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ULTRA HIGH TEMPERATURE
INSTRUMENTATION AMPLIFIER
AMPLIFIER FINAL REPORT

MASTER

MRI-2942-FI

September 1977

Prepared for:

Energy Research and Development Administration
Division of Geothermal Energy

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MRI-2942-F1

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Mechanics Research, Inc.
Santa Monica, California (USA)

Prepared for

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Geothermal Energy

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INSTRUMENTATION AMPLIFIER

AMPLIFIER FINAL REPORT, SEPTEMBER 1976 - SEPTEMBER 1977

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1.0 - INTRODUCTION

This report describes the results of a program to develop an instrumentation amplifier for downhole geothermal well logging at temperatures up to 500°C. This work was sponsored by the U. S. Energy Research and Development Administration (ERDA) under contract number E(04-3)-1330, and was performed by the Mechanics Research Division of System Development Corporation (SDC).

This program really had two primary purposes. The first was the development of a useful electronic instrumentation amplifier for downhole well logging. The second purpose was to evaluate the suitability/feasibility of developing electronic circuitry capable of 500°C operation with "off of the shelf" hardware.

The activities on this twelve month program included not only the design, development and test of the amplifier, but also the development of a protective package for the amplifier and extensive high temperature component evaluation. Components evaluated included ceramic vacuum tubes, resistors, capacitors, connectors, terminals, wire, circuit board materials, cements. The results of these components tests are reported separately in Reference 1.

The performance and characteristics of this 500°C amplifier are summarized in Section 2.0 of this report. The circuit design of this amplifier and other circuits considered are discussed in Section 3.0. The features of the packaging design are presented in Section 4.0 and the tests are detailed in Section 5.0. Supporting information is contained in the Appendices.

2.0 - SUMMARY

The following sections briefly describe the electrical performance, thermal performance and physical characteristics of the 500°C amplifier.

2.1 - Electrical Performance

Gain

- Closed loop Gain = 100
- Linearity = 2 % of rated output

Frequency Response (Normal)

- Small Signal, 1% = 0 to 8K Hz
- Small Signal, 3 db = 0 to 75K Hz
- Full Power, 3 db = 0 to 70K Hz
- Slew rate = 7 volts/ μ sec

Frequency Response (Through 15,000 ft. of Standard 7 Conductor Logging Cable)

- Small Signal, $\pm$ 1% = 0 to 150 Hz
- Small Signal, $\pm$ 3 db = 0 to 1200 Hz
- Full Power, $\pm$ 3 db = 0 to 1100 Hz
- Slew Rate = .03 volts/ μ sec

Output

- Voltage Range = 10 volts rms
- Current = 10 mA
- Impedance = 25 ohms

Input

- Voltage Range = 10³ mV rms
- Impedance = > 10³ K./ohms
- Common Mode Rejection = 55 db

Noise

- Voltage (RTO) = 5 mV rms

Power Supply

- B+ Voltage = +200 volts
- B+ Current = 20 mA
- B- Voltage = -200 volts
- B- Current = 16 mA
- Filament Voltage = 5.3 volts/tube
- Filament Current = 210 mA Total

2.2 - Thermal Performance

This amplifier is designed for use over a temperature range of 0 to 500°C. The major change in performance with temperature is a decrease in closed loop gain of approximately 11% or one db. at 500°C. Performance (frequency response and linearity) at 300°C is actually slightly better than at room temperature. The gain decrease at ultra high temperature occurs between 400 and 500°C and is primarily due to the inherent increase in negative grid current that the electron tubes exhibit at this temperature.

2.3 - Physical Characteristics

The amplifier is designed for installation in a cylindrical sonde. However, it is packaged in a cylindrical waterproof high pressure housing to protect the internal elements of the amplifier in the event of downhole leakage of the sonde. The housing is also designed for use of an inert gas, such as nitrogen, inside of the package for protection of the components from oxidation. Electrical connections are made through feedthroughs external to both ends of the package. Figure 2.3.1 is a photograph of the amplifier. Major details are summarized in the following:

Dimensions

- Diameter = 2.95 inches
- Length (case only) = 7.70 inches

Ambient Environment

- Temperature = 0 to 500°C
- Shock and Vibration = Normal Downhole Logging
- Pressure = 0 to 11,000 psi

Figure 2.3.1 Photo of Amplifier

Figure 2.3.1 Photo of Amplifier

3.0 - CIRCUIT DESIGN

A number of candidate circuit configurations were considered for this application. After initial evaluations, several were built in breadboard form and tested. The most promising of these designs were selected for development. These designs are discussed in the following.

3.1 - Prototype Design

Figure 3.2.1 is a schematic drawing of the 500°C amplifier. Its basic design consists of a differential input stage, followed by a differential gain stage and a single ended cathode follower line driver output stage. Negative feedback is used around the entire amplifier to fix the gain at 100 and to improve linearity, drift and output impedance.

3.1.1 - Electronic Characteristics

Equal value (200 volt) B+ and B- power supplies are used to permit quiescent operation of both the input and output at zero volts, and to reduce interstage coupling losses. The filaments are connected in series to minimize line loss in the logging cable.

The tubes are all General Electric type 7462 ceramic planer triodes. These tubes were selected after tradeoff of the following factors: high temperature capability, size, amplification factor, transconduction, cost, plate dissipation, filament power requirement and suggestions.

Nominal amplification (μ) and plate resistance (r_p) value for the 7462 type tubes are 90 and 12 K ohms, respectively. The gain for a differential amplifier is

$$K = \frac{\mu}{2(1 + r_p/R_L)} \quad (\text{Eq. 1})$$

Where R_L = the load resistance

Thus, the gain of both the input and inner stages are nominally

$$\begin{aligned} K_1 = K_2 &= \frac{90}{2(1 + 12K/40K)} \\ &= 35 \end{aligned}$$

The gain of each coupling network is nominally (2/3) and the gain of the cathode follower stage is approximately unity. The open loop gain (K_o) is approximately:

$$\begin{aligned} K_o &= (35)^2 (2/3)^2 \\ &= 544 \end{aligned}$$

In fact, the measured open loop gain is slightly greater than 500 with reduced filament voltage.

Fig. 3.1.1 Prototype Amplifier Wiring Schematic

The output resistance of a cathode follower is:

$$R_o = \frac{r_p}{1 + \mu} \quad (\text{Eq. 2})$$

Therefore, the open loop output is impedance, with 2 output tubes in parallel is nominally

$$R_o = \frac{12 \times 10^3}{2(1 + 90)} = 66 \text{ ohms}$$

The reduction in output impedance from negative feedback is:

$$R_o' = \frac{R_o}{1 - AK} \quad (\text{Eq. 3})$$

where R_o' = the closed loop output resistance

A = the open loop gain

K = the fraction of output voltage feedback to the input

For the amplifier of Figure 2, the nominal output resistance is:

$$\begin{aligned} R_o' &= \frac{66}{1 - (544)(1/128)} \\ &= 20 \text{ ohms} \end{aligned}$$

The tubes are being operated at reduced filament voltage (5.3 volts instead of the nominal 6.3 volts) to maintain a reasonably long life under high temperature operating conditions. Therefore, the actual tube performance characteristics are degraded from the nominal values. The resultant amplifier characteristics were summarized in Section 2 and discussed in Section 5.

3.1.2 - Temperature Characteristics

The most significant factor in determining circuit performance over a wide temperature range proved to be the shift in electron tube characteristics at elevated temperature. This is evident in the data presented in Table 3.1.1 which gives the measured characteristics for several of type 7462 tubes at room temperature and 500°C. These measurements were made in order to pick the best matched set of tubes for the prototype amplifier.

The parameters which both change most significantly and have the greatest impact on circuit performance are plate current and negative grid current. With negative grid current, the grid becomes an emitter similar to the cathode and the tube input impedance, which normally consists of only the small inter-electrode capacitance, becomes essentially resistive.

The change in plate current affects the bias on the succeeding stage grid and in the case of direct coupled differential stages a relatively small shift in biases, if not equal and in the same direction, can cause cutoff and loss of signal. The increase in grid current is also bothersome since the input impedance of a triode is reduced proportionately thereby presenting a load to the preceding stage and reduction of open loop gain.

The amplification of the tubes decreases slightly at high temperature as indicated in Table 3.1.1 but not to the extent of presenting a design problem. The transconductance, on the other hand shows a moderate increase with temperature which is beneficial since it produces both a lower stage and overall output impedance.

In addition to the characteristic shift with temperature, the miniature planar ceramic tubes when operated for several hours at elevated temperatures develop an internal low impedance path between grid and plate. In some cases it becomes relatively low or less than 10 megohms (at room temperature) when compared to a fresh tube which is typically greater than 10^3 megohms. The grid to plate impedance apparently becomes much less at high temperature. It was determined from experience that if the circuit after working well for one or two cycles from room temperature to 500°C started to exhibit a diminishing open and closed loop gain above 300°C , the cause was a tube with low grid to plate resistance.

Referring to Table 3.1.1, tubes 1 and 2 were chosen for tubes V1 and V2 which comprise the input differential stage (figure 3.1.1). Tubes 3 and 4 were used for V3 and V4 and tube 5, which had the highest measured transconductance, was chosen for the output cathode follower stage. During testing, however, tube performance of tube 5 became considerably degraded due to a reduced grid to plate resistance and was replaced by tubes 6 and 8 in parallel. Tube 3 was also replaced by Tube 7 in the final prototype for the same reason.

Table 3.1.1 Measured Tube Characteristics for Prototype Amplifier

Tube	Room Temperature				500°C			
	Plate Current (ma)	Amplification	Trans-conductance (mho)	Grid Current (ma)	Plate Current (ma)	Amplification	Trans-conductance (mho)	Grid Current (ma)
1	5.5	106	8,420	< .001	9.9	105	11,500	- .20
2	4.7	98	5,220	< .001	9.6	98	8,240	- .07
3	3.5	94	5,470	< .001	10.4	89	9,870	- .22
4	2.1	104	4,600	< .001	7.3	100	5,650	- .05
5	6.4	90	8,490	< .001	12.8	87	13,500	- .01
6	6.2	86	7,890	< .001	13.1	79	11,300	- .22
7	2.7	94	5,160	< .001	10.4	85	9,530	- .15
8	2.3	98	5,630	< .001	9.2	94	9,480	- .30
9	1.4	97	4,140	< .001	9.2	85	8,330	- .10

Notes: (1) Plate Voltage = 100 Volt.
(2) Heater Voltage = 5.3 Volt.
(3) Amplification and transconductance measured with 0 Volt grid base
(4) Grid current measured with - 1.0 volt grid bias.

3.2 - Other Designs

A number of other circuit designs were initially considered as discussed in References 2 and 3. The major features of these circuits are summarized in Table 3.2.1. The circuit schematics are presented in Appendix A.

The primary design parameters were tube types, number of power supplies (1 or 2) and the circuit configuration. After analytical evaluation, the circuits chosen for evaluation on a breadboard were numbers 4, 8 and 11. Configuration number 11, whose schematic is repeated in Figure 3.2.1, was selected because of its potential for small size and simplicity. This circuit employed the type Y-2191 tube especially developed for this program by the General Electric Company. A breadboard circuit was constructed and evaluated at room temperatures. The maximum gain obtained with this circuit was only 70; therefore, this configuration was abandoned.

Configuration number 4, whose schematic is repeated in Figure 3.2.2, was built and tested on a room temperature breadboard. The open loop gain was quite high. This caused initial instabilities and the need for compensating capacitors on the breadboard. This circuit was dropped because of the probable need for high temperature capacitors on the prototype to prevent instabilities.

Configuration 8, whose schematics repeated in Figure 3.2.3, was also built on a room temperature breadboard. A high temperature breadboard was also built and the circuit was developed into the prototype configuration. The major modifications and their rationale were:

1. One overall feedback loop was eliminated when it was quickly discovered that the product of two negatives is a positive.
2. One cathode follower was moved from a cascade arrangement to a parallel arrangement. Item one eliminated the need for a differential output and the parallel connection halved both the output impedance and power dissipation of this stage.
3. The interstage positive feedback loops were eliminated because the amplifier gain could not be maintained at high temperatures.

Table 3.2.1 Circuit Configuration

Figure No. (Appendix A)	Tube Type	Type Input Stage	Type Gain Stages	Type Output Stage	No. of Tubes	No. of Power Supplies	Special Features	Open Loop Gain
1	7296	Differential	2 Differential	Single Ended	5	1		3,250
2	7588	Differential	2 Differential	Single Ended	5	1		11,500
3	7462	Differential	2 Differential	Single Ended	5	1		2,500
4	7462	Differential	1 Differential 2 Single Ended	Single Ended	5	2	$\pm 250V$ B+	34,000
5	7462	Differential	1 Differential 2 Single Ended	Single Ended	5	2	$\pm 150V$ B+	13,800
6	7462	Differential	1 Differential 1 Single Ended	Single Ended	4	2	0.5V Input Bias	1,300
7	7462	Differential	1 Differential 1 Single Ended	Single Ended	4	2	1.0V Input Bias	837
8	7462	Differential	2 Differential	Differential	6	2	Interstage Positive Feedback	TBD
9	7462	Single Ended	3 Single Ended	Single Ended	4	2		10,000
10	7462	2 Single Ended	1 Single Ended 1 Differential	Single Ended	5	1		1,818
11	Y- 2191						Specially Developed Tubes	70

Figure 3.2.1 Two Tube Amplifier

Figure 3.2.2 High Gain Amplifier

Figure 3.2.3 Amplifier with Positive Feedback in the Interloops

4.0 - Packaging Design

4.1 - Prototype Mechanical Design

Table 4.1.1 below summarizes data for the components used in the prototype amplifier, based on the circuit diagram in Figure 4.1.1 which also shows the power which must be dissipated by each resistor. Dale wirewound .3" dia. x 1" long resistors are used for all cases where $P > .16W$ and the small .25" x .2" x .1" Caddock thick film resistors are used where P is .16 watts or less.

Table 4.1.1 Prototype Amplifier Components		
Item	Qty.	Description
1.	6	GE ceramic vacuum tubes .33" dia. x .5" long.
2.	11	Dale Electronics Evanohm wirewound resistors, Type RS-5, .312" dia. x 1" long; 8 40K, 1 20K, 1 10K and 1 200 Ω resistors required.
3.	15	Caddock thick film resistors, type TK133, .2 x .25 x .1"; 1 Meg, 1 700K, 3 400K, 1 200K, 6 100K, 1 70K, 2 10K resistors required.

The packaging design is shown in Figures 4.1.2 and 4.1.3. The overall dimensions are 3" dia. x 9.6" long. It is designed to be pressure proof at an external pressure of 7500 psi at a temperature of 930°F (500°C), in the event that the logging tool fails as it did in the downhole test of the 500°F amplifier at LASL. The material is $\frac{1}{4}$ " wall thickness 4130 steel with a tensile yield strength of 70K psi for which the allowable pressure is $P = 2t\sigma/d = 2 (.25)(70,000)/3 = 11,670$ psi. It can be heat treated to over twice this value for higher pressure applications, if necessary.

Seven electrical feedthroughs are furnace brazed into each end of the housing. They are available from H & W Products and are made by Alberox Corporation, New Bedford, Massachusetts. They are made of alumina and Kovar alloy which is a nickel/cobalt/iron alloy with nearly the same coefficient of thermal expansion versus temperature as the alumina (aluminum oxide). They are brazed together at the factory at 960°C so they could be safely furnace brazed into the housing end caps at 800°C. They are rated for 30K psi pressure and 500°C temperature. They were tested at MRI for resistance between the feedthrough pin and the outer metal housing and it was found to be 1000 meg ohms at room temperature and > 200 meg ohms at 500°C which is very satisfactory.

A Conax MK-062-A all metal fitting rated at 7500 psi and 500°C is used together with an .062 dia. stainless steel pinch-off tube to permit the amplifier housing to be purged and filled with N_2 , in the event that an inert atmosphere was required for any of the components (which it turned out was not necessary).

The circuit board material is 1/8" thick Mykroy 1100 glass bonded mica sheet from Mykroy Ceramics Corporation, Ledgewood, N.J. It is rated for continuous operation at 1100°F and can be drilled easily with a carbide drill and can be cut with a bandsaw with a high speed blade - 14 teeth set. This material was used in the form of 1/4" thick x 6" diameter discs for the amplifier breadboard tests and it performed very satisfactorily.

The latest layout of the components on the circuit boards is shown in Figures 4.1.4 and 4.1.5. The use of the small thick film resistors in place of the wirewound resistors for cases where the power is less than .16W, results in a much less crowded design than that shown in Figure 4.1.2.

Table 4.1.2 lists all the resistors with data showing resistor number, circuit board number, type, resistance value and power dissipated.

The thick film resistors were received from Caddock uncoated and without any leads attached as they have no means of attaching leads other than by low temperature solder. They were sent out to Hughes Ground Systems in Fullerton, California as they have a Hughes Industries Parallel Gap Welder which they used to attach 2 x 10 mil gold leads. The leads are very delicate, however, and kept breaking off so MRI purchased a Parallel Gap Welder attachment for our Hughes Industries opposed electrode welder.

The gold leads were spot welded to 3/16" dia. x 5 mil thick Ni foil which was spot welded to both ends of 1/8" diameter x 1/8" long stainless steel rods in the holes drilled in the Myroy circuit board.

The hook up wire used was Gulton Industries Duroflex I, insulated 22 gage (25 mil) solid nickel wire, which was used previously in all the component tests and was found to be very satisfactory. It can also be welded to the 5 mil thick nickel foil discs and to the heavy 40 mil nickel leads on the wirewound resistors.

The ceramic vacuum tubes and the thick film resistors were cemented to the Mykroy circuit board by means of Aremco Ultrabond 552, high temperature (3000°F), high thermal conductivity ceramic adhesive. The wirewound resistors were attached to the circuit board by passing the nickel leads through holes in the circuit board.

The two end caps of the amplifier housing have left and right hand threads respectively so they can be unscrewed without winding up the leads from the circuit boards to the feedthrough terminals. Sufficient excess length is provided for the latter leads so that the entire circuit board can be withdrawn from the housing for access to the components.

Figure 4.1.1 Prototype Amplifier Power Dissipation

Figure 4.1.2

BOARD #1, SIDE #1

BOARD #1, SIDE #2

Figure 4.1.4 Prototype Amplifier Circuit Board #1

Figure 4.1.5 Prototype Amplifier Circuit Board No. 2

Table 4.1.2 Resistor Summary

No.	Type	Board	R, K Ω	Power
FB1	F	1-2	1000	0
FB2	F	2	100	0
FB2*	F	2	100	0
FB2*	F	2	70	0
1	F	1-1	10	0
2	F	1-1	10	0
3	F	1-1	200	.05
4	F	1-1	100	} .05
4*	F	1-1	100	
5	F	1-1	400	.1
6	F	1-1	400	.1
7	W	1-2	40	.25
8	W	1-2	40	.25
11	F	1-2	100	} .05
11*	F	1-2	100	
17	W	1-1	40	.25
18	W	1-1	40	.25
20	F	1-2	400	.1
22	F	1-2	700	.06
23A	W	1-1	40	} .67
23B*	W	1-2	20	
25A	W	1-2	40	} 1.0
25B*	W	1-1	40	
27A	W	1-2	40	} .8
27B*	W	1-1	10	
28	W	2	200 Ω	0

* Additional resistors required due to unavailability of correct value.

4.2 - Prototype Thermal Analysis

As shown in Figure 4.1.1, the total power to be dissipated from the resistors and tubes is 13.2W. The ΔT for conduction of this heat through the 1/4" thick steel housing wall is less than .1°F as shown below:

$$\Delta T = \frac{Qt}{kA} = \frac{(13.2)(3.4)(.25)(144)}{(24)(67)(12)} = .08^{\circ}\text{F}$$

where Q = heat production, rate, BTU/hr.

$$(1 \text{ watt} = 3.4 \text{ BTU/hr.})$$

t = wall thickness

k = thermal conductivity of 4130 steel

$$= 23.7 \text{ BTU/hr. ft. } ^{\circ}\text{F at } 530^{\circ}\text{F.}$$

$$\begin{aligned} A &= \text{area of housing wall} = \pi dL + \frac{2\pi d^2}{4} \\ &= \pi (2.75)(6.0) + 2\pi (3^2)/4 = 67 \text{ in}^2 \end{aligned}$$

The highest power resistor = 1W as shown in Figure 4.1.1. An equation for heat transfer by natural convection from horizontal cylinders in air is given by McAdams, p. 177 as follows:

$$\text{Heat transfer coef. } h_c = .27 (\Delta T/d)^{.25}$$

$$\text{and } T = \text{surface temperature} - \text{air temperature} = Q/h_c A$$

$$d = \text{resistor diameter} = .312"/12 = .026'$$

$$\begin{aligned} A &= \text{resistor area} = \pi (dL + 2d^2/4) \\ &= \pi [(.312)(1) + .312^2/2]/144 = .0079 \text{ ft.}^2 \end{aligned}$$

An iterative calculation leads to

$$h_c = .27 (175/.026)^{.25} = 2.45 \text{ BTU/hr.ft}^{20}\text{F}$$

$$\Delta T = 3.4/(2.45)(.0079) = 176$$

This results in a surface temperature of $930 + 176 = 1106^{\circ}\text{F}$ which is satisfactory as this is less than the initial bake temperature of 1200°F for the wirewound resistors to stabilize them.

The power dissipated by each tube is 1.35W as shown on Figure 4.1.1. The tube diameter is $.33/12 = .0275'$. Its surface area

$$A = \pi[dL + d^2/2] = .0048 \text{ ft.}^2$$

$$h_c = .27 (336/.0275)^{.25} = 2.84$$

$$\Delta T = 1.35(3.4)/(2.84)(.0048) = 337^\circ\text{F}$$

The surface temperature = $930 + 337 = 1267^\circ\text{F}$ which is very high. A test was therefore made using a tube inside of the inert gas fixture in the oven at 930°F with a thermocouple to measure its surface temperature with a power dissipation of 2.0W. The temperature was found to be only 955°F so the above equation grossly overestimates the temperature.

4.3 - Other Designs Investigated

The following packaging designs were investigated in chronological order:

1. 1 11/16 in. dia. x 19.6" long sonde using Dale Evanohm wirewound resistors. This design was later superseded by the shorter length design below.
2. 1 11/16 in. dia. x 11.9" long sonde using Dale Evanohm wirewound resistors. This design is shown in Figure 4.3.1. It is based on the wiring diagram shown in Figure 4.3.2. Table 4.3.1 shows a summary of the components required. It makes use of the small .33" dia. x .5" long ceramic tubes and includes provisions for 5 of the small El Menco ceramic capacitors.
3. An alternate shorter length 1 11/16 in. dia. design using the small Caddock thick film resistors was planned but was discarded when it was found that for power requirements $>.2W$, the temperature stability degraded excessively.
4. At the suggestion of Larry Ball, ERDA Program Manager, a 3" dia. x 9.6" long sonde was designed using a pressure vessel capable of withstanding an external pressure of 7500 psi at 500°C, to protect the amplifier in the event that the primary sonde failed as it did in the downhole test of the 500°F amplifier. This design is shown in Figures 4.1.2 and 4.1.3. It is based on the use of Dale wirewound resistors and the small diameter ceramic tubes. In the amplifier breadboard tests it was found that the capacitors were not required.
5. The final design consists of the external packaging design shown in Figures 4.1.2 and 4.1.3 but it makes use of the small Caddock thick film resistors for all cases except where the power dissipated is greater than .16W. In these cases the wirewound resistors are used. The layout of the components on the two circuit boards is shown in Figures 4.1.4 and 4.1.5. Details of this design were discussed in Section 4.1.

Figure 4.3.1 Packaging of Amplifier in Figure 4.3.2

Figure 4.3.2 Typical Amplifier Circuit Diagram 1

Table 4.3.1

Resistors Required for the Amplifier Wiring Diagram in Figure 2.3.1

<u>R, Ω</u>	<u>Quantity in Wiring Diagram</u>	<u>Evanohm Type</u>	<u>No. Req'd for Each</u>	<u>Total</u>	
200	1	RS5**	1	1	} 13
low R*	6	↓	1	6	
10K	1		1	1	
31.25K	1		1	1	
40K	4	↓	1	4	
202K	2	RS10***	1	2	} 22
203K	1	↓	1	1	
400K	3		2	6	
500K	3		2	6	
600K	1	↓	3	3	
1000K	<u>1</u>		4	<u>4</u>	
	24			35	

* 6 low values not yet identified.

** Dale Electronics, Type RS-5 wire wound coated resistor using Evanohm wire. Dimensions are .312 dia x 1" long. They are available in resistance values from .1 Ω to 95K Ω and are rated at 5W at room temperature.

*** Dale Electronics, Type RS-10 wire wound coated resistor using Evanohm wire. Dimensions are 3/8" dia x 1-7/8" long. They are available in resistance values from .1 Ω to 273K Ω and are rated at 13W at room temperature.

5.0 - AMPLIFIER TESTS

The test program for the amplifier included a series of breadboard evaluations, testing of the prototype circuit boards, tests on the assembled prototype amplifier and a simulated down hole test with the prototype mated to an actual logging cable. All of the tests were successful with the exception of the simulated down hole. Tests had to be aborted due to component failure.

5.1 - Breadboard Tests

After initial circuit evaluation and selection, three circuits (Figures 3.2.1-2 and -3) were breadboarded and tested for overall performance at room temperature. Type 7462 ceramic electron tubes were used with low temperature carbon resistors.

The circuit in Figure 3.2.2 consists of an input differential stage, two cascaded single ended amplifying stages and a single ended cathode follower output. The circuit utilizes both a plus and minus power supplies and has a high open loop gain. Tests with the breadboarded circuit, however, showed that high frequency compensating networks were required to cancel the phase lag due to multiple poles introduced by the three amplifying stages. The design of stabilizing circuits is relatively straight forward (see Appendix B) but requires the use of capacitors. With stabilization, the circuit had an open loop gain in excess of 20,000 and a stable closed loop gain of over 1000 was possible.

The final circuit to be breadboarded which was also the forerunner of the prototype amplifier is shown on figure 3.2.3. The conceptual circuit incorporated dual negative feedback loops for symmetry with differential inputs. The two loops as shown, however, resulted in overall positive feedback and an unstable circuit. One of the loops was therefore eliminated. Positive feedback is purposefully provided in the second differential amplifying stage, however, to increase the open loop gain without the destabilizing effect of additional amplifying stages. The amount of positive feedback is adjustable by varying the relative resistance values between plate and grid of alternate tubes.

After the redundant negative feedback loop was eliminated, the circuit exhibited a very high open loop gain and a stable closed loop gain of 1000 could be achieved. The primary disadvantage was the sensitivity of the positive feedback adjustment for maximizing open loop gain. The adjustment had to be periodically altered to compensate for tube drift. Also, without the positive feedback feature the open loop gain was only about 500, making a closed loop gain of over 100 impractical.

After positive results were achieved with the modified circuit of Figure 3.2.3, it was chosen as the preferred circuit for the prototype amplifier. A high temperature breadboard using type 7462 ceramic tubes

and both high temperature thick film and wire wound resistors was assembled using screw and bolt connections. Use of stainless steel fittings and glass bonded mica circuit boards provided a satisfactory and convenient method for building temporary circuits. Initial testing at 500°C showed that the positive feedback that was incorporated on the second stage was very sensitive to temperature. A gain much greater than 100 was not achievable over more than 100°C temperature range. Also, as noted in the room temperature breadboard, the positive feedback required frequent adjustment to compensate for tube drift. The positive feedback was therefore eliminated to simplify the circuit. The open loop gain without positive feedback was approximately 500.

Two component problems surfaced during the high temperature breadboard tests. The first was an initial high failure rate of the wire wound resistors when first installed in the circuit. The failures occurred at both room temperature and at 500°C. If a resistor survived two or more temperature cycles, however, it tended to remain good.

A more subtle problem was a form of aging of some of the ceramic electron tubes after as little as 10 hours of operation at 500°C. The aging was characterized by a relatively low grid to plate dc. resistance which apparently became quite low at high temperature. The consequence was a loss of both open and closed loop gain at high temperature. The problem developed mainly, but not always, in the output cathode follower which operates at high plate voltage and power dissipation. As a result, a second output cathode follower was added in parallel to the baseline circuit to share the power dissipation. The output impedance was also lowered. A theory as to the cause of this phenomenon is that the cathode material partially vaporizes at very high temperatures and deposits inside the tube envelope providing a resistance path between electrodes. When this happens the tube input impedance is greatly reduced and the gain expression (equation 1) is no longer valid.

The tubes can be screened at room temperature by measuring the grid to plate resistance with a high value ohm meter. It was found from experience that if the measured resistance was on the order of 10 megohms or less instead of a normal 10^3 megohms the tube would be inoperative at high temperature.

The results of the high temperature breadboard showed that the modified circuit operated satisfactorily from room temperature to 500°C. The gain, however, decreased approximately 10% at 500°C.

5.2 - Prototype Tests

The breadboard circuit was mounted on two glass bonded mica boards as shown on Figures 4.1.4 and 4.1.5. The circuit was then verified by testing at room temperature, 300°C and 500°C. Results are summarized below in Table 5.2.1. Data sheets for the tests are included in Appendix C.

Table 5.2.1

Preliminary Test Results, Prototype Amplifier Circuit Boards			
Temperature	Room T.	300°C	500°C
Gain	100	100	89
Rated Voltage			
Input, mv rms	10	10.0	8.9
Output, volt rms	10	10.0	8.9
Frequency Response (No load)			
-1%, Hz	40K	60K	37K
- 3db, Hz	75K	100K	70K
Linearity, % rated	3%	1.3%	4%

Results of the frequency response and linearity tests are shown plotted on Figures 5.2.1 through 5.2.5. (Data sheets are included in Appendix C). Figure 5.2.1 shows the frequency response for the unattached amplifier at room temperature and for the amplifier connected to a simulated 15,000 foot logging cable. Figures 5.2.2 and 5.2.3 show the frequency responses, unattached and with load, for 300°C and 500°C. Figure 5.2.4 compares the frequency responses with load for all three temperatures. The response at 300°C is slightly better than that at room temperature while the gain at 500°C is down approximately one db. Finally, figure 5.2.5 shows the linearity data for the amplifier under load at three temperatures compared to the unloaded amplifier at room temperature.

As with the high temperature breadboard, the overall gain is down 11% or 1 db at 500°C. The frequency response and linearity however are still essentially the same at all temperatures,

Following verification of the circuit boards, they were assembled in the enclosure hardware to complete the amplifier and were further tested. Results of the frequency response and linearity tests on the completed amplifier were essentially the same. Though the frequency response was not quite as good, this was due to the fact that one of the output cathode followers failed and had to be replaced with a slightly weaker tube (i.e. lower transconductance).

Figure 5.2.1, Measured Frequency Response of Prototype Amplifier, Room Temperature

Figure 5.2.2, Measured Frequency Response of Prototype Amplifier, 300°C

Figure 5.2.3 Measured Frequency Response of Prototype Amplifier, 500°C

Figure 5.2.4 Comparison of Frequency Response with 15,000 ft. Load;
Room Temperature, 300°C and 500°C

Figure 5.2.5 Linearity Measurements; Room Temperature, 300°C and 500°C

46 1322

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1.0 In all of the preceding cases the cable load was simulated by a Multi-path single section, RC' filter as shown in figure 5.2.6

Figure 5.2.6, Simulated Logging Cable Line Load

5.3 - Down Hole Test

A simulated down hole test had been planned to obtain data with the amplifier coupled to a seven conductor logging cable. As with the other tests, high temperature conditions were to be simulated with an oven.

Facilities for the test were made available by the Sandia Corporation in Albuquerque, New Mexico. The logging cable, which was approximately 15,000 feet long was rolled up on a large reel and therefore presented a sizeable inductance in addition to a distributed capacitance in excess of one microfarad.

One end of the 15,000 ft. logging cable was connected to the amplifier. An oscillator was also connected to simulate a logging instrument. The plate and filament power supplied were placed in the trailer holding the logging cable reel and connected to the other end. The bench holding the amplifier was in a building about 25 yards from the trailer without visual or sound communication.

After all connections were checked and found to be correct, the filament power supply was turned on. A surge (voltage and current) was evidently induced by the large inductance of the coil and the power supply overloaded. It was turned off. It was not possible to reactivate the power supply without overload. A check of the amplifier showed one tube had failed with an open filament. The tube was replaced and it was again attempted to activate the filaments by turning the supply on and slowly cranking up voltage. An overload again resulted.

The filament power supply was moved back to the bench and connected directly to the amplifier by-passing the cable. It was possible to turn on the filaments normally without overloading. However, the filament current settled out at an abnormally high value (>0.3 amp) and low voltage (<10 volts). Normal would be 0.2 amp at 30 volts. Measurement of individual tubes showed that the only good tube was the one that had been replaced. All the others exhibited a very low filament impedance with the result that most of the filament power was being dissipated by one tube and the others were barely warm. Again all connections were checked and found to be correct. Also, there were no shorts or open connections. It was concluded after further probing and checking that the initial turn-on transient that had caused the one tube to fail had also damaged the other 5 tubes. Since no more tube replacements were available, the test was scrubbed.

REFERENCES

1. Ultra High Temperature Amplifier Components Final Report, Sept. 1977, MRI-2942-F2.
2. Status Report No. 6, Contract E(04-3)-1330, "Ultra High Temperature Electronic Amplifier" 7 March 1977, Mechanics Research, Inc.
3. "Ultra High Temperature Instrumentation Amplifier" (Mid-Term Progress Report), MRI-2942-E3, May 1977, Mechanics Research, Inc.

APPENDIX A
ALTERNATE CIRCUIT SCHEMATICS

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

A-9

Figure 8

Figure 9

Figure 10

APPENDIX B

DESIGN OF HIGH FREQUENCY COMPENSATOR

DETERMINE R_s , C_s AND C_c TO
PROVIDE HIGH FREQUENCY STABILIZATION

C'_i = TUBE GRID - CATHODE CAPACITANCE
+ $(1 - \mu) \times$ GRID - PLATE CAPACITANCE
+ CIRCUIT CAPACITANCE

C'_o = TUBE OUTPUT CAPACITANCE

High Frequency Compensation

(S = LAPLACE VARIABLE)

High Frequency Compensation

If $R_s \ll r_p$ & $C_s \gg C_o''$

HIGH FREQUENCY COMP

$$\frac{\Delta e_o}{\Delta e_i} = \frac{-K \left(s + \frac{1}{C_s R_s} \right)}{s^2 (r_p' R_s C_o'' C_s) + s (R_s C_s + r_p' C_o'' + r_p' C_s) + 1}$$

$$K = \frac{M r_p' R_2 R_s C_s}{(R_1 + R_2) (r_p + (1+M) R_k)}$$

$$C_o' = C_o' + \frac{C_c C_1'}{C_1' + C_c}$$

$$r_p' = \frac{R_p (r_p + (1+M) R_k) (R_1 + R_2)}{R_p (R_1 + R_2) + (r_p (1+M) R_k) (R_p + R_1 + R_2)}$$

Place poles & zeros to alternate:

$$P_1 = \frac{1}{R_s C_o''}$$

$$P_2 = \frac{1}{r_p' C_s}$$

$$Z_1 = \frac{1}{R_s C_s}$$

For 7462 tubes

$$r_p = 10,000 \text{ ohm}$$

$$M = 94$$

$$C'_i = C_{gk} + (94-1) C_{gp} + 10 \approx 100 \text{ pf}$$

$$C'_o = .045 \text{ pf}$$

Let

$$R_p = 39K, R_k = 0$$

$$R_1 = 255K$$

$$R_2 = 510K$$

$$r'_p = \frac{R_p \times r_p \times (R_1 + R_2)}{R_p \times (R_1 + R_2) + r_p (R_p + R_1 + R_2)}$$

$$= 7,877 \text{ ohm}$$

$$C_c = C'_i \frac{R_2}{R_1} \approx \boxed{200 \text{ pf}}$$

$$C''_o = C'_o + \frac{C_c C'_i}{C'_i + C_c} = 67 \text{ pf}$$

$$\text{If } \boxed{R_s = 100 \text{ ohm}}; P_1 = \frac{1}{R_s C''_o} = 1.5 \times 10^8$$

$$\text{If } \boxed{C_s = 2000 \text{ pf}}; Z_1 = \frac{1}{R_s C_s} = 5 \times 10^6$$

$$\text{and } P_2 = \frac{1}{r'_p C_s} = 6.3 \times 10^4$$

APPENDIX C
TEST DATA SHEETS

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: FREQUENCY RESPONSE - Circuit Boards

DATE: 8-1-77

LOCATION: SDC, Santa Monica

TEST CONDITIONS:

B+ 200 VOLTS
B- 200 VOLTS
E_f 33.0 VOLTS: _____ AMP

TEMPERATURE	ROOM T.		ROOM T.			590°F/310°C		
LOAD	NONE		15,00 ft			15,00 ft		
FREQUENCY (Hz)	INPUT SIG. (MV)	AMP OUTPUT (VOLT)	INPUT (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	INPUT SIG. (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10	10.0	1.00	10.0	1.00	1.00	10.0	1.00	1.00
50	↓	1.00	↓	↓	↓	↓	↓	↓
100	↓	↓	↓	↓	↓	↓	↓	↓
200	↓	↓	↓	1.00	1.00	↓	1.00	1.00
400	↓	↓	↓	.98	.96	↓	.98	.96
700	↓	↓	↓	.93	.87	↓	.94	.88
1000	↓	↓	↓	.885	.785	↓	.89	.79
1200	↓	↓	↓	.85	.72	↓	.86	.73
1400	↓	↓	↓	.82	.655	↓	.835	.67
1700	↓	↓	↓	.78	.57	↓	.80	.59
2000	↓	↓	↓	.75	.50	↓	.77	.525
4000	↓	1.00	↓	.655	.265	↓	.68	.28
7000	↓	1.01	↓	.63	.158	↓	.66	.17
10000	↓	1.02	↓	.63	.113	↓	.65	.12
	↓	↓	↓	-	-	↓	-	-
	↓	↓	↓	-	-	↓	-	-
	↓	↓	↓	-	-	↓	-	-

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: FREQUENCY RESPONSE - Circuit Boards

DATE: 8-1-77

LOCATION:

TEST CONDITIONS:

B+ 200 VOLTS
B- 200 VOLTS
E_f 27.7 VOLTS: _____ AMP

TEMPERATURE	ROOM T.		ROOM T.			930°F/500°C		
LOAD	NONE		15,000 ft.			15,000 ft.		
FREQUENCY (Hz)	INPUT SIG. (MV)	AMP OUTPUT (VOLT)	INPUT (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	INPUT SIG. (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10	10.0		10.0			10.0	.89	.89
50	↓		↓			↓	.89	.89
100							.88	.87
200							.85	.84
400							.81	.79
700							.77	.72
1000							.72	.64
1200							.70	.59
1400							.68	.55
1700							.65	.49
2000							.63	.43
4000							.57	.25
7000							.54	.14
10000							.52	.114
	↓		↓			↓	-	-
							-	-
							-	-

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: LINEARITY - Circuit Boards

DATE: 8-1-77

LOCATION:

TEST CONDITIONS:

B+ 200 VOLTS
 B- 200 VOLTS
 E_f 33 VOLTS _____ AMP

TEMPERATURE	ROOM T.	ROOM T.	590°F/310°C		
LOAD	NONE	15,000 ft.	15,000 ft.		
FREQUENCY	100 Hz	100 Hz	100 Hz		
INPUT SIGNAL STRENGTH (MV)	AMP OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10	1.00	1.00	(SAME)	1.00	(SAME)
20	2.00	2.00		2.02	
40	4.05	4.02		4.05	
60	6.03	6.01		6.05	
80	8.00	7.99		8.00	
100	9.90	9.70		9.99	
125	12.2	11.3		11.9	
150	14.4	12.2		13.2	
175	16.6	13.0		14.2	
200	18.6	14.0		14.9	
250	22.0	15.1		15.8	

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: LINEARITY - Circuit Boards

DATE: 8-1-77

LOCATION: SDC, Santa Monica

TEST CONDITIONS:

B+ 200 VOLTS
 B- 200 VOLTS
 E_f 27.7 VOLTS _____ AMP

TEMPERATURE	ROOM T.	ROOM T.		930°F/500°C	
LOAD	NONE			15,000 ft.	
FREQUENCY	100 Hz	100 Hz		100 Hz	
INPUT SIGNAL STRENGTH (MV)	AMP OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10				.88	(SAME)
20				1.74	
40				3.47	
60				5.21	
80				6.8	
100				8.4	
125				10.1	
150				11.5	
175				12.5	
200				13.3	
250				14.7	

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: FREQUENCY RESPONSE - Assembled Amp.

DATE: 8-25-77

LOCATION: S.D.O.

TEST CONDITIONS:

B+ $\frac{200}{200}$ VOLTS
B- $\frac{33.0}{33.0}$ VOLTS
E_f $\frac{33.0}{33.0}$ VOLTS: _____ AMP

TEMPERATURE	ROOM T.		ROOM T.			300°C		
LOAD	NONE		15,000 ft.			15,000 ft		
FREQUENCY (Hz)	INPUT SIG. (MV)	AMP OUTPUT (VOLT)	INPUT (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	INPUT SIG, (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10	10	1.00	10	1.00	1.00	10	1.00	1.00
50		↓		↓	↓			
100					↓			
200				↓	1.00			1.00
400				1.00	0.98		1.00	.95
700				0.93	0.88		.93	.88
1000				0.84	0.75		.83	.75
1200				0.79	0.67		.79	.67
1400				0.72	0.60		.75	.61
1700				0.68	0.51		.70	.52
2000				0.62	0.43		.67	.46
4000		↓		0.52	0.22		.58	.25
7000		1.00			0.13		.55	.15
10000		0.99		0.48	0.09		.54	.10
20000		0.96						
40000		0.89						
76000		0.7						
100000		0.585						

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: LINEARITY - Assembled Amp.

DATE: 8-25-77

LOCATION: S.D.C.

TEST CONDITIONS:

B+ 200 VOLTS
 B- 200 VOLTS
 E_f 33.0 VOLTS _____ AMP

TEMPERATURE	ROOM T.	ROOM T.		300°C	
LOAD	NONE	15,000 ft		15,000 ft.	
FREQUENCY	100 Hz	100 Hz		100 Hz	
INPUT SIGNAL STRENGTH (MV)	AMP OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10	1.00	1.00	(SAME)	1.00	(SAME)
20	2.01	2.01		2.00	
40	4.02	4.06		4.01	
60	6.03	6.20		6.17	
80	8.02	8.42		8.35	
100	10.0	10.4		10.5	
125	12.6	12.2		12.6	
150	15.1	13.5		14.2	
200	19.3	14.4	(SAME)	16.3	(SAME)
250	23.3			16.8	

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: LINEARITY - Assembled Amp.

DATE: 8-26-77

LOCATION: S.D.C.

TEST CONDITIONS:

B+ 200 VOLTS
 B- 200 VOLTS
 E_f 27.7 VOLTS AMP

TEMPERATURE	ROOM T.	ROOM T.		500°C	
LOAD	NONE			15,000 ft.	
FREQUENCY	100 Hz	100 Hz		100 Hz	
INPUT SIGNAL STRENGTH (MV)	AMP OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10				.89	
20				1.8	
40				3.5	
60				5.5	
100				8.90	
125					
150					
175					
200				14.2	

HIGH TEMPERATURE AMPLIFIER PERFORMANCE TEST

TEST: FREQUENCY RESPONSE - Assembled Amp

DATE: 8-26-77

LOCATION: S.D.C.

TEST CONDITIONS:

B+ 200 VOLTS
B- 200 VOLTS
E_f 27.7 VOLTS: _____ AMP

TEMPERATURE	ROOM T.		ROOM T.			500°C		
LOAD	NONE					15,000 ft.		
FREQUENCY (Hz)	INPUT SIG. (MV)	AMP OUTPUT (VOLT)	INPUT (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)	INPUT SIG. (MV)	AMP OUTPUT (VOLT)	LINE OUTPUT (VOLT)
10						10	.89	.89
50								
100							.89	.88
200							.85	.84
400								
700								
1000							.70	.60
1200								
1400								
1700								
2000							.60	.40
4000								
7000								
10000							.49	.09