DEVELOPMENT OF A PROTOTYPE HIGH TEMPERATURE AMPLIFIER FOR GEOTHERMAL WELL LOGGING

FINAL REPORT

MASTER

MRI-2870

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1.0 INTRODUCTION

This report describes the development of a high temperature amplifier for use in geothermal well logging. This development was based on the use of ceramic vacuum tubes as the active circuit element since these tubes have the capability to operate in the high ambient temperature environment.

The primary goal of this program was to design, build, and deliver a prototype amplifier capable of continuous operation in a 250°C environment. A development program designed to meet this goal covered four phases. These phases were 1) development of the basic circuit configuration with conventional, low cost glass envelope vacuum tubes; 2) modification of the circuitry to accommodate the ceramic vacuum tubes; 3) a 1000-hour duration temperature cycle (48 hours at 260°C and 2 hours at 20°C); and 4) development of a prototype, deliverable amplifier.

The following sections discuss the high temperature amplifier development program. Section 2 describes the amplifier performance, including design requirements, circuit design, development program, and the prototype amplifier. Section 3 presents test results from two breadboard models, one with conventional glass tubes and one with ceramic tubes, and the prototype amplifier. Section 4 describes the operation of the prototype amplifier. Circuit equations used for analysis and tube characteristics are contained in the appendices.

2.0 AMPLIFIER PERFORMANCE

2.1 Requirements

The general requirements for the amplifier include the following:

(1) continuous operation in a 250°C environment

(2) a stabilized gain of 40 db ± 3 db over an expanded bandpass from 1 Hz through 5,000 Hz

(3) the capability to mate to a four-to-five mile long, seven-wire logging cable

(4) packaged so as to readily pass down through a narrow drill pipe and to withstand the rugged pipe handling environment

(5) a cumulative operating lifetime of at least 1,000 hours.

An important design goal was to minimize the number of cable conductors required to power the amplifier and transmit the output signal to the ground. One means of achieving this goal is to utilize a constant current plate power supply and use the B+ line to also carry the output signal. While this eliminates the need for one conductor, it provides a limited output bandwidth. Also, the use of a negative power supply in addition to the positive supply, which would simplify the problem of circuit design, was not considered in order to minimize conductor requirements.

2.2 Performance Summary

Requirements 1 and 5 were conclusively demonstrated by a 1,000-hour thermal test. This test consisted of a thermal of 48 hours at 260°C and 2 hours at room temperature. The prototype amplifier was also tested for three 50-hour thermal cycles at 250°C.

Requirement 3, the ability to drive the logging cable was demonstrated by operating into a simulated line impedance.

Requirement 4 was incorporated by designing the amplifier housing to be compatible with the LASL sonde and potting the resistors and wiring.

Requirement 2 was not met explicitly. The deviations are:

- The gain is a function of the operational mode. As presently wired the gain is 45 db in a constant voltage, direct coupled mode; 31 db in a constant voltage, AC coupled mode; and 47 db in a constant current mode. The gain is easily modified by change in a feedback resistor.
- There is a db difference in gain between room temperature and 250°C.
- The frequency response of the amplifier is flat from below 1 Hz to above 40 kHz. However, the impedance of the logging cable limits the net frequency response to 1.2 kHz. A zero source impedance amplifier driving an infinite load through this transmission line would have a -3 db frequency of 1.6 kHz.

These results are discussed in more detail in the following sections.

2.3 Circuit Design

The amplifier circuit diagram is shown on Figure 1. The design consists of two class A differential input stages that are DC coupled and a cathode follower output. Feedback from the cathode follower to the grids of the first input stage is also included to minimize drift.

The output from the geophones is connected directly to grids of the first differential input stage. The plates of the first stage tubes are, in turn, directly coupled to the second differential stage. The output of one of the second stage tubes (V3) is then coupled to the grid of the output cathode folower through a resistor divider network. The other output of the second differential stage (V4) is not used. The tube V4 acts an electronic valve and tends to keep the current flow in the common cathode resistor constant, thereby maximining open loop gain. This scheme overcomes the large degenerative feedback that would result from the large resistor required for bias matching in raising the DC cathode level to match the grid levels.

The basis of the design for high temperature operation is the use of ceramic and metal vacuum tubes. The tubes chosen for this application are high-mu triodes of planar construction. Data sheets for the two tube types that were utilized are included in Appendix B of this report. In general, ceramic tubes of this type are designed for VHF and UFH applications so that there is a general lack of information available concerning their use in constructing low frequency and DC amplifiers. High frequency noise and oscillations which are a common characteristic of these types of tubes proved, however, to be only a minor problem during the development phase of this program.

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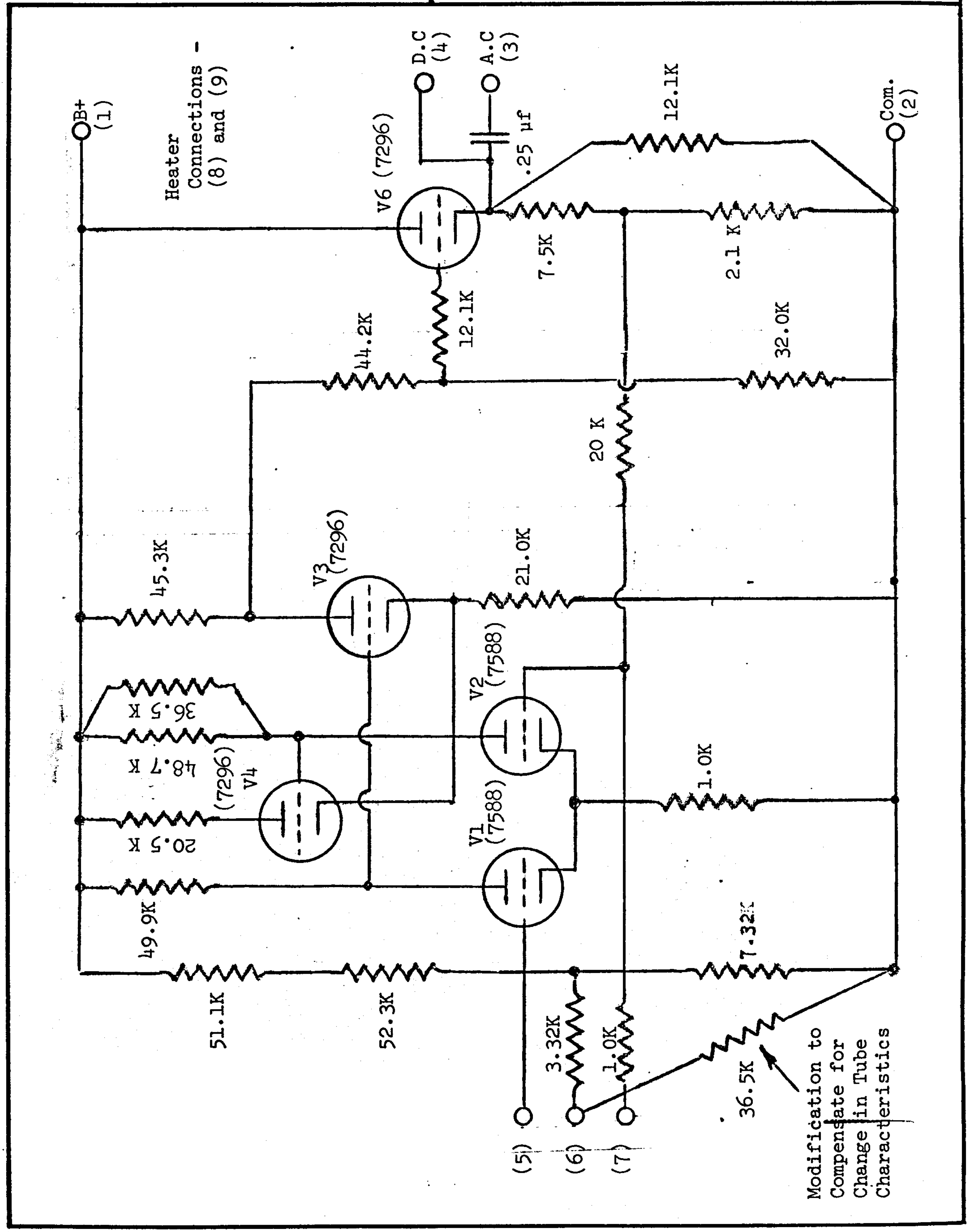
PREPARED WJC	DATE 4/14/76	SECTION NO.	SHEET 1 OF 1
CHECKED	DATE	PROTOTYPE AMPLIFIER, FINAL CIRCUIT DESIGN	



Modification to Compensate for Change in Tube Characteristics

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Figure 1. Prototype Amplifier Circuit

2.4 Development Program

The development program for the high temperature amplifier consisted of 1) building a breadboard model using conventional glass envelope tubes and finalizing the circuit design, 2) building a high temperature model of the final circuit design using ceramic tubes and testing for 1000 hours, and 3) building a prototype amplifier and testing for three 50-hour cycles. A circuit analysis was also performed concurrent with the testing using the equations developed in Appendix A. A serious drawback in the analysis was the fact that the ceramic tube characteristics varied somewhat from design.

The initial design of the amplifier which was breadboarded is shown in Figure 2:

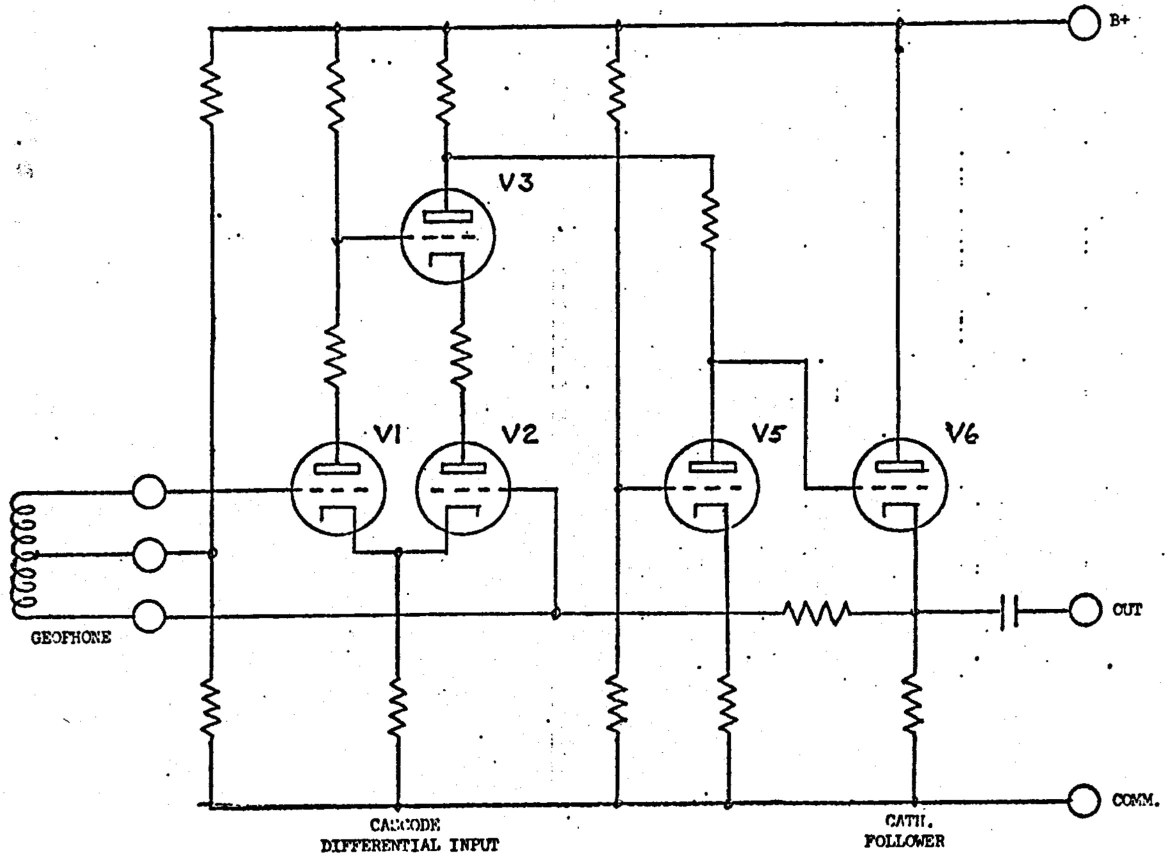


Figure 2. Initial Circuit Design

Starting with this circuit a breadboard model using conventional type 6ER5 Triodes was constructed as shown in Figure 3 and tested. Based upon the results of the initial tests, design improvements were made that led to superior performance. The first modification was to make the cascode circuit into a second differential class A amplifier (V3 and V4 in Figure 1) in order to achieve a greater open loop gain. The purpose of the original design was to transform the output of the differential stage into a single-ended signal. However, since the current flow through both tubes which were in series must at all times be equal, the lower tube essentially acted as a large cathode resistor providing degenerative feedback and a low output from V3. By adding the additional branch to the second stage and connecting both cathodes to a common grounded resistor (instead of the plate of V2), a relatively constant cathode voltage can be maintained. This also resulted in a 6 tube circuit as indicated on Figure 3.

Further testing of the conventional tube breadboard showed that the tube V5 connected to grid of the cathode follower provided as much attenuation of the signal as a simpler resistor network did in dropping the DC plate voltage of V3 back down to ground level, and was therefore eliminated resulting in the final five tube circuit shown in Figure 1.

Following the finalization of the basic circuit, a breadboard model using ceramic tubes was constructed on an aluminum chassis for life-cycle tests as shown in Figure 4. The initial results of the life cycle tests showed that the ceramic tubes exhibit wide tube to tube veriation in characteristics which also change with both time and temperature. As a result, prior to building the prototype a low temperature breadboard using ceramic tubes was built for bench testing as shown in Figure 5. Both the tubes and resistors were tested and verified (at room temperature) with this breadboard before installing on the final prototype chassis.

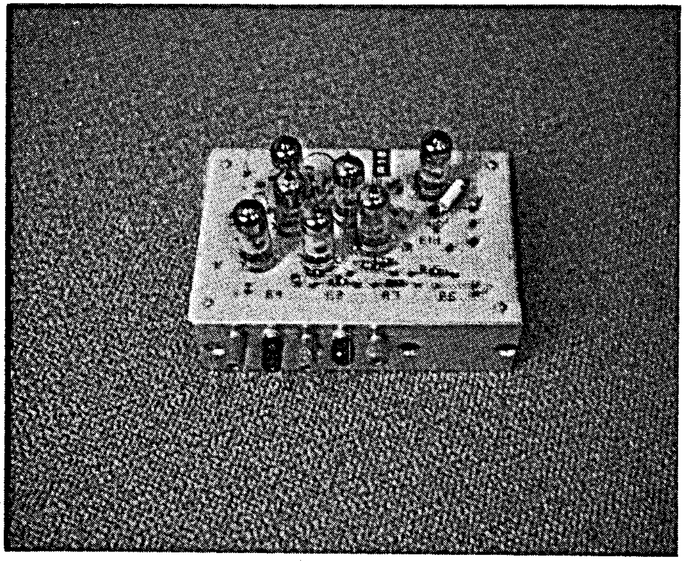


Figure 3. Low Temperature Breadboard, Conventional Tubes

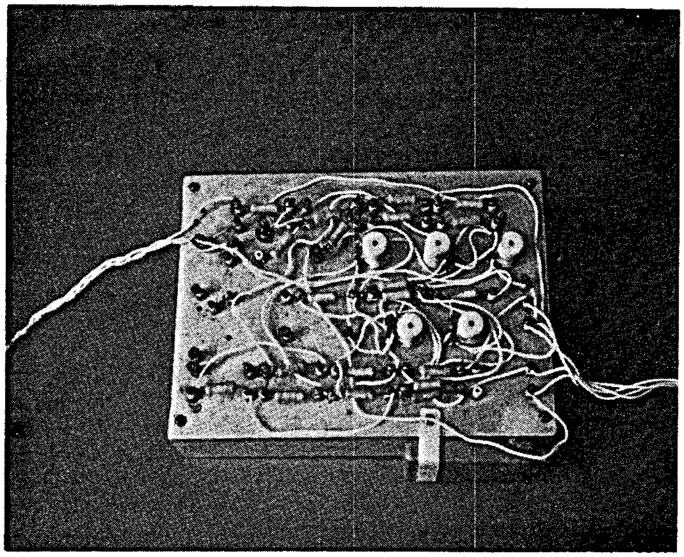


Figure 4. High Temperature Breadboard

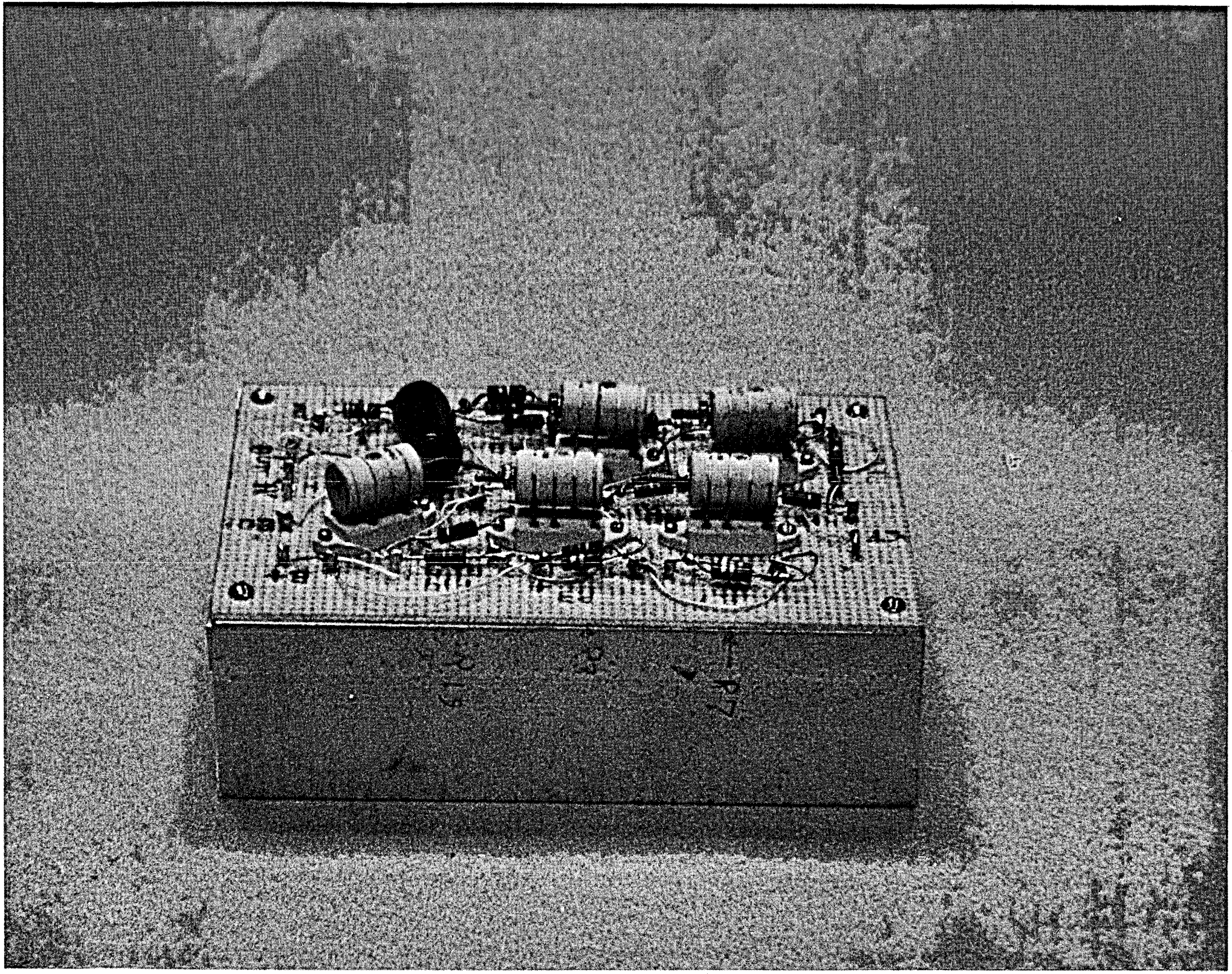


Figure 5. Low Temperature Breadboard, Ceramic Tubes

The laboratory test setup for both the life cycle tests on the high temperature breadboard and checkout of the prototype amplifier is shown on Figure 6.

2.5 Prototype Model

A photograph of the prototype model is shown on Figure 7. The amplifier is enclosed by the cylindrical shell which measures 3 inches in diameter. The overall length of the assembled amplifier is $8\frac{1}{2}$ inches.

The resistance values for the prototype amplifier were first determined using the low temperature ceramic tube breadboard (Figure 5). It was found that the characteristics of different tubes of the same model number varied sufficiently to prevent using the exact same values as used in the high temperature breadboard. The major differences were in the plate resistors required to obtain optimum (i.e., maximum) open loop response.

All of the resistors used in both the high temperature breadboard and prototype model were one percent tolerance with temperature coefficients of 20 ppm. In addition, all of the plate resistors had a power rating of 6.5 watts at room temperature, derated to 2 watts at 250°C.

Following assembly of the prototype, it was tested for three cycles of 48 hours at 250°C followed by a two-hour cooldown period. As discussed in the next section on test results, a minor modification of the circuit was required part way through the test period to compensate for a change in input stage bias resulting from a shift in tube characteristics at high temperature.

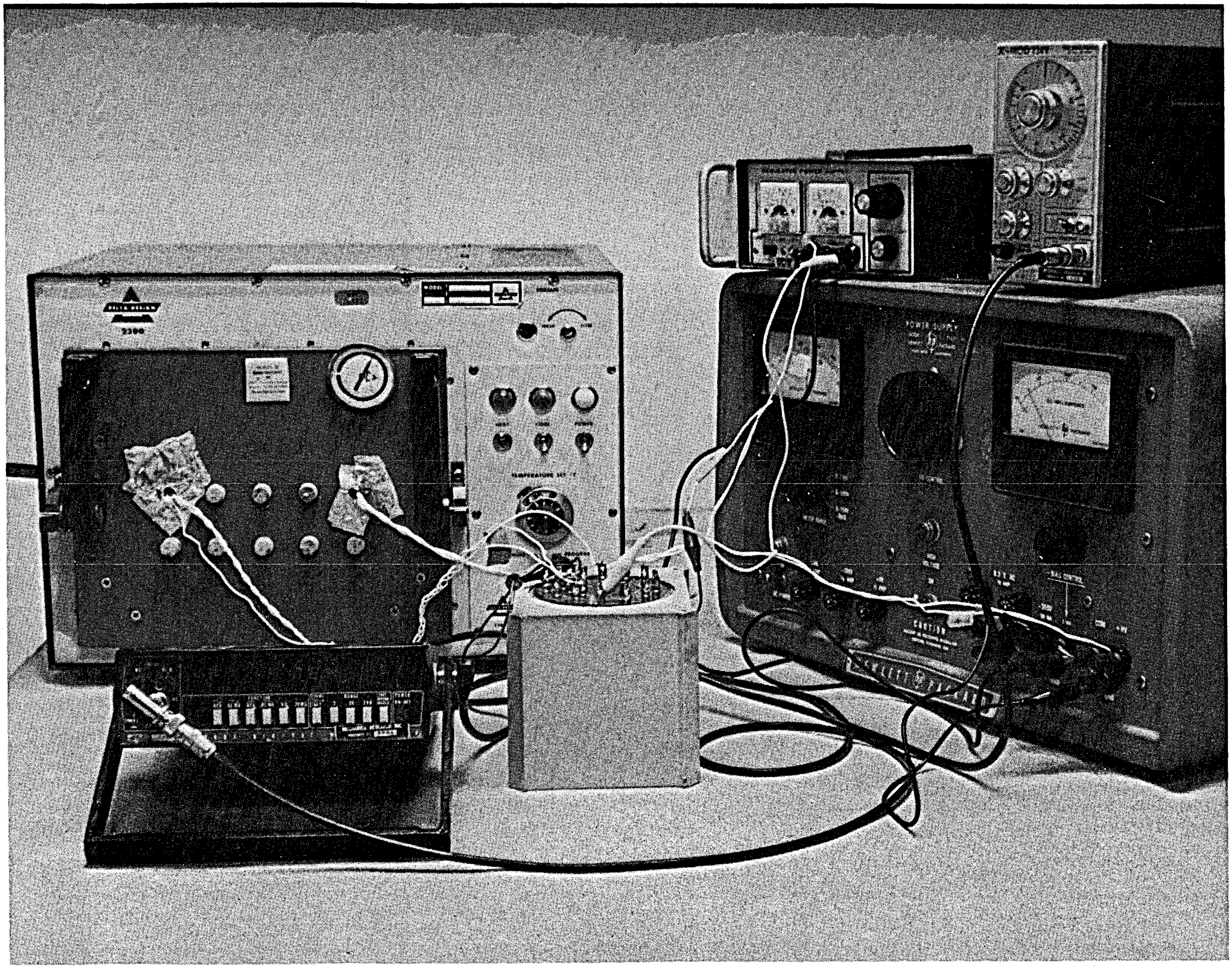


Figure 6. Laboratory Test Setup

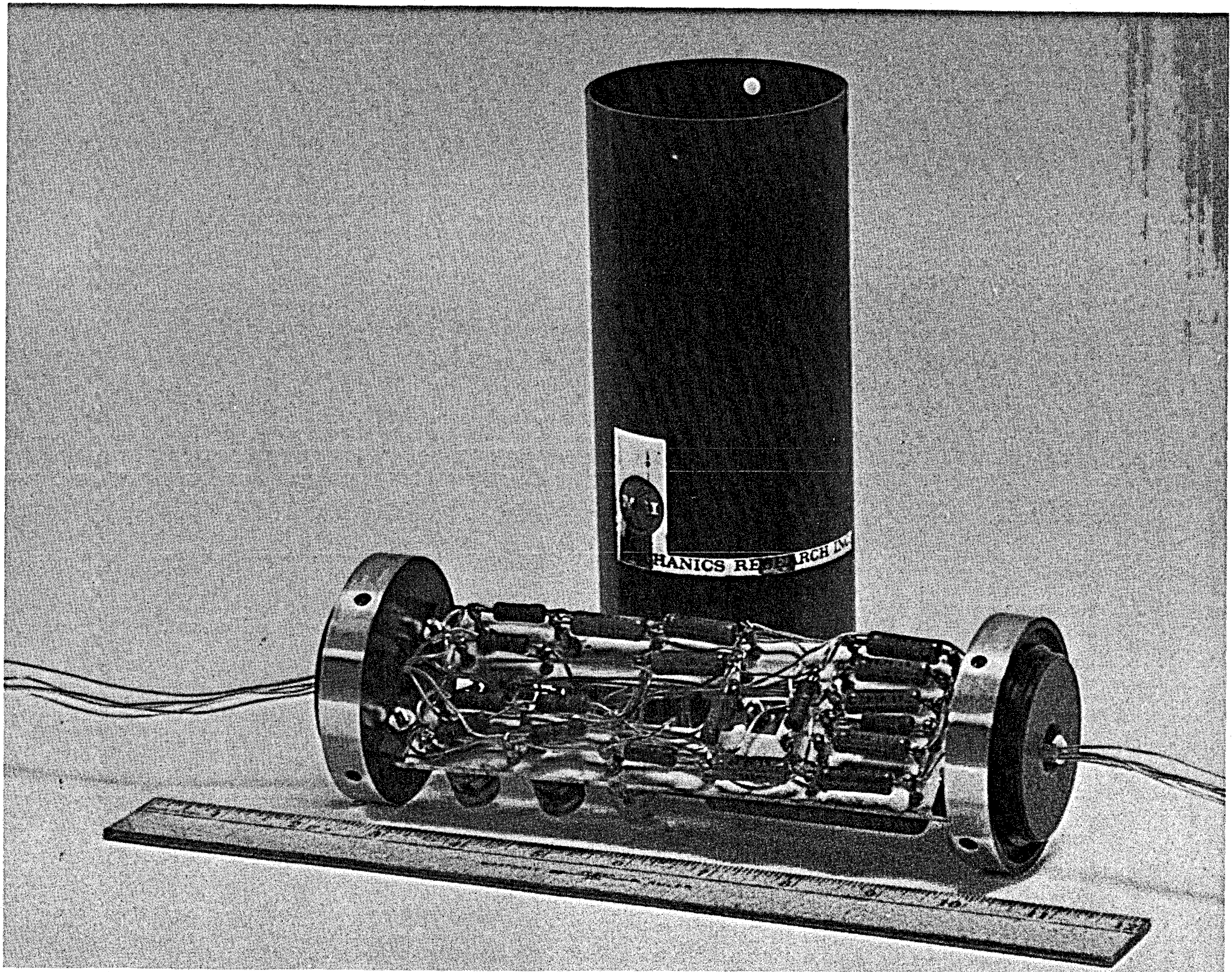


Figure 7. Prototype Amplifier Before Potting

3.0 TEST RESULTS

Included in this section are the test results and evaluations for the conventional tube breadboard, high temperature breadboard, and prototype amplifier.

3.1 Breadboard With Conventional Tubes

Initial testing with the breadboard employing conventional tubes resulted in circuit improvement, over the initial design as discussed in Section 2.3 of this report.

Potentiometers, rather than fixed resistors, were used for all tube plate resistors and for adjusting grid biasing. In this manner, optimum performance could be obtained by simple adjustment.

Results of performance tests run on the optimized circuit are given on Figures 8 and 9, which show frequency response and amplitude linearity. At the higher frequencies, the response based on scope measurements was down 10% at 10Hz and 30 kHz and down 20% at 50 kHz. The roll-off at both the high and low frequencies, however, is attributable to the transformer used to generate the differential input signal.

The linearity test results also showed good performance. The design full scale output was 2.8 volts peak to peak (10 mv-rms input). At approximately four times the design output, the output signal (10.4 volts peak to peak) showed an approximate 6% deviation from linearity. The signal to noise ratio was about 400 with 7 millivolts peak-to-peak noise on the output.

The gain of the amplifier was fairly insensitive to the B+ voltage. The design point is 250V. There was no change in gain between 240 and 290 volts. At a B+ voltage of 230, the gain was down 2%; at 220V, it was down 2%; at 210V, it was down 4%; and at 200V, it was down 6%. Reducing filament voltage from the 6.3V design value gave the following gain changes: 6.0V, gain change 0%; 5.5V, -5%; 5.0V, -7%; 4.75V, -11%; 4.5V, -18%; and 4.0V, -53%.

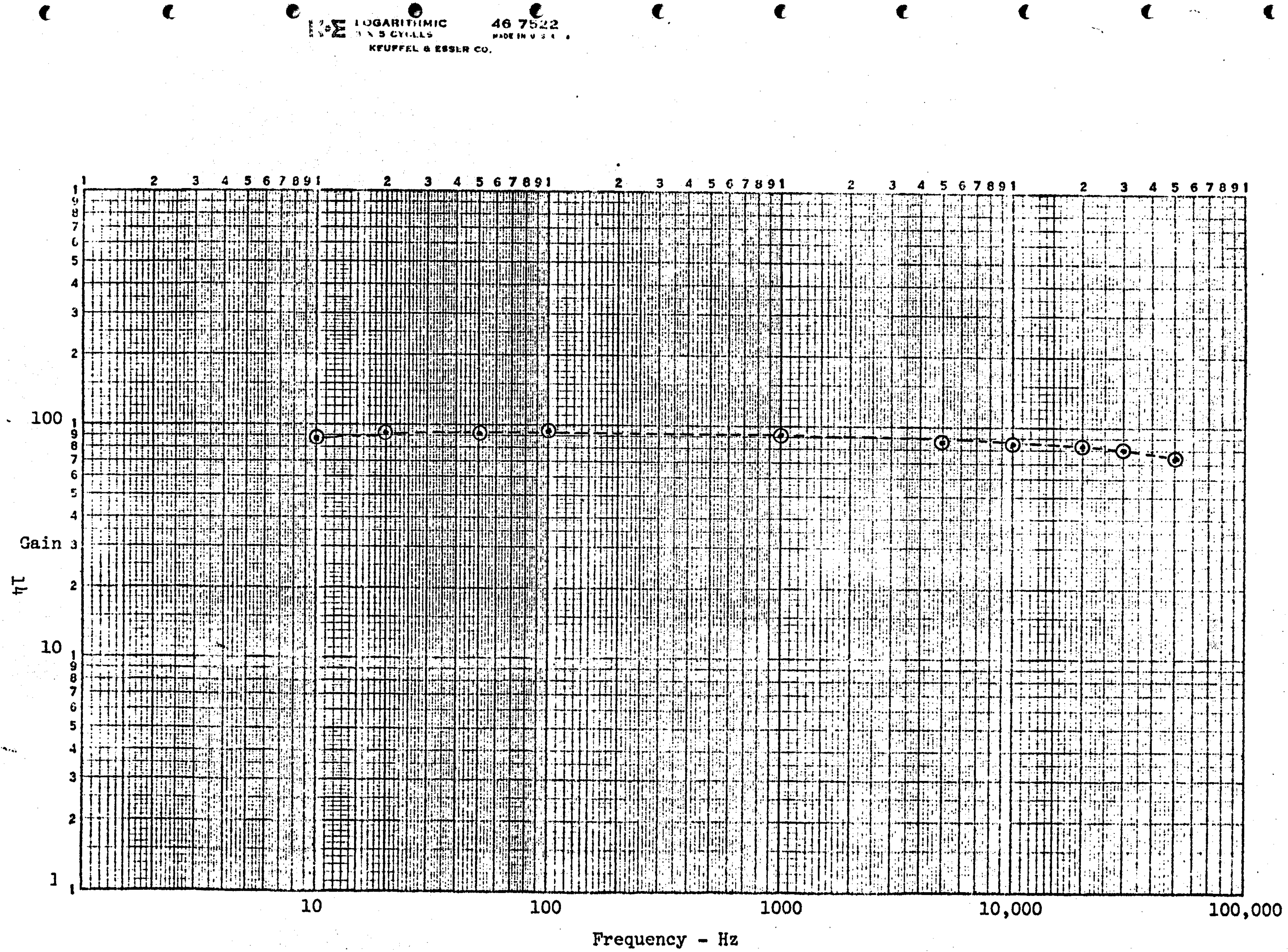


Figure 8. Frequency Response, Conventional Tube Breadboard

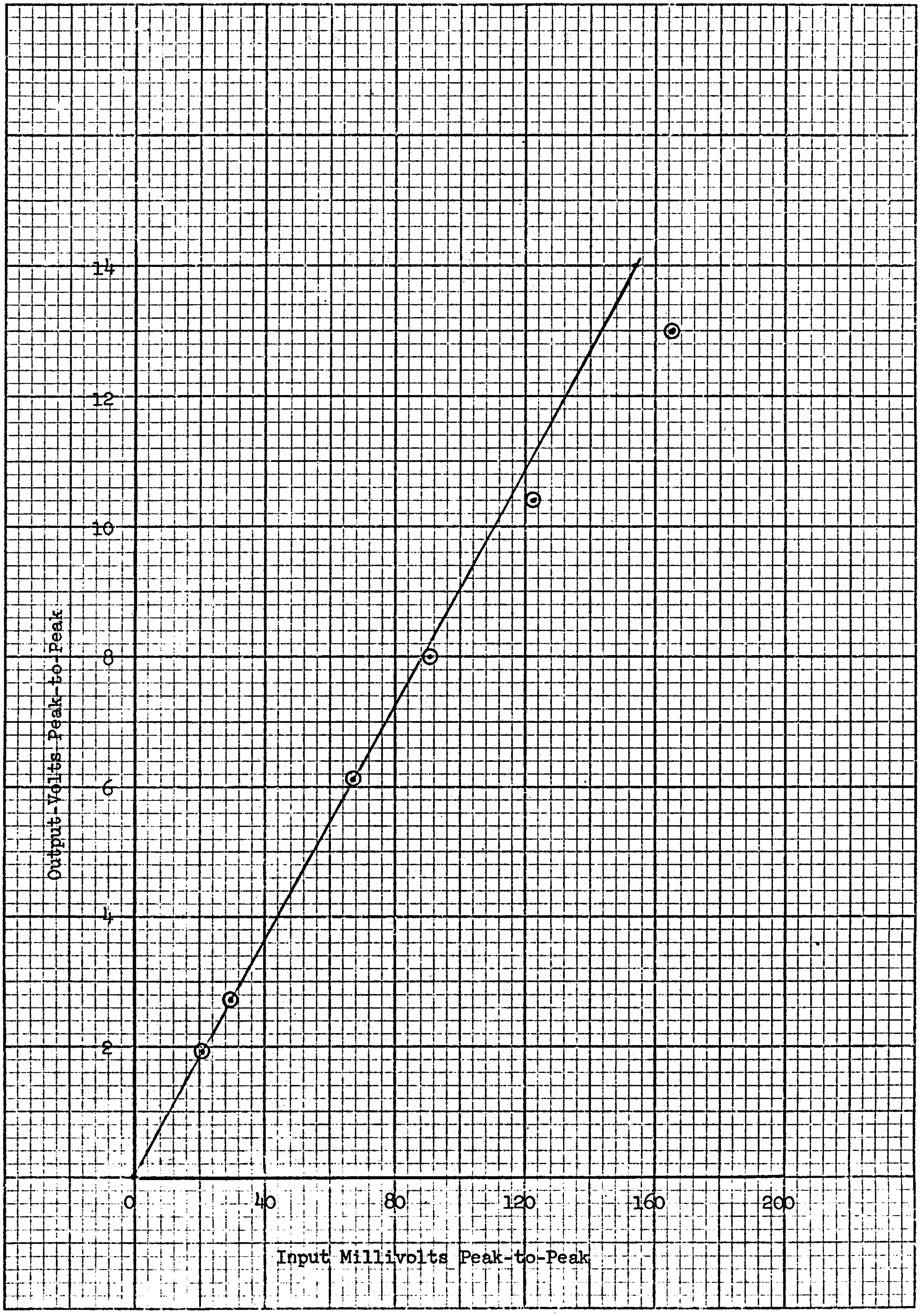


Figure 9. Amplitude Linearity, Conventional Tube Breadboard

3.2 High Temperature Breadboard With Ceramic Tubes

A high temperature breadboard using ceramic tubes and high temperature resistors was assembled on an aluminum chassis for extensive life cycle tests (see Figure 4). The same circuit developed with the conventional tube breadboard was used. Potentiometers were initially utilized to determine optimum values for the resistors. This proved necessary since the characteristics of the ceramic tubes can vary by ± 50 percent from nominal (see Appendix B).

Performance tests were run at room temperature. The frequency response showed no variation between 10 kHz and 10 Hz. At 5 Hz the gain was down 2%, and at 2 Hz it was down 9%. The frequency response of the transformer used to simulate the geophone input is included in the above figures and its gain falls off at frequencies below 10 Hz. Since the circuit is a DC amplifier, its frequency response should be flat from DC to some upper limit.

The linearity was good, with the gain down only 2% at 3 volts rms output. The signal-to-noise ratio was either 350 to 1 or 2800 to 1 depending on the test setup. (The noise level was 8 mv peak to peak in one case and about 1 mv peak to peak in the other case.) The circuit showed excellent tolerance to excitation voltage variations. The gain dropped only 2% from its value at 250 volts when the B+ was dropped to 220 volts or raised to 260 volts. At 200 volts the gain drops 7%. At 280 volts the gain drops 8%. Filament voltage changes between 20 and 31.5 volts resulted in only a 1% change in gain. At 19 volts the gain really drops. It is down about 29%. At 33 volts the gain is down 8%.

The life cycle tests were initiated on 2 March 1976 with the high temperature breadboard by operating the amplifier in a controlled temperature environment at 260°C for twenty-one 48-hour periods. Each 48-hour temperature cycle was terminated by a cooling period to room temperature for two hours. The cumulative test time was 1075 hours with 1028 hours at high temperature. Results of the high temperature tests are summarized in Table 1.

After completion of third cycle, it became apparent that the gain had drifted down from 90 to about 73. Measurements made during the cooldown period indicated that the plate voltages of the input tubes (V1 and V2) had become approximately 1 volt apart. In order to correct this difference, the plate resistor on V1 was changed from 40K to 20K on March 9. As can be seen from the data, however, the change had little effect on the amplifier gain. Additional modifications to improve gain were attempted during the cooldown period on March 30. It was determined, however, that a simple change in one or two resistors would not both increase the gain and make the circuit temperature insensitive. The circuit was therefore returned to the original state and the test resumed. It was discovered the following day that the feedback resistor had been inadvertently left at a lower value, which is the reason for the higher gain (88) recorded at the end of the March 30 cycle. The feedback resistor was changed back to the original value during the cooldown period of April 1.

The results of the life cycle tests showed that the ceramic tubes and amplifier circuit have excellent life characteristics. The tests also showed that the gain stabilizes after 100 to 200 hours of operation and varies by less than 0.5 db from cycle to cycle with 0.1 db being typical. The average gain change from operation at 260°C to room temperature was 0.25 db.

An extremely encouraging result of the life cycle tests was the demonstrated capability of the amplifier to withstand thermal shock. Both heatup and cooldown were performed rapidly. The test chamber took approximately 15 minutes to go from 20°C to 260°C. Cooldown was accomplished by removing the amplifier from the chamber and setting on the bench. The performance of over 40 rapid temperature changes had no adverse effects on the amplifier performance.

Table 1. Life-Cycle Test - High Temperature Breadboard

Cycle No.	Start of Cycle		Hours at 260°C	Hours at ~20°C	Amplifier Output; Volt (rms) for 10 mv (rms) Input		
	Date	Time			Start of Cycle	End of 260°C	End of 20°C
1	3/2	17:20	48	2	0.89	0.88	0.87
2	3/4	19:20	48	2	82	0.81	0.87
3	3/6	21:20	58.7	2	.81	0.77	0.79
4	3/9	9:00	48	2	.73	.74	0.85
5	3/11	11:00	48	2	.72	.75	0.85
6	3/13	13:00	48	2	.73	.78	0.84
7	3/15	15:00	48	2	.74	.78	0.84
8	3/17	17:00	48	2	.76	.77	0.83
9	3/19	19:00	48	2	.73	.75	0.83
10	3/21	21:00	58	2	.74	.76	0.80
11	3/23	9:00	48	2	.75	.77	0.78
12	3/26	11:00	48	2	.76	.77	0.76
13	3/28	13:00	48	2	.74	.77	—
14	3/30	20:30	45.8	7	.78	.88	.83
15	4/1	18:00	40	2	.75	.74	.67
16	4/3	19:00	48	2	.73	.73	.68
17	4/5	21:00	58	2	.72	.71	.67
18	4/8	9:00	48	2	.72	.72	.67
19	4/10	11:00	48	2	.70	.71	.71
20	4/12	13:00	48	2	.71	.72	.68
21	4/14	15:00	48	2	.71	.71	.71

Note: Plate voltage = 250V
Filament voltage = 25V (5V per tube)

3.3 Prototype Amplifier

The prototype amplifier was tested for three thermal cycles at 250°C. Initial test results indicated that the gain was more sensitive to temperature than the breadboard model. During the first qualification cycle, the linearity and amplitude of the output progressively decreased. By lowering the B+ voltage the linearity and gain could be restored. However, it was necessary to continuously decrease the voltage to maintain the output.

Following completion of the first 48-hour test at 250°C, measurements showed that the plate voltages of the first differential input stage (V1 and V2) were drifting apart with the consequence that the second stage output (V3) was being driven to cutoff. Temporary circuit modifications were made so that the plate and biasing resistors could be paralleled with other resistors outside of the temperature chamber and the second cycle was initiated. Results at this time showed that the trend in drift was continuing requiring lower plate voltages to maintain output. Further measurements during this cycle showed that the cause was due to a shift in the grid bias on the differential input stage which, in turn, was caused by a change in the cathode voltage of the output cathode follower feeding through the feedback resistor to the input grids.

Following completion of the second 48-hour cycle, the circuit modification noted on Figure 1 was made in order to correct the input biasing, and the gain slowly increased to approximately 190 (45.5 db) and settled. This is almost double the goal. It was decided, however, to leave the gain at this value rather than trimming back to 100 (40 db) in order to compensate for some of the attenuation of the amplifier output by the transmission line. This gain can be easily set to 40 db by changing the feedback resistor if desired.

The sensitivity of the amplifier output to changes in B+ voltage is shown on Figure 10 for both before and after the modification.

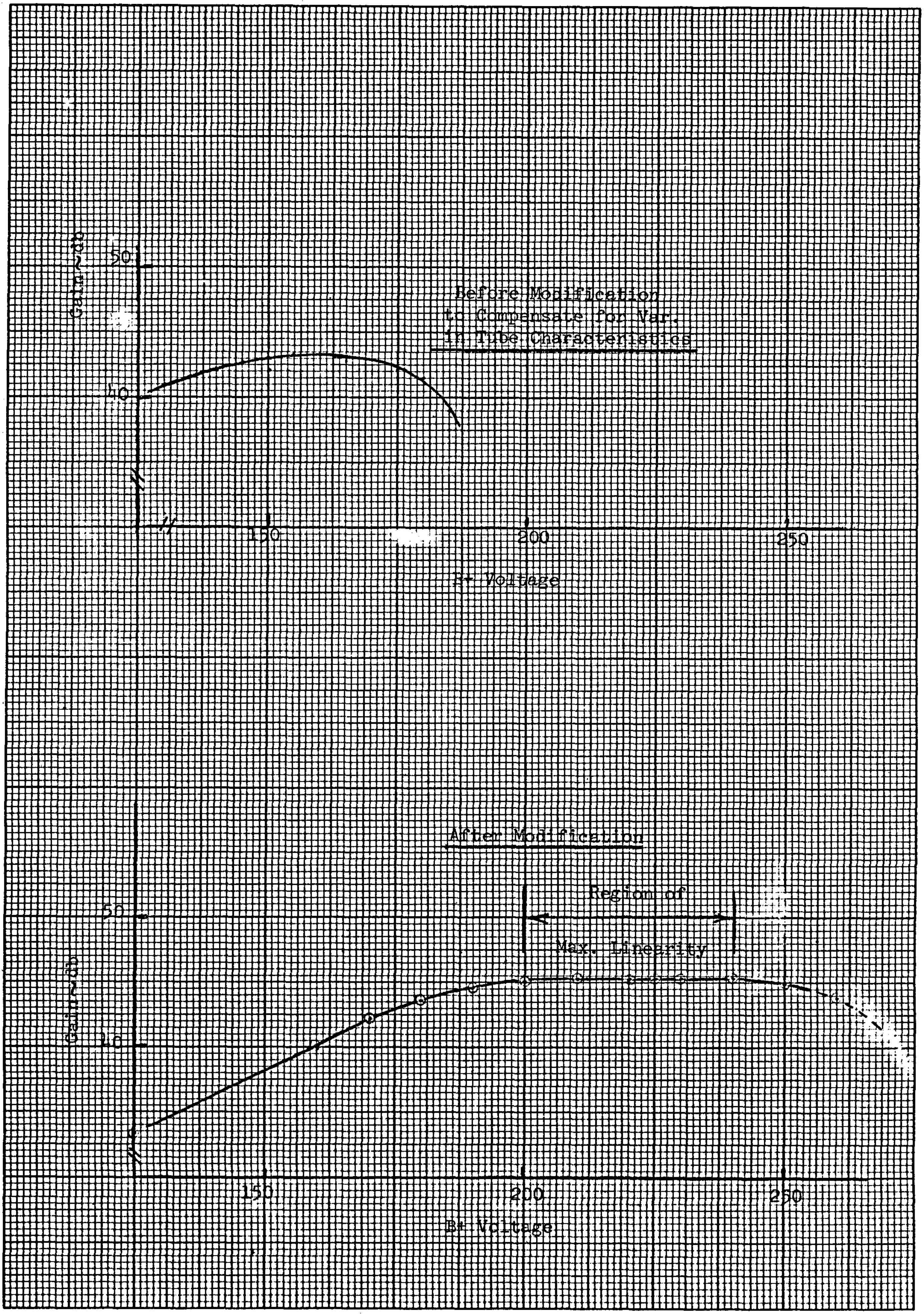
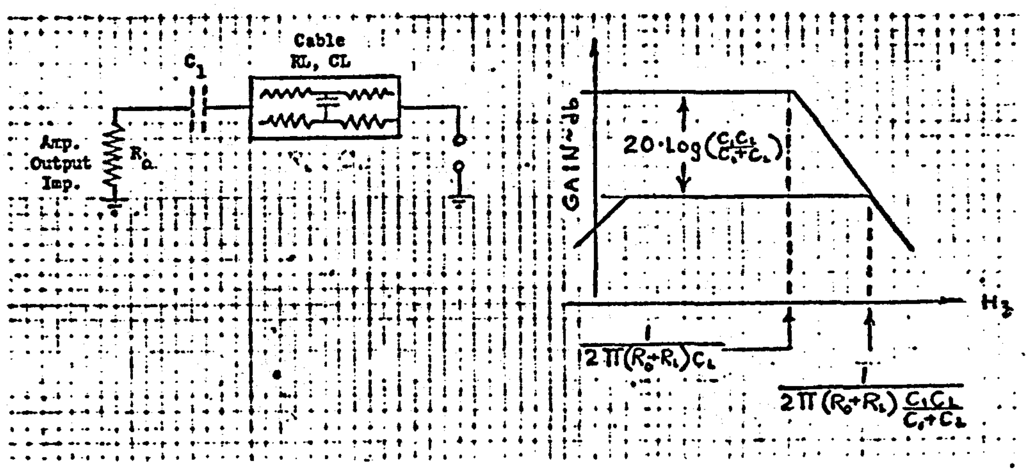


Figure 10. Sensitivity of Prototype Amplifier Gain to Variation in B+ Voltage

As indicated, the output is now linear and constant for plate voltages of 200 volts to 240 volts. The effect of plate voltage on amplitude linearity is further indicated on Figure 11. The output is linear in all cases for the design input of 10 mv (rms). With large amplitude inputs the linearity is greater with lower plate voltage.

The signal to noise ratio was over 500. As with the high temperature breadboard, changing filament voltage from 25V to 30V produces only a 1% decrease in gain.

The unattached amplifier when tested on the bench has a frequency response that is flat from 0 Hz to over 40,000 Hz. The interconnector capacitance of the logging cable, however, places an upper limit on the frequencies that can be transmitted from the well bottom to the ground. Assuming a 15,000 ft. cable with No. 20 wire conductors which have interconductor capacity of 35 pf/ft., the bandwidth for a three conductor transmission line model (B+, common and signal output) is on the order of 1,200 Hz. The bandpass can be increased by coupling the amplifier output to the logging cable through a capacitor. The apparent increase in frequency is at the expense of a significant amplitude loss and the basic transmission line characteristic is not altered as shown below.



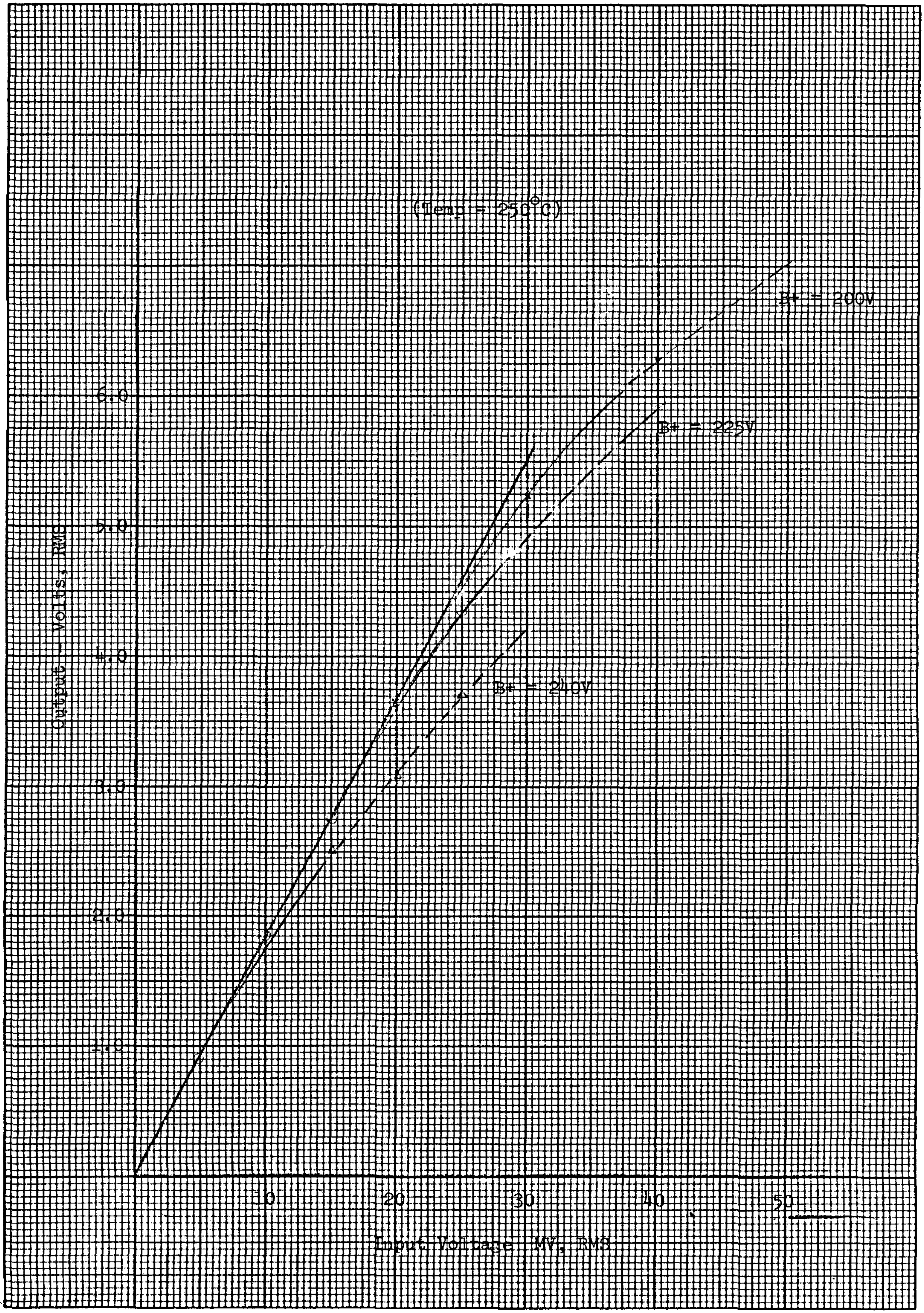
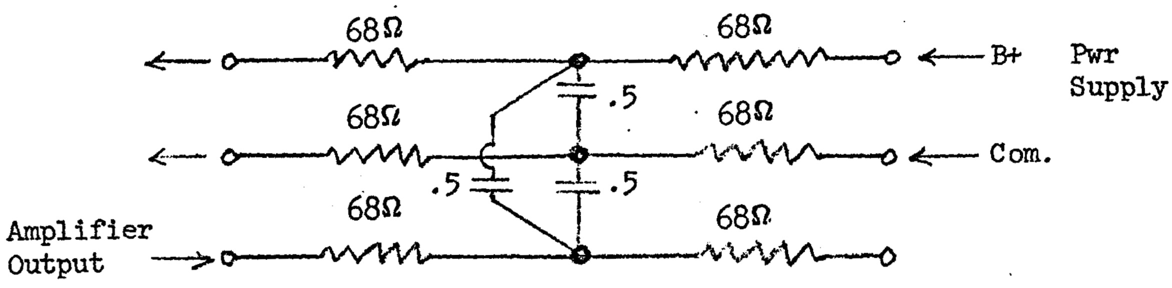


Figure 11. Amplitude Linearity, Prototype Amplifier

The measured frequency response of the prototype amplifier when connected to a simulated transmission is shown on Figure 12. The 15,000 ft. transmission line was simulated by pi-section filters as indicated below:



A summary of the results for the three modes of output is as follows:

Mode	DC Gain	Bandwidth (-3 db)
Constant Voltage DC Output	45 db	1200 Hz
Constant Voltage AC Output Through Capacitor	31-33 db	5000
Constant Current Taken Off B+	47 db	50 Hz

In addition, the amplifier output impedance is estimated to be 40 ohms with constant voltage and 4000 ohms with constant current (based on the test results shown on Figure 12).

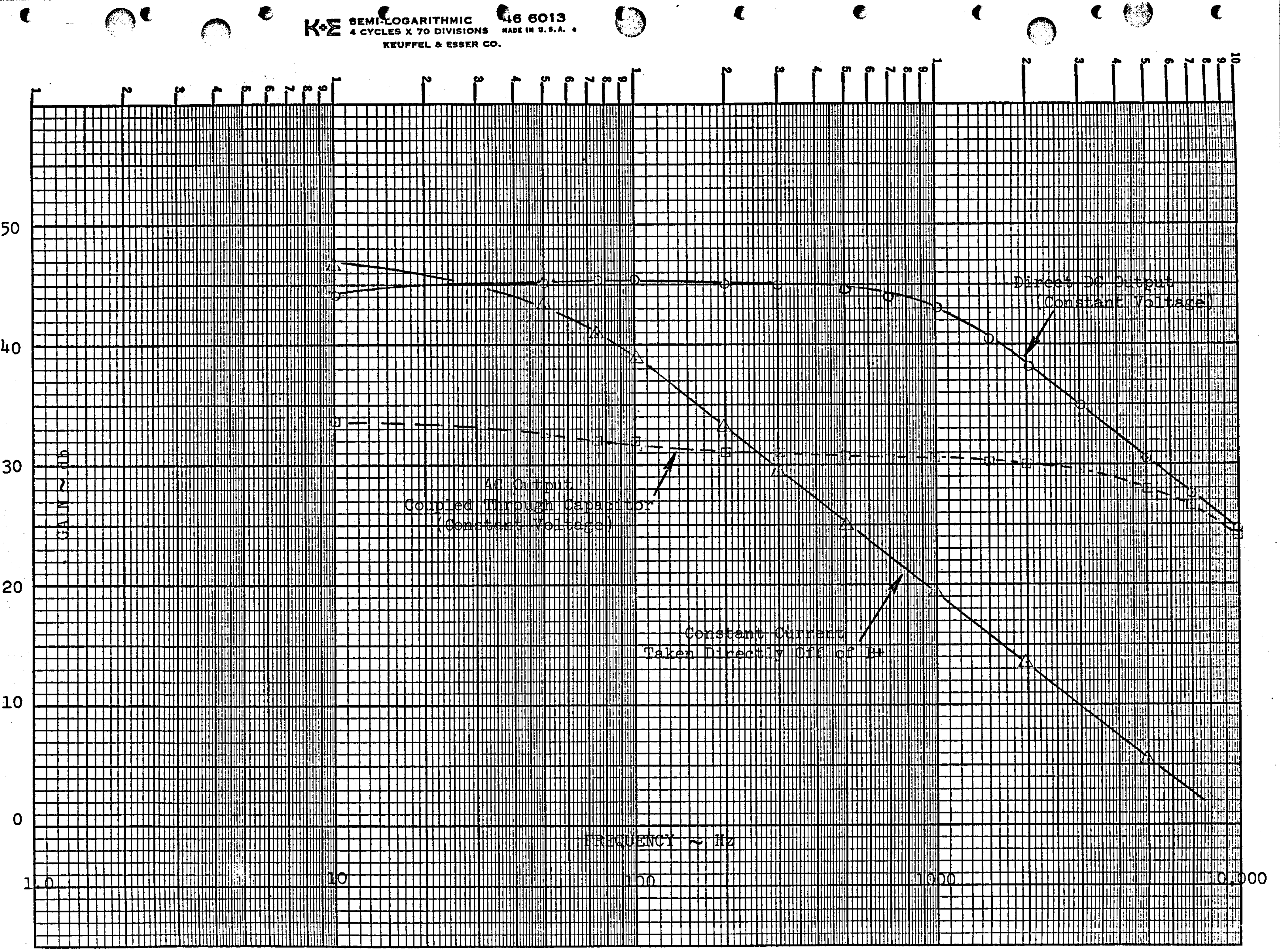


Figure 12. Frequency Response Prototype Amplifier Coupled to Simulated Transmission Line

4.0 OPERATION OF PROTOTYPE AMPLIFIER

Connections of the prototype amplifier to the logging cable for the three different modes of output are shown on Figure 13 and Table 2. Operating voltages and currents for the amplifier are as follows:

Heater Voltage ac (across amplifier)	Volt	25
Heater Current	Amp	.33
B+ (plate voltage)	Volt	225
Plate Current	ma	23.5

The conditions apply for both constant plate voltage and constant plate current. When operating in either mode (voltage or current) the limit for the other parameter (current or voltage) on the B+ power supply should be set well above the nominal value to avoid distortion.

Three options are provided for obtaining the output signal. In one, the DC plate supply line is utilized for transmitting the output signal to the surface and thereby eliminates one conductor. In order to utilize this scheme it is required to operate the plate power supply in the constant current mode. The output is then taken directly off of the amplifier plate supply line. Due to the relatively high output impedance this mode gives a frequency bandpass of less than 50 Hz. In the second, the power supply is operated in a constant voltage mode and the output taken directly off of the cathode of the cathode follower output stage. A signal bandpass of approximately 1000 Hz can be obtained in this mode. The third option is to take the output signal from the output capacitor which blocks the DC bias (approximately 50 volts) giving a frequency bandpass of approximately 5000 Hz, but at the expense of a factor of 4 to 5 reduction in signal amplitude.

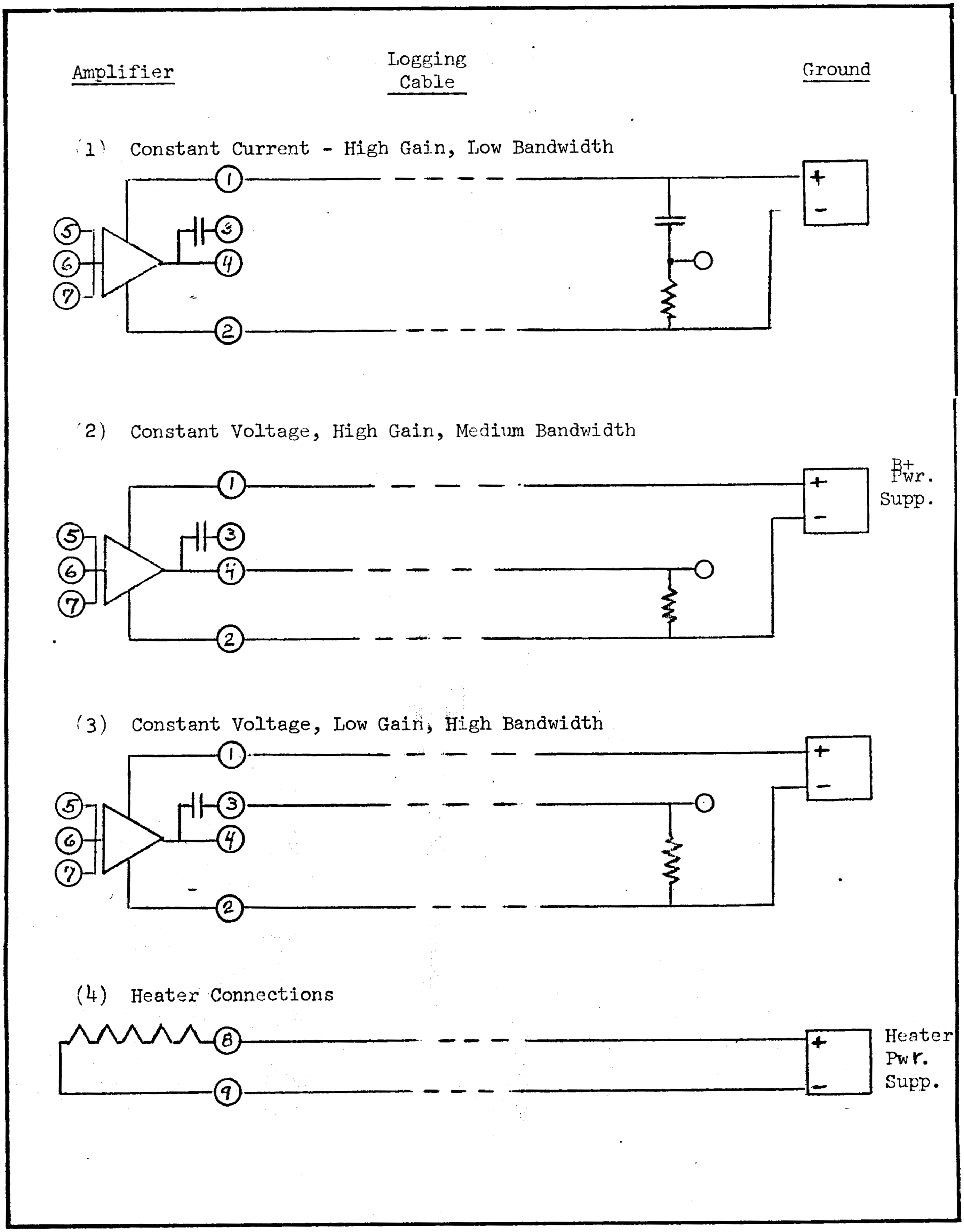


Figure 13. Amplifier Connections

Table 2. MRI High Temperature Amplifier Wiring

Tag Number	I.D.
1	B+
2	Common
3	AC Output
4	DC Output
5	Input (V1)
6	Input - Center Tap
7	Input (V2)
8	Heater
9	Heater
10	Spare - (through amp)
11	Spare - (through amp)
12	Spare - (through amp)
13	Spare - (through amp)
14	V4 Output (Spare)

5.0 APPENDICES

(A) Circuit Equations

(B) Vacuum Tube Characteristics

APPENDIX A

CIRCUIT EQUATIONS

PREPARED	WLC	DATE		SECTION NO.	SHEET 1 OF
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DIRECT CURRENT EQUATIONS (See Figure A1)

$$E_{bb} - R_1 i_1 - e_{P1} - e_8 = 0$$

$$E_{bb} - R_2 i_2 - e_{P2} - e_8 = 0$$

$$E_{bb} - R_3 (i_3 + i_7) - e_{P3} - e_{10} = 0$$

$$E_{bb} - R_4 i_4 - e_{P4} - e_{10} = 0$$

$$e_{10} - e_{P5} - e_{11} = 0$$

$$E_{bb} - e_{P6} - e_7 = 0$$

e_1 = INPUT #1

e_2 = INPUT #2

$$e_3 = E_{bb} - R_1 i_1$$

$$e_4 = E_{bb} - R_2 i_2$$

e_5 = CONSTANT

$$e_6 = e_9 - R_7 i_7$$

$$e_7 = R_6 (i_6 - i_6)$$

$$e_8 = R_{10} (i_1 + i_2)$$

$$e_9 = E_{bb} - R_3 (i_3 + i_7)$$

$$e_{11} = R_9 i_5$$

e_{FB1} = Feedback To V1

e_{FB2} = Feedback To V2

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CHECKED DATE

LINEAR EQUATIONS

In General:

$$\Delta e_P = r_P \Delta i - \mu \Delta e_c$$

Where plate Voltage, e_P, and Grid voltage, e_c, are Relative To Cathode. Plate resistance, r_P, and Amplification Factor, μ, are assumed Constant.

Therefore:

$$\Delta e_{P1} = r_{P1} \Delta i_1 - \mu_1((\Delta e_1 + \Delta e_{FB1}) - \Delta e_8)$$

$$\Delta e_{P2} = r_{P2} \Delta i_2 - \mu_2((\Delta e_2 + \Delta e_{FB2}) - \Delta e_8)$$

$$\Delta e_{P3} = r_{P3} \Delta i_3 - \mu_3(\Delta e_3 - \Delta e_{10})$$

$$\Delta e_{P4} = r_{P4} \Delta i_4 - \mu_4(\Delta e_4 - \Delta e_{10})$$

$$\Delta e_{P5} = r_{P5} \Delta i_5 - \mu_5(\Delta e_5 - \Delta e_{11})$$

$$\Delta e_{P6} = r_{P6} \Delta i_6 - \mu_6(\Delta e_6 - \Delta e_7)$$

1) $-(R_1 + r_{P1} + R_{10})\Delta i_1 - R_{10}\Delta i_2 = -\mu_1((\Delta e_1 + \Delta e_{FB1}) - \Delta e_8)$

2) $-(R_2 + r_{P2} + R_{10})\Delta i_2 - R_{10}\Delta i_1 = -\mu_2((\Delta e_2 + \Delta e_{FB2}) - \Delta e_8)$

3) $-(R_3 + r_{P3})\Delta i_3 - R_3 \Delta i_7 = -\mu_3(\Delta e_3 - \Delta e_{10}) + \Delta e_{10}$

4) $-(R_4 + r_{P4})\Delta i_4 = -\mu_4(\Delta e_4 - \Delta e_{10}) + \Delta e_{10}$

5) $-(R_5 + r_{P5} + R_9)\Delta i_5 = -\mu_5(\Delta e_5 - \Delta e_{11}) - \Delta e_{10}$

6) $-(r_{P6} + R_6)\Delta i_6 + R_6 \Delta i_L = -\mu_6(\Delta e_6 - \Delta e_7)$

OPEN LOOP EQUATIONS

NoTe ThaT:

$$\Delta e_3 = -R_1 \Delta i_1$$

$$\Delta e_4 = -R_2 \Delta i_2$$

$$\Delta e_5 = 0$$

$$\Delta e_6 = R_8 \Delta i_7 = \frac{R_8}{R_7 + R_8} \Delta e_9$$

$$\Delta e_8 = R_{10}(\Delta i_1 + \Delta i_2)$$

$$\Delta e_9 = -R_3(\Delta i_3 + \Delta i_7)$$

$$\Delta e_{11} = R_9 \Delta i_5$$

Therefore:

1) $-(R_1 + r_{p1} + (\mu_1+1)R_{10})\Delta i_1 - (\mu_1+1)R_{10}\Delta i_2 = -\mu_1 \Delta e_1$

2) $-(R_2 + r_{p2} + (\mu_2+1)R_{10})\Delta i_2 - (\mu_2+1)R_{10}\Delta i_1 = -\mu_2 \Delta e_2$

3) $\Delta e_9 - r_{p3}\Delta i_3 - \mu_3 R_1 \Delta i_1 = (\mu_3+1)\Delta e_{10}$

4) $-(R_4 + r_{p4})\Delta i_4 - \mu_4 R_1 \Delta i_2 = (\mu_4+1)\Delta e_{10}$

5) $-(R_5 + r_{p5} + (\mu_5+1)R_9)\Delta i_5 = = -\Delta e_{10}$

6) $-(r_{p6} + (\mu_6+1)R_6)\Delta i_6 = -\mu_6 \frac{R_7}{R_7+R_8}\Delta e_9$

And:

$$\Delta i_5 = \Delta i_3 + \Delta i_4$$

$$\Delta i_3 = -\Delta e_9\left(\frac{1}{R_3} + \frac{1}{R_7+R_8}\right)$$

$$\Delta e_2 = -\Delta e_1 = \text{INPUT}$$

$$\Delta e_{OUT} = R_6 \Delta i_6$$

Solution of equations 1 & 2 for the currents associated with the input differential stage yields (see equations 6-63 and 6-64, Ref 1)*:

$$1A)\quad \Delta i_1 = \frac{\mu_1 (R_2 + r_{p2} + (\mu_2+1)R_{10})\Delta e_1 - (\mu_1+1)R_{10}\mu_2 \Delta e_2}{(R_1 + r_{p1} + (\mu_1+1)R_{10})(R_2 + r_{p2} + (\mu_2+1)R_{10}) - (\mu_1+1)(\mu_2+1)R_{10}^2}$$

$$2A)\quad \Delta i_2 = \frac{\mu_2 (R_1 + r_{p1} + (\mu_1+1)R_{10})\Delta e_2 - (\mu_2+1)R_{10}\mu_1 \Delta e_1}{(R_1 + r_{p1} + (\mu_1+1)R_{10})(R_2 + r_{p2} + (\mu_2+1)R_{10}) - (\mu_1+1)(\mu_2+1)R_{10}^2}$$

If both branches of the differential circuit are balanced so that common cathode voltage is constant ($\Delta e_8 = 0$), the above relationships simplify to:

$$1B)\quad \Delta i_1 = \frac{\mu_1}{(R_1 + r_{p1})}\Delta e_1$$

$$2B)\quad \Delta i_2 = \frac{\mu_2}{(R_2 + r_{p2})}\Delta e_2$$

For equations 1A and 2A let

$$A = \mu_1 (R_2 + r_{p2} + (\mu_2+1)R_{10})$$

$$B = (\mu_1+1)R_{10}\mu_2 \simeq (\mu_2+1)R_{10}\mu_1$$

$$C = \mu_2 (R_1 + r_{p1} + (\mu_1+1)R_{10})$$

$$D = (R_1 + r_{p1} + (\mu_1+1)R_{10})(R_2 + r_{p2} + (\mu_2+1)R_{10}) - (\mu_1+1)(\mu_2+1)R_{10}^2$$

* Ref 1 =

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Then if $\Delta e_2 = -\Delta e_1$

$$1c) \quad \Delta i_1 = \frac{A+B}{D}\,\Delta e_1$$

$$2c) \quad \Delta i_2 = \frac{-C-B}{D}\,\Delta e_1$$

Solution of equations 1C, 2C, 3, 4 and 5

$$\overset{-}{\Big(}1+r_{p3}\Big(\frac{1}{R_3}+\frac{1}{R_7+R_8}\Big)\Big)\Delta e_9 - (\mu_3+1)\big(R_5+r_{p5}+(\mu_5+1)R_9\big)\Delta i_5 = \mu_3 R_1 \frac{A+B}{D}\Delta e_1$$

$$-(R_4+r_{p4})\underset{+}{\Big(}\frac{1}{R_3}+\frac{1}{R_7+R_8}\Big)\Delta e_9 - \Big[(\mu_4+1)\big(R_5+r_{p5}+(\mu_5+1)R_9\big)+(R_4+r_{p4})\Big]\Delta i_5$$
$$= -\mu_4 R_2 \frac{C+B}{D}\Delta e_1$$

And solving for the output of V8:

$$\Delta e_9 = \frac{\Big\{-\mu_3 R_1 \frac{A+B}{D}\Big[(\mu_4+1)\big(R_5+r_{p5}+(\mu_5+1)R_9+(R_4+r_{p4})\big)\Big] - \mu_4 R_2 \frac{B+C}{D}\Big[(\mu_3+1)\big(R_5+r_{p5}+(\mu_5+1)R_9\Big]\Big\}\Delta e_1}{\Big\{-\Big[1+r_{p3}\Big(\frac{1}{R_3}+\frac{1}{R_7+R_8}\Big)\Big]\Big[(\mu_4+1)\big(R_5+r_{p5}+(\mu_5+1)R_9\big)+(R_4+r_{p4})\Big] - \Big[(R_4+r_{p4})\Big(\frac{1}{R_3}+\frac{1}{R_7+R_8}\Big)\Big](\mu_3+1)\big(R_5+r_{p5}+(\mu_5+1)R_9\big)\Big\}}$$

As a design simplification Tube V5 can be eliminated leaving a simple cathode bias resistor for Tubes V3 and V4. In this case $\mu_5 = 0$, $r_{p5} =$ and $R_9 = 0$ in the above equation.

MRI-198

Finally, for the cathode follower output:

$$e_{out} = \frac{R_6 \mu_6 \frac{R_8}{R_7+R_8}}{\left(r_{p6} + (\mu_6+1)R_6\right)} \Delta e_g$$

Where $R_6 = R_{6A} + R_{6B}$

The output impedance equals:

$$R_o = \frac{r_{p6} R_6}{(\mu_6+1) R_6 + r_{p6}}$$

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CLOSED LOOP

feedback is provided by a voltage divider from The cathode of V6 To The grids of V1 and V2.

$$\Delta e_{FB1} = \frac{R_{6B}}{R_{6A}+R_{6B}} \times e_{OUT} \times \frac{R_{17}}{R_{17}+R_{18}+R_{FB}}$$

$$\Delta e_{FB2} = \frac{R_{6B}}{R_{6A}+R_{65}} \quad e_{OUT} \quad \frac{R_{17}+R_{14}}{R_{17}+R_{18}+R_{FB}}$$

Where as before

$$\Delta e_{OUT} = \frac{\mu_c R_c \left(\frac{R_8}{R_7+R_8}\right) \Delta e_q}{\left(r_{pc}+(\mu_c+1)R_c\right)}$$

In order To simplify the final expression, LeT:

$$\Delta e_{FB1} = K_1 \Delta e_q \; ; \; K_1 = \frac{R_{6B}}{(R_{6A}+R_{6B})} \times \frac{R_{17}}{(R_{17}+R_{14}+R_{FB})} \times \frac{\mu_c R_c \frac{R_4}{R_7+R_4}}{(r_{pc}+(\mu_c+1)R_c)}$$

$$\Delta e_{FB2} = K_2 \Delta e_q \; ; \; K_2 = \text{same} \times \frac{R_{17}+R_{14}}{R_{17}+R_{18}+R_{FB}} \times \text{same}$$

so ThaT:

$$\Delta i_1 = \frac{A+B}{D} \Delta e_1 + \frac{K_1 A + K_2 B}{D} \Delta e_q$$

$$\Delta i_2 = \frac{-C-B}{D} \Delta e_1 - \frac{(K_2 C + K_1 B)}{D} \Delta e_q$$

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The closed loop equation for Tube V3 Then becomes:

$$\Delta e_9 = \frac{\begin{array}{l}\{-\mu_3 R_1 \frac{A+B}{D}\left[(\mu_4+1)(R_5+r_{p5}+(\mu_5+1)R_9+(R_4+r_{p4})\right] \\ \quad -\mu_4 R_2 \frac{B+C}{D}\left[(\mu_3+1)(R_5+r_{p5}+(\mu_5+1)R_9\right]\}\ \Delta e_1\end{array}}{\begin{array}{l}\{-\left[1+r_{p3}\left(\frac{1}{R_3}+\frac{1}{R_7+R_8}\right)-\mu_3 R_1\left(\frac{K_1A+K_2B}{D}\right)\right]\left[(\mu_4+1)(R_5+r_{p5}\right. \\ \quad \left.+(\mu_5+1)R_9)+(R_4+r_{p4})\right] \\ \quad -\left[(R_4+r_{p4})\left(\frac{1}{R_3}+\frac{1}{R_7+R_8}\right)-\mu_4 R_2\left(\frac{K_2C+K_1B}{D}\right)\right](\mu_3+1)(R_5 \\ \quad +r_{p5}+(\mu_5+1)R_9)\}\end{array}}$$

Which is used To calculate Δe_{OUT}

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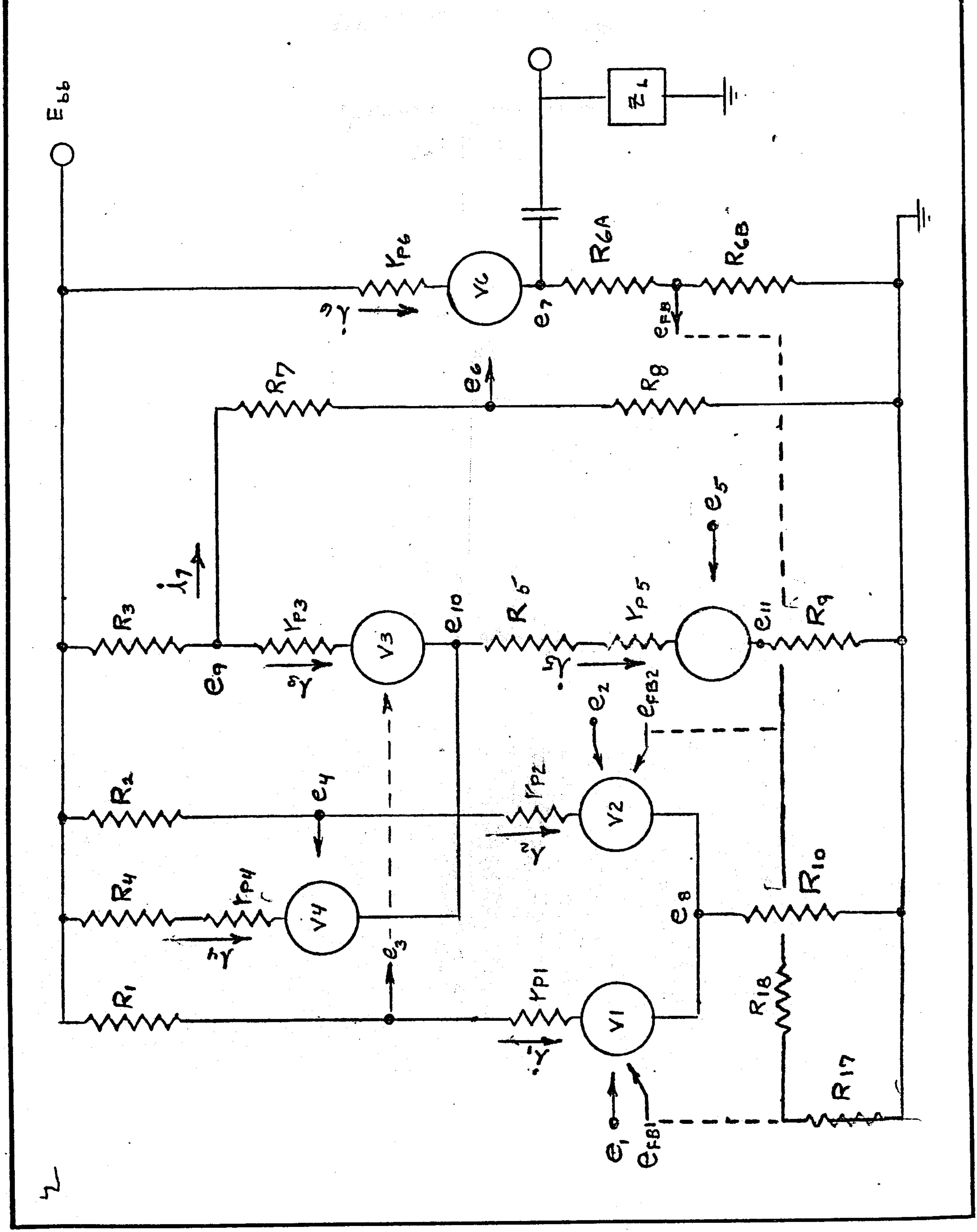
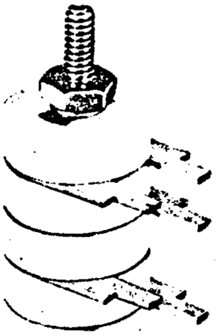


Figure a1. Circuit for Linear Analysis

APPENDIX B

TUBE CHARACTERISTICS

ELECTRONICS 7588
METAL-CERAMIC TRIODE



DESCRIPTION AND RATING

The 7588 is a high-mu triode of ceramic-and-metal planar construction. The tube is intended for use as a broadband radio-frequency amplifier at frequencies up to 500 megacycles.

GENERAL

ELECTRICAL

Cathode—Coated Unipotential

Heater Characteristics and Ratings

Heater Voltage, AC or DC*	6.3 ± 0.3	Volts
Heater Current†	0.4	Amperes
Direct Interelectrode Capacitances‡		
Grid to Plate: (g to p)	2.8	pf
Input: g to (h+k)	6.5	pf
Output: p to (h+k)	0.075	pf
Heater to Cathode: (h to k)	2.6	pf

MECHANICAL

Mounting Position—Any§

See Physical Dimensions on page 4 for dimensions and electrical connections.

MAXIMUM RATINGS

ABSOLUTE-MAXIMUM VALUES

Plate Voltage	300 Volts
Positive DC Grid-to-Cathode Voltage	0 Volts
Negative DC Grid Voltage	50 Volts
Plate Dissipation	5.5 Watts
DC Cathode Current	30 Milliamperes
Heater-Cathode Voltage	
Heater Positive with Respect to Cathode	50 Volts
Heater Negative with Respect to Cathode	50 Volts
Grid Circuit Resistance	
With Fixed Bias	0.025 Megohms
With Cathode Bias	0.1 Megohms
Envelope Temperature at Hottest Point	250 C

Absolute-Maximum ratings are limiting values of operating and environmental conditions applicable to any electron tube of a specified type as defined by its published data and should not be exceeded under the worst probable conditions.

The tube manufacturer chooses these values to provide acceptable serviceability of the tube, making no allowance for equipment variations, environmental variations, and the effects of changes in operating conditions due to variations in the characteristics of the tube under consideration and of all other electron devices in the equipment.

The equipment manufacturer should design so that initially and throughout life no absolute-maximum value for the intended service is exceeded with any tube under the worst probable operating conditions with respect to supply-voltage variation, equipment component variation, equipment control adjustment, load variation, signal variation, environmental conditions, and variations in the characteristics of the tube under consideration and of all other electron devices in the equipment.

CHARACTERISTICS AND TYPICAL OPERATION

AVERAGE CHARACTERISTICS

Plate Voltage	200 Volts
Positive Grid Voltage	6.0 Volts
Cathode-Bias Resistor	270 Ohms
Amplification Factor	175
Plate Resistance, approximate	3900 Ohms
Transconductance	45000 Micromhos
Plate Current	24 Milliamperes
Grid Voltage, approximate	
Ib = 100 Microamperes	−5 Volts
Noise Figure¶	3.0 Decibels

GENERAL ELECTRIC

Supersedes 7588 D & R Sheet ET-T1620, dated 6-60

FOOTNOTES

- * The equipment designer should design the equipment so that heater voltage is centered at the specified bogey value, with heater supply variations restricted to maintain heater voltage within the specified tolerance.
- † Heater current of a bogey tube at Ef=6.3 volts.
- ‡ Without external shield.
- § One method of mounting the 7588 is to use a stainless-steel "T" bolt (see drawing) to attach the mounting base of the tube to a chassis or circuit board. The "T" bolt should be inserted in the slot in the base of the tube, turned 90 degrees, and attached to the chassis or circuit board with a 4-40 nut and lock washer. Torque used to tighten the nut should not exceed 3 inch-pounds.
- ¶ Measured at 200 megacycles in a grounded-grid amplifier and corrected for second-stage noise figure and diode temperature.

INITIAL CHARACTERISTICS LIMITS

	Min.	Bogey	Max.	
Heater Current				
Ef=6.3 volts	370	400	430	Milliamperes
Plate Current				
Ef=6.3 volts, Eb=200 volts, Rk=22 ohms	17	25	33	Milliamperes
Transconductance				
Ef=6.3 volts, Eb=200 volts, Ec=+6 volts, Rk=270 ohms (bypassed)	35000	45000	55000	Micromhos
Amplification Factor				
Ef=6.3 volts, Eb=200 volts, Ec=+6 volts, Rk=270 Ohms (bypassed)	140	175	210	
Transconductance Change with Heater Voltage				
Difference between transconductance at Ef=6.3 volts and transconductance at Ef=5.7 volts (other conditions the same) expressed as a percentage of transconductance at Ef=6.3 volts	.....	.....	20	Percent
Grid Voltage Cutoff				
Ef=6.3 volts, Eb=200 volts, Ib=100 μa	.....	−5.0	−8.0	Volts
Noise Figure				
Ef=6.3 volts, Ebb=265 volts, Ec=0 volts, R_L=3300 ohms, (bypassed), Rk=22 ohms, F=200±10 MC	.....	3.0	4.8	Decibels
Interelectrode Capacitances				
Grid to Plate: (g to p)	2.1	2.8	3.5	pf
Input: g to (h+k)	5.1	6.7	8.3	pf
Output: p to (h+k)	0.05	0.075	0.1	pf
Heater to Cathode: (h to k)	1.9	2.6	3.3	pf
Negative Grid Current				
Ef=6.3 volts, Eb=200 volts, Ecc=−1.0 volts, Rk=22 ohms (bypassed), Rg=0.1 meg		.....	0.5	Microamperes
Heater-Cathode Leakage Current				
Ef=6.3 volts, Ehk=100 volts				
Heater Positive with Respect to Cathode		.....	20	Microamperes
Heater Negative with Respect to Cathode		.....	20	Microamperes
Interelectrode Leakage Resistance				
Ef=6.3 volts. Polarity of applied d-c interelectrode voltage is such that no cathode emission results.				
Grid to All at 100 volts d-c	50	.....	.....	Megohms
Plate to All at 300 volts d-c	50	.....	.....	Megohms
Grid Emission Current				
Ef=7.0 volts, Eb=200 volts, Ecc=−15 volts, Rg=0.1 meg		.....	2.0	Microamperes

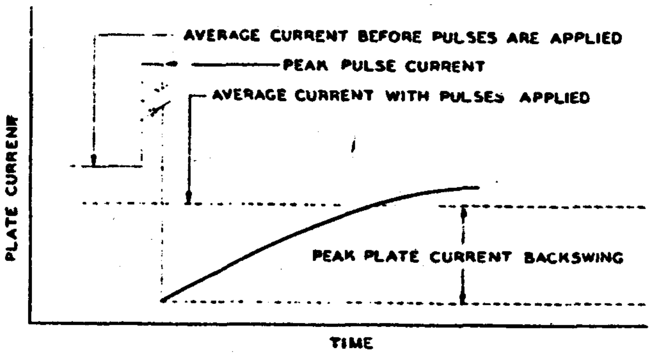
SPECIAL PERFORMANCE TESTS

	Min.	Bogey	Max.	
Grid Recovery				
Change in Average Plate Current		....	1.0	Milliamperes
Peak Plate Current Backswing		....	2.0	Milliamperes

Tubes with poor grid recovery affect circuit operation when the grid is driven positive by a pulse of signal or noise, somewhat as if a parallel RC circuit were in series with the grid. This effect may occur in tubes of any type but is unimportant in many applications. In the majority of 7588 tubes the effect is negligible, but to eliminate the few in which it may be excessive, tubes are tested under the following conditions: Ef = 6.3 volts, Ebb = 250 volts, R_L = 0.01 meg. EC is adjusted for Ib = 10 ma.

Upon application to the grid of a pulse driving it 3 volts positive with respect to cathode (prr = 60 pps, duty cycle = 0.12%) the change in average plate current is noted, and the peak plate current backswing is measured. The following diagram shows qualitatively the plate current-time relationship for a tube (with poor grid recovery) subjected to this test:

PLATE CURRENT VS TIME
—GRID RECOVERY TEST



	Min.	Bogey	Max.	
Low Frequency Vibrational Output Statistical sample is subjected to vibration in each of two planes at 40 cps, with peak acceleration 15G. Tube is operated with Ef = 6.3 volts, Ebb = 250 volts, Rk = 68 ohms (bypassed), R_L = 2000 ohms	....	......	25	Millivolts RMS
Variable Frequency Vibrational Output Statistical sample is subjected to vibration according to the procedure given below. Tube is operated with Ef = 6.3 volts, Ebb = 250 volts, Rk = 68 ohms (bypassed), R_L = 2000 ohms	....	......	75	Millivolts RMS

The variable-frequency vibration test shall be performed as follows:

1. The frequency shall be increased from 100 to 2000 cps with approximately logarithmic progression in 3 ± 1 minutes. The return sweep (2000 to 100 cps) is not required.
2. The tube shall be vibrated with simple harmonic motion in each of two planes: first, parallel to the cylindrical axis; second, perpendicular to the cylindrical axis and parallel to a line through the major axis of a terminal lug. At all frequencies from 100 to 2000 cps, the total harmonic distortion of the acceleration wave form shall be less than 5%.
3. The peak acceleration shall be maintained at 10 ± 1.0 G throughout the test.
4. The value of the alternating voltage produced across the load resistor (R_L), as a result of the vibration, shall be measured with a suitable device having a response to the RMS value of the voltage to within ± 0.5 db of the response at 400 cps for the frequency range of 100 to 3000 cps, and having a band-pass filter with an attenuation rate of 24 db per octave below the low frequency cutoff point of 50 cps and above the high frequency cutoff point of 5000 cps. The meter shall have a dynamic response characteristic equivalent to or faster than a VU meter (operated in accordance with ASA Standard No. C16.5–1954).

Low Pressure Voltage Breakdown Test

Statistical sample tested for voltage breakdown at a pressure of 8mm Hg, to simulate an altitude of 100,000 feet. Tubes shall not give visual evidence of flashover or corona when 300 volts RMS, 60 cps, is applied between the plate and grid terminals.

DEGRADATION RATE TESTS

Fatigue

Statistical sample vibrated for a total of six hours, three hours in each of two planes, at a peak acceleration of 10 G. Frequency is continuously varied from 30 cps to 2000 cps and back to 30 cps, with a period of ten minutes. Tubes are operated during the test with Ef = 6.3 volts, Eb = 250 volts, and Rk = 68 ohms. Following the test, tubes are evaluated for low frequency vibrational output, heater-cathode leakage, heater current, and transconductance.

DEGRADATION RATE TESTS (Continued)

Shock

Statistical sample subjected to 5 impact accelerations of approximately 450 G in each of four positions. The accelerating forces are applied by the Navy-type, High Impact (flyweight) Shock Machine using a 30° hammer angle. Tubes are mounted by T-bolt with 3 inch-pounds torque, and operated during the test with Ef = 6.3 volts, Eb = 250 volts, Ehk = +100 volts, Rg = 0.1 meg, and Rk = 68 ohms. Following the test, tubes are evaluated for low frequency vibrational output, heater-cathode leakage, heater current, and transconductance.

Stability Life Test

The statistical sample subjected to the Intermittent Life Test is evaluated for percent change in transconductance of individual tubes, from the initial reading to readings following 2 hours and 20 hours of the life test.

Survival Rate Life Test

The statistical sample subjected to the Intermittent Life Test is evaluated for shorted and open elements, and transconductance, following approximately 100 hours of life test.

Intermittent Life Test

Statistical sample operated 1000 hours under the following conditions: Ef = 6.3 volts, Eb = 200 volts, Ecc = +6 volts, Ehk = −70 volts, Rk = 270 ohms, Rg = 0.1 meg. Heater voltage is cycled (on 1¾ hours, off ¼ hour). Tubes are evaluated, following 500 and 1000 hours of life test, for shorted or open elements, heater current, transconductance, negative grid current, noise figure, heater-cathode leakage, and interelectrode leakage resistance.

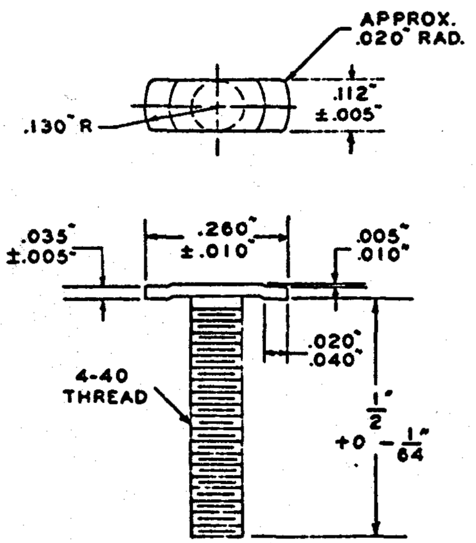
Interface Life Test

Statistical sample operated for 1000 hours with Ef = 6.6 volts, no other voltages applied, and evaluated for cathode interface resistance following the life test.

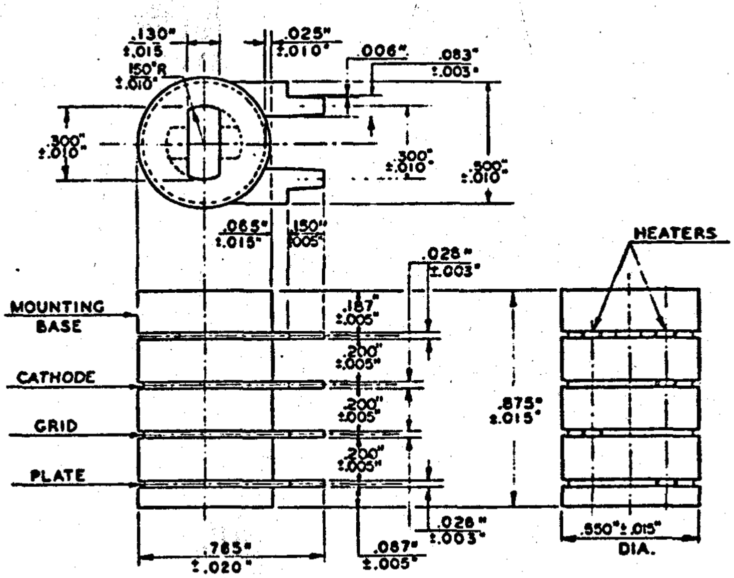
Heater-Cycling Life Test

Statistical sample operated for 2000 cycles minimum to evaluate and control heater-cathode defects. Conditions of test include Ef = 7.5 volts cycled for one minute on and one minute off, Eb = Ec = 0 volts, and Ehk = 70 volts with heater positive with respect to cathode. Following this test, tubes are evaluated for open heaters, heater-cathode shorts, and heater-cathode leakage current.

MOUNTING BOLT

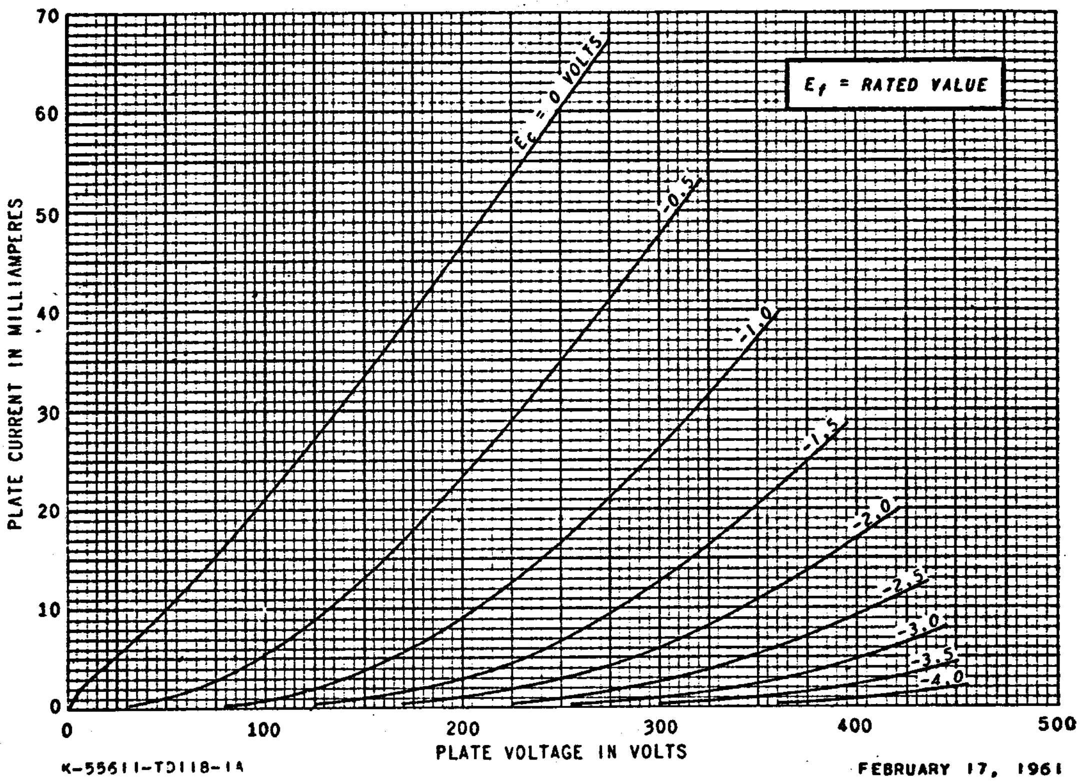


PHYSICAL DIMENSIONS



Maximum eccentricity of insulators 0.015 in. from center line.

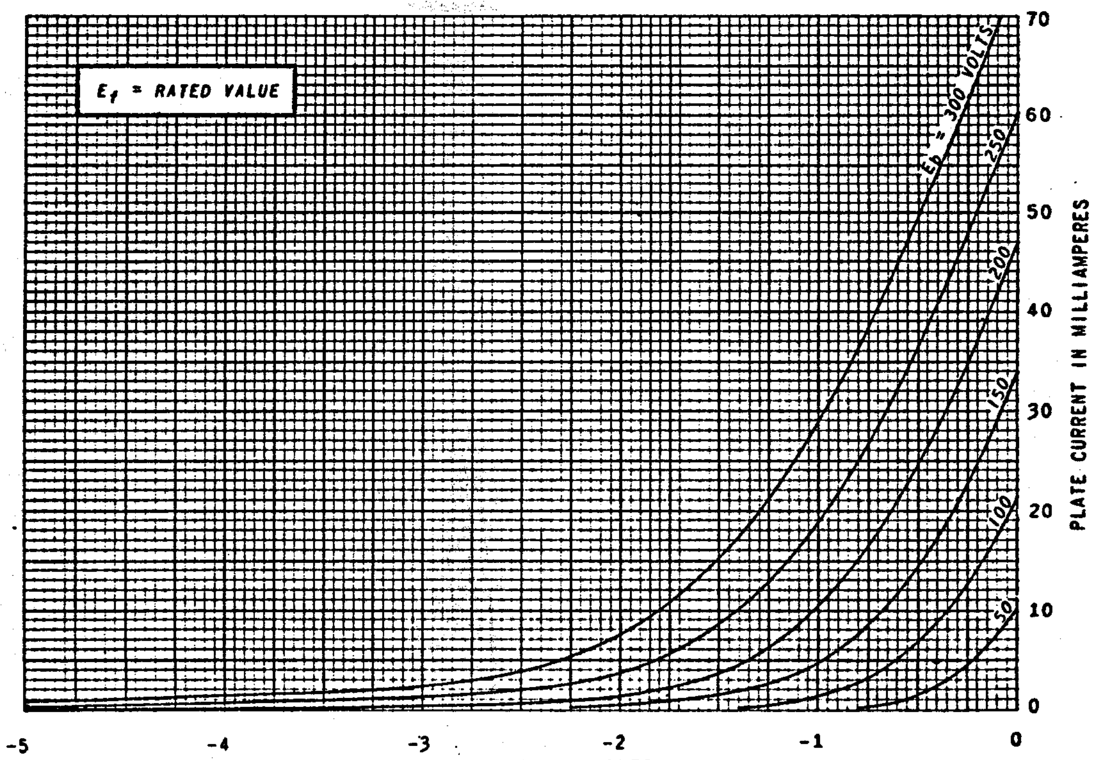
AVERAGE PLATE CHARACTERISTICS



K-55611-TD118-1A

FEBRUARY 17, 1961

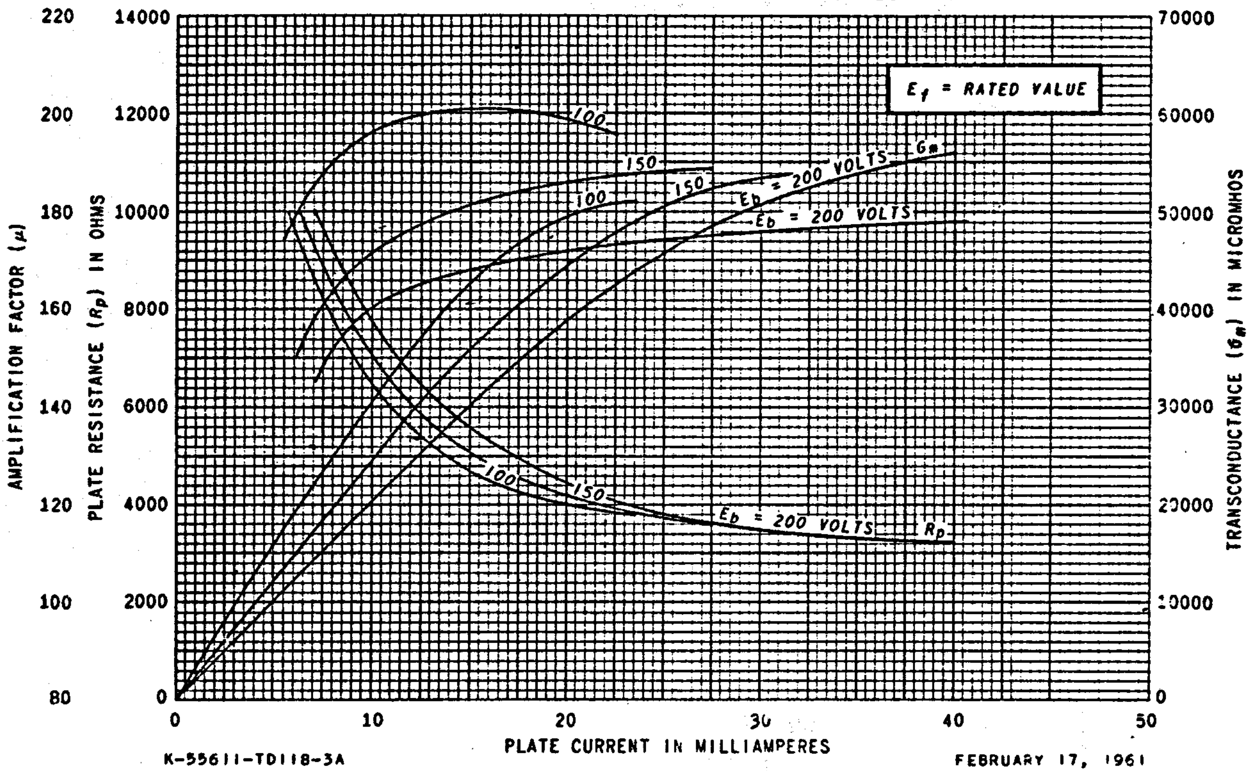
AVERAGE TRANSFER CHARACTERISTICS



K-55611-TD118-2A

FEBRUARY 17, 1961

AVERAGE PLATE CHARACTERISTICS



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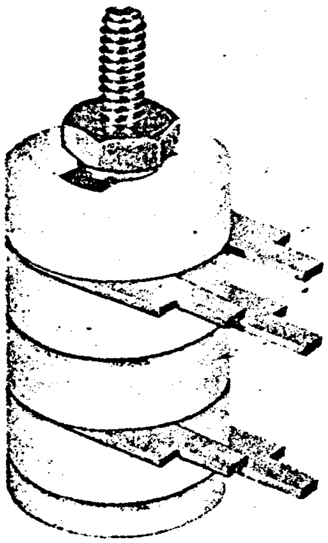
FEBRUARY 17, 1961

RECEIVING TUBE DEPARTMENT
GENERAL ELECTRIC
Owensboro, Kentucky

GE ELECTRONICS

7296

METAL-CERAMIC TRIODE



DESCRIPTION AND RATING

FOR VHF OSCILLATOR AND AMPLIFIER APPLICATIONS

The 7296 is a high-mu triode of ceramic-and-metal planar construction primarily intended for use as an oscillator, broadband radio-frequency amplifier, or VHF power amplifier. The 7296 is especially suited for use where unfavorable conditions of mechanical shock, mechanical vibration, and nuclear radiation are encountered.

GENERAL

ELECTRICAL

Cathode—Coated Unipotential

Heater Voltage, AC or DC *	6.3±0.3	Volts
Heater Current +	0.4	Amperes
Direct Interelectrode Capacitances ‡		
Grid to Plate: (g to p)	2.2	pf
Input: g to (h + k)	5.0	pf
Output: p to (h + k)	0.075	pf
Heater to Cathode: (h to k)	2.8	pf

MECHANICAL

Mounting Position—Any §

MAXIMUM RATINGS

ABSOLUTE-MAXIMUM VALUES

Plate Voltage	330	Volts
Positive DC Grid Voltage	0	Volts
Negative DC Grid Voltage	50	Volts
Plate Dissipation	5.5	Watts
DC Grid Current	10	Milliamperes
DC Cathode Current	30	Milliamperes
Peak Cathode Current	120	Milliamperes
Heater-Cathode Voltage		
Heater Positive with Respect to Cathode	50	Volts
Heater Negative with Respect to Cathode	50	Volts
Grid Circuit Resistance		
With Fixed Bias	0.1	Megohms
With Cathode Bias	0.18	Megohms
Envelope Temperature at Hottest Point #		
Plate Dissipation not over 3.3 Watts	300	C
Plate Dissipation up to 5.5 Watts	250	C

Absolute-Maximum ratings are limiting values of operating and environmental conditions applicable to any electron tube of a specified type as defined by its published data and should not be exceeded under the worst probable conditions.

The tube manufacturer chooses these values to provide acceptable serviceability of the tube, making no allowance for equipment variations, environmental variations, and the effects of changes in operating conditions due to variations in the characteristics of the tube under consideration and of all other electron devices in the equipment.

The equipment manufacturer should design so that initially and throughout life no absolute-maximum value for the intended service is exceeded with any tube under the worst probable operating conditions with respect to supply-voltage variation, equipment component variation, equipment control adjustment, load variation, signal variation, environmental conditions, and variations in the characteristics of the tube under consideration and of all other electron devices in the equipment.

GENERAL ELECTRIC

Supersedes ET-T1538A dated 2-60

CHARACTERISTICS AND TYPICAL OPERATION

AVERAGE CHARACTERISTICS

Plate Voltage	200	Volts
Cathode-Bias Resistor	68	Ohms
Amplification Factor	90	
Plate Resistance, approximate	5450	Ohms
Transconductance	16500	Micromhos
Plate Current	17	Milliamperes
Grid Voltage, approximate Ib = 10 Microamperes	−5.5	Volts

• The equipment designer should design the equipment so that the heater voltage is centered at the specified bogey value, with heater supply variations restricted to maintain heater voltage within the specified tolerance.

† Heater current of a bogey tube at Ef = 6.3 volts.

‡ Without external shield.

§ One method of mounting the 7296 is to use a stainless-steel "T" bolt (see drawing) to attach the mounting base of the tube to a chassis or circuit board. The "T" bolt should be inserted in the slot in the base of the tube, turned 90 degrees, and attached to the chassis or circuit board with a 4-40 nut and lock washer. Torque used to tighten the nut should not exceed 3 inch-pounds.

Operation below the rated maximum envelope temperatures is recommended for applications requiring the longest possible tube life. The 7296 is also capable of operation at envelope temperatures much higher than the rated maximum values. For specific recommendations concerning higher temperature operation, contact your General Electric tube sales representative.

INITIAL CHARACTERISTICS LIMITS

	Min.	Bogey	Max.	
Heater Current Ef = 6.3 volts	370	400	430	Milliamperes
Plate Current Ef = 6.3 volts, Eb = 200 volts, Rk = 68 ohms (bypassed)	10	17	24	Milliamperes
Transconductance Ef = 6.3 volts, Eb = 200 volts, Rk = 68 ohms (bypassed)	13000	16500	20000	Micromhos
Amplification Factor Ef = 6.3 volts, Eb = 100 volts, Rk = 68 ohms (bypassed)	65	90	115	
Zero-Bias Transconductance Ef = 6.3 volts, Eb = 100 volts, Ec = 0 volts	13000	20000	.....	Micromhos
Grid Voltage Cutoff Ef = 6.3 volts, Eb = 200 volts, Ib = 10 μa	.....	−5.5	−9.5	Volts
Interelectrode Capacitances				
Grid to Plate (g to p)	1.9	2.2	2.5	pf
Input: g to (h + k)	3.7	5.0	6.3	pf
Output: p to (h + k)	0.05	0.075	0.1	pf
Heater to Cathode: (h to k)	2.1	2.8	3.5	pf
Negative Grid Current Ef = 6.3 volts, Eb = 200 volts, Ecc = −1.0 volts, Rk = 68 ohms (bypassed), Rg = 0.18 meg	.....	.....	0.5	Microamperes
Heater-Cathode Leakage Current Ef = 6.3 volts, Ehk = 100 volts				
Heater Positive with Respect to Cathode	.....	.....	20	Microamperes
Heater Negative with Respect to Cathode	.....	.....	20	Microamperes
Interelectrode Leakage Resistance Ef = 6.3 volts. Polarity of applied d-c interelectrode voltage is such that no cathode emission results.				
Grid to All at 100 volts d-c	100	.....	.....	Megohms
Plate to All at 300 volts d-c	100	.....	.....	Megohms
Grid Emission Current Ef = 7.0 volts, Eb = 200 volts, Ecc = −15 volts, Rg = 0.18 meg	.....	.....	2.0	Microamperes

SPECIAL PERFORMANCE TESTS

	Min.	Bogey	Max.	
400 Megacycle Oscillator Power Output	1.6	2.0	.....	Watts

Tubes are tested for power output as an oscillator under the following conditions: F = 400 mc, Ef = 6.3 volts, Eb = 300 volts, Rg = 1400 ohms, Ib = 20 ma maximum, Ic = 6.0–9.0 ma.

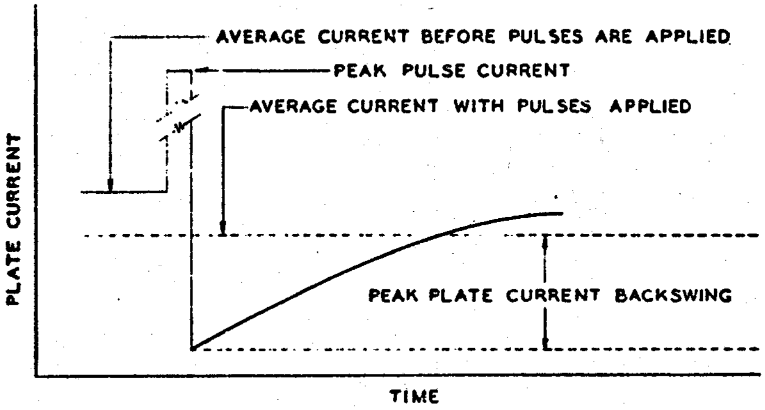
	Min.	Bogey	Max.	
Pulse Emission	320	.....	.....	Milliamperes

Tubes are tested for pulse emission under the following conditions: Ef = 6.3 volts, Eb = 200 volts, Ec = −20 volts, egk = +12 volts, prr = 1000 pps, duty cycle 1%. Pulse cathode current is measured.

	Min.	Bogey	Max.	
Grid Recovery..... Change in Average Plate Current	.....	.....	1.0	Milliamperes
Peak Plate Current Backswing	.....	.....	2.0	Milliamperes

Tubes with poor grid recovery affect circuit operation, when the grid is driven positive by a pulse of signal or noise, somewhat as if a parallel RC circuit were in series with the grid. This effect may occur in tubes of any type, but is unimportant in many applications. In the majority of 7296 tubes the effect is negligible, but to eliminate the few in which it may be excessive, tubes are tested under the following conditions: Ef = 6.3 volts, Ebb = 250 volts, R_L = 0.01 meg. Ec is adjusted for Ib = 10 ma.

Upon application to the grid of a pulse driving it 3 volts positive with respect to cathode (prr = 60 pps, duty cycle = 0.12%) the change in average plate current is noted, and the peak plate current backswing is measured. The following diagram shows qualitatively the plate current—time relationship for a tube (with poor grid recovery) subjected to this test:



	Min.	Bogey	Max.	
Low Frequency Vibrational Output	.....	.....	15	Millivolts RMS

Statistical sample is subjected to vibration in each of two planes at 40 cps, with peak acceleration 15 G. Tube is operated with Ef = 6.3 volts, Ebb = 200 volts, Rk = 68 ohms (bypassed), R_L = 2000 ohms.

Variable Frequency Vibrational Output

The tube is designed to be free of vibrational outputs in excess of 100 mv RMS at any frequency within the range 100–2000 cps, when vibrated in either of two planes at 10 G peak acceleration. Electrical conditions for this test are the same as for Low Frequency Vibrational Output.

Low Pressure Voltage Breakdown Test

Statistical sample tested for voltage breakdown at a pressure of 8 mm Hg, to simulate an altitude of 100,000 feet. Tubes shall not give visual evidence of flashover or corona when 300 volts RMS, 60 cps, is applied between the plate and grid terminals.

DEGRADATION RATE TESTS

Fatigue

Statistical sample vibrated for a total of six hours, three hours in each of two planes, at a peak acceleration of 10 G. Frequency is continuously varied from 30 cps to 2000 cps and back to 30 cps, with a period of ten minutes. Tubes are operated during the test with Ef = 6.3 volts, Eb = 200 volts, and Rk = 68 ohms. Following the test, tubes are evaluated for low frequency vibrational output, heater-cathode leakage, heater current, and transconductance.

Shock

Statistical sample subjected to 5 impact accelerations of approximately 600 G in each of four positions. The accelerating forces are applied by the Navy-type, High Impact (flyweight) Shock Machine using a 42° hammer angle. Tubes are mounted by T-bolt with 3 inch-pounds torque, and operated during the test with Ef = 6.3 volts, Eb = 200 volts, Ehk = +100 volts, Rg = 0.1 Meg, and Rk = 68 ohms. Following the test, tubes are evaluated for low frequency vibrational output, heater-cathode leakage, heater current, and transconductance.

Stability Life Test

The statistical sample subjected to the Dynamic Life Test is evaluated for percent change in zero-bias transconductance of individual tubes, from the initial reading to readings following 2 hours and 20 hours of the life test.

Survival Rate Life Test

The combined statistical samples subjected to the Dynamic and Pulse Life Tests are evaluated for shorted and open elements following approximately 100 hours of life test.

Dynamic Life Test

Statistical sample operated, with a 60 cps grid signal, at maximum rated DC grid current and cathode current for a period of 1000 hours. Heater voltage is cycled (on 1¾ hours, off ¼ hour). Tubes are evaluated, following 500 and 1000 hours of life test, for shorted or open elements, heater current, zero-bias transconductance, oscillator power output, and heater-cathode leakage.

Pulse Life Test

Statistical sample operated with 400 ma peak cathode current, 1% duty cycle, for 1000 hours. Heater voltage is cycled (on 1¾ hours, off ¼ hour). Tubes are evaluated, following 500 and 1000 hours of life test, for shorted or open elements, heater current, pulse emission, and heater-cathode leakage.

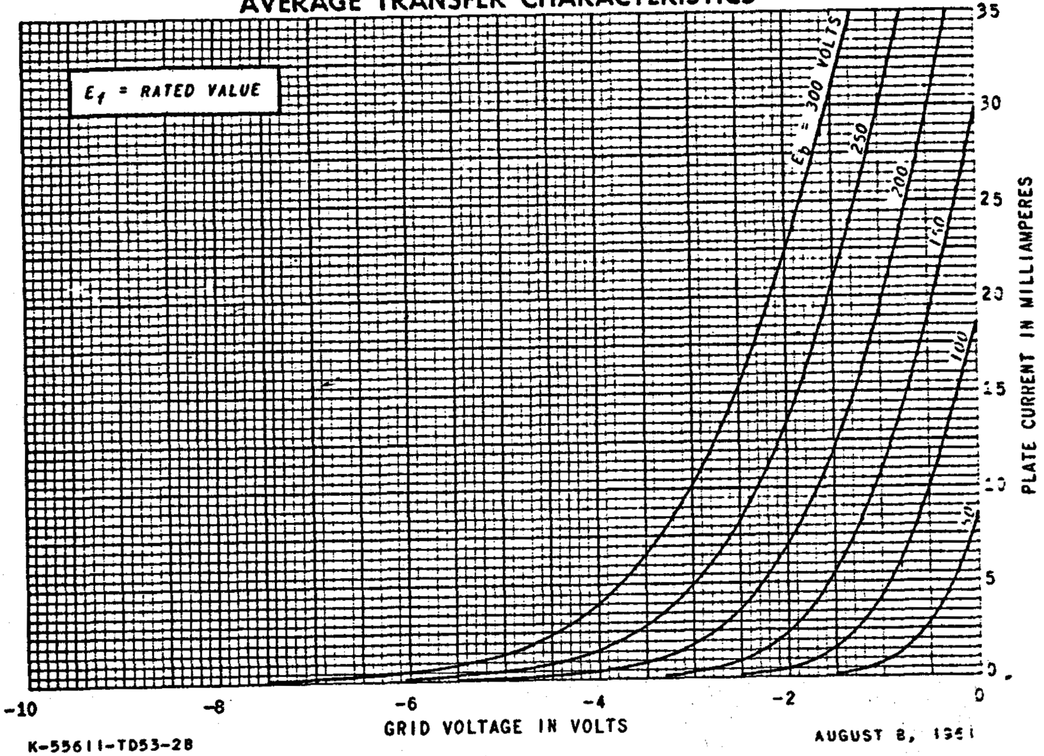
Interface Life Test

Statistical sample operated for 1000 hours with Ef = 6.6 volts, no other voltages applied, and evaluated for cathode interface resistance following the life test.

Heater-Cycling Life Test

Statistical sample operated for 2000 cycles minimum to evaluate and control heater-cathode defects. Conditions of test include Ef = 7.5 volts cycled for one minute on and one minute off, Eb = Ec = 0 volts, and Ehk = 70 volts with heater positive with respect to cathode. Following this test tubes are evaluated for open heaters, heater-cathode shorts, and heater-cathode leakage current.

AVERAGE TRANSFER CHARACTERISTICS



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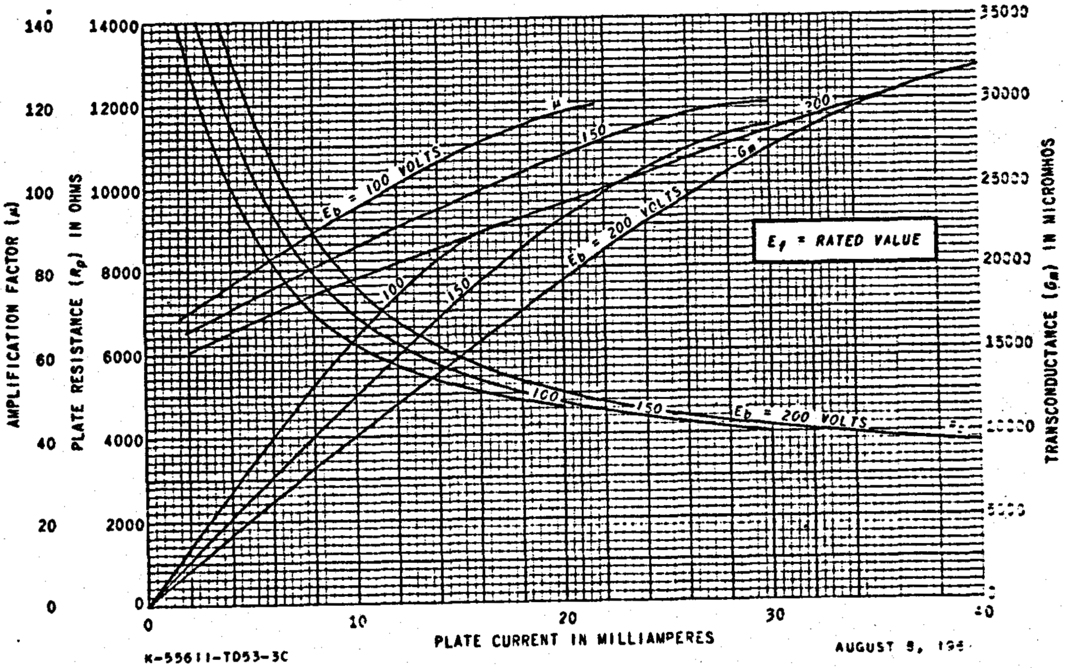
AVERAGE CHARACTERISTICS



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