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DEVELOPMENT AND ENDURANCE TESTING OF HIGH-TEMPERATURE CERAMIC VOLTAGE-REGULATOR TUBES

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16. Abstract

The long-term performance capability of inert gas filled voltage-regulating tubes was evaluated in a high-temperature high-vacuum environment. The tube design utilized was based on investigations conducted earlier under contracts NAS 3-2548 and NAS 3-6469. The feasibility of operating these tubes at a wall temperature of 800° C at 0.05-ampere current and at a stable running voltage of 110 volts dc was demonstrated for periods exceeding 10,000 hours. Tests at room temperature indicated a stable running voltage of 108 volts. A variation of tube running voltage of less than ±2 percent over the current range of 0.025 to 0.075 ampere was achieved.

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FOREWORD

The research described in this report 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.

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	2
TUBE DESIGN AND PROCESSING	3
TEST APPARATUS AND CIRCUITS	12
TEST PROCEDURES	18
TEST RESULTS	18
DISCUSSION OF RESULTS	22
CONCLUSIONS	36
REFERENCES	37

DEVELOPMENT AND ENDURANCE TESTING OF HIGH-TEMPERATURE CERAMIC VOLTAGE-REGULATOR TUBES

by

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General Electric Company
Microwave Tube Operation

SUMMARY

The purpose of this program was to develop the technology required to design and fabricate 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 voltage-regulator tube design. The objective of the work described herein was to demonstrate the feasibility of operating such tubes for 10, 000 hours at a wall temperature of 800° C at a stable running voltage of approximately 125 volts dc and at a current range of 0. 025 to 0. 075 ampere.

After improvements were made in the envelope and cathode of the basic tube design, tubes were fabricated for use in conducting endurance tests under high-temperature vacuum conditions. Using equipment fabricated during the earlier work, ten tubes were endurance tested for periods up to 10, 800 hours. Stable tube operation at 800° C occurred at 110 volts dc. At this voltage, a voltage variation of less than ± 2 percent over the current range of 0. 025 to 0. 075 ampere was achieved. Tests at room temperature indicated a stable running voltage of 108 volts. These tests have demonstrated the practicability of operating gas-filled voltage-regulator tubes under the aforementioned conditions.

Of two variations of the metal-ceramic tube envelope design one proved reliable during endurance tests. It was demonstrated that an electrode geometry which closely confines the discharge within the cathode, combined with uniform and effective cathode operation, provides tube operation with a minimum rate of cleanup to the extent that tube life of 10, 000 hours can be attained. In addition, the possibility exists that a small volume reservoir can provide sufficient stored gas to enable a several-fold increase in basic tube life.

Tube processing and working fluid purity were found to be closely related in achieving consistent voltage regulation performance and long tube life at high operating temperature. Factors governing tube operating stability, use of lower working fluid density, and symmetrical geometry to improve stability were also studied and discussed.

Further improvements leading to better tube performance have been identified. These include more rigorous tube processing, fabrication of cathodes by welding rather than by brazing, use of a larger cathode area and more symmetrical electrode geometry as well as a more rugged tube structure.

INTRODUCTION

The achieving of the high electrical power levels contemplated for future space missions will probably require nuclear prime power sources. The electrical control devices needed for power conditioning functions related to such power systems are expected to be applied in a high temperature, high radiation environment. The available solid state control devices which are electrically suited to such applications are completely unsuited to operation at temperatures up to 800°C in high radiation environments, although gaseous discharge devices have been found to tolerate high radiation environments at moderate temperature.[1]

The purpose of this work has been to develop the technology required to design voltage-regulator and voltage-reference tubes which will withstand a high temperature environment and provide reliable long term operation as space hardware components. The performance objectives specified for these tubes were a tube voltage of 125 volts ±2 percent at 25 to 75 milliamperes tube current and heat rejection at 800°C.

This work was initiated several years ago[2] to investigate the basic problems expected in the development of such voltage-regulator tubes. Later work[3] had the general objectives of developing basic tube design concepts and evaluating short-term tube performance. These two earlier work phases included evaluation of metal-ceramic seals at high temperature for periods of several thousand hours. Noble gas-filled voltage-regulator tubes were also fabricated and operated at temperatures as high as 800°C for up to 1500 hours to evaluate gas cleanup and operating stability characteristics of these tubes.

Based on the work of the earlier phase and the theory of gaseous discharges, the development of long term performance capability for these voltage-regulator tubes required investigations in three major technical areas:

a) vacuum integrity of the tube envelope

b) gas cleanup due to electrode sputtering

c) operating stability characteristics and processing.

Work efforts in these areas are described and discussed in this report.

The development of a high temperature voltage-regulator tube suitable for evaluation in long-term endurance tests required fabrication of experimental tubes, extensive performance evaluation tests and redesigning where improvements were indicated. Ten tubes were fabricated and operated for periods up to 10, 800 hours in a vacuum environment at 800°C.

The endurance test procedures and tube performance tests are described in this report and test results are presented and discussed. Tube modifications indicated by the results of this program and which will lead to achieving greater reliability and improved performance in future high-temperature voltage regulator tube work are also discussed in the following sections.

TUBE DESIGN AND PROCESSING

Voltage-regulator and voltage-reference tubes have been principal applications of the cold-cathode glow discharge phenomenon for many years. Generally these devices are operated at envelope temperatures below 100°C, but operating temperatures up to 400°C have been investigated.[4] The earlier work phases of this program affirmed that high temperatures produce only minor effects for glow discharges up to a maximum of 800°C. These effects are covered in the "Discussion of Results" section.

Figure 1 represents a portion of the generalized volt-ampere curve for a cold cathode discharge. The operating range for a voltage regulator device is the "normal glow" region of the curve, where tube voltage V_n is nearly constant for a fairly large range of current. For "normal glow" operation, the current density at the cathode tends to remain constant. The "abnormal glow" region represents operation where the tube current for a given cathode results in a higher current density than the cathode will inherently provide for the cathode-gas combination (molybdenum and neon) being utilized. This results in higher tube voltage drop as depicted in Figure 1. Below the "subnormal" transition region the charge carriers in the gas become too scattered to maintain a discharge.

To initiate the glow discharge, a breakdown voltage, identified as V_s (the "starting" voltage) in Figure 1, is required. The starting voltage is inherently the Paschen breakdown voltage of the most favorable gap in the tube. Generally, a starting gap is designed for the tube so the starting voltage will be 1.5 to 2 times greater than the running voltage, V_n. Figures 2 and 3 show the starting gap in each of the two cross-sections of the voltage-regulator tube designs which were endurance tested during this program.

VACUUM INTEGRITY OF THE TUBE ENVELOPE

Endurance tests of the voltage-regulator tubes were initiated using the tube design shown in Figure 2. During the tests, several vacuum integrity failures (leaks) were experienced at braze joints "A" and "B". The tube was redesigned to enclose joints "A" and "B" in a nickel cup as shown in Figure 3. A tube of the Figure 3 design and its component parts are illustrated in Figure 4. Also included in the photo is the gas reservoir shown in the Figure 2 design.

In all respects, other than those described above, the tube envelope configurations shown in Figures 2 and 3 are identical. Nickel is used in the fabrication of all other metal envelope parts. The nickel is joined to the alumina by metal-ceramic seals using the nickel-rich active alloy

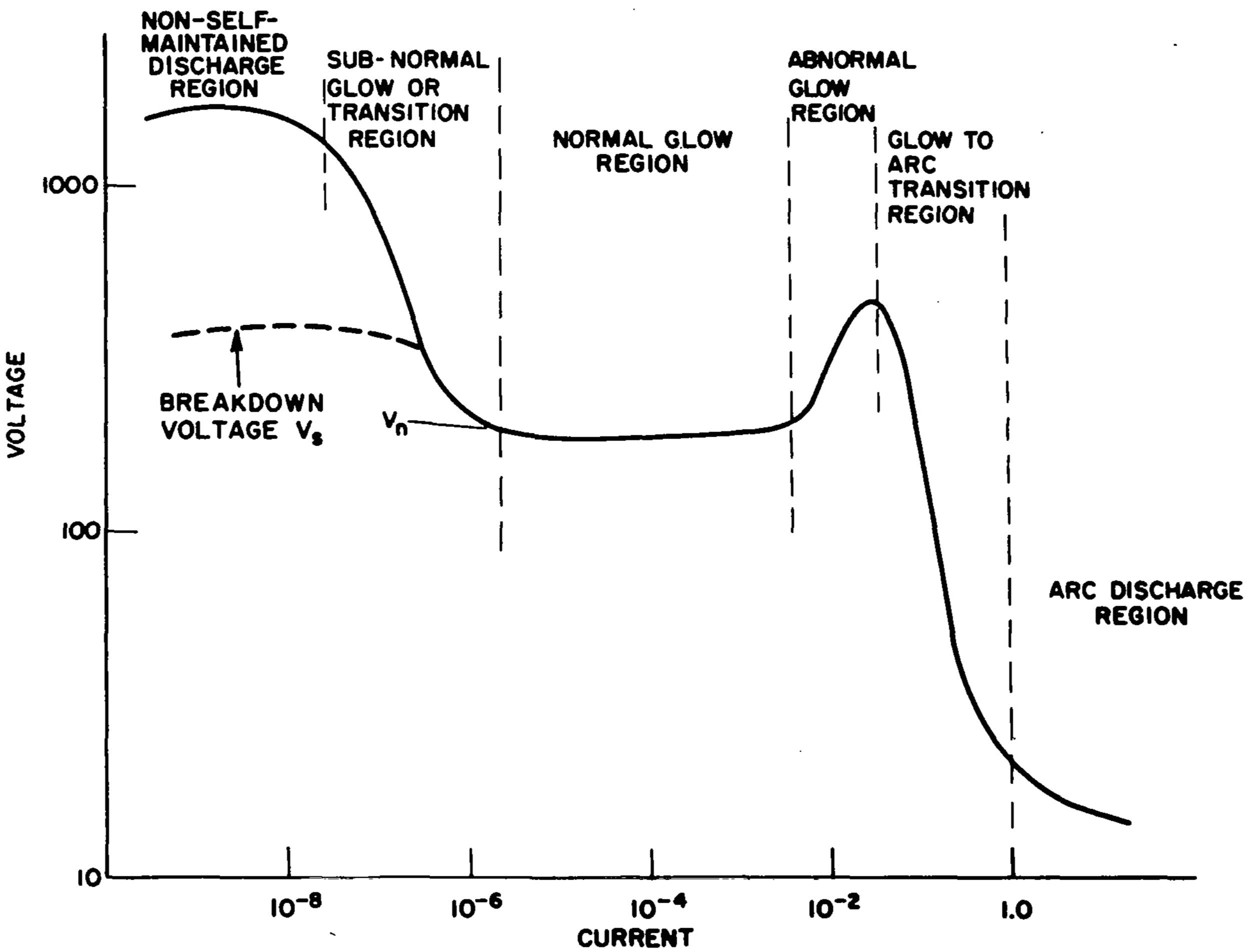

Figure 1 - Generalized Volt-Ampere Characteristics for a Cold Cathode Discharge

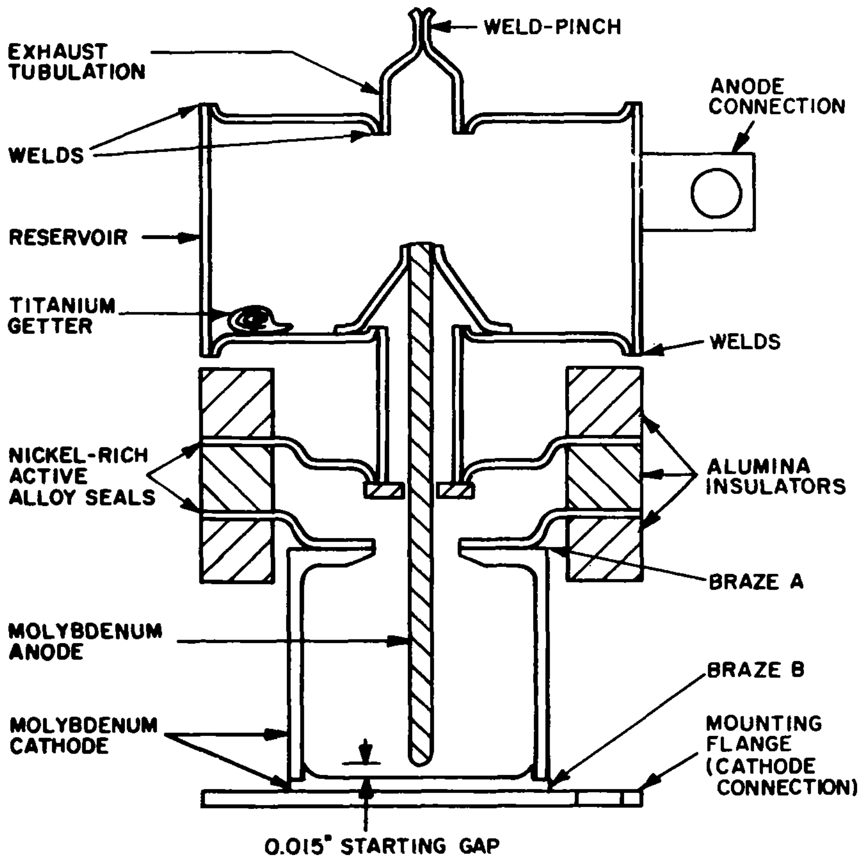

Figure 2 - Design II Voltage-Regulator Tube
(with Additional Gas Reservoir)

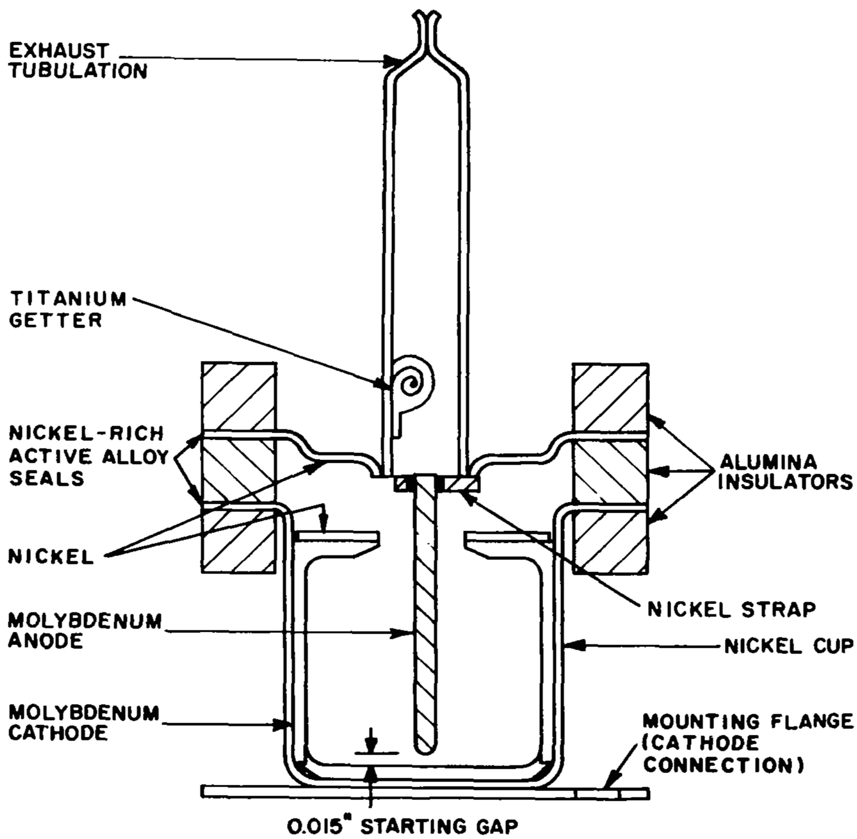

Figure 3 - Design III Voltage-Regulator Tube

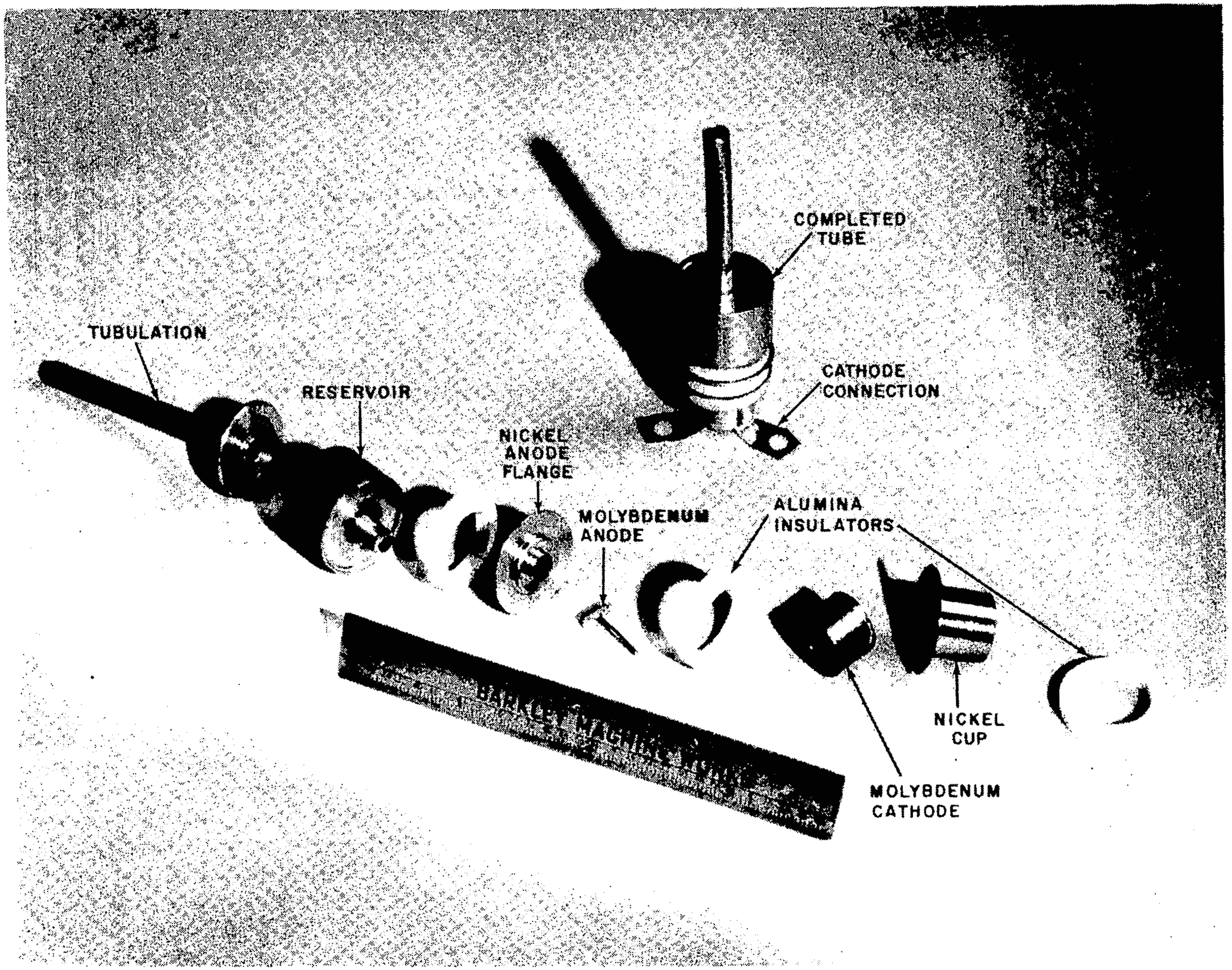

Figure 4 - Design III Voltage-Regulator Tube and Component Parts

process (titanium-nickel). This process has been found to be very reliable in the earlier work. Another reliable joining process is the fabrication of nickel-to-nickel welds by TIG welding. In related high-temperature work[5] an effective resistance-welding process was also used to accomplish the weld-pinch tubulation seal-off.

The configuration of the support for the molybdenum anode shown in Figure 2 was used for tubes with a reservoir. This structure can conveniently be welded in place after the main body of the tube has been brazed, but before the top of the reservoir is welded in place. The configuration shown in Figure 3 was used for tubes without a reservoir and must be brazed in place when the main body is brazed.

GAS CLEANUP DUE TO ELECTRODE SPUTTERING

To maintain a glow discharge, a small electron current must be generated at the cathode by positive ion bombardment. The ion bombardment also continuously sputters atoms from the cathode at a low rate, and the material sputtered from the cathode is usually responsible for the gas cleanup phenomenon experienced by inert gas-filled glow discharge devices. This is because all sputtered deposits efficiently trap gas molecules in the atomic lattice. To minimize the gas cleanup caused by this sputtering process, an electrode design which confines the sputtered material within the cathode structure has been employed in some gas discharge devices. The molybdenum cathode configuration used for these voltage-regulator tubes is this type of a confining structure. Only a minimal opening is provided in the cathode chamber, and thus most sputtered material deposits on the cathode surface are re-sputtered. Since the process of re-sputtering releases most of the trapped gas molecules the rate of gas cleanup is lower in the confined structure than in a more open cathode configuration.

Another factor which tends to minimize sputtered cleanup is to obtain uniform cathode operation, by using the entire cathode area as a target for ion bombardment. Because of traces of contaminants or atomic crystal orientation of the cathode surface, cathode effectiveness (electrons emitted per bombarding ion) will differ slightly for various areas of any cathode surface. The glow discharge will tend to remain in the more effective cathode areas while the less effective areas will tend to become inactive as a cathode. Thus, the less effective areas are inclined to collect sputtered material, but the material does not re-sputter so the confinement scheme is negated. To avoid this tendency, the glow discharge can be forced to use virtually the whole cathode area in normal operation by providing the minimum cathode area suitable for the tube current range, ie the cathode should be operated as close to the "abnormal glow" region as is feasible (refer to Figure 1). In order to accomplish this, the molybdenum cathode area of tubes endurance tested, was reduced to approximately two thirds of the area used for the tubes investigated in the earlier work. Based on experiments conducted prior to the long-term tests, this area reduction resulted in no loss in voltage regulation capability, although the running voltage is one to two volts higher for the smaller cathodes.

The voltage-regulator tube cathode must also be designed to confine the glow discharge cathode action to the molybdenum cathode cavity so the sputtering confinement principle will prevail. This is usually accomplished by making the other parts of the cathode structure of a material which has a characteristic running voltage considerably higher than the cathode. Since nickel has a running voltage approximately 30 volts higher than molybdenum, a nickel sheet was brazed over the molybdenum cathode structure opposite the anode of this design.

Another approach to alleviate gas cleanup is to simply provide more gas. Conventional voltage regulator tubes usually have a volume 5 to 10 times larger than the cathode, while the tubes without reservoirs used in this program have a volume approximately 1.5 times larger than the cathode volume. This, compared to conventional tubes, greatly reduced the amount of available stored gas.

To evaluate the utility of the storage factor, tubes without reservoirs (shown in Figure 3) as well as tubes with a reservoir volume equal to, and 3 times larger than the tube volume (see Figure 2) were endurance tested. The internal dimensions of the reservoirs were 0.70 inch in diameter by 0.12- and 0.36-inch long, respectively.

OPERATING STABILITY CHARACTERISTICS AND PROCESSING

Three degrees of tube voltage operating stability are desirable for these voltage-regulator tubes:

1. Minimum deviation from running voltage (regulation) over the specified current range.

2. Minimum variation of characteristics with temperature for the temperature range of interest (only minor variations occur over the 400°C to 800°C range -- refer to the "Discussion of Results" section).

3. Minimum tendency to develop periodic voltage instability (oscillation). For long-term reliability it is also desirable for all three degrees of stability to show minimum variations with time.

Both regulation and oscillation characteristics are influenced by gas density, gas purity, cathode surface conditions and tube geometry. Tube geometry was not investigated for these tubes except as described in the previous sub-section. The cathode and anode configuration was based on an earlier comprehensive investigation[6] and further refinement in geometry was generally beyond the scope of the work reported here. Possible geometry improvements are covered in the "Discussion of Results" section.

The effects of gas density had been investigated in earlier work phases[2, 3] and brief tests made during this work confirmed the earlier findings that tube gas loading pressure above 40 torr (at room temperature) resulted in higher tube running voltage and a greater tendency of tubes to oscillate. Therefore, endurance test tubes were loaded to 40 torr.

Gas purity and cathode surface conditions are closely inter-related, and it is often difficult to analytically separate the effects of these two factors. The glow discharge literature cites examples were impurities of less than one part per million in the gas have measurable effects[7] on the cathode surface. Experience indicates similar sensitivity of the cathode surface to impurities. To obtain the "ultra-clean" conditions required by these high-temperature tubes, the clean techniques, normal to the tube industry, were applied to all of the tubes and tube parts fabricated for this program. Ultra-clean neon gas was used, and processing utilized a very clean all-metal ion-pumped vacuum system of 10^{-8} torr capability. Tube bakeout temperature was as high as 1000°C.

Another process which was found to improve performance and stability was high-voltage sputtering of the cathode surface, in conjunction with a titanium getter. By maintaining a careful balance of neon pressure (less than 1 torr), temperature and current, the neon discharge could be operated at 450 to 600 volts. In a few minutes, this high-voltage sputtering removes all absorbed contaminants and leaves an atomically clean molybdenum surface on the cathode. During this process, some of the contaminants are absorbed by the getter (placed in the reservoir as shown in Figure 2) and other tube parts. However, when the tube is re-evacuated and baked out again to re-activate the getter and to again outgas the other tube parts, some of the gases are re-absorbed by the very clean molybdenum cathode. Therefore, the entire process is repeated 3 or 4 times to obtain stable tube operation at 40 torr neon pressure.

After the tube is sealed off, the titanium getter preferentially absorbs active gases such as oxygen, nitrogen, hydrogen, CO and CO_2 but has little affinity for neon or other noble gases, and thus the neon gas purity is improved. All endurance tested tubes contained titanium getters and were processed using this sputtering technique.

TEST APPARATUS AND CIRCUITS

The apparatus used for tube processing, short-term tests and long-term endurance tests are described in this section. The overlap in apparatus functions is such that categorizing apparatus does not appear appropriate. A general order of apparatus is presented in this section, proceeding from processing, to short term tests and finally to endurance tests. An overall view of the apparatus used for this program is shown in Figure 5.

The processing station includes a high temperature vacuum oven (contained by the vacuum belljar) capable of attaining temperatures up to 1000°C, and an all-metal tube vacuum system which is ion-pumped and bakeable to 400°C. The processing station also includes the gas-loading system, consisting of a tank of ultra-pure neon, appropriate piping and valves, and an accurate pressure measuring system derived from a Wallace-Tiernan 0-100 mm gage. The gage measures pressure

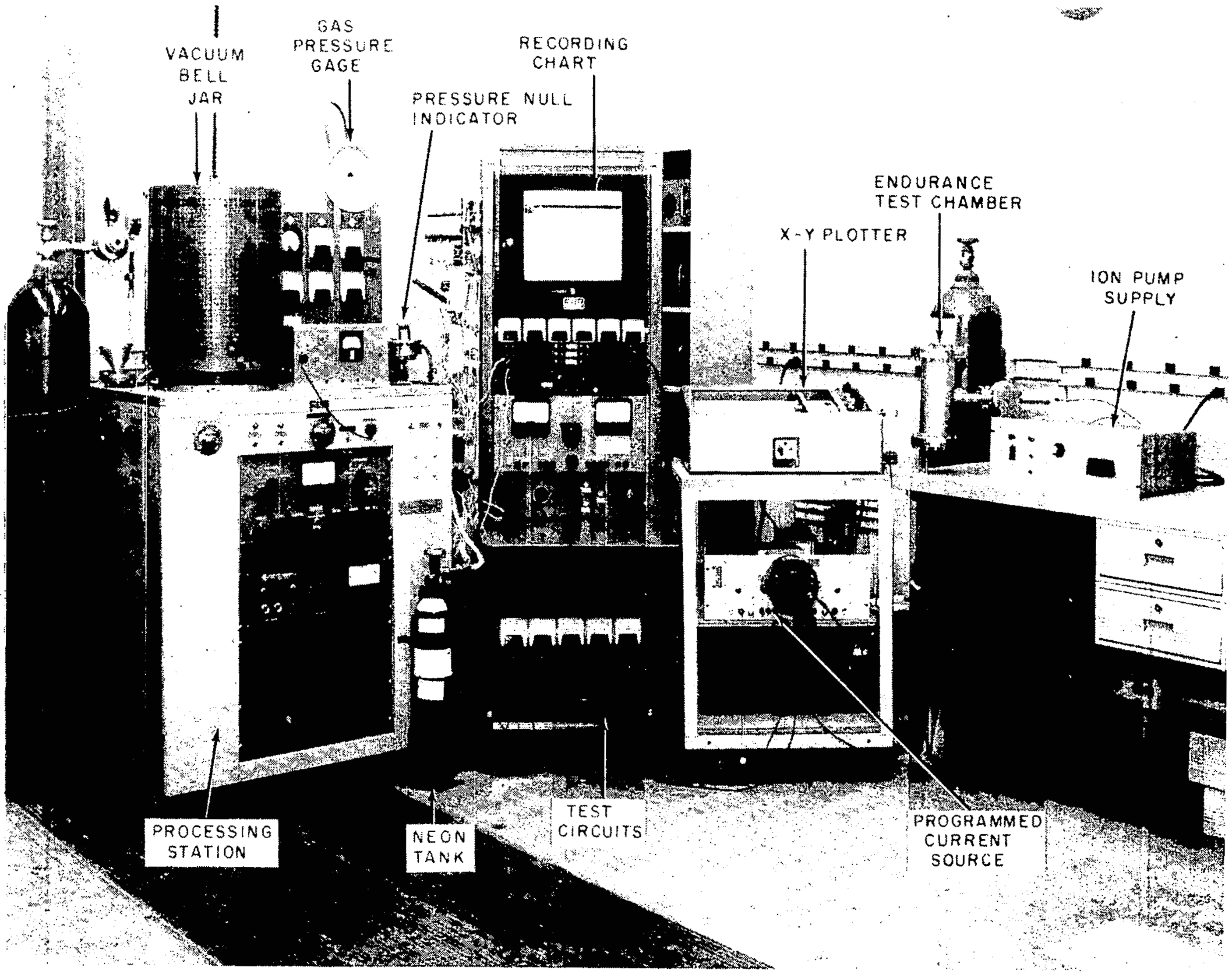

Figure 5 - Overall View of Exhaust Processing Station for Regulator Tubes

in an auxiliary vacuum system separated from the gas-loading system by a thin stainless steel diaphragm. The diaphragm forms one plate of a capacitor which is in a capacitance bridge and the null position of the bridge is used to accurately indicate equal pressure in the two systems. The overall accuracy of measurement is within ± 0.5 torr, and the separation of the systems permits the gas loading portion of the system to be a clean, bakeable (200°C) system minimizing contaminants introduced in the gas.

All tubes were processed on this system and short-term tests at varying pressures were conducted on this system.

Both long and short-term tests on sealed-off tubes were conducted in endurance test positions and monitored by a 20-position strip chart recorder. This recorder was instrumented to record tube voltage, tube current and temperature for each of the six test positions. The recorder response is 10 millivolts full scale and temperature-monitoring thermocouple output was read directly. The test circuit used for the six-test positions is shown in Figure 6, with current and voltage instrumentation shown for one tube. All six voltage circuits were connected to the 85 volt balancing voltage and each had a separate 5000x voltage divider to convert the 10 millivolts recorder range to a 50 volt range (85 to 135 volts). The current for each tube was monitored from a 0.1-ohm resistor, as depicted in Figure 6, to give a 0-100 mA current range. The accuracies were within 0.5 volt and 0.2 mA, respectively. Temperature accuracy was within ±25°C at the higher temperatures.

One of the three all-metal endurance test vacuum chambers and its ion pump supply is shown in Figure 5. The test chamber is also shown in Figure 7 and the components from one of the two test positions contained in each test chamber are shown in Figure 8. The electrically heated oven, consisting of a tungsten coil, alumina insulation and tantalum radiation shields, is capable of reaching temperatures well above 1000°C.

Usually, the regulation characteristics of these tubes were measured with the x-y plotter and programmed current source shown in Figure 5. The recording of volt-ampere curves and starting (breakdown) voltage data was mechanized primarily to minimize the short-term transient effects which had been investigated in earlier work,[2]

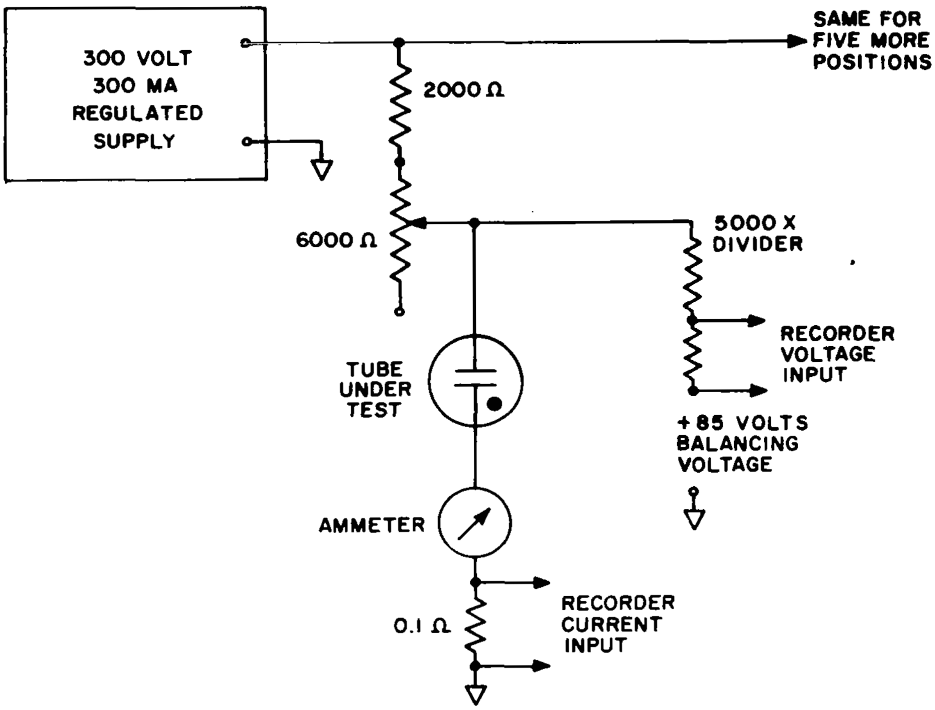

Figure 6 - Voltage-Regulator Tube Endurance Test Circuit

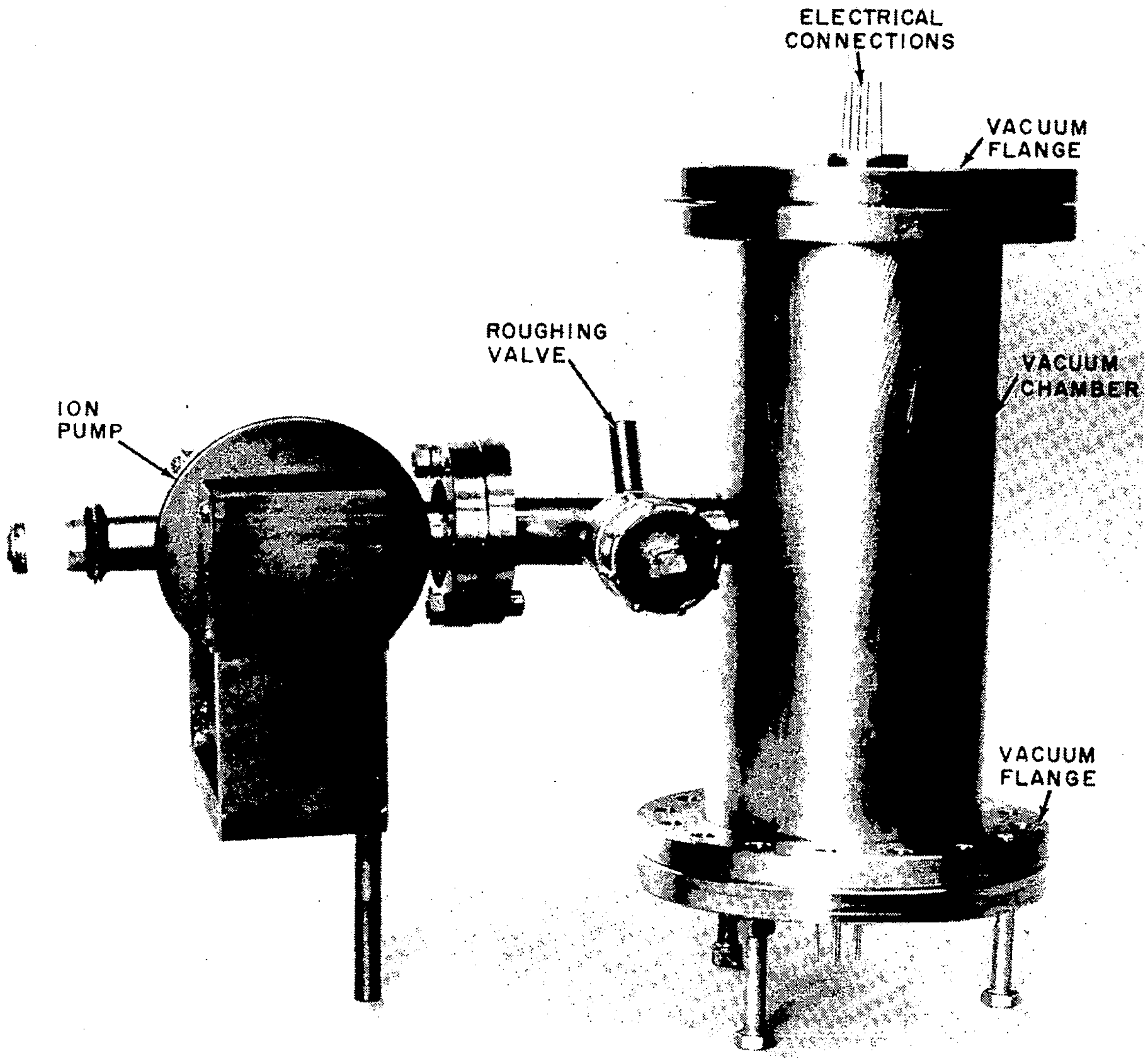

Figure 7 - High-Temperature Regulator Tube Test Station

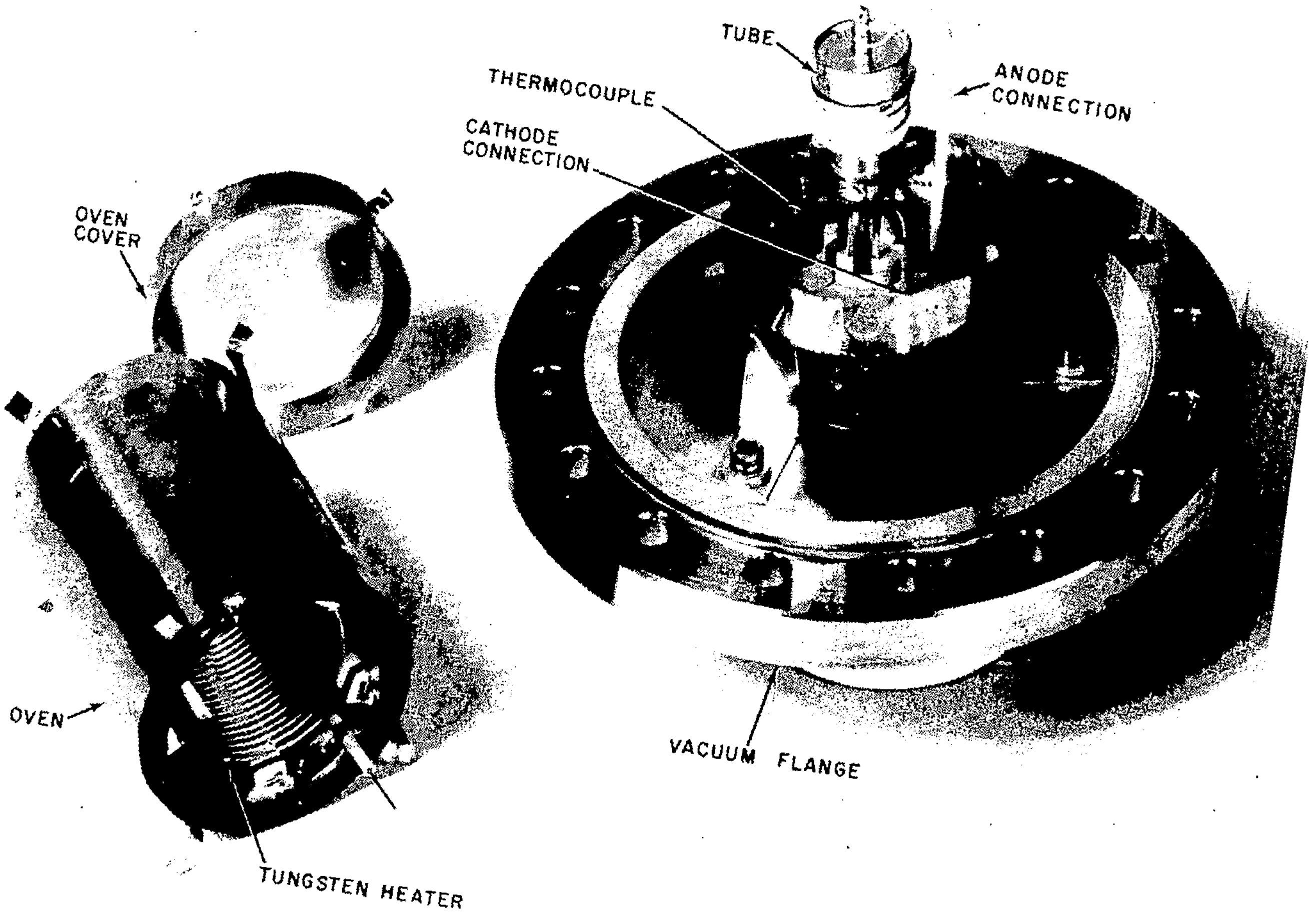

Figure 8 - Voltage-Regulator Tube Mounted in Test Station

and to eliminate human error thus allowing a more accurate comparison of various tube characteristics. Figure 9 is a block diagram of the circuit used for these tests. As in the Figure 6 circuit, a balancing voltage is used here to permit amplification of voltage variations in order to maintain a sensitivity to variations of 0.2 volt. Current accuracy is within 0.2 mA and current range is 5 to 75 mA for most data taken.

TEST PROCEDURES

Most of the pertinent data obtained were recorded automatically on the strip-chart recorder or x-y plotter described in the previous section. Because of the constant chart speed (1/2 inch per hour), the strip chart was used to record test hours. It also proved valuable as a monitor for tube failures or unusual events (such as power interruptions) that occurred at night or weekends.

Before endurance tests were started, tubes were operated in air at room temperature for 50 to 100 hours to allow running voltage to stabilize and initial tube characteristics were recorded on the x-y plotter. An oscilloscope was utilized to check for oscillation of the tube voltage. Tube starting voltage was also recorded. The tubes were then operated at 50 mA tube current at 800°C or 10^{-6} torr or better vacuum, and tube characteristics were rechecked every 500 hours until tests were terminated or the tubes failed. The test interval was increased to 1000 hours for endurance tests exceeding 5000 hours.

TEST RESULTS

The results of endurance tests and of earlier long-term tests which preceded the endurance tests are combined in this section since both sets of tubes tested contributed significant information about long-term operation of glow discharge devices at high temperature. The results of these tests are summarized in Table I for the 14 tubes tested. Tube Nos. 1 through 4 were subjected to long-term tests preliminary to the endurance tests conducted for tube Nos. 5 through 14. Tube Nos. 1 through 4 were fabricated in the configuration shown in Figure 10,

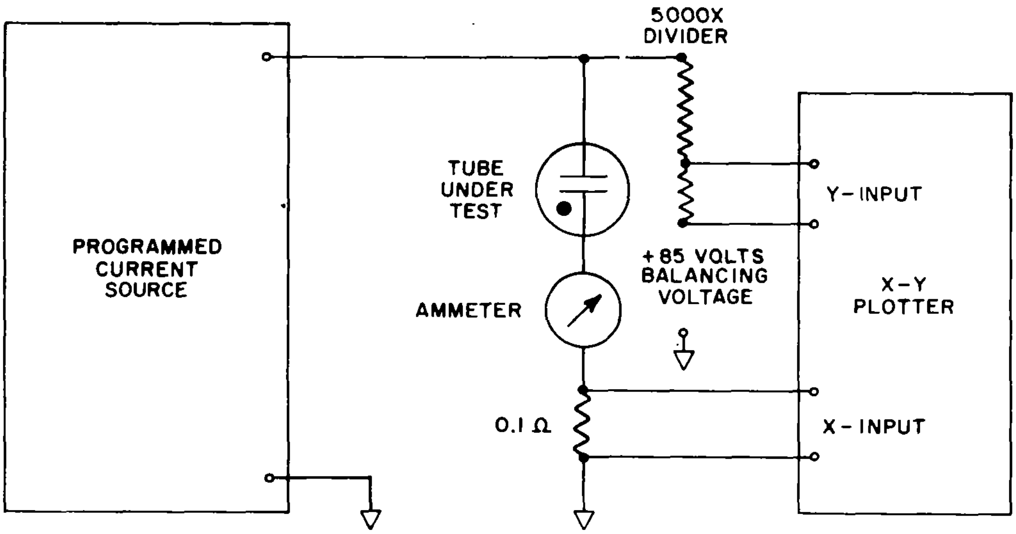

Figure 9 - Volt-Ampere Characteristic Test Circuit

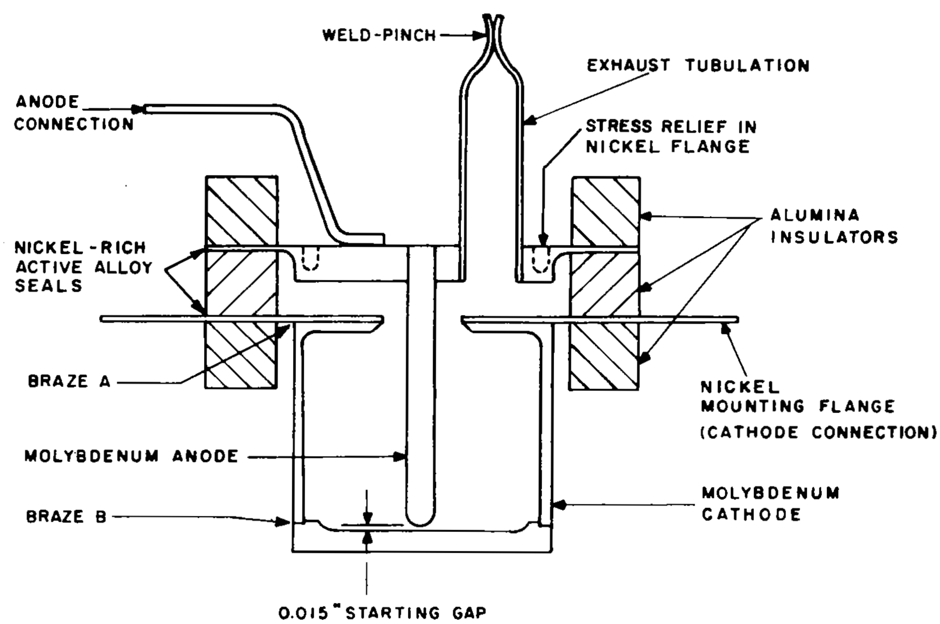

Figure 10 - Design I Voltage-Regulator Tube

Table I - Summary of Endurance and Long-Term Tests

Tube No.	Hours on Test 800°C	Room	Reason for Failure	Notes
1	960	600	Gas cleanup	
2	880	500	Gas cleanup	(1)
3	2600	100	Leak at Braze B	
4	5510	100	Gas cleanup	(1)
5	1680	200	*	(3) 3R
6	2440	50	Leak at Braze A	3R
7	1700	50	Leak at Braze A	3R
8	9080	50	Leak at Braze B	1R
9	8690	50	Leak at Braze B	1R
10	470	50	Leak at Braze B	
11	10,800	550	*	
12	6400	500	*	(2)
13	5600	550	*	(2)
14	6320	80	Gas cleanup	(2)(4) 1R

* Denotes tubes which are still operable

Notes

(1) NASA-LeRC performed a helium mass spectrometer leak check while the tube was at 800°C, after tests were completed.

(2) Same as (1) except before tubes were processed and tested.

(3) Tube 5 had been repaired at braze B with gold alloy. Removed from test to start tests on tube 9.

(4) Tube failed after operating 30 hours in air at low temperature, after 800°C tests. Tube voltage was approximately 130 volts (very high) the last 30 hours.

3R and 1R denote tubes with reservoirs having volumes equal to three and one tube volumes, respectively. All other tubes are without reservoirs.

while tube Nos. 5 through 11 were fabricated in the Figure 2 design. Tube Nos. 12, 13 and 14 were of Figure 3 configuration. These design changes and the reasons for the changes are covered in the "Discussion of Results" section.

Tube Nos. 1 through 4 were operated up to 600 hours at low temperature in room atmosphere before being tested in vacuum at 800°C. The former procedure verifies vacuum integrity of the tube envelope. Similarly, tube No. 5 was operated for 150 hours while tube Nos. 11, 12 and 13 were operated 500 hours at low temperature in air, to verify vacuum integrity after endurance tests were completed. All four of these tubes are still operable. Most tubes were also operated approximately 50 hours at low temperature before the 800°C tests.

The variations in tube running voltage at 50 milliamperes tube current, condensed from the strip chart recorder data, are shown in Figure 11 for endurance test tubes and in Figure 12 for tube Nos. 1, 2 and 4.

Typical regulation curves obtained from four endurance test tubes are shown in Figure 13. These data were obtained from the x-y plotter system described earlier.

The running voltage versus pressure for tube Nos. 5 and 6 is shown in Figure 14. This response was typical of tubes checked on the processing system where minimum tube operating temperature is 250 to 350°C. The pressure data shown in Figure 15 is standardized to the equivalent 27°C pressure by the ideal gas law relation, since tubes are loaded at approximately 27°C. The variation of running voltage with temperature for tube Nos. 11 and 13 is shown in Figure 15. The variation of running voltage over the 300°C to 800°C range was generally 1 to 2 volts for tubes operating at less than 115 volts, or as much as 5 volts for higher running voltages. The relation of this phenomenon to variable cathode conditions is discussed in the next section.

DISCUSSION OF RESULTS

The endurance tests and other long-term tests have served to fulfill the basic objectives of this program. It has been demonstrated that ceramic glow-discharge devices can be operated for long periods at

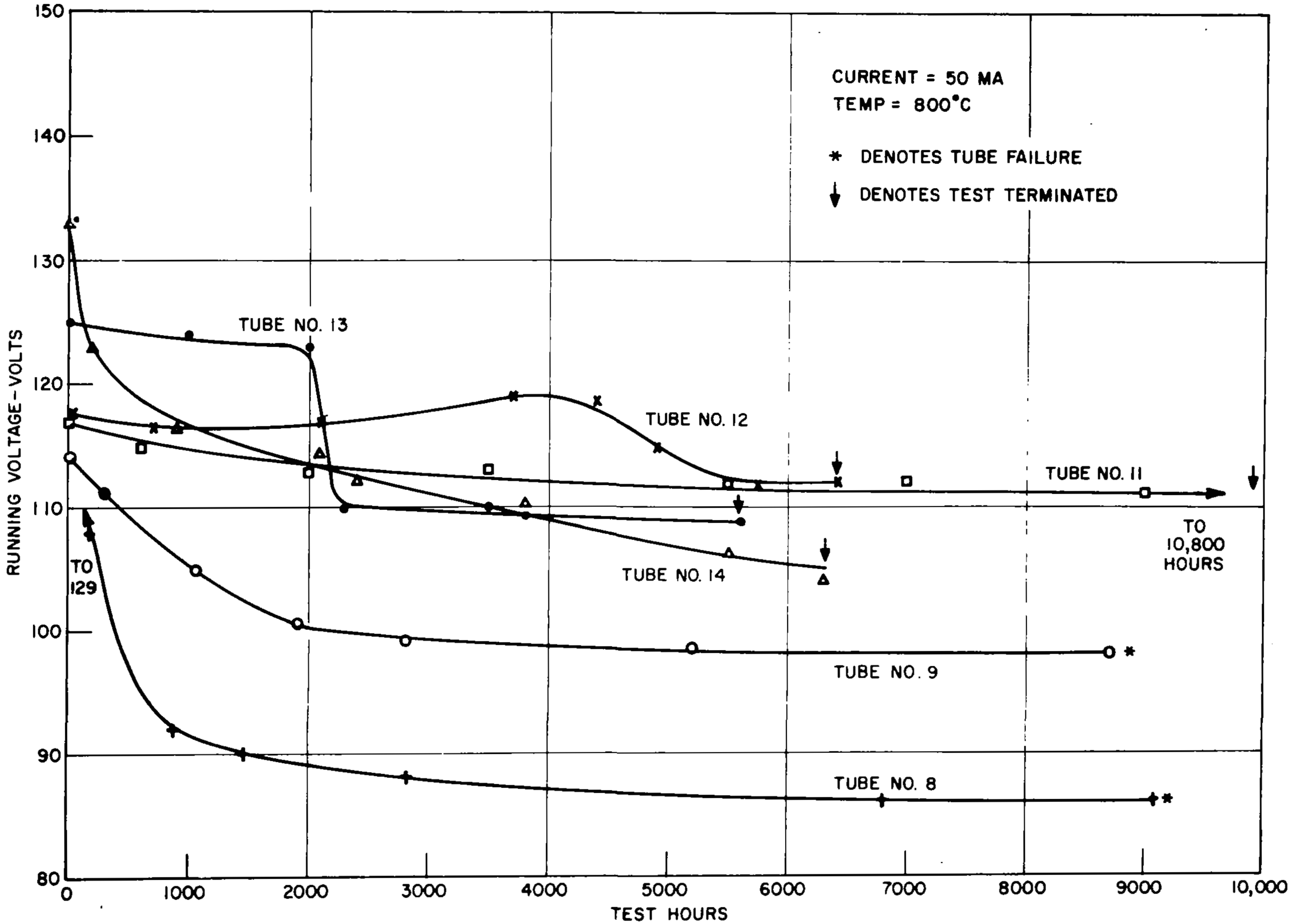

Figure 11 - Variations of Running Voltage for Tubes on Endurance Test

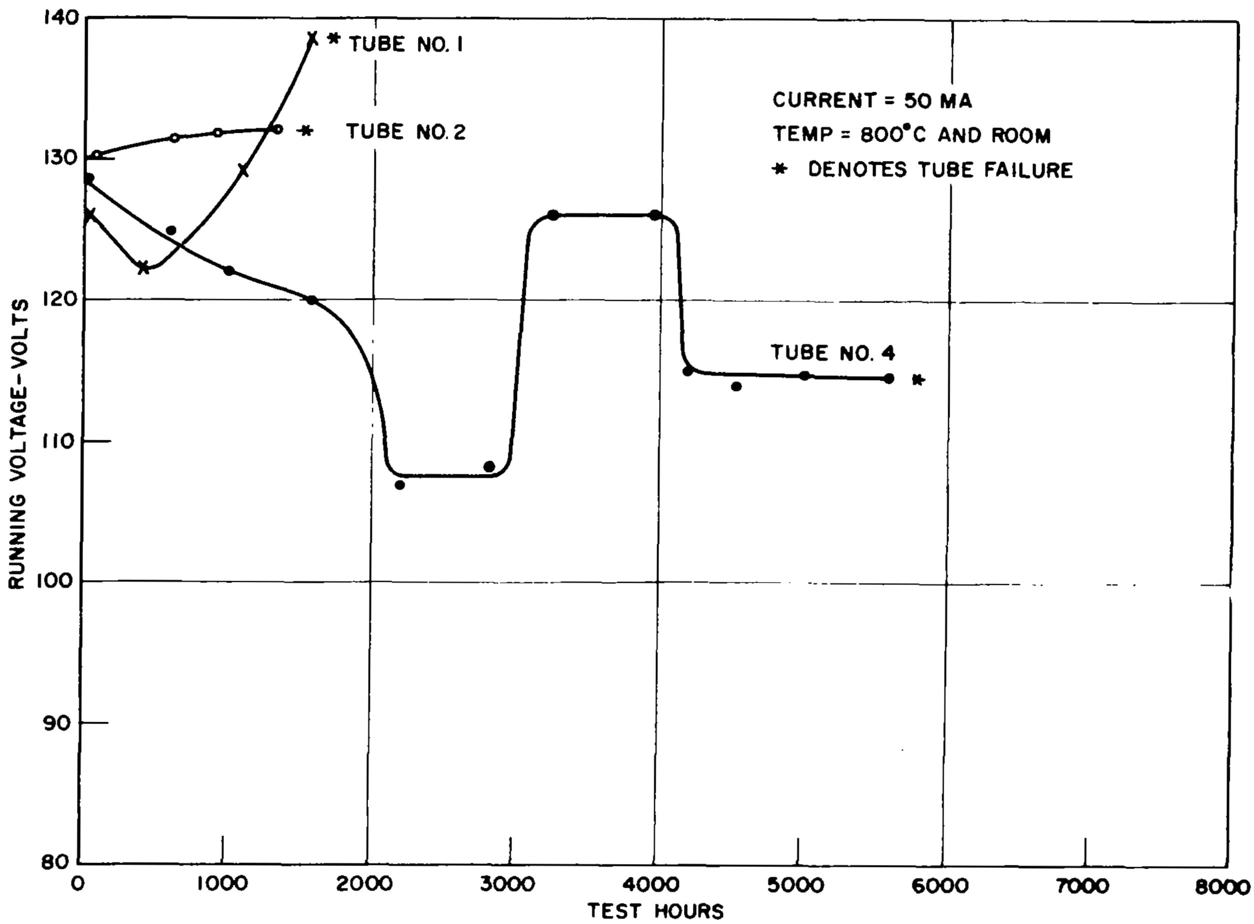

Figure 12 - Variations of Running Voltage for Tubes on Long Term Test

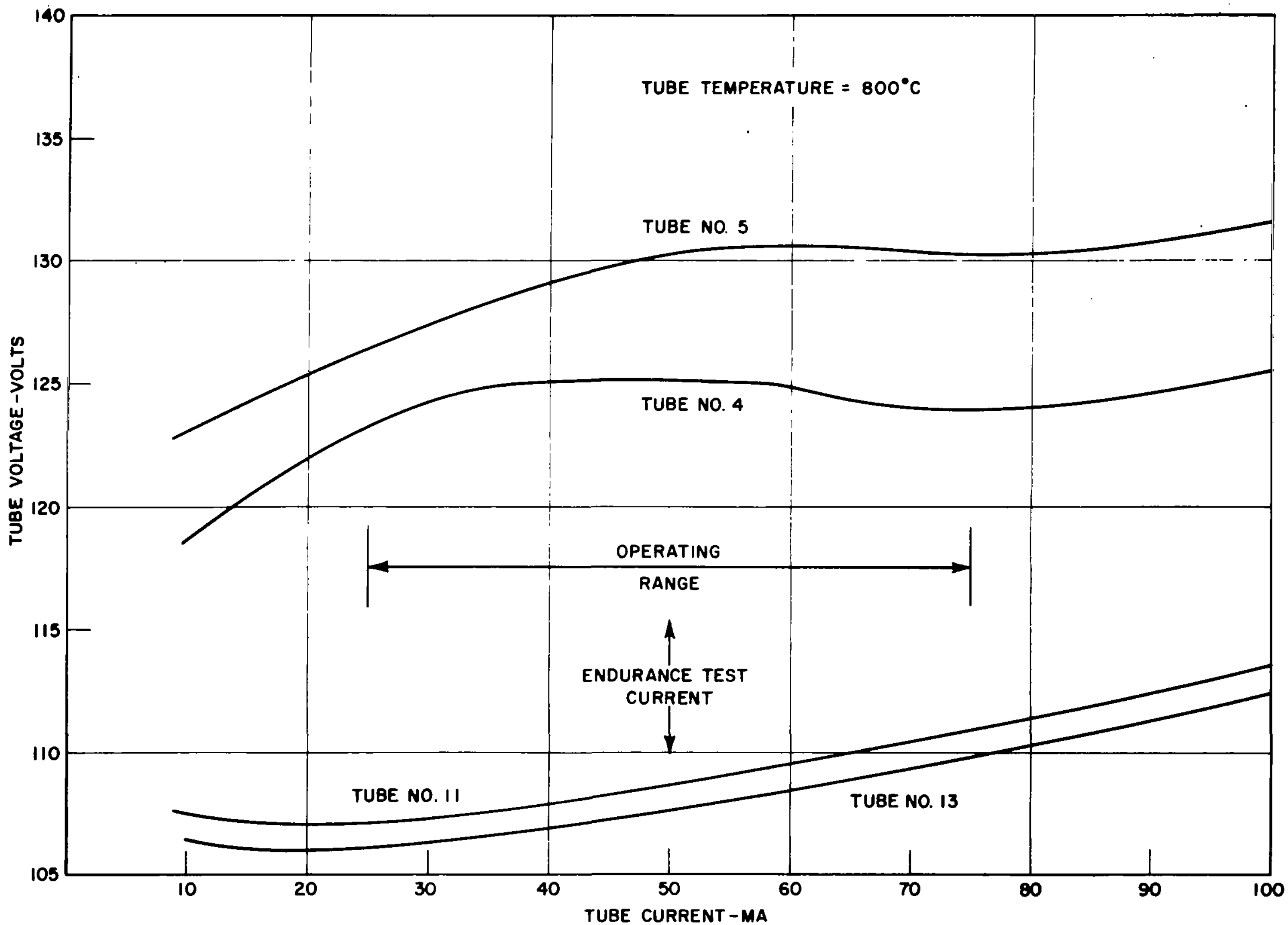

Figure 13 - Typical Volt-Ampere Characteristics of a Voltage-Regulator Tube at 800°C

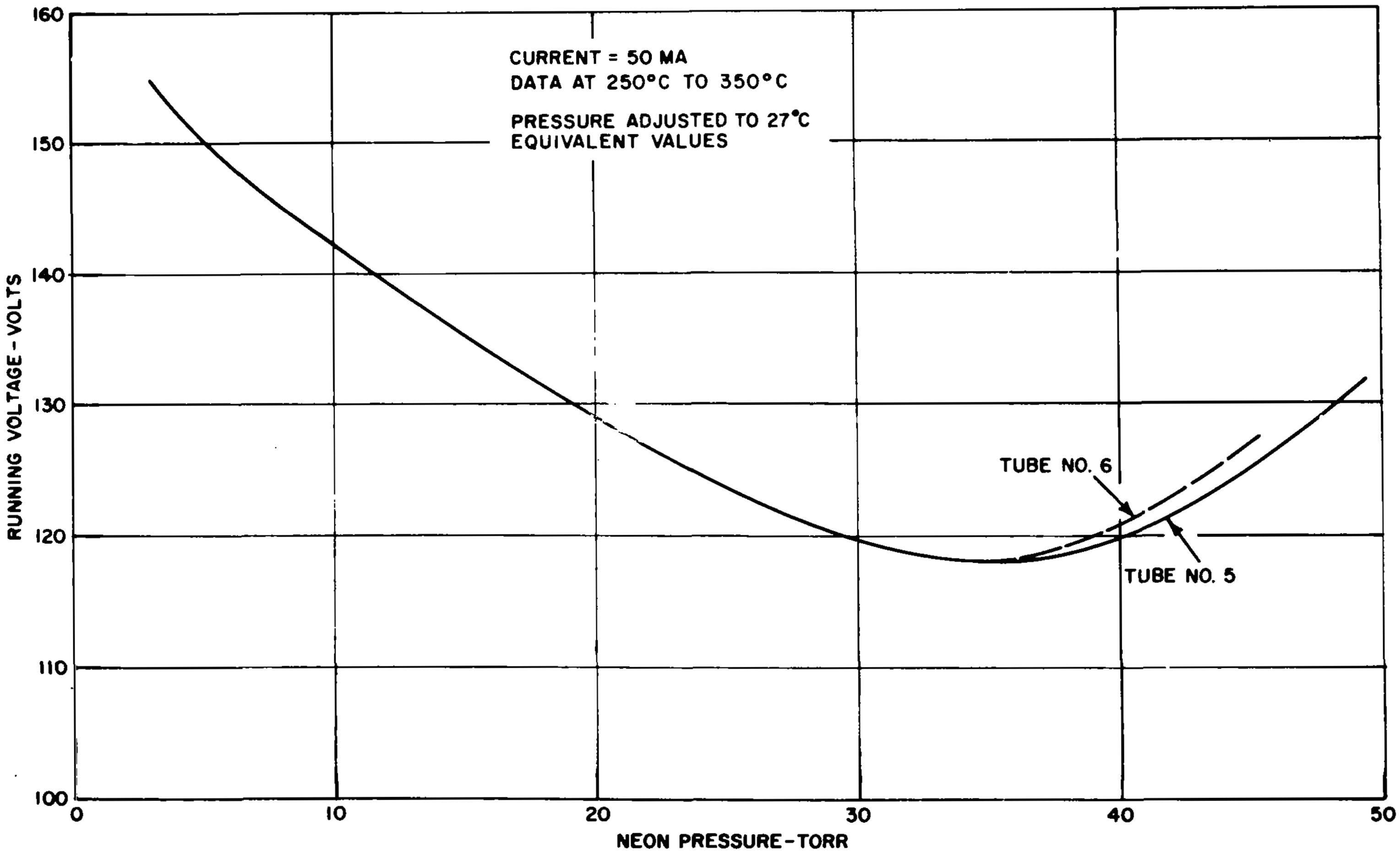

Figure 14 - Variations of the Tube Running Voltage with Gas-Loading Pressure

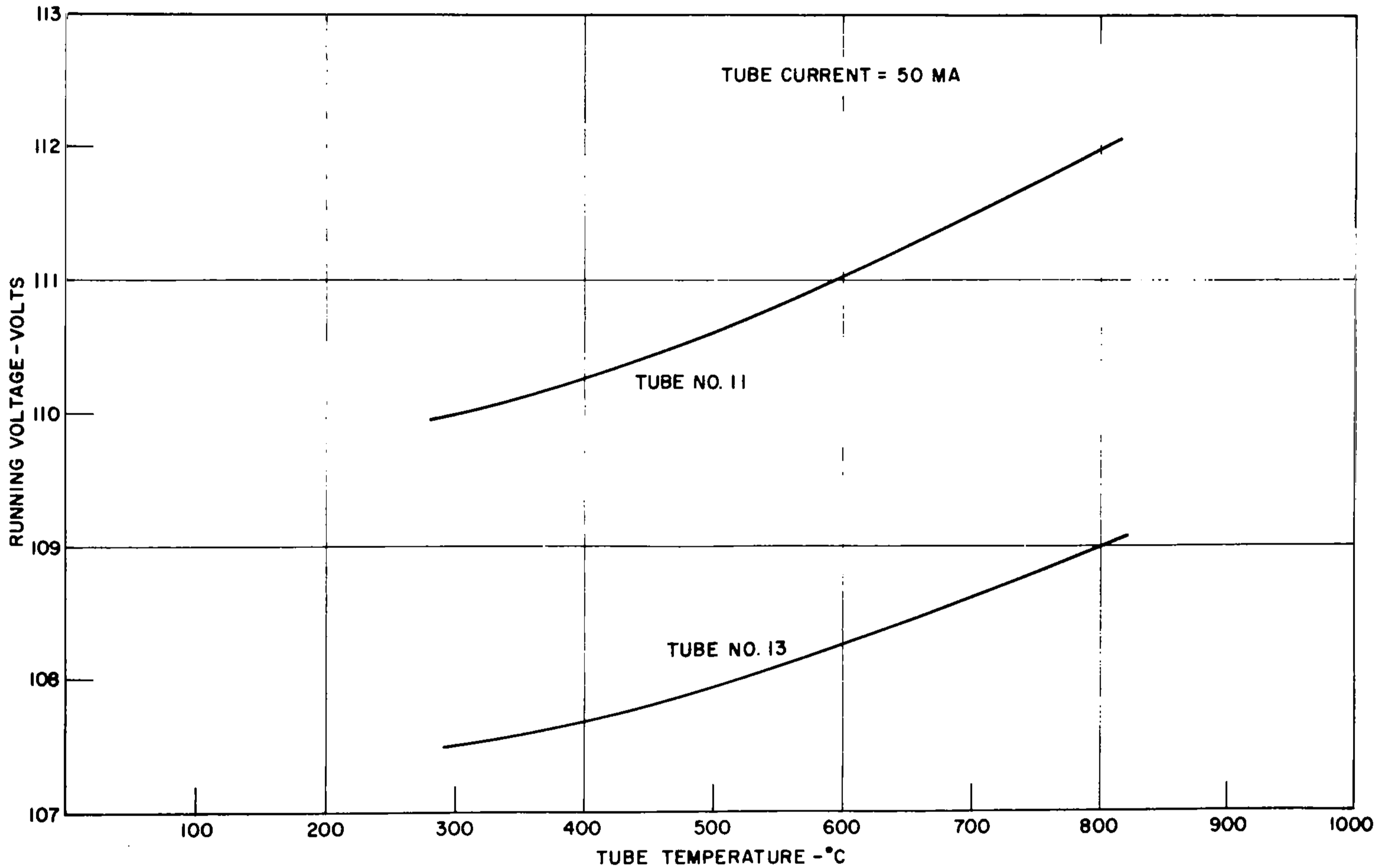

Figure 15 - Variations of Tube Running Voltage with Temperature

temperatures up to 800^{o}C. This program has also indicated some areas of potential improvement and areas where further investigation is needed and these items are discussed in the latter part of this section.

VACUUM INTEGRITY OF THE TUBE ENVELOPE

Test results in relation to the envelope integrity are directly related to the three joining techniques used, ie, active-alloy metal-ceramic sealing, TIG welding and metal-to-metal brazing. In the tests summarized in Table I, the first two have been highly successful while the molybdenum-nickel braze at "A" and the molybdenum-molybdenum braze at "B" in Figures 2 and 10 have proved unreliable. The "A" braze utilized copper-platinum alloy as the braze material while the "B" braze utilized copper-platinum for some tubes and a proprietary alloy derived from "Hastalloy X"* for other tubes, with comparable results. This problem has been resolved by eliminating the need for these braze joints by the use of the nickel cup shown in Figure 3. None of the three endurance test tubes of Figure 3 design suffered leaks. Several tubes were also fabricated or repaired using nickel-gold alloy or copper-platinum for nickel-to-nickel joints. These joints also had a tendency to develop leaks after a few hundred hours of high temperature operation. Thus, it would appear that TIG welds are far superior to brazes as vacuum joints for high temperature operation.

The metal-ceramic sealing processes are a metallurgically complex joining system which usually suffer from built-in stresses and thus are generally very critical in terms of seal design and processing. The parameters affecting active-alloy seals operated at high temperature had been studied in earlier high temperature work[8] and this experience was utilized to advantage in this program.

The first tubes fabricated for long-term tests (tube Nos. 1, 2, 3 and 4) were of the configuration shown in Figure 10. After some difficulty was experienced in fabricating the nickel-rich active alloy seals, it was reasoned that the configuration of the nickel members in the Figure 10 design was over-stressing the seals. Therefore, the nickel members were re-designed as shown in Figure 3 to reduce radial stresses at the seal.

*Registered trademark of Haynes-Stellite, Kokomo, Indiana

The Figure 3 design utilizes only nickel-to-nickel TIG welds and active-alloy metal-ceramic seals for envelope joints so the structure would be expected to be very reliable. It is recommended, where possible, that tube structures for high temperature operation be restricted to the use of these types of joints.

GAS CLEANUP DUE TO ELECTRODE SPUTTERING

Based on the data obtained during this work, gas cleanup in these glow discharge devices should not severely limit useful life, in that five of the seven tubes which experienced no envelope failures operated for 5600 hours or more, while one tube has operated 10,800 hours at high temperature plus 550 hours at room temperature and is still operable.

As described in the "Tube Design" section, variations in cathode effectiveness can be detrimental to the cathode confinement scheme which is intended to reduce sputtering-induced gas cleanup. The less effective cathode also would exhibit a higher running voltage, and this leads to consideration of the relationship between operation at higher than normal voltage and the time rate of cleanup. Taking a simple empirical approach and using the performance of tube Nos. 1, 2 and 4 as depicted in Figure 12, a consistent relationship between hours operated above 115 running volts and cleanup can be contrived for these three tubes. If the product of (running volts minus 115) times (thousands of hours voltage is above 115) is called "C", then "C" is approximately 24 for tube No. 1, 22 for tube No. 2 and 23 for tube No. 4. "C" for operable endurance test tubes (refer to Figure 11) is 1 for tube No. 11, 15 for tube Nos. 12 and 18 for tube No. 13. Tube No. 14 is anomalous in having a "C" factor of only 4 and being a cleanup failure. Also, the tube was found to have a structural anomaly; a small nickel strap (usually used to position the anode) had inadvertently been dropped into the cathode during fabrication and was found brazed inside the cathode when tests were completed and the tube was dismantled. Logically, this would have affected the performance of tube 14. The one tube which failed due to cleanup after operating for more than 1000 hours in earlier phases of this program would have a "C" factor of approximately 18, and therefore also fits the picture reasonably well.

Thus, a generalized tendency of high voltage to enhance gas cleanup is apparent. Two other considerations also lend support to this general thesis: (1) the most stable, long-lived tubes (Nos. 11, 12 and 13) tend to operate near 110 volts at 800^{o}C and at 108 volts at room temperature; (2) the theoretical tube voltage[9] -- well substantiated by other experiments[6] -- is 108 volts for neon and molybdenum.

Two factors, other than cathode effectiveness, which cause higher running voltages are: working fluid (the gas fill), and to a lesser extent, geometry. There were no changes in the anode and cathode geometry, therefore, the second factor is eliminated. It is also highly unlikely that the working fluid is a significant factor in increased running voltage, because a comparatively large fraction of impurity (several percent) must be added to the working fluid to induce such increases. If the impurities are chemically active (oxygen, carbon monoxide, hydrogen and hydrocarbons are candidates) the cathode effects occur at much lower concentrations compared to those of the working fluid. Among the inert gases, only helium would cause an increase in running voltage, but it is improbable that an appreciable amount of helium could be introduced as an impurity.

Thus the most viable hypothesis for the high running voltage-gas cleanup relationship is that the cathode has areas which are less effective as a cathode and other areas which are more effective. The more effective areas are sources of sputtered material, while the less effective areas tend to collect sputtered material, leading to the sputtering-induced gas cleanup described earlier.

Cathode effectiveness may be reduced either by traces of gaseous contaminants introduced into the gas fill or adsorbed on interior tube surfaces during fabrication or processing, or by traces of metallic contaminants being deposited on the cathode surface during fabrication. There is indirect evidence that these phenomena occur based on indications that the running voltage is lowered both by more rigorous exhaust processing, which tends to minimize gaseous contaminants, and by eliminating the braze at B in Figure 2, which tends to reduce traces of brazing materials from being deposited on the cathode surfaces. Figure 3 shows the improved design used for tube Nos. 12, 13 and 14. Because of the high temperature operation, contaminants are evaporated and desorbed much more readily from all interior surfaces as the tube operates, making the general contamination problem much more severe compared to conventional glow-discharge tubes.

This approach leads to the recommendation that more rigorous processing -- tube bakeout to perhaps 1100°C to better outgas the titanium getter and other tube parts, with a gas-loading system bakeout of 400°C combined with the high-voltage sputtering technique described in the "Tube Design" section -- should be explored for future work on such high temperature tubes. The use of TIG or electron beam welding to fabricate cathode parts would also be a means of eliminating impurity-inducing brazing techniques.

Based on the performance of tube Nos. 11, 12 and 13, the expected life of a tube without a gas reservoir would be at least 6000 operating hours, or 24,000 hours projected life for a tube with a three-volume reservoir. Thus a potential life expectancy of at least 20,000 operating hours would be readily realized.

OPERATING VOLTAGE STABILITY CHARACTERISTICS

Tube stability that is, deviation from running voltage over the specified current range of 25 to 75 mA (regulation), is so overshadowed by the variations in cathode performance that much of the regulation data are of doubtful validity. The data for tube Nos. 11 and 13 plotted in Figure 13 have perhaps the best validity since these tubes exhibited proper running voltages for thousands of hours. Data obtained for tube Nos. 4 and 5, which were more variable in their behavior are also shown in Figure 13. The last regulation data for tube Nos. 12 and 14 were very similar to the data obtained for tube Nos. 11 and 13. The slope in volts/mA at low currents for the tube Nos. 4 and 5 regulation curves is also very high for a normal glow discharge, lending more credibility to the allegation that these are not typical regulation curves.

The less effective, uneven cathode performance discussed earlier would also lead to poorer regulation as well as higher running voltage. It is reasoned that the more rigorous processing and lower levels of contaminants achieved for tube Nos. 11 through 14 contributed to their better performance. Further improvements in reducing cathode contaminants discussed earlier would also lead to improved regulation and operating stability characteristics.

It should also be feasible to improve the regulation performance by operating at lower cathode current density, ie using a larger cathode area, which should shift the regulation performance to resemble the 17 to 50 mA section of the tube Nos. 11 or 13 curves of Figure 13. When the cathode is uniformly effective, and current is drawn uniformly from the whole cathode, the cleanup rate (as discussed above) should not be appreciably increased due to a 50 percent larger cathode area. Earlier experience[6] has indicated that a more symmetrical geometry and larger anode diameter in relation to the cathode are both factors which tend to improve stability, and these changes are incorporated in an "Improved Design" tube shown in Figure 16.

The improved design features both a cathode and anode of approximately spherical geometry with the cathode formed from two hemispheres TIG welded together to eliminate braze material contaminants. The starting probe as part of the cathode combined with the "dumbell" shape of the anode allows the use of a larger anode diameter without increasing the anode surface area. This is advantageous because the anode collects sputtered cathode material proportional to its area and thus contributes to gas cleanup. The nickel cathode structure, TIG welded to the brazed metal-ceramic seal assembly (weld C of Figure 16), would be a convenience in fabrication. Compared to the Figure 3 design the reservoir structure is less complicated and more rugged. The overall dimensions of the improved design tube are approximately the same as those of the Figure 3 design.

The tendency of these tubes to oscillate (exhibit a periodic voltage instability) was observed but no further investigation was made. All endurance test tubes oscillated early in life. Oscillation was more frequent at lower currents and all tubes stopped oscillating at currents in excess of 10 mA before the tests were completed. Tubes with envelope leaks (Nos. 8 and 9) stopped oscillating after 1000 to 2000 hours and non-leaking tubes (Nos. 11 through 14) about 2000 hours before tests were terminated. This supports the thesis that reducing the gas loading pressure of 40 torr would reduce the tendency to oscillate. The earlier tubes (Nos. 2 and 4) exhibited less tendency to oscillate, perhaps due to the more rapid gas cleanup rate they experienced. The typical waveform of these oscillations is shown in Figure 17, with 15 to 20 KHz frequencies most commonly observed.

As better cathode performance was obtained, the variations of characteristics with temperature and operating hours tended to decrease.

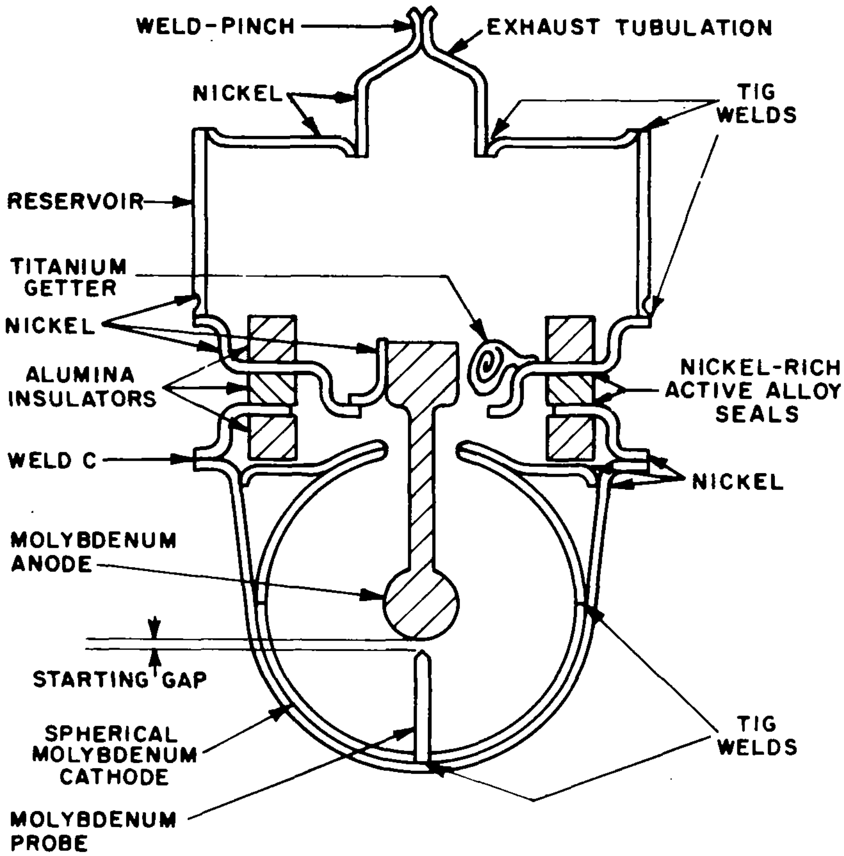

Figure 16 - Improved Voltage-Regulator Tube Design

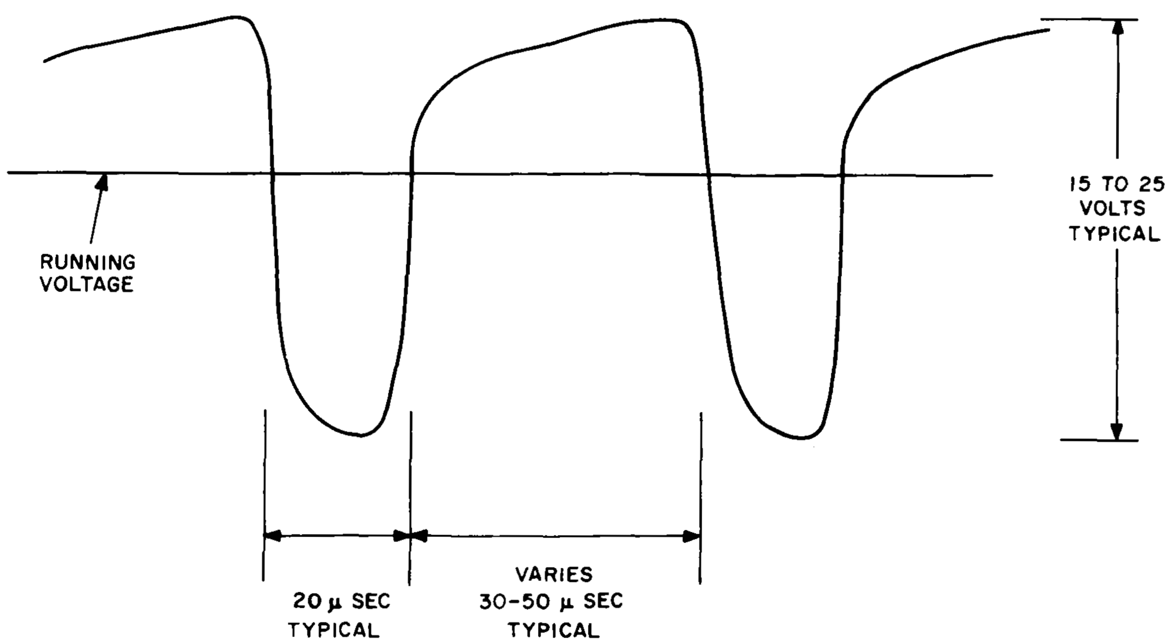

Figure 17 - Typical Waveform of Oscillating Voltage-Regulator Tubes

The deviations of running voltage over the temperature range of 400°C to 800°C shown in Figure 15, are so slight -- about one volt higher at 800°C -- that they will have little effect in the usual voltage-regulator circuit. Variations at lower temperature are of less interest, but were investigated in earlier work.[2] It is not surprising that variations with time have also improved with better cathode performance, since cathode effectiveness directly determines tube running voltage.

The running voltage these tubes exhibit at high temperature is also significantly different from the experience reported in earlier work[2,3] where running voltage was typically 120 to 125 volts. It is reasoned that the higher running voltage was due to less effective, uneven cathode performance as discussed earlier, and that the running voltage to be expected for neon-molybdenum voltage regulator tubes operated at 800°C would be 110 volts with regulation of ±2 volts over the 25 to 75 mA current range. With a larger cathode and better processing regulation performance of ±1.5 volts should be feasible.

THE LOW VOLTAGE ANOMALY: TUBE NOS. 8 AND 9

As discussed earlier in this section, most of the undesirable elements which could be introduced into these tubes would result in higher running voltage, so the behavior of tube Nos. 8 and 9 was somewhat surprising. Mixtures of the inert gases (except helium) have been found to exhibit lower running voltages,[10] with the lowest running voltage (approximately 83 volts) being 99.7 percent neon - 0.3 percent argon. As little as 0.01 percent argon would explain the behavior of tube No. 9, or 0.1 percent for tube No. 8. The source of the argon would be room air which contains 0.9 volume percent argon. The reason for the availability of a higher concentration of argon (compared to oxygen or nitrogen) as an impurity is that neither the ion pump nor the titanium getter will pump the inert gases (especially argon) efficiently. Thus a residue of argon can accumulate in the ion pump and then be partly absorbed by the titanium getter at low temperatures. At 800°C, the getter would slowly release the argon creating the characteristics shown for tube Nos. 8 and 9.

To overcome this tendency in tube Nos. 10 through 14, the ion pump was flushed with neon at least once each processing cycle to sweep out the argon. The evidence indicates that accumulated argon had negligible effects in these tubes.

CONCLUSIONS

1. The feasibility of operating inert gas voltage-regulating tubes for periods exceeding 10,000 hours at temperatures of 800°C in vacuum at 0.05 ampere was demonstrated. Stable tube running voltage was 110 volts ±2 percent for the specified current range of 0.025 to 0.075 ampere.

2. A life capability of 10,000 hours was demonstrated for the basic tube body and for tubes without a gas reservoir. The use of a gas reservoir is expected to increase life capability to beyond 20,000 hours.

3. It was found that neon-filled voltage-regulator tubes using a molybdenum cathode, operated at 800°C, experience abnormally high running voltages and are subjected to rapid gas cleanup unless very rigorous tube processing is undertaken prior to seal-off.

4. Tube operation at 800°C results in an increase of less than 2 volts in tube running voltage, compared to room temperature operation. Better tube performance and stability were found to occur with a gas loading pressure of 30 to 40 torr. Less tendency of tubes to oscillate was noted for conditions of lower tube gas pressure.

5. Improved tube operating stability was accomplished by more rigorous tube processing. Further improvements in performance are expected to result from suggested tube improvements which include still more rigorous processing, a molybdenum cathode fabricated by welding and more symmetrical electrode geometry.

REFERENCES

1. Kohl, W. H. and Rice, P.: Electron Tubes for Critical Environments, ASTIA No. AD-151158.

2. Baum, E. A.: Development of High-Temperature Ceramic Rectifiers, Thyratrons, and Voltage-Regulator Tubes, NASA Contractor Report NASA CR-54303 (1964).

3. Baum, E. A. and Jones, N. D.: High-Temperature, Gas-Filled Ceramic Rectifiers, Thyratrons, and Voltage-Reference Tubes, NASA Contractor Report NASA CR-72054.

4. Lafferty, J. M.: New Voltage-Regulator and Voltage-Reference Tubes for Critical Environments, General Electric Technical Information Series Report RL-1803 (1957).

5. Jones, N. D.: Development and Endurance Testing of High-Temperature Ceramic Rectifiers and Thyratrons, NASA CR-1684, 1970.

6. Kearns, W. J.: Applied Research on Glow Discharge Pheonomena, General Electric Technical Information Series Report R63ETI-27 (1963).

7. Acton, J. R. and Swift, J. D.: Cold Cathode Discharge Tubes, Academic Press, New York (1963) p. 127.

8. General Electric Company, Power Tube Department: Vapor Filled Thermionic Converter Materials and Joining Problems; Plasma Research Pertinent to Thermionic Converter Operation, Final Report (AFCRL-63-69), March 1963. Air Force Contract No. AF19(628)-279.

9. Acton, J. R. and Swift, J. D.: Cold Cathode Discharge Tubes, Academic Press, New York (1963) p. 239.

10. Benson, F. A.: Comparison of Argon, Krypton and Xenon as Admixtures in Neon Glow-Discharge Reference Tubes, Proceedings of IEE (Brit.) Vol. 108, Part B, Sept. 1961.

NASA-Langley, 1971 —— 3