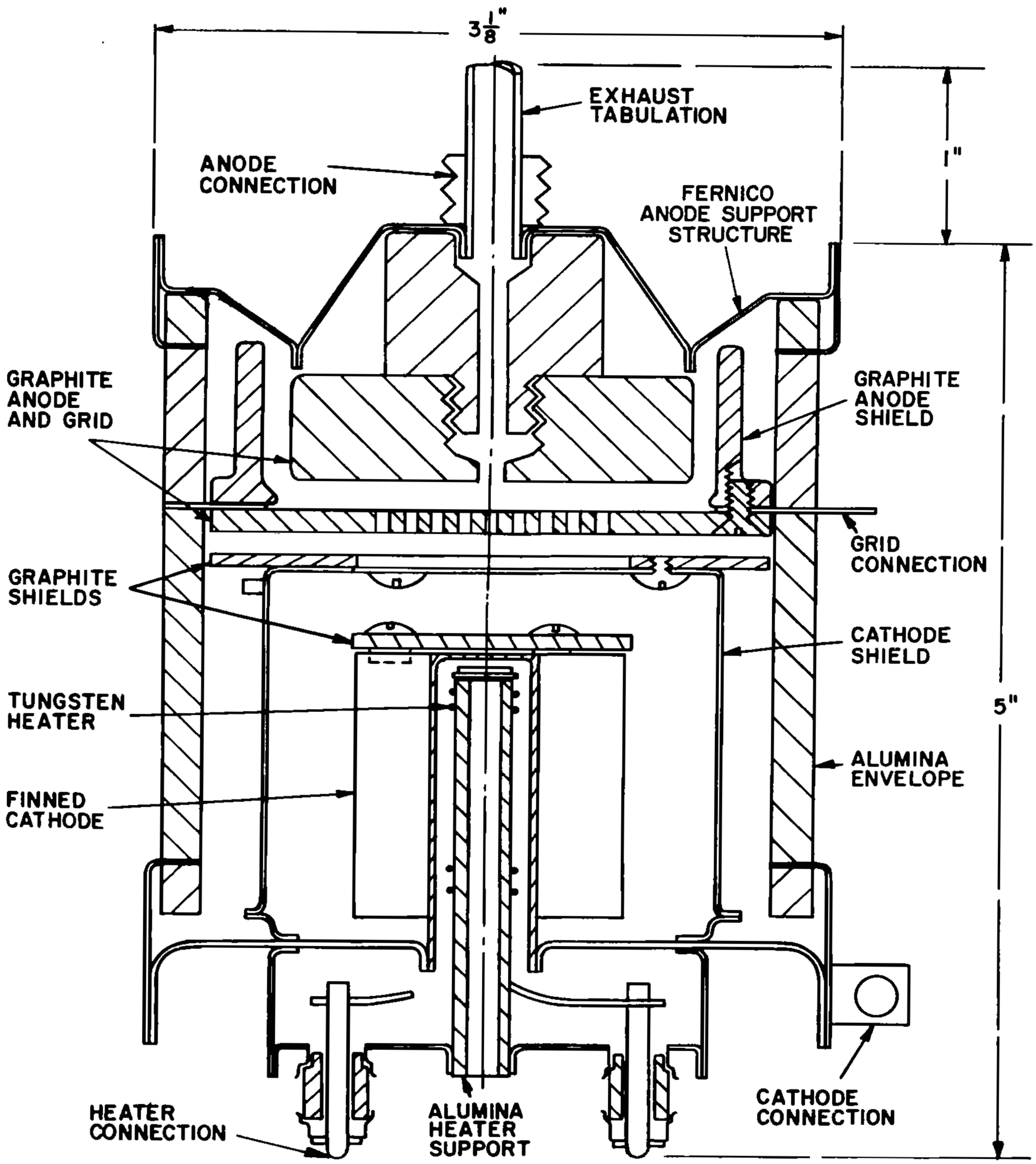



Figure 17 - Tube 6 Design Showing Graphite Anode Shield Configuration and Oxide Coated Cathode

## DISCUSSION OF RESULTS

The durability of the basic tube envelope or "body" of the thyratron can be ascertained from the results of the endurance tests conducted during this program. Of the eleven tube envelopes which were tested, two developed seal leaks (tubes 4 and 10) after more than 13,000 and 10,500 total hours of temperature, respectively, where the total hours include endurance test time as shown in Table I, periodic performance test time, and standby time during which the tube was maintained at full temperature with no applied voltage. The reliability expected for the tube body at 5000 hours of life would therefore be very high, while the reliability expected for 10,000 hours of life would be on the order of 75 percent, based on the samples tested.

The critical joining process for any high-temperature electrical device is the metal-ceramic seal, because these seals are more complex and usually more bulky than metal-to-metal joints. Processing conditions of temperature and atmosphere generally are also more critical for metal-ceramic seal processes. The reliability of these metal-ceramic seals (described in the "Tube Design" section) could probably be improved by undertaking an extensive study of the seal materials and processes, similar to other studies of high-temperature seal processes.[6,7] The referenced studies have not covered seals as large as those used for these thyratrons, where the seals are operated at temperatures as high as those associated with this program. Some seal studies were also undertaken during the earlier work of this program, but the seals again were smaller than those utilized here. The size factor is important because temperature during processing must be critically controlled and even small differences in the expansion coefficients of the mating parts will result in large residual stresses. It appears feasible to reduce the volume of the seals required for these thyratrons by 2:1, and this step is recommended for future high-temperature tube designs.

The performance of these metal-ceramic seals in regard to reaction with the working fluid or other tube materials is excellent -- visual and spectrographic examination of tubes 4, 6 and 10 after endurance testing indicates that no appreciable reactions occurred either between the tube structures and the braze alloy, or with the thallium vapor which is a very "active" metal.

Metal-to-metal joining problems are usually less severe, especially where similar (preferably identical) metals are joined by arc or resistance welding and where no filler metals are required. Thus it is not surprising that the heliarc welds joining Fernico to Fernico and tantalum to tantalum did not fail in any of the endurance test tubes.

Weld-pinch sealing of the Fernico exhaust tubulation also proved completely reliable for the later endurance test tubes. The weld-pinch process constitutes mechanically pinching the tubulation closed, followed by a resistance weld, and is widely used to seal off vapor-filled electronic tubes. Some earlier tubes had experienced failures of this seal (such as tube 6, shown in Table I) but no further weld-pinch problems were experienced after a simple quality-control check was instituted, ie., the reduction of material thickness due to the weld-pinch process was held to between 30 and 50 percent of the original thickness.

The metal-to-metal joint which developed a vacuum leak for every thyratron operated more than 500 test hours was braze B (refer to Figure 2) which joins the tantalum cathode support structure to the Fernico envelope. The braze filler material used here is a proprietary alloy, derived from Hastalloy X*, utilized in high-temperature turbine applications. This alloy has also been used in related work for molybdenum-to-molybdenum brazes, and these brazes too, developed vacuum leaks during endurance tests conducted at 800°C. Obviously this braze should be eliminated in future high-temperature designs. The design shown in Figure 18 suggests that it is feasible to use tantalum for the entire cathode-end envelope structure to accomplish this. Where such brazes cannot be eliminated, they should be relocated more distant from the cathode heater, preferably near the cathode connection or other such heat sink (as suggested in Figure 18) in order to subject them to lower temperatures. This is because lower temperatures will reduce the metallurgical changes in the brazing alloys which lead to braze failure. It is also recommended that other high-temperature braze alloys such as palladium-cobalt or nickel-titanium (as used in metal-ceramic seals) be used for this joint.

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*Haynes-Stellite Company, Kokomo, Indiana

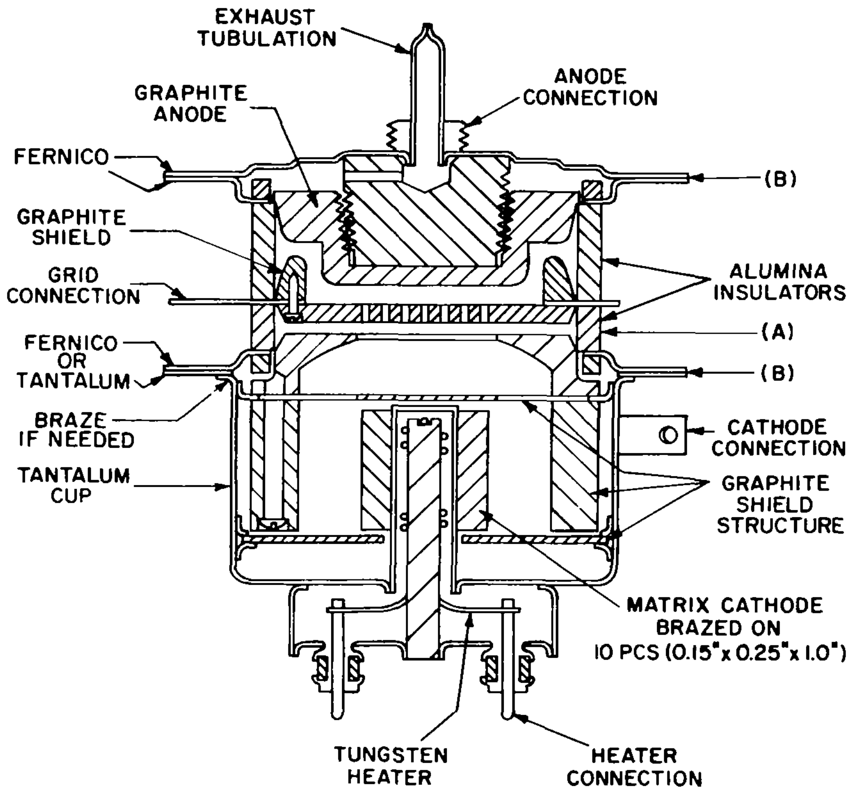


Figure 18 - Improved Thyratron Design

## CATHODE PERFORMANCE

The electron emission performance of the tungsten matrix cathodes was uniformly excellent. There was no indication that the cathodes were approaching end of life, even with as much as 10,900 test hours and 14,000 hours at temperature (tube No. 3). The cathodes are compatible with the working fluids, and they endured severe ion bombardment conditions in two of the test modes (HVPR and AIV).

The mechanical and thermal joining of the matrix cathode disks to the cathode structure was adequate and reliable as well, evidenced by the relatively consistent requirement for heater power needed to maintain cathode emission in the various tests. In brief, the endurance tests indicated no obvious shortcoming related to the materials or fabrication techniques used for the cathode per se.

As discussed in the previous subsection, the cathode temperature for all tubes was increased to 1100°C or higher during the later stages of endurance tests, presumably because the thallium working fluid lost through a braze joint leak was being replaced by barium or calcium. While the evidence indicates this was the case, it is important to realize that it is not feasible to unequivocally separate temperature-related emission performance from temperature-related working fluid performance. For example, tube performance could be maintained at reduced cathode heater input during a given test after tube wall temperatures had been increased, but higher tube wall temperatures also reduce the heater input required for a given cathode temperature, making such effects difficult to assess accurately. On the other hand, the cathode emission capability, as measured by 100-ampere peak emission tests, tended to increase with increasing cathode temperature, indicating that cathode performance had not deteriorated appreciably. This performance is shown in Figure 15 for tubes 3 and 10, where the lower peak voltage drop indicates better emission performance.

The operating temperature characteristics of the matrix cathodes operated in a gaseous arc discharge differed from conventional oxide cathodes in some interesting respects. Early experience with tubes 3 and 7 indicated that the cathode would operate well at the relatively low temperature of 1000°C, or less, after the cathode had been well activated. It was reasoned that this was because the activating process leaves some excess of barium on the tungsten matrix surface, which will persist for many hours and permit good operation at the lower temperatures. Tube 3 was first started on HVPR test under these conditions, and within a few hours the cathode emission capability had deteriorated such that tube voltage drop was approximately 200 volts. A conventional oxide cathode would have had its emission coating destroyed in a matter of minutes under these severe conditions, but the matrix cathode not only survived, but was readily reactivated, and continued to operate properly for hundreds of hours. (It should be noted that the current is only 3 RMS amperes in HVPR test; at full load conditions of 23 RMS amperes, the tube structure probably would be damaged by such operation). The tube 3 matrix cathode disks had been sputtered heavily enough to erode away 0.001 to 0.002 inch of cathode surface when it was examined after a few hundred hours of operation. By comparison, the cathodes for tubes 9, 10 and 11 indicated negligible erosion of cathode material after several thousands of hours of HVPR operation, indicating that the 200 volt drop described above caused most of the erosion of the tube 3 cathode.

Comparing the observed requirements of an operating temperature of 1100°C for matrix cathodes in these thyratrons with earlier data for matrix cathodes operated at 1050°C in vacuum, it is noted that matrix cathodes operated in gaseous-discharge devices require somewhat higher operating temperatures than those operated in vacuum devices. This logically could be another consequence of the ion bombardment experienced by cathodes in gas-discharge devices.

It had been observed in related vapor tube work[3] that there was some evidence of reaction between matrix cathodes and thallium vapor, as evidenced by an appreciable decline in cathode emission as the thallium vapor pressure was increased. Experience from this program indicates that the process is reversible and not cumulative, in that cathode performance continued to be excellent for the longest tests conducted. The tendency to react may inhibit use of matrix cathodes at high thallium vapor pressures (above 100 micron) but it is doubtful that this will pose practical problems at the pressure levels used in gaseous-discharge tubes.

Based on recommendations of the fabricators of the matrix cathode disks used for these cathodes*, operation at 1100°C results in a cathode life expectancy of not more than 20,000 hours, and life could be approximately doubled by lowering the cathode temperature to 1050°C. This would require approximately doubling the cathode area, operating at the same current level. The present cathode area of 25 $cm^2$ should therefore be increased to about 50 $cm^2$ for future tube designs. (This would also require 30 percent to 60 percent greater cathode heater input, which is within the capabilities of the present heater.) As a convenience in tube fabrication, it would also be advantageous to braze the matrix material on the cathode in the form of a series of rectangular pieces or fins, rather than the washer configuration used for these tubes. This finned

*eg. Semicon Associates, Inc., Lexington, Kentucky, or Spectra-Mat, Inc. San Jose, California configuration, which is geometrically similar to that shown in Figure 4, is represented in the improved design thyratron shown in Figure 18.

To correct the cathode-grid leakage problem discussed in the next section, the cathode-grid insulator, grid, and shields could be designed to provide a geometry similar to the Figure 2 anode structure, as shown at "A" in the improved design thyratron of Figure 18. The nickel cathode shield is also eliminated in this improved design and replaced by a graphite shield structure, which is expected to alleviate spurious grid and anode emission as discussed below.

The cathode metal support structure should be all tantalum because tantalum is more resistant to sputtering, is a poorer electron emitter, and is more refractory than nickel (less subject to evaporation and migration of deposits). The structure of Figure 18 also moves the braze joint required to join the tantalum and Fernico to a location readily cooled by heat-sinking (as discussed previously in this section). The structure, which must be fabricated by a metal-ceramic sealing (brazing) process, is also reduced in length, as was similarly discussed.

The cylindrical geometry of the anode and cathode support structure of Figure 2 is also changed to a flat disk geometry at "B" in Figure 18, as a more practical structure with respect to assembling the close-clearance graphite parts to the metal-ceramic seals.

The thallium working fluid performed very well in these tubes, based on endurance test performance, and therefore should be the choice as a working fluid in future work. The working fluid aspects of this work are discussed in Appendix A.

## SPURIOUS ELECTRON EMISSION

Based on the endurance test data for these thyratrons, electrodes and tube shield structures fabricated of graphite and uncontaminated by metal deposits exhibit desirably low levels of spurious electron emission in high-temperature gaseous-discharge devices utilizing thallium as the principal working fluid. Only two of the twelve tubes endurance tested exhibited serious problems related to spurious emission (Nos. 2 and 10), and subsequent analysis indicated that their graphite surfaces had been contaminated by metal deposits.

Tube 2 exhibited erratic grid control due to grid emission at 3000 hours on full-load test, and the problem gradually worsened until the tube failed at 9350 test hours because of inverse arcing at the anode. Tube 2 was severely damaged by the arc-back failure, and the metal structure was partly melted so that metal was evaporated over much of the anode and grid structures. It was therefore doubtful that analysis of metal deposits in tube 2 would be meaningful. Tube 10 exhibited an occasional tendency to arc-back prior to 5000 hours on HVPR test and then began to exhibit severe electrical leakage problems up to the time of its failure at 7580 test hours. Tubes 10 and 4 were analyzed for surface deposits by x-ray emission spectroscopy, and the results of the analysis are tabulated in Table II. These data indicate that the metallic coatings are approximately 90 percent nickel, and that the nickel coatings are much heavier on the cathode-grid insulator and on the cathode side of the grid than on other surfaces. The source of the nickel must have been the nickel cathode shield because there was also visible evidence of heavy sputtering on the inside surfaces of the shield. The heavy nickel deposits on the cathode side of the grid evidently originated from inside the shield. It is likely that re-evaporation or re-sputtering of the nickel from the grid led to the heavy deposits on the anode of tube 10, resulting in the occasional arc-backs. The same phenomena must have led to the arc-back failure of tube 2.

There was also visible evidence of sputtering on the outer surface of the nickel shield opposite the grid-cathode insulator in all endurance test tubes, indicating that there was sufficient electron emission from the outer surface of the shield to set up discharges between the shield and the grid structure. This is not surprising since the shield experiences temperatures of 800°C to 900°C during tube tests. The sputtering outside the shield produced a metallic coating which was visible on the grid-cathode insulator with the exception of the area shielded by the graphite grid. This led to measurable electrical leakage for all endurance test tubes and severe leakage (approximately 100 ohms) for tube 10.

The anode-grid region showed little evidence of sputtering near the insulator, by comparison. The symmetry of the grid shield and anode positions with respect to the grid-anode insulator, plus the close shielding of the insulator by graphite, produces less metallic coating due to sputtering than the grid-cathode configuration.

A related phenomenon was observed in the first thyratrons fabricated during this contract, including tube 6 which exhibited more severe arcing problems than the other tubes tested. These first tubes were designed with a graphite anode shield as shown in Figure 17, and visible metallic coatings were found on the anode insulator, graphite anode, and shield when the tubes were dismantled after test. The analysis of tube 6 (refer to Table II) indicated that the Fernico anode structure was the source of the deposits. This problem was alleviated by changing the anode and shield design to the configuration shown in Figure 2, which was used for all other endurance test tubes. The Figure 2 design minimizes electric fields at the metal anode support structures and thus reduces the likelihood of arcing and sputtering at these surfaces. The endurance test tubes incorporating this anode shield configuration indicated no problem due to sputtering of the anode structure.

## PYROLITIC GRAPHITE

Two thyratrons were also fabricated using all pyrolitic graphite for the graphite parts in the Figure 17 design, and comparatively brief tests were made at 60 hertz and under HVPR conditions. The pyrolitic material was expected to absorb or desorb less gas and cause less "sooting". However, it was found that grid emission with pyrolitic graphite was much higher than with amorphous graphite, so the use of the former was discontinued. The flat grid plane was the AB plane of the pyrolitic graphite.

## THYRATRON ELECTRICAL PERFORMANCE

Test data obtained relevant to electrical performance -- specifically the grid control, recovery time and voltage "holdoff" capabilities -- indicate that the tube design provides basically adequate performance. As discussed previously, there is evidence that the two tubes which did not provide adequate performance (tubes 2 and 10) performed poorly because of nickel deposits on the electrodes and insulators, a shortcoming which can be alleviated.

Because of the envelope leaks which all endurance tubes experienced, the working fluid density was often low enough to result in marginal operating conditions, as evidenced by poor grid control characteristics. Thus the data obtained after approximately 3000 operating hours were variable and are considered less typical of tube performance than earlier data. Typical periodic test data are shown in Appendix C.

The grid control voltage required to fire tube 3 versus peak anode voltage (on full load test) is shown in Figure 19. The early data are shown as a solid curve while the range of later data is shown by dashed curves. These data were typical of all thyratrons tested except for tubes 2 and 10. All other thyratrons tested would not start at zero or negative grid volts, and it is reasoned that more than 10 volts were required only when the working fluid density was very low.

The grid current required for endurance test tubes to conduct the rated current of 15 average amperes at 60 hertz and 117 RMS volts is shown in Table I, and representative trends in grid current during endurance tests are shown in Figure 16 for tubes 3 and 5. Other tubes also experienced variable higher current excursions, indicative of low working fluid density due to envelope leaks, as discussed earlier. Although tube 3 appears much better in this respect in Figure 16, the tube 5 data are not directly comparable due to lower cathode temperature conditions (heater voltage) during the tube 5 tests. It is considered very unlikely that low-frequency applications will require more than 0.1 ampere of grid current with the proper working fluid density. Where the tube is used in high-frequency applications or where the grid is fired by a short pulse, such as in the AIV test, a peak current of approximately one ampere would be required. Typical tube application parameters are described in the Technical Data included as Appendix B of this report.

The peak anode voltage holdoff capability was found adequate in short-term tests at 2500 volts in the AIV and HVPR test circuits, and to at least 2200 volts (equipment limited) in full load tests. In the first few operating hours, tubes required some conditioning to achieve good voltage capability, which is normal for gas tubes. Higher initial gas loading with xenon also reduced voltage holdoff capability early in life, which is merely a confirmation of the Paschen law voltage breakdown phenomenon. The rapid improvement in voltage capability during initial seasoning was another indicator of xenon-cleanup in these tubes.

The recovery time (deionization time) tests provide a more reliable indicator of working fluid density than the grid control characteristics. For the simple one-fluid case in a particular grid geometry,

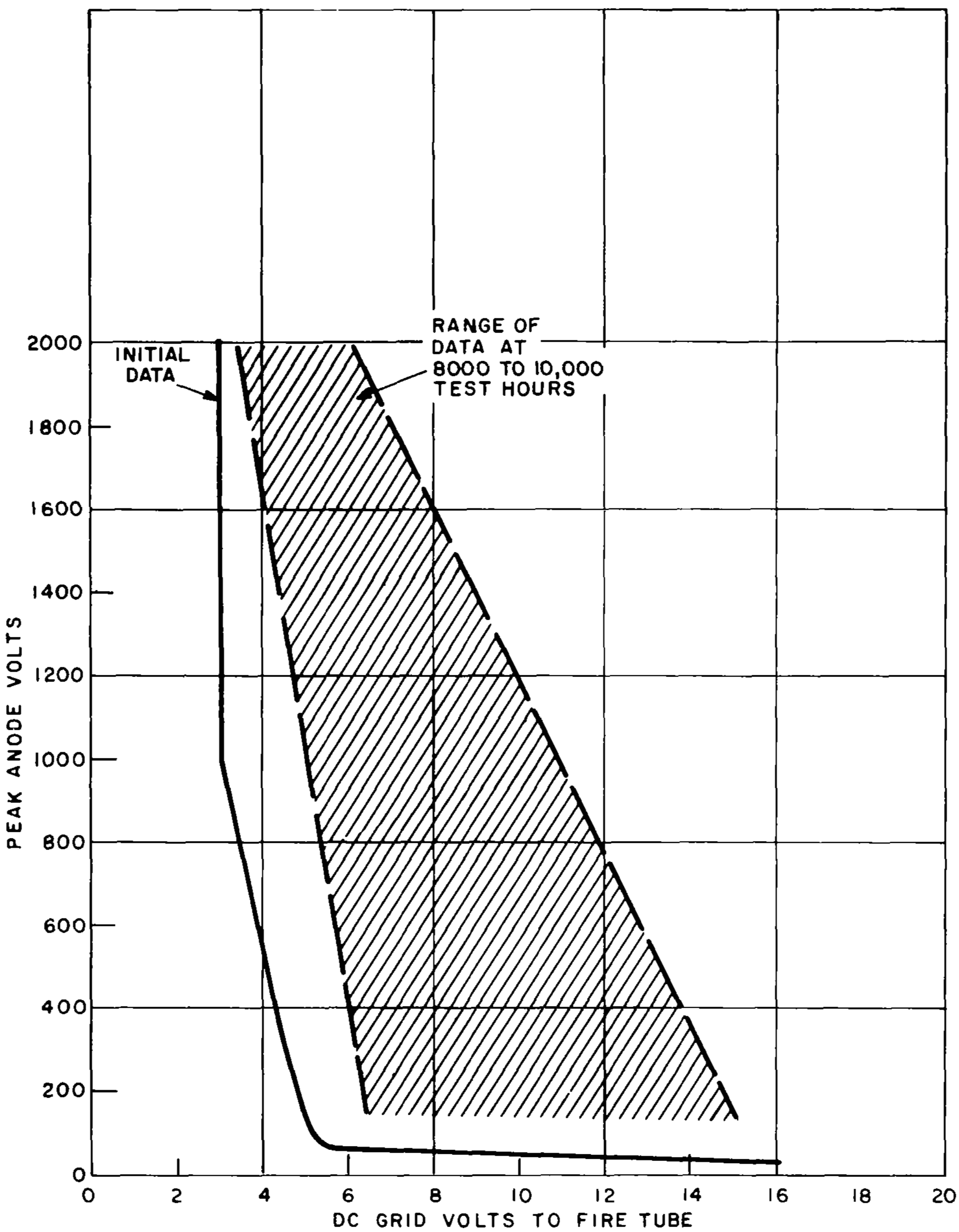


Figure 19 - Grid Firing Volts Versus Peak Anode Volts (Tube No. 3)

recovery time is governed by the degree of ionization and the working fluid density. Since the degree of ionization is proportional to the current as the tube is switched, the recovery time is proportional to tube current.

The variation of working fluid density with reservoir temperature is reflected by the variation of recovery time with reservoir temperature shown by the upper curves in Figure 20, for tube 3. This was typical for all tubes early in life. However, after thousands of hours, the recovery time indicated a lower working fluid density, even though the reservoir temperature was higher than for the earlier data. These data are shown in the lowest curve in Figure 20 for tube 3. As discussed in Appendix A, this behavior apparently resulted from a leak in the cathode support braze joint, which permitted the working fluid to escape to the vacuum bell. The higher temperature was required to evaporate residual working fluid from the graphite members of the tube structure. Typical trends in minimum reservoir temperature and recovery time during endurance tests are shown in Figure 21 for tube 5. The early data represents behavior with xenon present until approximately 500 hours. The flat characteristic from approximately 1000 hours to 4000 hours represents operation while the liquid thallium supply in the reservoir is slowly leaking out of the tube. Subsequently, the minimum temperature requirement gradually increased, as discussed above. Tube 5 was the only tube to be removed from test when very marginal performance indicated depletion of the working fluid. The envelope leak at the cathode support of tube 5 was quite large when the tube was checked after endurance tests, which probably contributed to earlier failure. The increase of minimum recovery time with increasing temperature logically is a consequence of higher spurious emission at the higher temperatures.

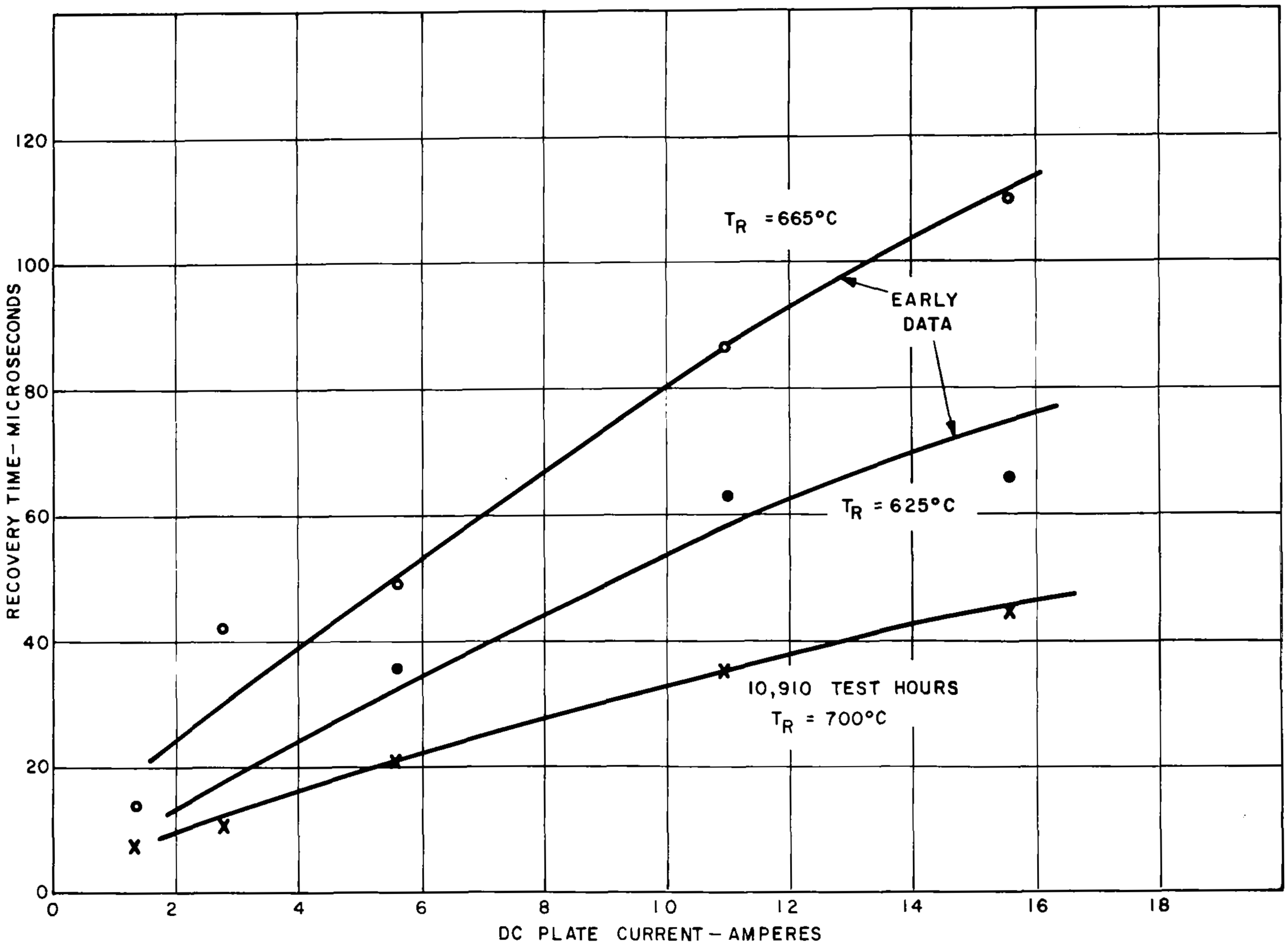


Figure 20 - Recovery Time Versus Plate Current for Tube 3 ($T_R$ = Reservoir Temperature)

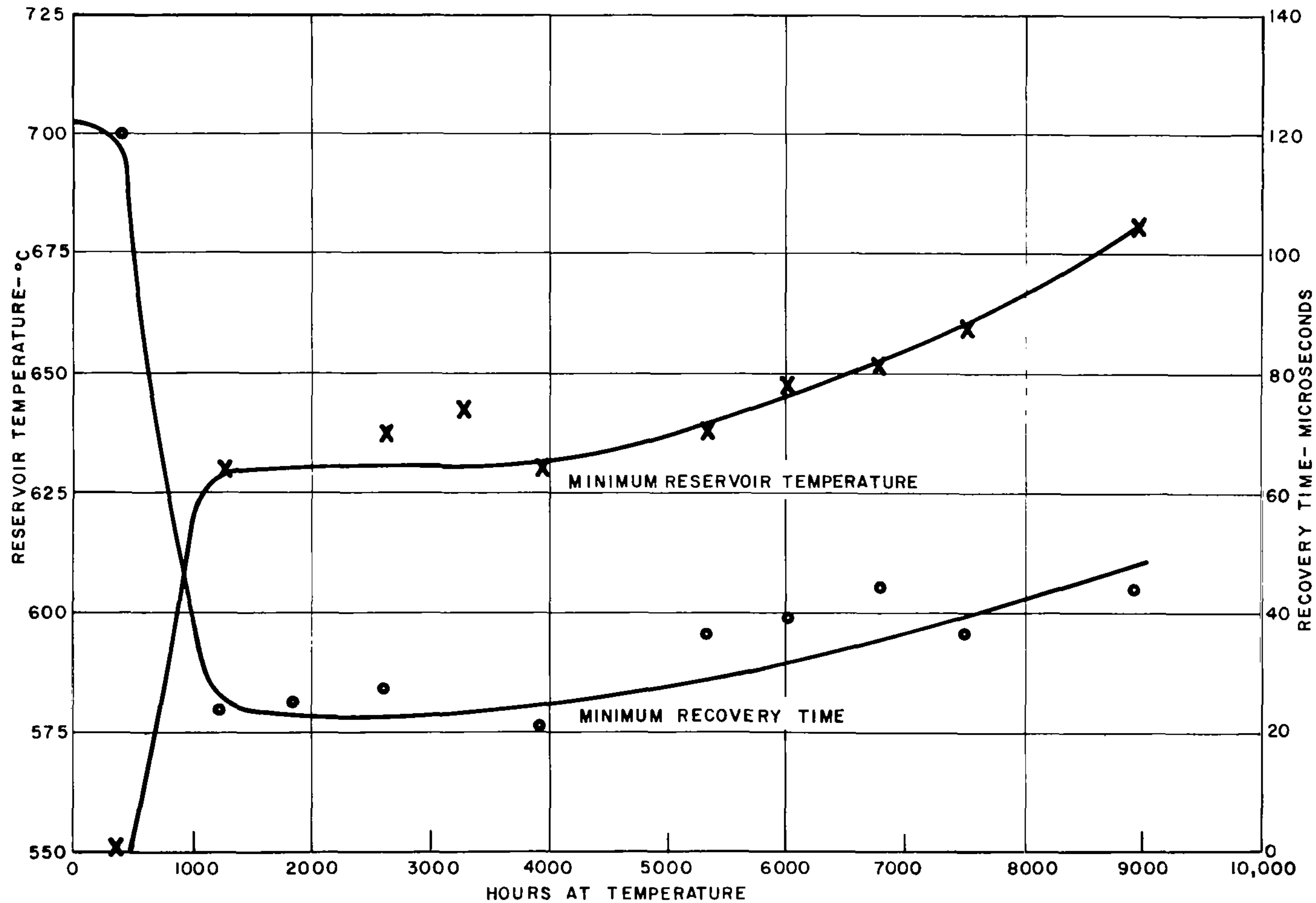


Figure 21 - Working Fluid Characteristics Versus Life for Tube 5 (15 DC Amperes)

## CONCLUSIONS

1. The feasibility of operating thyratrons at tube envelope temperatures up to 750°C with peak voltage ratings of 2000 volts forward and inverse, at 3200 hertz, and at a current rating of 15 average amperes, for periods of up to 11,000 hours was demonstrated.

2. A basic tube envelope life of 10,000 hours was demonstrated.

3. Thallium vapor proved to be very useful as a working fluid in that arc drop was low, recovery time was low, and sputtering and contamination of electrodes and insulators was not serious. Also, the relatively large mass of thallium which can be stored in a small temperature-controlled reservoir (630 to 680°C) permitted the attainment of very long life, even in tubes with small leaks in the envelope. Thyratrons using only xenon as the working fluid were found subject to rapid sputtering-induced cleanup in 3200-hertz 2000-volt circuits.

4. Graphite proved to be a useful material for tube electrode and shield structures because of its low sputtering rate and tendency to inhibit spurious electron emission.

5. Matrix cathodes provided excellent performance in terms of long life, adequate emission, and resistance to sputtering damage.

6. Since eight of the ten thyratrons endurance tested fully met the electrical performance specifications throughout endurance testing, any of the tube shortcomings which occurred are considered to be amenable to correction by straightforward design improvements. Such revision might include substitution of a graphite shield for the nickel cathode shield and the modification of insulator and shield geometry to minimize the influence of metal tube structural parts. Also to improve long-term reliability, a larger cathode area should be provided. The metal-ceramic seal design should be optimized to reduce the stress induced during fabrication and processing. Design of the cathode support structure should be such that all metal-to-metal envelope joints are arc welded.

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## Appendix A

## THALLIUM AND XENON AS WORKING FLUIDS

### THALLIUM

The successful long-term performance of these tubes during endurance testing is evidence that working fluid depletion is not a problem in thyratrons using thallium vapor as the principal working fluid. These tubes were loaded with the equivalent of approximately 200 tube volumes of vapor at normal working fluid density, ie approximately 80 milligrams of thallium was used per tube. The volume of this amount of liquid thallium is miniscule -- about .001 in.$^3$ ($1.6 \times 10^{-8}$ M$^3$). Thus loading could be increased a hundredfold or more if desired without the need for an excessive volume of thallium.

Thallium vapor is effectively present only when temperature throughout the tube are above 600$^\circ$C. Thyratron operation is particularly good when the temperature range of the thallium reservoir is between 620$^\circ$C and 680$^\circ$C. The pressure of the thallium vapor is controlled by varying the temperature of this small reservoir, which takes the form of a one-inch extension of the exhaust tubulation with a fill of liquid thallium. The vapor pressure versus temperature characteristics of thallium are shown in Figure 22.

The actual rate of thallium consumption by tubes in test cannot be determined from the endurance test data because these tubes leaked into the vacuum chambers at an appreciable but unknown rate during a significant portion of the endurance test time, as discussed previously. After times ranging from 1000 to 3000 operating hours, there was no evidence of xenon in the tubes. After 2000 to 5000 operating hours, there were no longer any indications that reservoir temperature was controlling the working fluid density, based on recovery time tests. This behavior suggests that the liquid thallium supply in the reservoir had been depleted, due to the envelope leak.

After times ranging from 4000 to 7000 operating hours, the tubes began requiring progressively higher tube wall temperature and cathode temperature for proper operation. This was especially noted during

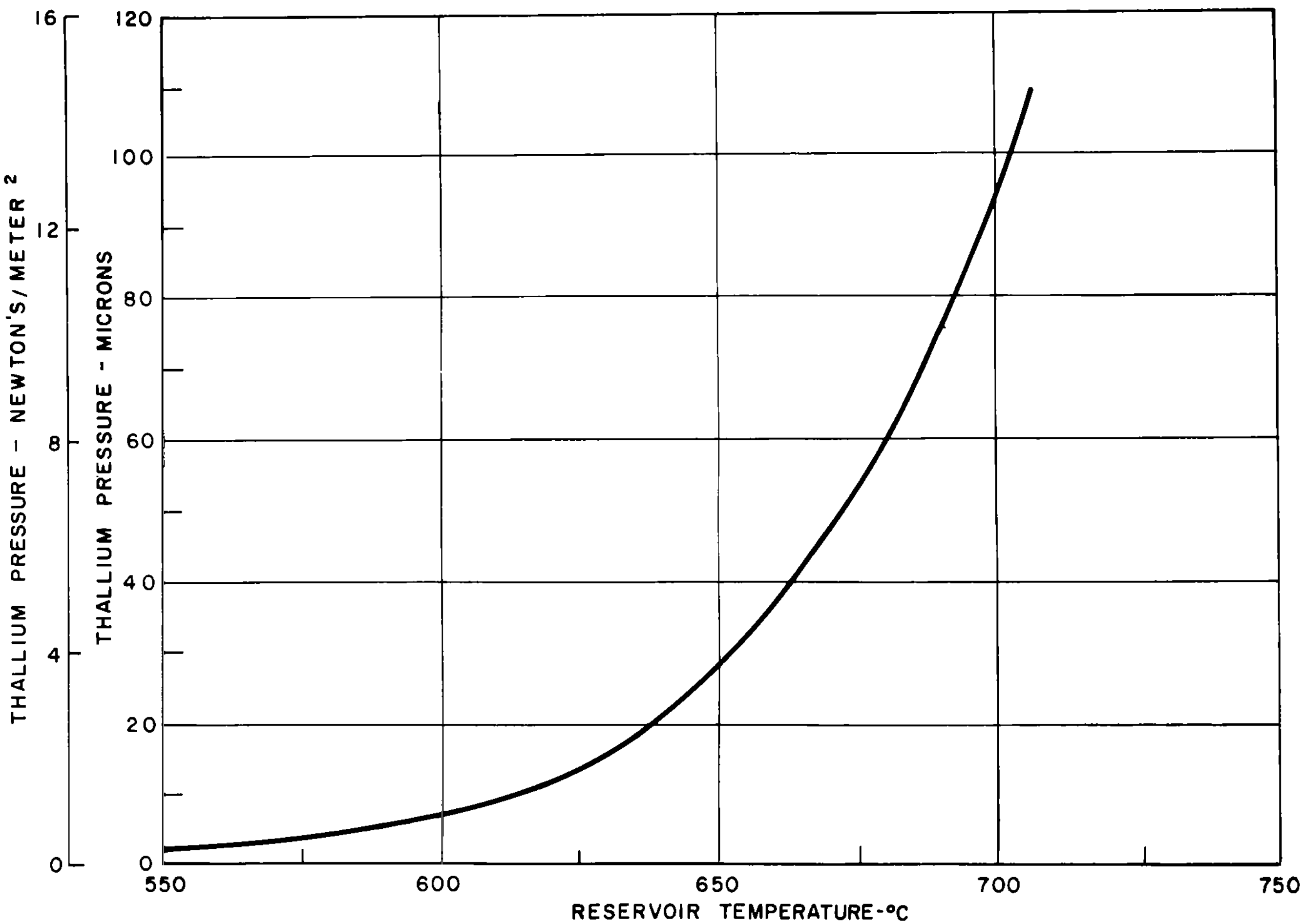


Figure 22 - Vapor Pressure Versus Reservoir Temperature
Characteristics for Thallium

periodic pulse-emission and AIV tests where the average anode heat dissipation is low. During full load endurance testing, where average grid and anode dissipations are high, the wall and cathode temperature demands did not increase. The behavior of the full load and AIV tubes implies that the porous graphite surfaces in the tubes had absorbed appreciable amounts of thallium vapor which was subsequently liberated as temperatures were increased or as anode and grid dissipation raised the anode and grid temperatures.

When cathode temperature increases, the temperatures of the tube structures on the cathode end increases and the rate of evaporation of barium and calcium from the cathode also increases. Since barium and calcium vapor pressure are approximately 25 percent of thallium vapor pressure for a given temperature, and barium and calcium have first ionization potentials of 5.2 and 6.1 volts respectively, compared to 6.1 volts for thallium, it is believed that barium and calcium ions provide an appreciable fraction of the ions in the arc plasma, due to the high-temperature conditions.

Three endurance test tubes were examined by x-ray emission spectroscopy after tests were completed to determine the nature of the materials deposited on the tube surfaces. The results of this analysis are shown in Table II. Apparently almost all the thallium supply had been depleted, since only the graphite anodes indicated even a small amount of thallium. Barium was present in comparatively large quantities and calcium in moderate quantities, indicating that barium and calcium were the principal working fluids at the end of endurance testing.

It is possible that some endurance test thyratrons operated several thousand hours after losing all of the thallium loading, based on another observation. Both HVPR test stations were provided with windows such that the color of the light of the gaseous discharge could be observed. Of the three tubes that were operated for long intervals in HVPR test -- tubes 9, 10 and 11 -- all exhibited a green discharge early in life, with the strong thallium line at 5350 Å being easily discernible with a simple hand-held spectrometer. However, the green glow slowly faded with time, and no thallium line was discernible by the time the tubes began to require higher temperatures to operate properly, as described above. Conditions were such that no definite identification of barium or calcium lines (which are weaker than the thallium line) could be made. Progressive darkening of the ceramic insulators by deposits also would tend to inhibit such observation. Tube 2, operating on full load test, was also provided with a window for the last few months of its test period. The green thallium glow persisted in tube 2 until the tube was damaged by an inverse arc at 9350 operating hours, at which time the glow abruptly disappeared. After this, the tube would not operate at high voltage without arcing; it would, however, operate properly at low voltage, with slightly higher tube temperatures than before. It was found later that the arc failure had caused the alumina insulators in the tube body to fracture, apparently allowing the small amount of thallium still in the tube to rapidly escape through the cracks. The usual leak at the cathode support braze (shown at B in Figure 2, as discussed earlier) was also found in tube 2. It is hypothesized that the leak at B was smaller for tube 2, such that the thallium was leaking out more slowly than for tubes 9, 10 and 11.

Since the calculated time to lose most of the working fluid, with a middle-range leak rate of a few micron liters per second (hundredths of Newton-meters per second) and with 30 microns (4 Newton/meters$^2$) internal tube pressure, is approximately 5000 hours at temperature, the performance of these tubes conforms to the behavior expected of the tubes which gave up their working fluid to a leak. Thus it is reasoned that the phenomena which usually cause gas cleanup in gas-discharge tubes consumed only a small fraction of the 200-volume loading of thallium during these endurance tests. These phenomena are discussed below.

## GAS CLEANUP

The cleanup phenomenon of surface absorption generally has little influence on cleanup rates unless porous materials with very large surface areas, such as porous graphite, are used for tube structures. This phenomenon is reversible to a considerable degree, ie gas or vapor is absorbed at lower temperatures and will be desorbed if temperatures are raised.

Material sputtered from the anode structure by ion bombardment is usually the major factor leading to gas cleanup for inert gas-filled tubes. Graphite also has the lowest sputtering rate among the materials suitable for these tubes[4] and these considerations led to the choice of graphite as the material for the anode, grid, and shields in these tubes.

The other factors which govern the anode sputtering rate are the degree of ionization of the gas working fluid at current cessation and the energy with which these ions bombard the anode as the tube ceases conduction, or commutates. These two factors are customarily combined into one term, the Commutation Factor (CF), to describe the susceptibility to gas cleanup for industrial thyratron or diode applications. This is expressed as:

$$CF = \left(\frac{di}{dt}\right)_o \cdot \left(\frac{dv}{dt}\right)_o$$

The $(di/dt)_o$ term defines the rate of decrease of current at commutation, and this governs the degree of ionization which persits after commutation. The average energy with which ions bombard the anode is governed by the $(dv/dt)_o$ term which defines the rate of rise of inverse voltage at commutation. Thus, gas cleanup depends upon wave shape, forward current and inverse voltage. Since commutation recurs every cycle, the cleanup rate is also directly proportional to frequency.

The circuit operating conditions experienced by these thyratrons can be compared with severe industrial thyratron applications at 60 hertz, where CF is approximately 200 volt-amperes per microsecond[2], to evaluate the cleanup conditions. The CF for both the full load tests and the phase retard tests is about 50 at 3000 to 3200 hertz, or approximately 13 times more severe than the industrial case. The accelerated inverse voltage test, intended to be a very severe test from the gas cleanup standpoint, features a CF of more than 10,000 at 3000 hertz, or approximately 2500 times the severe industrial case. The sputtering due to these tests is graphically obvious from visually examining anodes of AIV endurance test tubes, such as tube 4 shown in Figure 23. The grooved pattern reflects the heavier concentration of ions at the grid slots.

## XENON

Xenon was used as the sole working fluid for the first tubes fabricated during this contract, based on favorable experience in the earlier work,[1,2] and the first ionization potential of xenon (12.13 electron volts) being the lowest of the usable noble gases. The first tests conducted under this contract were intended to evaluate gas cleanup. The tubes

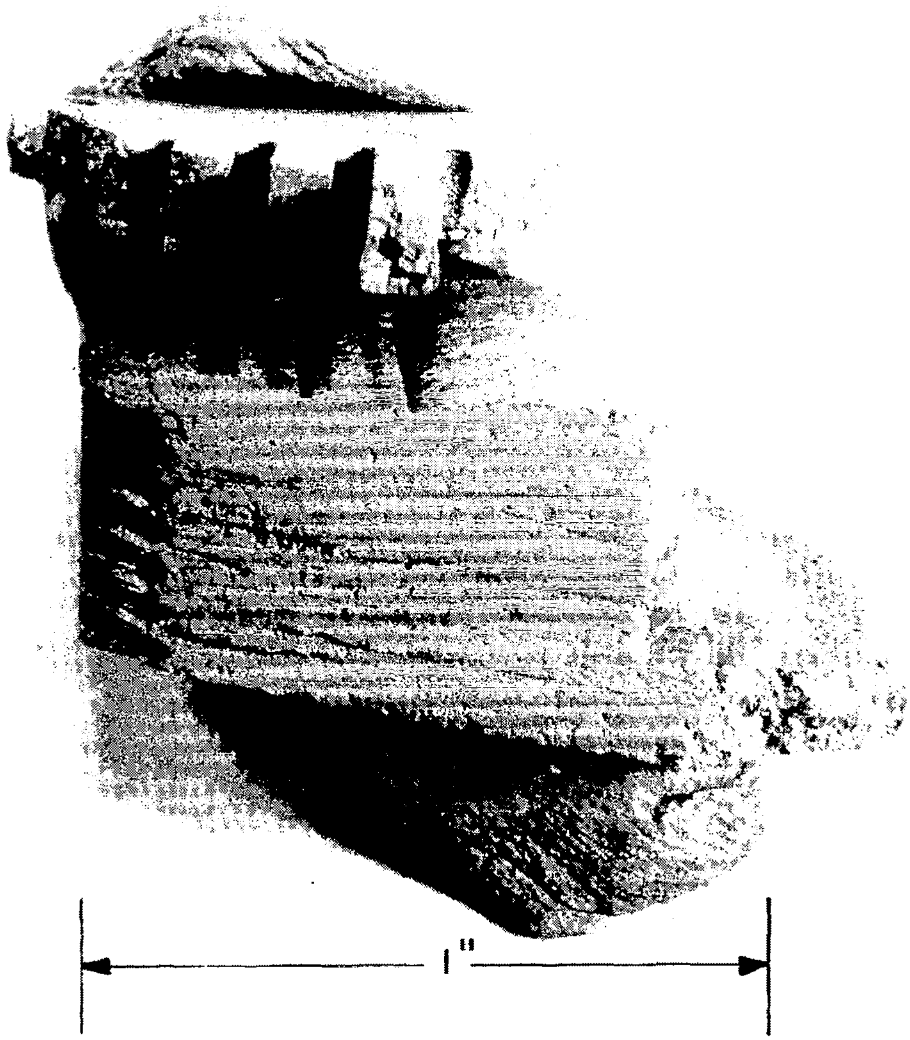


Figure 23 - Section of Graphite Grid (Upper) and Anode (Lower) of Tube 4 After Endurance Tests (Material was eroded from the anode by sputtering and deposited on the grid.)

were operated in the HVPR mode at high frequency (3200 hertz) because the phase retard mode proves higher voltage stresses at both anode and cathode, thus producing more stringent sputtering conditions than rectifier operation, which had been the operating mode for earlier tests.

Two xenon-filled thyratrons without the graphite shields were operated only approximately 20 hours before failing due to gas cleanup. Xenon-only filled tubes featuring the more extensive use of graphite in the shield structure, as shown in Figure 2, were expected to perform better with respect to gas cleanup, as discussed earlier in the "Tube Design" section. However, these latter xenon-filled thyratrons also failed in approximately 20 hours due to gas cleanup, leading to the conclusion that cathode sputtering becomes responsible for appreciable cleanup in high-frequency operation. One factor is the occurrence of many more events per unit of time (one per cycle) at high frequency, eg. 53 times as many events for 3200 hertz compared to 60 hertz. Thyratrons in the HVPR mode also experience comparatively high di/dt and dv/dt conditions as the tube is switched on with 2000 forward volts applied. From oscilloscope traces, the circuit demand for several amperes instantaneously results in a tube forward drop on the order of 50 volts for a few microseconds, consequently causing some sputtering of the cathode structure.

As noted earlier, this discovery led to the use of xenon-thallium mixture as the working fluid. No reference to the prior use of thallium as a working fluid was found in the literature. However, thallium was selected because it exhibits the necessary vapor pressure characteristic (shown in Figure 22) and has a low first ionization potential (6.11 electron volts).

## THE NON-SOOTING PHENOMENON

One disadvantage that graphite often exhibits as an electrode material is sooting, ie. a powdery residue of graphite gradually collects on tube surfaces, sometimes leading to excessive electrical leakage. In the earlier work, such an accumulation of soot was noticeable in xenon-loaded thyratrons after tests of a few hundred hours.[2] Although this could have become a problem after the thousands of hours of tests conducted under this contract, the thallium-loaded tubes showed little evidence of sooting even though considerable material was sputtered off the anode during test, as discussed previously. The sputtered anode material was deposited mainly on the grid as a dense, well-bonded residue in these latter tubes. Apparently then the powdery soot does not simply result from sputtering. It may even owe its origin to an entirely different phenomenon. In an earlier report,[2] for example, a hypothetical mechanism leading to sooting in inert-gas-filled tubes was attributed to an oxygen cycle. Such an oxygen cycle might have been inhibited by the chemically active thallium vapor in the working fluid to explain the lack of sooting observed in the xenon-thallium filled tubes.

## Appendix B

## TECHNICAL DATA
## FOR
## XENON/THALLIUM THYRATRONS

The xenon-thallium thyratron is useful in environmental temperature from 600 to 800 degrees centigrade. The use of a rugged tungsten matrix cathode enables application at frequencies of at least 3000 Hz at 2000 peak forward and inverse volts.

GENERAL

Electrical

Cathode - Externally Heated

| | |
|---|---|
| Heater Voltage AC or DC . . . . . . . . . . | 12 Volts |
| Heater Current . . . . . . . . . . . . . . . | 20 Amperes |
| Deionization Time, Approximate . . . . . . | 50 Microseconds |
| Ionization Time, Approximate . . . . . . . | 2 Microseconds |
| Anode Voltage Drop, Approximate . . . . . | 10 Volts |

Grid Drive Requirements, Typical (See Note 1)

10 Microseconds Duration: 100 volts x 1 ampere

100 Microseconds or More: 50 volts x 0.1 ampere

Mechanical

Mounting Position - Any

| | |
|---|---|
| Net Weight, Approximate . . . . . . . . . . | 1.5 Pounds |

Dimensions

| | |
|---|---|
| Diameter, Maximum . . . . . . . . . . . | 3.5 Inches |
| Overall Length, Maximum . . . . . . . | 8 Inches |

Thermal

Type of Cooling - Conduction or Radiation to a Heat Sink

Temperature Limits - Degrees Centigrade:

| Location | Miniumum | Nominal | Maximum |
|---|---|---|---|
| Tube Wall | 620 | 700 | 800 |
| Anode Terminal | 620 | 750 | 850 |
| Cathode Terminal | 620 | 720 | 800 |
| Thallium Reservoir | 620 | 630-680 | 700 |

Environment - Vacuum $10^{-4}$ Torr Maximum Pressure

MAXIMUM RATINGS

| | |
|---|---|
| Maximum Peak Anode Voltage . . . . . . . . . . . Forward or Inverse | 2000 Volts |
| Maximum Cathode Current | |
| Peak . . . . . . . . . . . . . . . . . . . . . | 50 Amperes |
| Average. . . . . . . . . . . . . . . . . . . . | 15 Amperes |
| Maximum Negative Grid Voltage | |
| Before Conduction . . . . . . . . . . . . . . . | 250 Volts |
| Maximum Commutation Limits (See Note 2) | |
| dv/dt in Volts per Microsecond . . . . . . . . . | 1000 |
| di/dt in Amperes per Microsecond. . . . . . . | 15 |

Note 1: Typical grid drive pulse duration and voltage are measured at the tube socket with thyratron grid disconnected. Duration = pulse width at 70 percent of peak voltage amplitude. The current is typical peak grid current with the tube operating or with the drive circuit shorted at the tube socket.

Note 2: Commutation is defined as the time of cessation of anode current. The di/dt is the rate of anode current decay just prior to commutation and dv/dt is the rise of inverse voltage just after commutation.

## Appendix C

## TYPICAL PERIODIC PERFORMANCE DATA

The data in Table III are shown for two operating modes for each tube, ie. 3000 or 3200 Hz operation on endurance test and 60 Hz data from periodic performance tests, as noted in the "Frequency" column.

The "Tube Drop" and "Grid Firing" data on endurance test were measured from an oscilloscope trace and therefore are not precise measurements as indicated; the 60 Hz (117 volt) data were accurately read from an oscilloscope especially calibrated for the purpose. The AIV "Tube Drop" at 3000 Hz also includes 10 to 15 volts added drop from the AIV circuitry. The 60 Hz "Grid Firing" volts are metered DC volts for 60 Hz tests.

"G-K Leakage" is the current drawn by the grid with 200 DC volts between grid (negative) and cathode, as a measure of grid-cathode electrical leakage and as a check for grid emission -- appreciable grid emission will cause erratic breakdown. The tube temperatures are thermocouple measurements at the anode and cathode ends of the tube body and on the reservoir as noted.

Referring to Table IV, the peak emission and recovery time tests were described previously in the "Test Procedure" section. The "C off/C on" column lists the minimum capacitance necessary to turn off the tube and the maximum capacitance which will allow the tube to continue conducting. The ".7RC" value uses the average of these.

## Table III - Tube Operating Data

| Tube No. | Test Station | Test Hours | Heater Volt/Amps | $I_{avg}$ Amps | Tube Drop Volts | Frequency Hz | Grid Fire Volts | G-K Leakage Ma | Temperature °C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Anode | Cathode | Reservoir |
| 2 | FL-1 | 9071 | 11.5 x 19.2 | 15 | ~12 | 3000 | ~+10 | | 695 | 720 | 680 |
| 3 | FL-2 | 9071 | 11.9 x 18.9 | 15 | ~12 | 3000 | ~+10 | | 710 | 710 | 670 |
| 2 | FL-1 | 9022 | 11.4 x 19 | 15 | 11.2 | 60 | +7 | 40 | 690 | 710 | 670 |
| 3 | FL-2 | 9022 | 12 x 19 | 15 | 10.0 | 60 | +5 | 5 | 700 | 700 | 665 |
| 4 | AIV-1 | 6360 | 11.5 x 18.9 | 0.59 | ~30 | 3000 | ~+40 | | 690 | 750 | 665 |
| 5 | AIV-2 | 5677 | 12.0 x 19.0 | 0.61 | ~50 | 3000 | ~+80 | | 720 | 730 | 670 |
| 4 | AIV-1 | 7110 | 11.4 x 18.9 | 15 | 10.2 | 60 | +10 | 10 | 715 | 720 | 670 |
| 5 | AIV-2 | 6160 | 12.0 x 19.0 | 15 | 10.5 | 60 | +20 | 20 | 740 | 750 | 680 |
| 10 | HVPR-1 | 6450 | 10.7 x 17.0 | 1.1 | ~12 | 3200 | ~+10 | high | 690 | 715 | 640 |
| 11 | HVPR-2 | 6540 | 11.4 x 16.4 | 1.1 | ~10 | 3200 | ~+10 | | 670 | 735 | 650 |
| 10 | HVPR-1 | 7400 | 11.2 x 15.5 | 15 | 10.0 | 60 | +8 | 80 | 695 | - | 630 |
| 11 | HVPR-2 | 6540 | 11.5 x 17.0 | 15 | 8.5 | 60 | +5 | 6 | 680 | 750 | 625 |

Table IV - Data for Tube No. 3 at 9022 Hours

| Emission Test | | Recovery Time Test | | | |
|---|---|---|---|---|---|
| $I_{pk}$ Amps | Drop Volts | Tube Amps | Load Ohms | C off/C on mfd/mfd | .7RC $\mu$sec |
| 100 | 26 | 15 | 7 | 6/4 | 24 |
| 70 | 12.6 | 11 | 10 | 3/2 | 17 |
| 40 | 9.2 | 5.5 | 20 | .7/.5 | 8 |
| 20 | 7.6 | 2.8 | 40 | .2/.1 | 4 |
| 10 | 7.3 | 1.4 | 80 | .1/0 | 3 |

| | | |
|---|---|---|
| Heater-Volts | 13.0 | 12.9 |
| Heater-Amps | 20.0 | 19.9 |
| Reservoir °C | 705 | 700 |
| Anode °C | 690 | 680 |

Grid Ma for full conduction = 20



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