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The construction and analysis of an amplifier for ultrasonic research

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THE CONSTRUCTION AND ANALYSIS OF AN AMPLIFIER FOR ULTRASONIC RESEARCH

BY

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A

THESIS

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ABSTRACT

An amplifier to be used for ultrasonic pulse methods was constructed and tested. The frequency range lies between 100 cycles per second and 2 mega-cycles per second and, if tuned circuit plug-in units are used, may be increased to approximately 4 mega-cycles per second. Special demands upon the amplifier are discussed along with basic acoustic attenuation measurements in solid state physics.

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The author also wishes to express thanks to Dr. Roger Nolte of the Electrical Engineering department of Missouri School of Mines and Metallurgy for the use of equipment used in testing the amplifier.

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I. INTRODUCTION

The energy loss of a sound wave propagated through a solid may be attributed to four different mechanisms: heat conduction, internal friction, elastic hysteresis, and scattering. Different mechanisms appear to be important at different regions of the frequency scale. The various types of losses obey different laws with regard to their frequency dependence. Also, the observed attenuation depends greatly on the type and structure of the material. One of the widely used methods for investigation of the internal losses in solid state physics is the pulse-echo technique. This method is being used almost exclusively in internal friction investigations (1).

In the pulse-echo technique, a piezo-electric transducer is placed in contact with the specimen, and an oscillatory voltage pulse of the order of microseconds in length is applied (2). The transducer converts the electrical signal to a pulse or train of mechanical waves which then are propagated through the specimen, being reflected back and forth between the end faces. If the transducer is used as both the receiver and transmitter, it reconverts part of the mechanical train back to electrical signals which, after amplification, are displayed on an oscilloscope or other recorder. The amplitudes of the successive reflections decay exponentially, with the rate of decay being proportional to the energy loss per unit length due to the absorption of the mechanical waves in the specimen.

Ultrasonic pulse-echo techniques require amplification of the returning signals in order to permit display on an oscilloscope or other recording device. The amplifier system discussed here performs such a function. Important characteristics of the amplifier were found, examined, and improved. The improvements were based on the needs of the pulsing and oscillator equipment to be used with the amplifier.

A power supply was designed and constructed to supply power to the amplifier.

II. DISCUSSION OF EQUIPMENT

A. Amplifier

A video frequency amplifier is one designed to amplify frequencies from the lower audio range to the middle radio frequency range. Such amplifiers, in addition to amplifying such an extremely wide frequency range, must have a minimum of amplitude, phase, and frequency distortion.

The basic design of the amplifier discussed here is similar to one designed by Skudrzyk (3). The oscillator and pulser units used with it are discussed in the thesis of Reinheimer (4).

The amplifier is shown in Figures 2 and 3. The first three tubes are operated as amplitude clippers. The clipping level is controlled by the selector switch at the input. The pentodes are operated to have a sharply defined limiting action; the plate current varies linearly with the control grid voltage as long as the grid voltage remains below a definite level. Above this point the plate current remains nearly constant, regardless of further increases in the grid potential. The location of the critical point depends on the electrode potentials and was determined by investigating the characteristic curves of the 6CL6 pentodes, shown in Figure 1. The characteristic plate curves in Figure 1a show the bias point (A) of the first three stages. However, the clipping action is more easily described by referring to the dynamic transfer

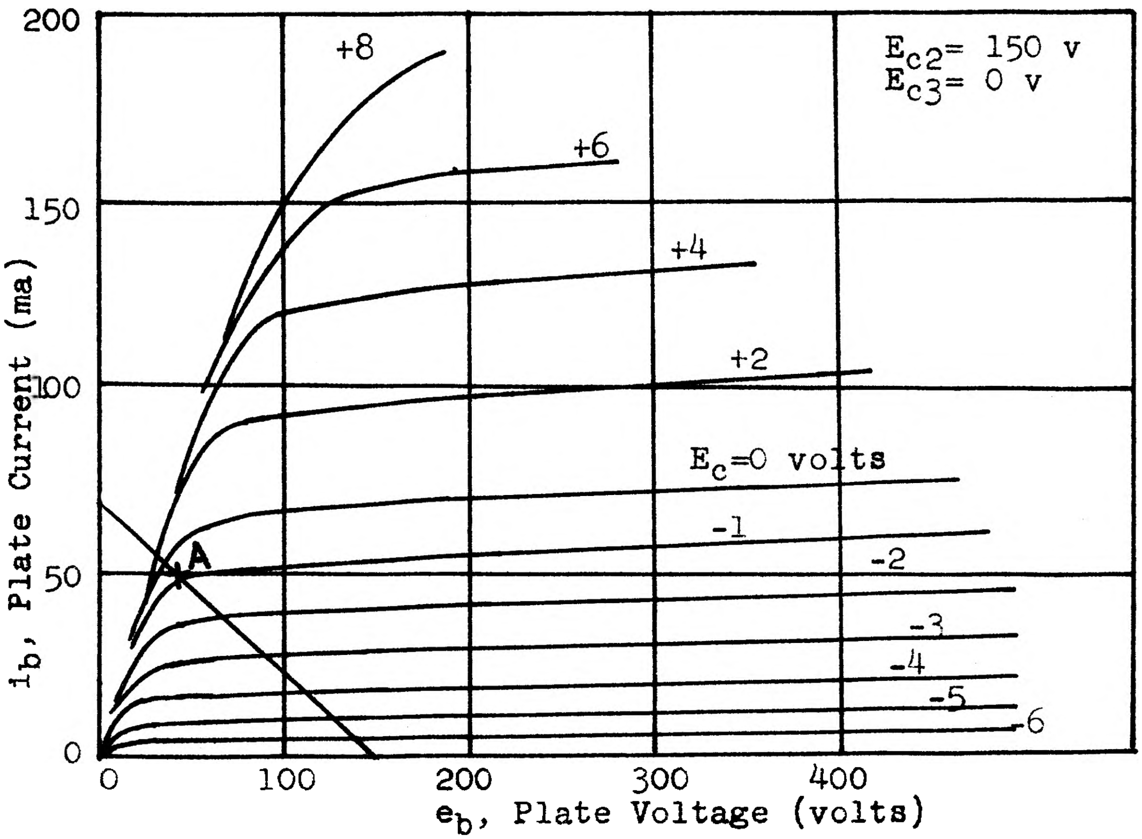


Figure 1a. Plate Characteristic Curves

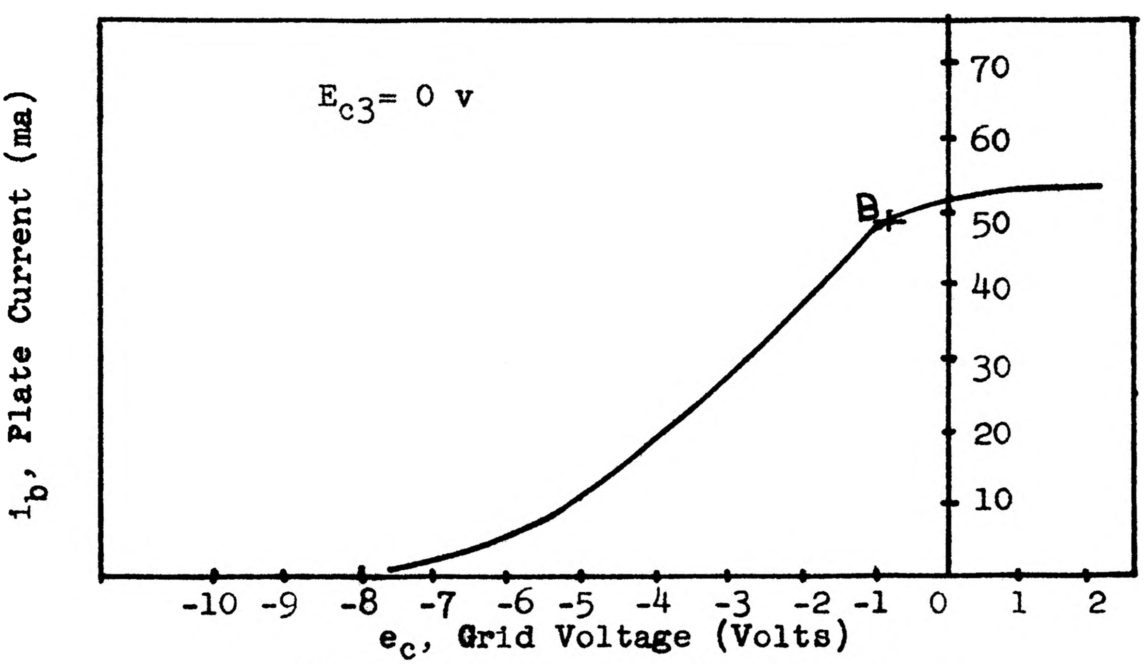


Figure 1b. Dynamic Transfer Curve

curve in Figure 1b, where the bias point is designated by point (B). For a negative pulse of 8.2 volts or greater, cutoff will occur. For a positive pulse of approximately 1 volt or greater, peak clipping occurs. If the top of the input pulse applied to the first tube is greater than the clipping level it will be clipped. However, if the top is less than the clipping level the pulse will continue to the next stage with a small amount of amplification. The second stage will clip the top (now negative) only if the cutoff of the tube is reached at -8.2 volts. If cutoff is avoided the pulse is amplified further, made positive, and applied to the third stage. If the pulse is greater than the clipping level at the plate of this tube it will be clipped and appear at the amplifier stage as a sharply defined rectangular pulse. If the pulse is less than the clipping level it will continue to the amplifier stage uneffected except for a small amount of amplification.

The selector switch following the second clipping tube adjusts the gain or overall amplification of the amplifier.

The smallest signal that may be amplified with an electron tube amplifier is determined by the level of the background noise generated within the amplifier itself. If the input signal is very weak, it will be completely obscured. Further amplification is useless since noise originating in early stages is amplified as much as the signal. Two of the most common noise types are found in the irregular electronic motions in the heated filaments or ''shot'' noise, and the thermal

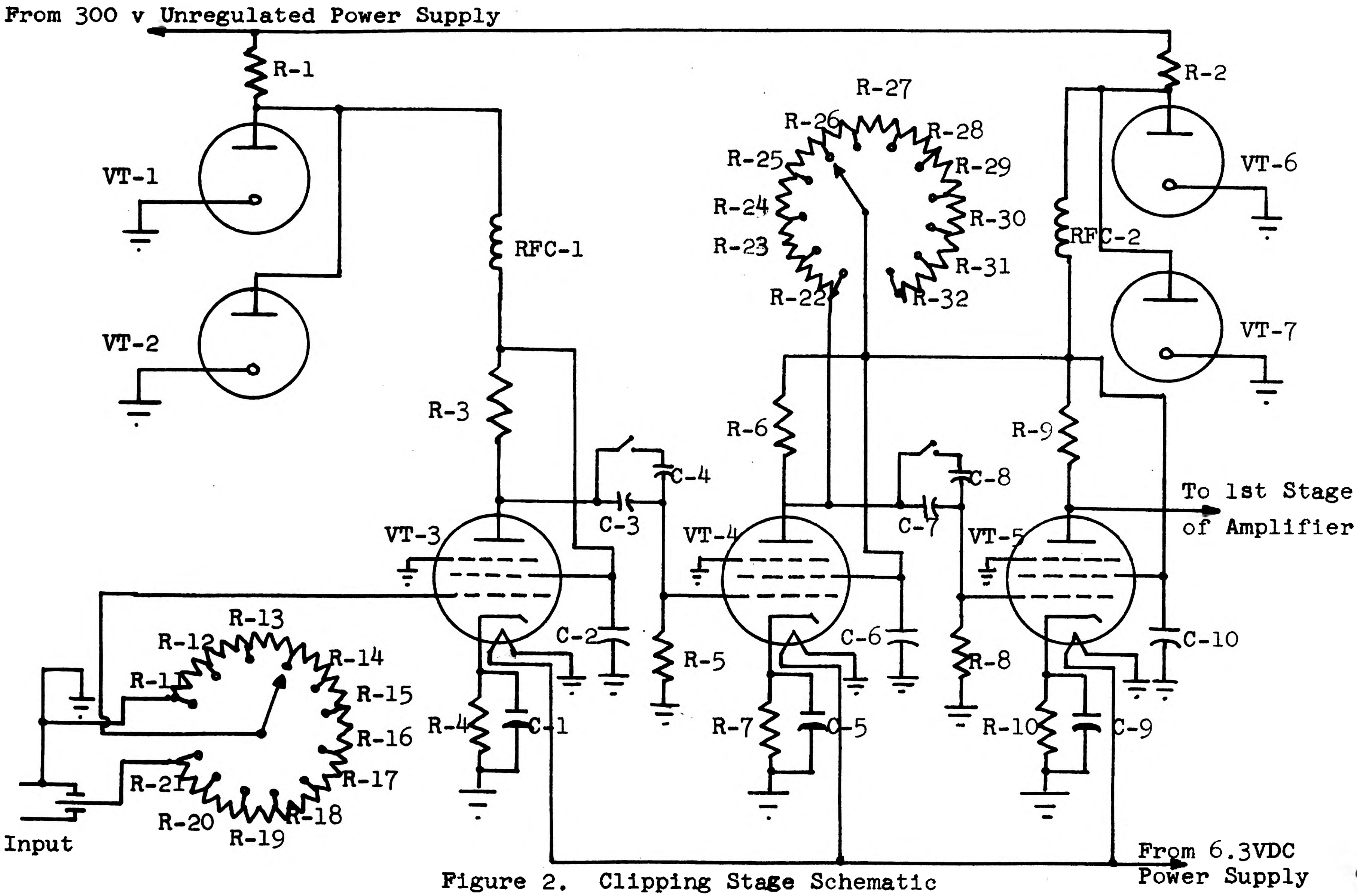


Figure 2. Clipping Stage Schematic

TABLE I

CLIPPING STAGE COMPONENTS

R-1	2500 ohms	R-2	1430 ohms	R-3	2200 ohms
R-4	180 ohms	R-5	2200 ohms	R-6	3600 ohms
R-7	35 ohms	R-8	2200 ohms	R-9	2200 ohms
R-10	100 ohms	R-11	1 ohm	R-12	5 ohms
R-13	10 ohms	R-14	18 ohms	R-15	47 ohms
R-16	100 ohms	R-17	180 ohms	R-18	470 ohms
R-19	1000 ohms	R-20	2000 ohms	R-21	2700 ohms
R-22	10 ohms	R-23	10 ohms	R-24	10 ohms
R-25	18 ohms	R-26	47 ohms	R-27	100 ohms
R-28	180 ohms	R-29	470 ohms	R-30	1000 ohms
R-31	2000 ohms	R-32	2700 ohms	C-1	0.02 mf
C-2	0.02 mf	C-3	100 mmf	C-4	4 mf
C-5	0.05 mf	C-6	0.02 mf	C-7	100 mmf
C-8	4 mf	C-9	500 mmf	C-10	0.02 mf
RFC-1	2.5 mh	RFC-2	2.5 mh	VT-1	OA2
VT-2	OA2	VT-3	6CL6	VT-4	6CL6
VT-5	6CL6	VT-6	OD3	VT-7	OD3

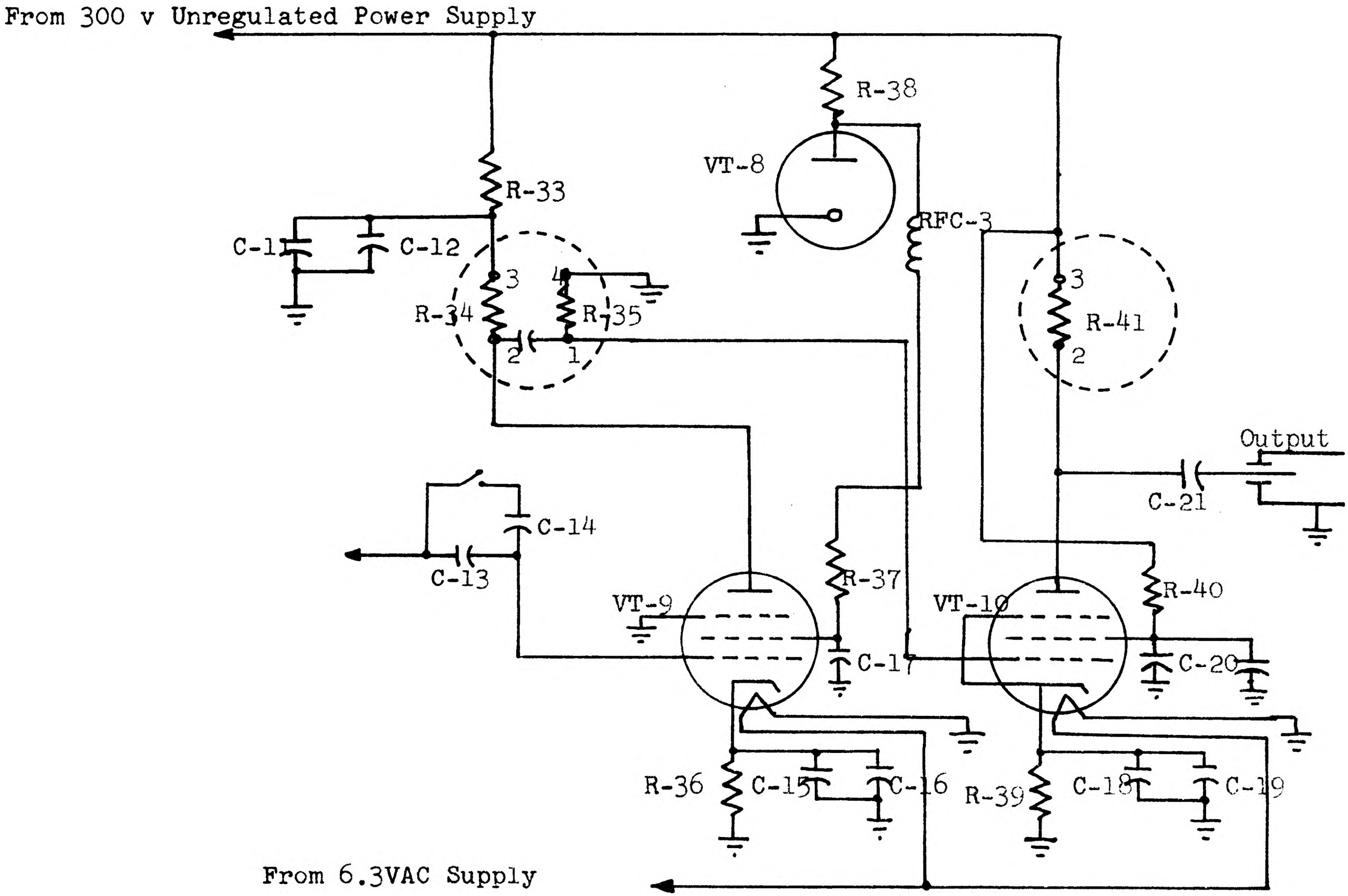


Figure 3. Amplifier Stage Schematic

TABLE II

AMPLIFIER STAGE COMPONENTS

R-33	1000 ohms, 2W	C-14	4 mf
R-34	2200 ohms, 2W	C-15	50 mf
R-35	6000 ohms, 2W	C-16	0.02 mf
R-36	50 ohms	C-17	0.02 mf
R-37	220 ohms	C-18	50 mf
R-38	5000 ohms	C-19	0.02 mf
R-39	150 ohms, 4W	C-20	0.02 mf
R-40	8000 ohms	C-21	0.5 mf
R-41	2000 ohms, 30W	RFC-3	2.5 mh
C-11	.25 mf	VT-8	OA2
C-12	.02 mf	VT-9	6CL6
C-13	100 mmf	VT-10	6L6

agitation of the atoms in the resistor materials (5). The filament noise is considered in the cathode heating method. Because of the resistor noise, the resistors used in critical positions of the entire circuit, and especially in the first stages, are of the low noise type. The noise level is proportional to the resistance, so that the effect is most evident in the high resistance portions of the circuit. The smallest signal that can be amplified over the noise level is called sensitivity.

The first three tubes and screen of the fourth are fed by three independent voltage sources to eliminate feedback through the power supply. Without this precaution the amplification would be a function of the pulse repetition rate and pulse widths. Table I lists the values of the dropping resistors chosen to meet the current requirements in the regulator tubes (6).

To eliminate low frequency hum the first three tube filaments are heated by direct current. The 6.3 VDC filament voltage is produced by a single-phase, full wave circuit shown in Figure 4. The ripple was experimentally determined to be 6.1 percent at full load.

Tuned plug-in units were made available for use in the plate circuits of the fourth and fifth stages. A typical set of plug-in units are shown in Figure 5. It is possible to obtain an increase in the plate impedance using a resonant circuit, and consequently, an increase in gain from that stage. Six pairs of the plug-in units were used in the investigation of the tuned plate circuit mode of operation.

Radio-frequency chokes were incorporated in each power supply plate lead to eliminate low impedance radio-frequency paths through the power supply.

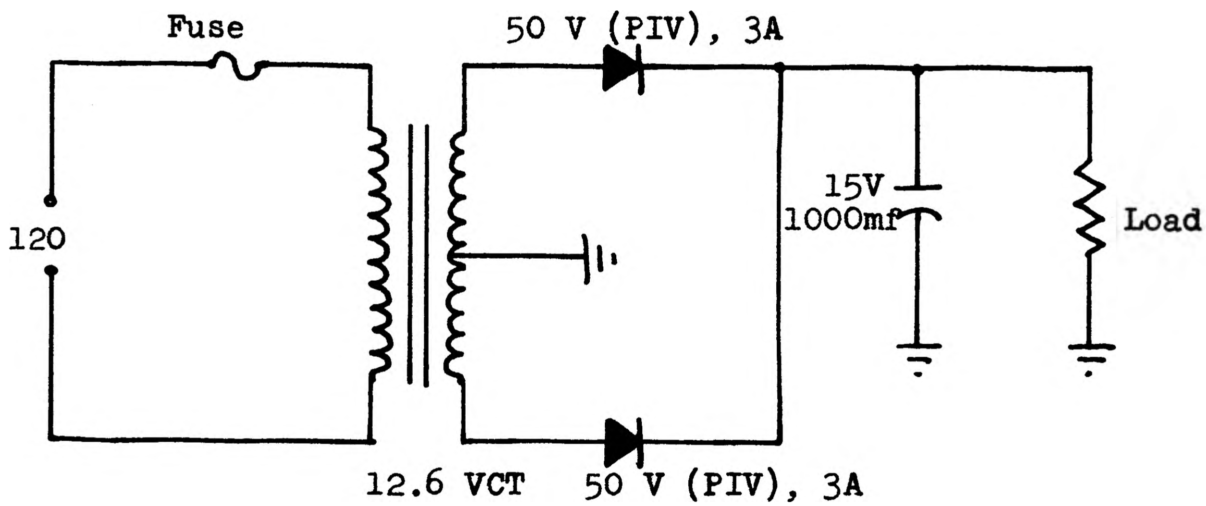


Figure 4. 6.3 VDC Filament Supply

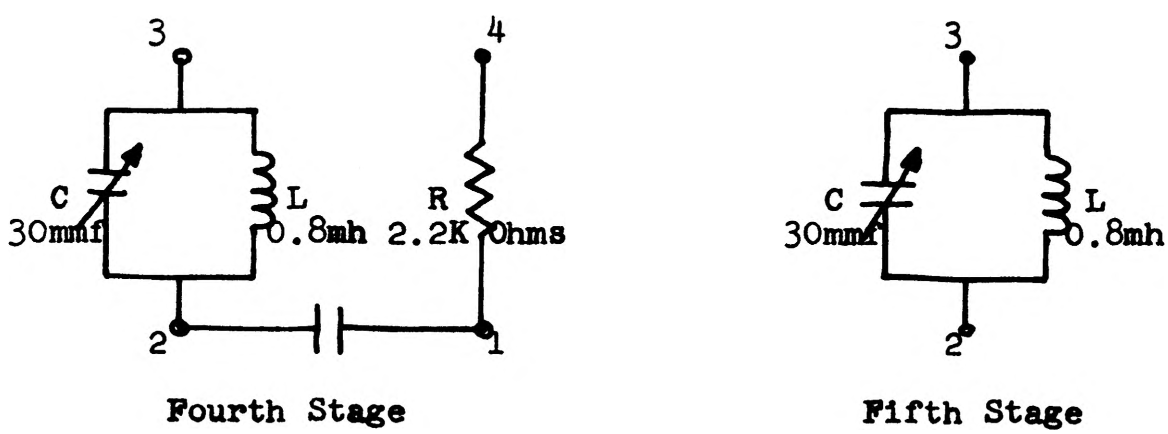


Figure 5. Tuned Plug-in Units

B. Power Supply

An unregulated power supply with an output of 0 to 300 volts at a maximum current of 300 milliamperes was designed and constructed to be used with the amplifier. The circuit chosen was for a single-phase, full wave type shown in Figure 6.

A variable autotransformer was connected to the primary of the transformer to enable a variation from 0 to 360 volts on either side of the secondary center-tap.

The rectification was accomplished by using three diodes in each leg of the transformer on either side of the center-tap. Three diodes were used to meet the peak inverse voltage requirements (7).

To insure uniform voltage division between the diodes, capacitors were connected across the individual cells.

To filter the alternating component from the B+, a single section capacitor input filter was used. In general, this type of filter provides a higher dc output voltage than a choke input filter because the input capacitor is charged to a voltage nearly equal to the peak of the rectifier voltage (8).

When operating the supply at 300 volts and full load, it was observed that the alternating component was 3.2 volts, a ripple content of 1.07 percent. The only component of the amplifier that senses this ripple is the 6L6 final output tube whose performance is not significantly affected. The other components of the amplifier are fed through individual voltage regulator tubes and thus are not affected by this ripple.

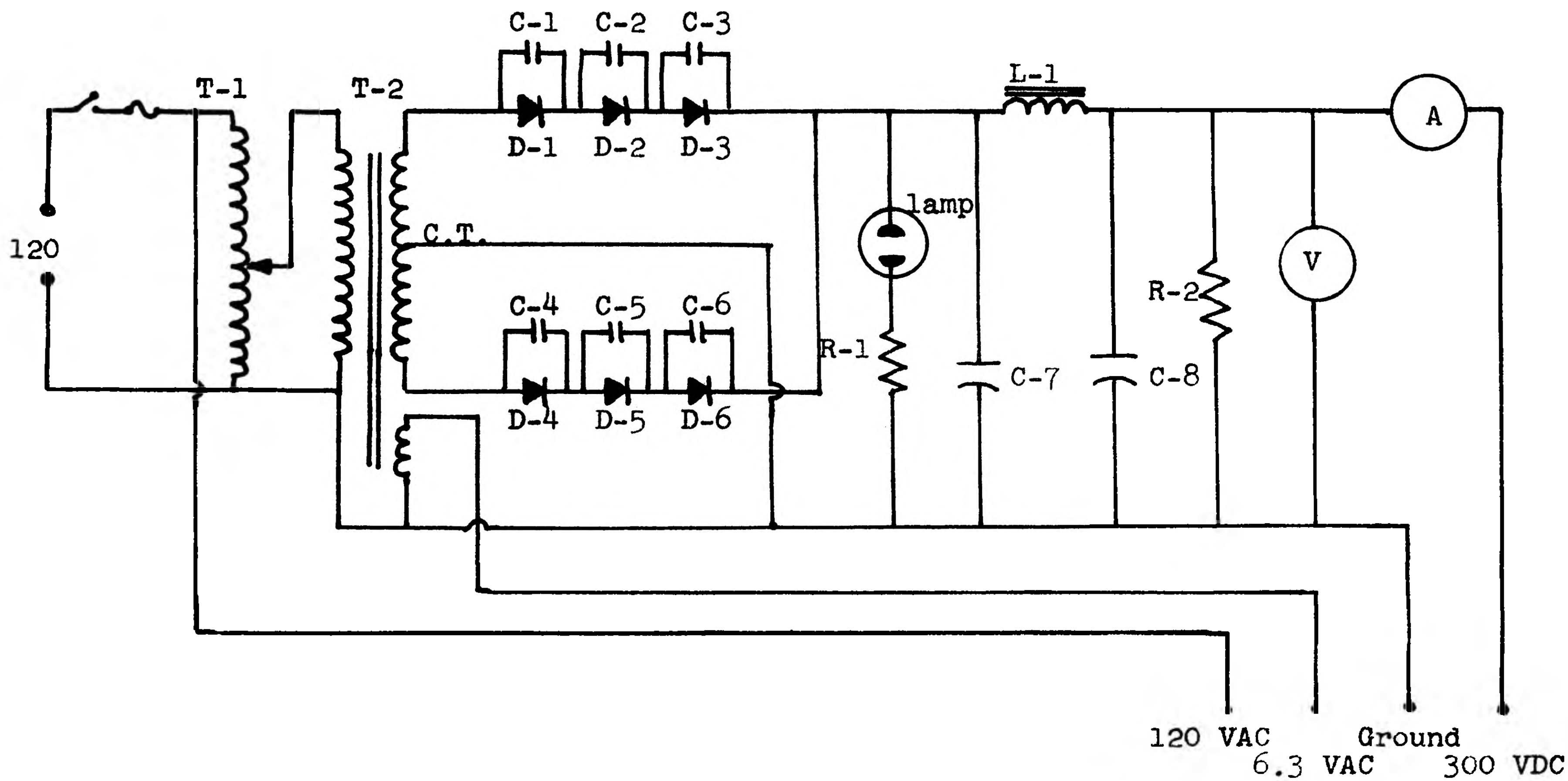


Figure 6. Power Supply Schematic

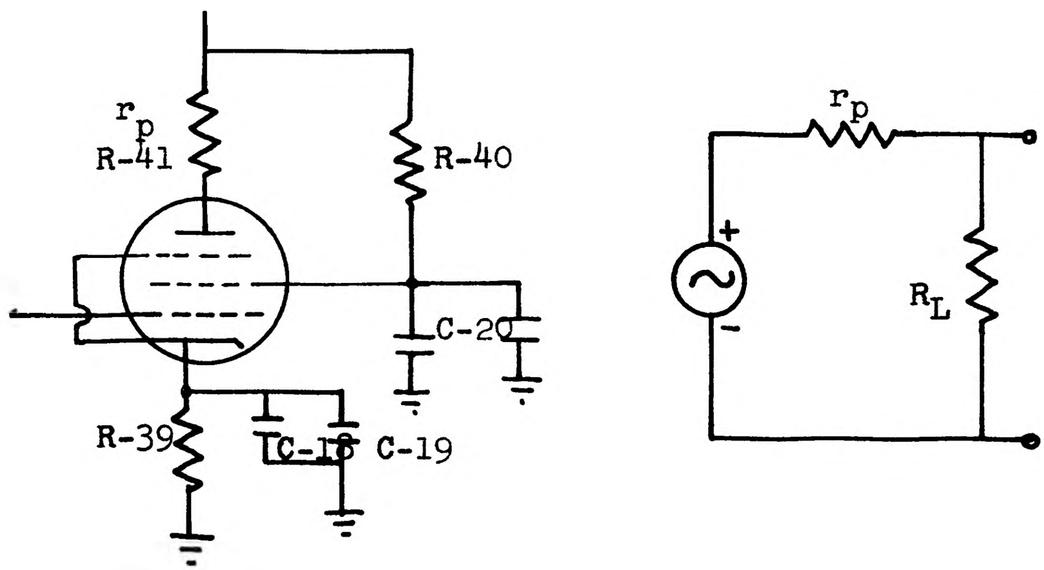
TABLE III

POWER SUPPLY COMPONENTS

C-1	0.005 mf, 600 volt
C-2	0.005 mf, 600 volt
C-3	0.005 mf, 600 volt
C-4	0.005 mf, 600 volt
C-5	0.005 mf, 600 volt
C-6	0.005 mf, 600 volt
D-1	5A6 600 volt (PIV) 750 ma (I_o)
D-2	5A6 600 volt (PIV) 750 ma (I_o)
D-3	5A6 600 volt (PIV) 750 ma (I_o)
D-4	5A6 600 volt (PIV) 750 ma (I_o)
D-5	5A6 600 volt (PIV) 750 ma (I_o)
D-6	5A6 600 volt (PIV) 750 ma (I_o)
T-1	Variable Autotransformer, 0-130 volt, 1.25 amp
T-2	Power Transformer, 640 VCT, 375 ma
R-1	270,000 ohms, 2 watts
R-2	30,000 ohms, 30 watts
L-1	5 henry, 275 ma Filter Choke
C-7	20 mf, 450 VDC
C-8	30 mf, 450 VDC
V-1	0-500 Voltmeter
A-1	0-800 Milliammeter

III. TESTING AND ANALYSIS

By adjusting the selector switch at the grid of the first tube the input impedance is varied from approximately 1 ohm to 6530 ohms. The output impedance was determined from the equivalent ac circuit of the output tube shown in Figure 7. The output impedance of the amplifier is equivalent to the resistance of the plate resistance and plate load



a. Isolated 6L6 Stage b. Equivalent ac Circuit

Figure 7. The 6L6 Stage Equivalent Circuit

resistor connected in parallel. This was found to be 1890 ohms. This is a good approximation; however, the plate resistance, in general, varies as it is defined to be (9),

$$r_p = \frac{\partial i_b}{\partial e_b} ,$$

where,

i_b = instantaneous plate current
e_b = instantaneous plate voltage.

The gains of the individual stages were experimentally determined, and the gains of the fourth and fifth stages were

TABLE IV

GAIN OF INDIVIDUAL STAGES

Stage	Experimental	Calculated
1	2.3	---
2	2.7	---
3	2.6	---
4	23.0	24.3
5	9.8	10.6

calculated. The results are given in Table IV. The gains of the fourth and fifth stages were calculated using:

$$\mu = g_m r_p ,$$

where

μ = gain
g_m = transconductance
r_p = plate load resistor.

The small gain of the first three tubes occurs because they are operated as peak clippers. The gain of these stages cannot be calculated with accuracy since the transconductance at their operating voltage varies greatly in the vicinity of the operating point.

The sensitivity was determined by adjusting an input pulse amplitude to a point immediately above the noise level. It was found to be 6 micro-volts.

The frequency response of the amplifier, in wide band operation, was measured by manually sweeping the frequency range with a sinusoidal oscillator. The experimental configuration used in measuring this frequency response is shown in

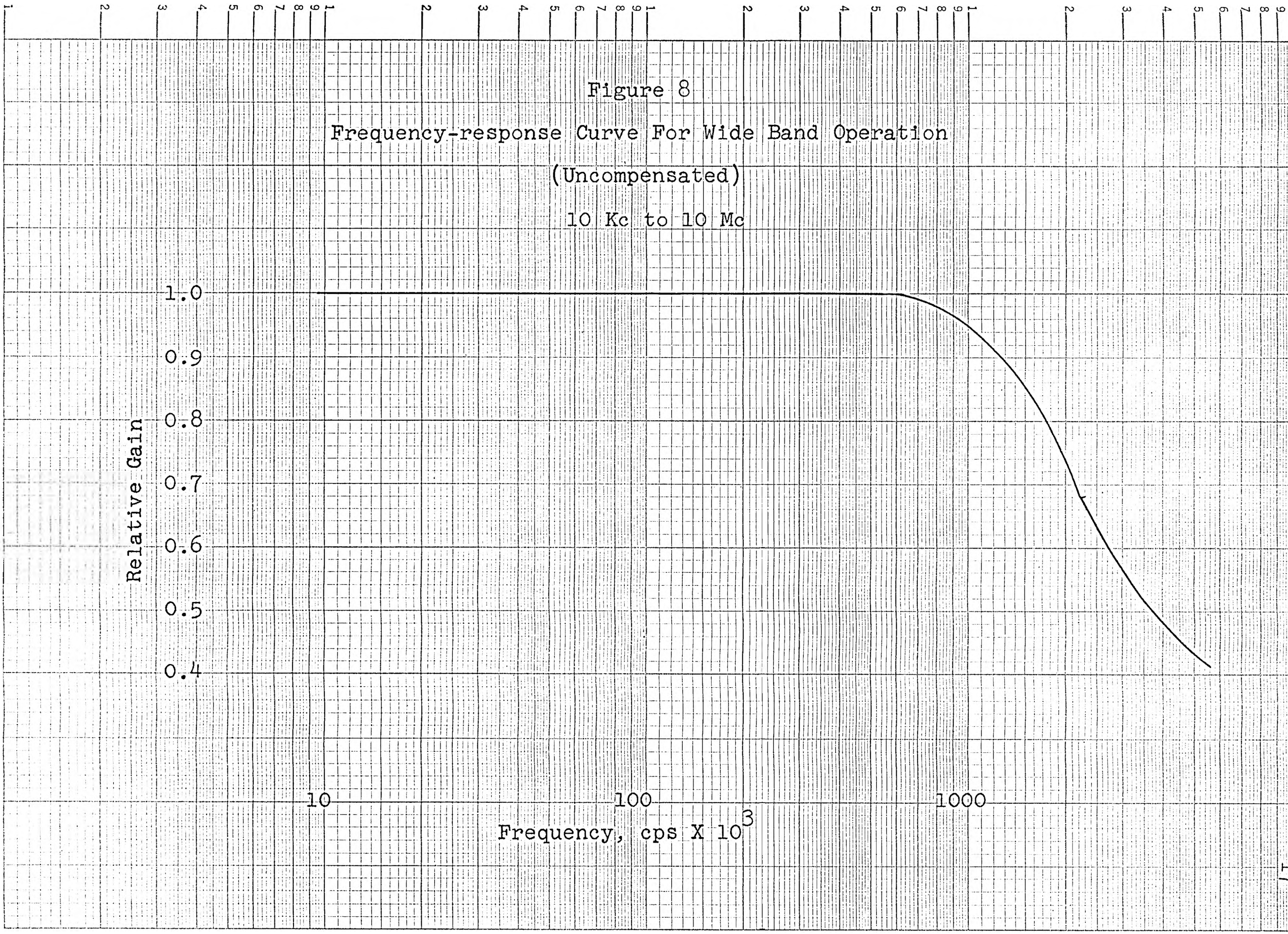


Figure 8

Frequency-response Curve For Wide Band Operation

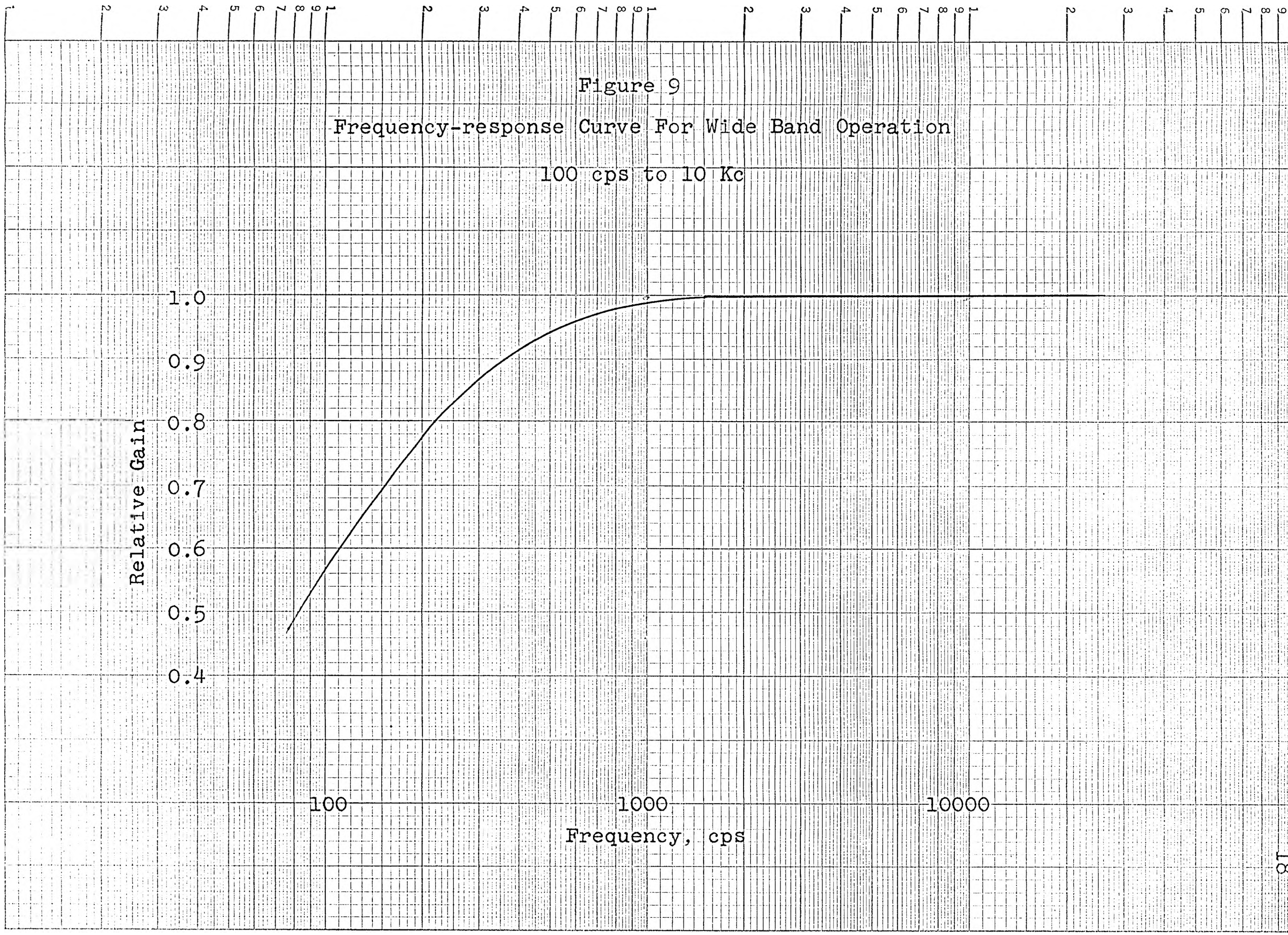
(Uncompensated)

10 Kc to 10 Mc

Figure 9

Frequency-response Curve For Wide Band Operation

100 cps to 10 Kc



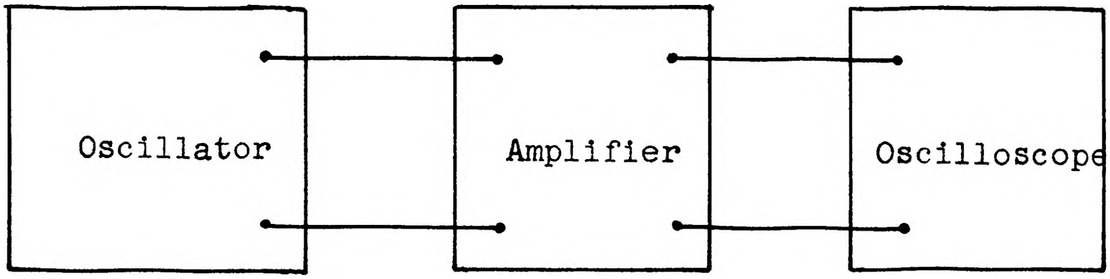


Figure 10. Frequency-response Equipment

Figure 10. The frequency response curve is shown in Figure 8 and 9 and has been normalized at its mid-band frequency of 500 Kc. The flat portion of the curve extends down to approximately 1 Kc and then drops off slowly to 100 cps. The gain at mid-band frequency is 3640.

The same equipment was used for measuring the frequency response while operating with the tuned plate circuit plug-in units in place. The observed response curves are shown in Figures 11 and 12. The unusual amount of gain illustrated in the response curves occur because of the resonant frequency of the tuned plate circuit. At this frequency the plate impedance is much larger than that of the plate load resistor used in wide band operation. The gain-bandwidth product is constant for a single stage and depends primarily on the quality factor of the resonant circuit, where the factor is defined as,

$$Q = \frac{R}{X},$$

where

R = parallel load resistor
X = reactance of either the inductor or capacitor.

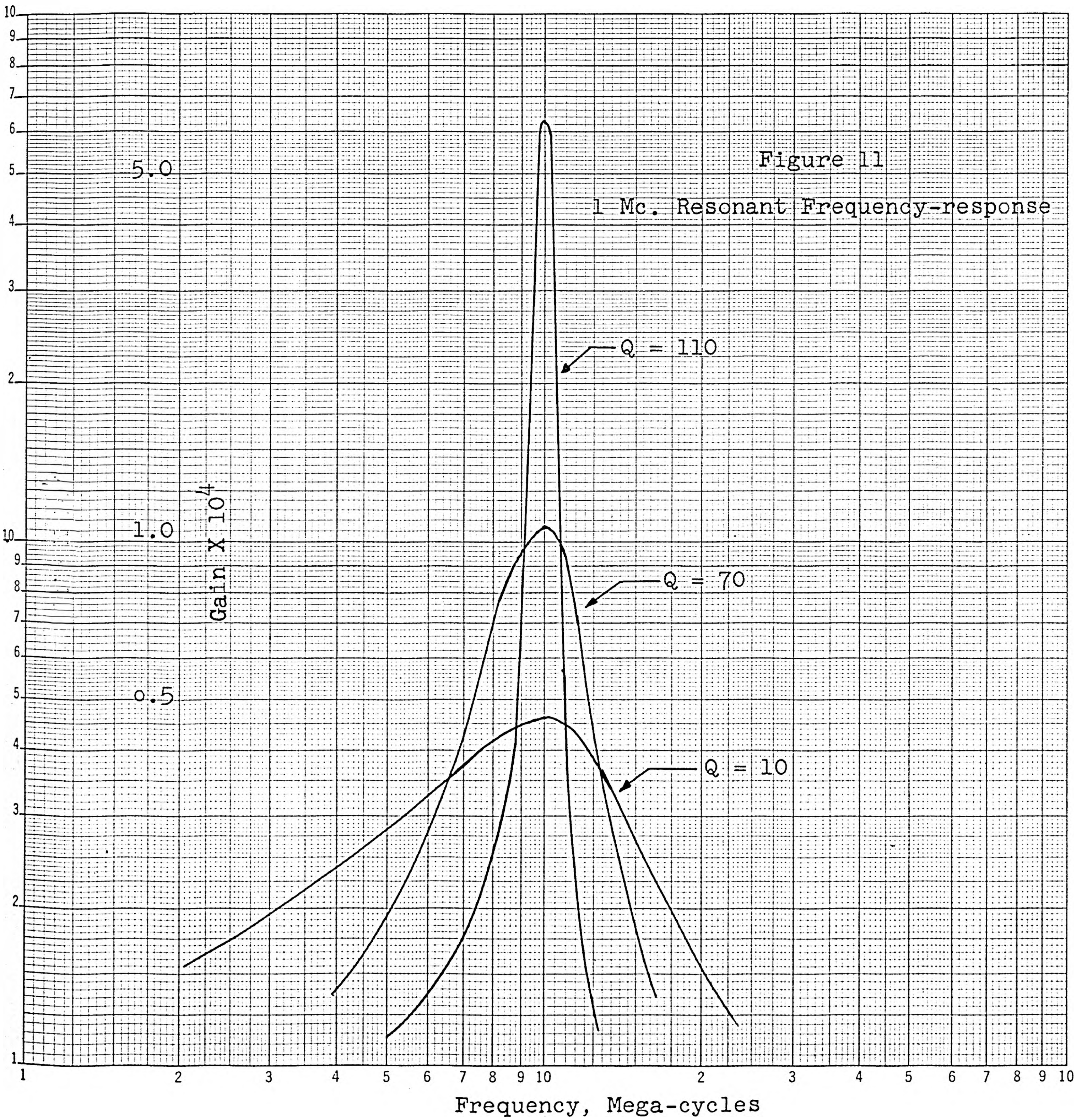


Figure 11
1 Mc. Resonant Frequency-response
5.0
1.0
0.5
Gain X 10^4
Q = 110
Q = 70
Q = 10
Frequency, Mega-cycles

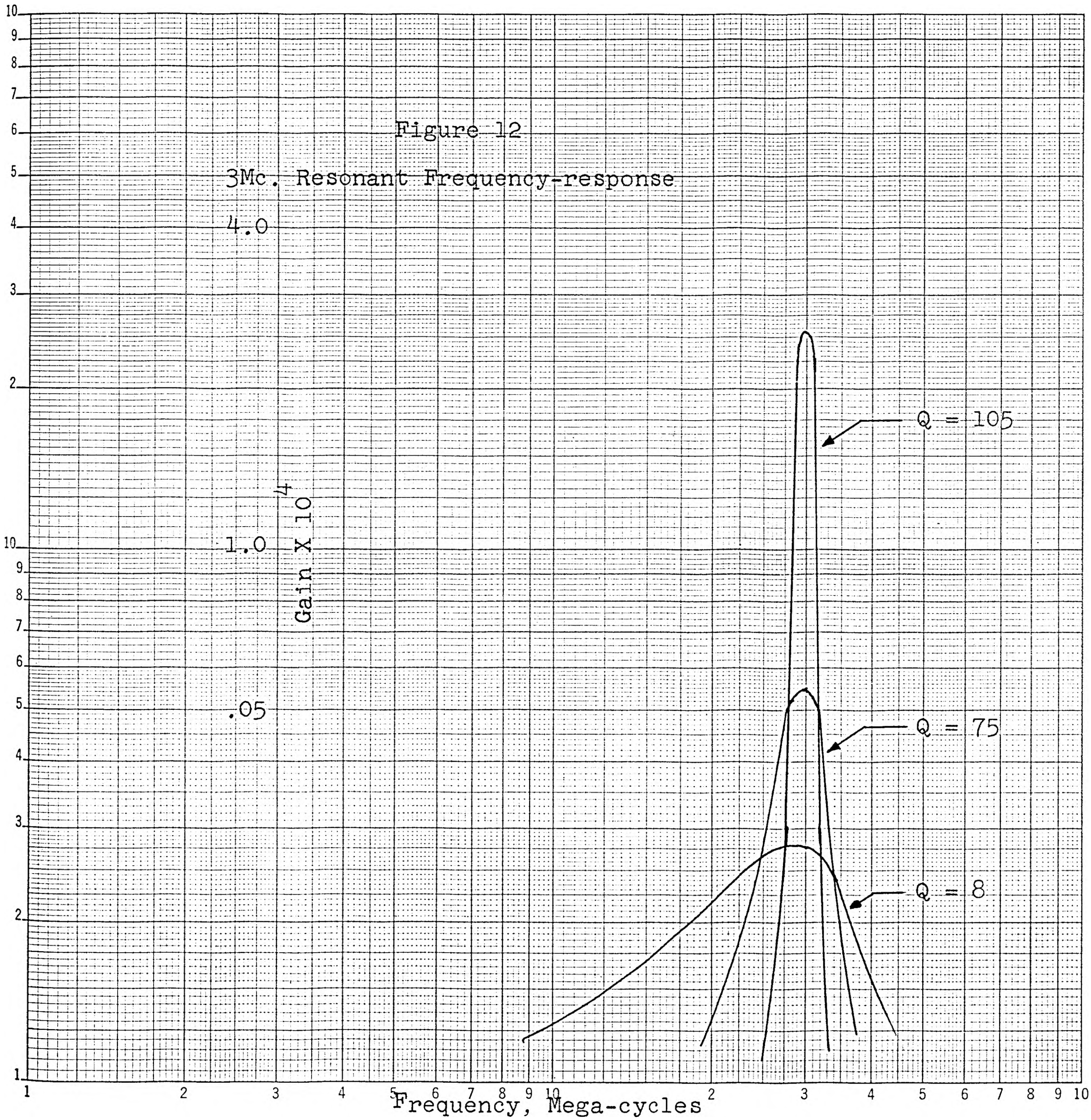


Figure 12
3Mc. Resonant Frequency-response
4.0
1.0
.05
Gain X 10^4
Q = 105
Q = 75
Q = 8
Frequency, Mega-cycles

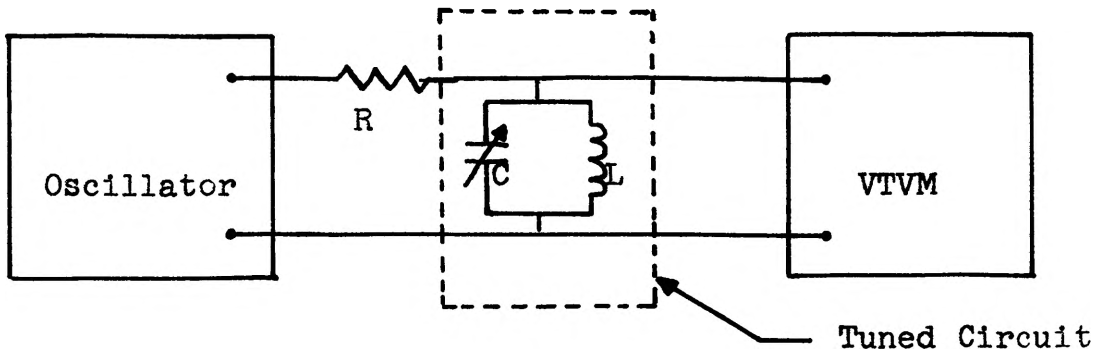


Figure 13. Resonant Point Equipment

By sweeping the approximate frequency range of the tuned circuit with an oscillator as shown in Figure 13 a point was found where the voltage indication of the VTVM was a maximum. At the resonant frequency, the largest ac voltage appears. Three pairs of resonant plate circuits were constructed. Using the equipment in Figure 13 the resonant frequencies were adjusted to 1 Mc. The values of Q for these circuits were determined by using a Q-meter. The results are listed in Table V. A frequency-response curve for each pair of resonant

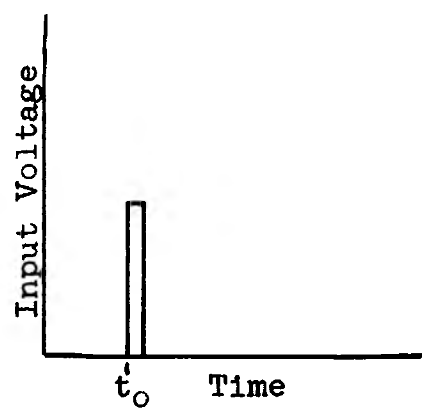
TABLE V

Q VALUES FOR TUNED PLATE CIRCUIT

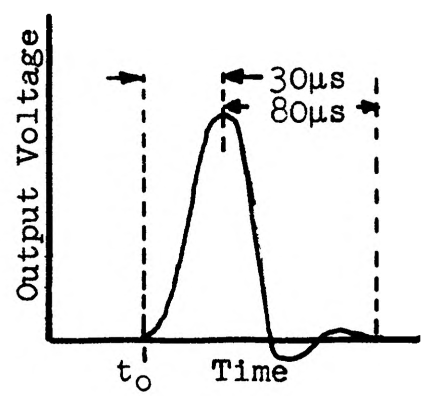
Resonant frequency	Q	Resonant frequency	Q
1 Mc	10	3 Mc	8
1 Mc	70	3 Mc	75
1 Mc	110	3 Mc	105

plate circuits are shown in Figure 11. The frequency-responses for these circuits readjusted to resonate at 3 Mc are shown in Figure 12.

An impulse test was used to determine the rise and recovery time of the amplifier (10). The equipment used was similar to that in Figure 10, except that the sinusoidal oscillator was replaced by a pulse generator. The recovery time was found in two ways. First, a very short pulse of 10 µsec was applied to the input of the amplifier as shown in Figure 14a. The output showed a rise of 30 µsec and a recovery time of 80 µsec as shown in Figure 14b. The rise time remained almost constant at 30 µsec with a corresponding recovery time of 80



a. Input

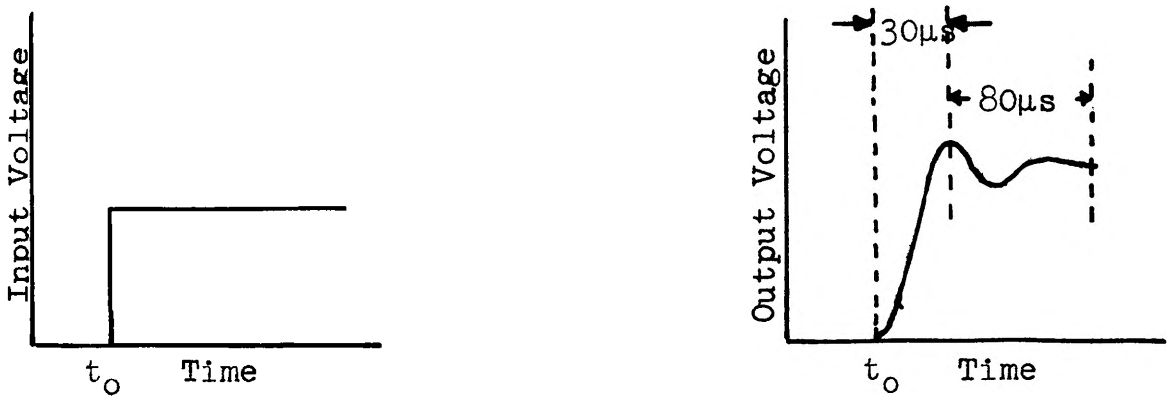


b. Output

Figure 14. Impulse Test

µsec for a variation of pulse width from 10 µsec to 50 µsec. For the second test, a step function was fed into the amplifier input as shown in Figure 15a. The response and recovery times were the same as those for the short duration pulses.

Series peaking coils were placed in series with the signal path between each stage to investigate the effect on the



a. Input b. Output

Figure 15. Step Function Test

uncompensated frequency response curve (11). Placement of the coils is shown in Figure 16. To produce the desired results the winding, orienting, and shielding of the coils was accomplished by trial and error. The compensated fre-

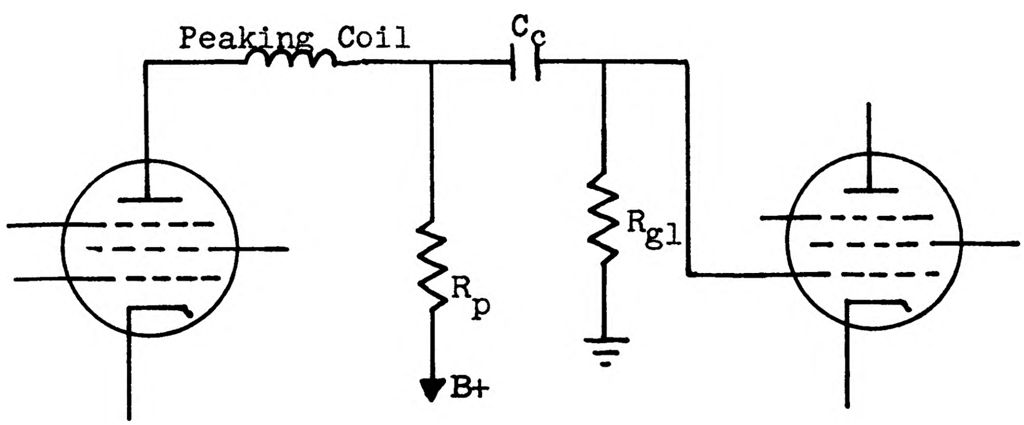


Figure 16. Placement of the Peaking Coils

quency-response is shown in Figure 17. The flat portion of the uncompensated curve has been extended from 700 Kc to 1.2 Mc by using the peaking coils. The compensated response curve drops abruptly to a relative gain of 0.38 at 3 Mc, whereas the uncompensated curve is less abrupt and has a gain of 0.58 at 3 Mc. The low frequency end of the compensated curve remained the same as the uncompensated curve shown in Figure 9.

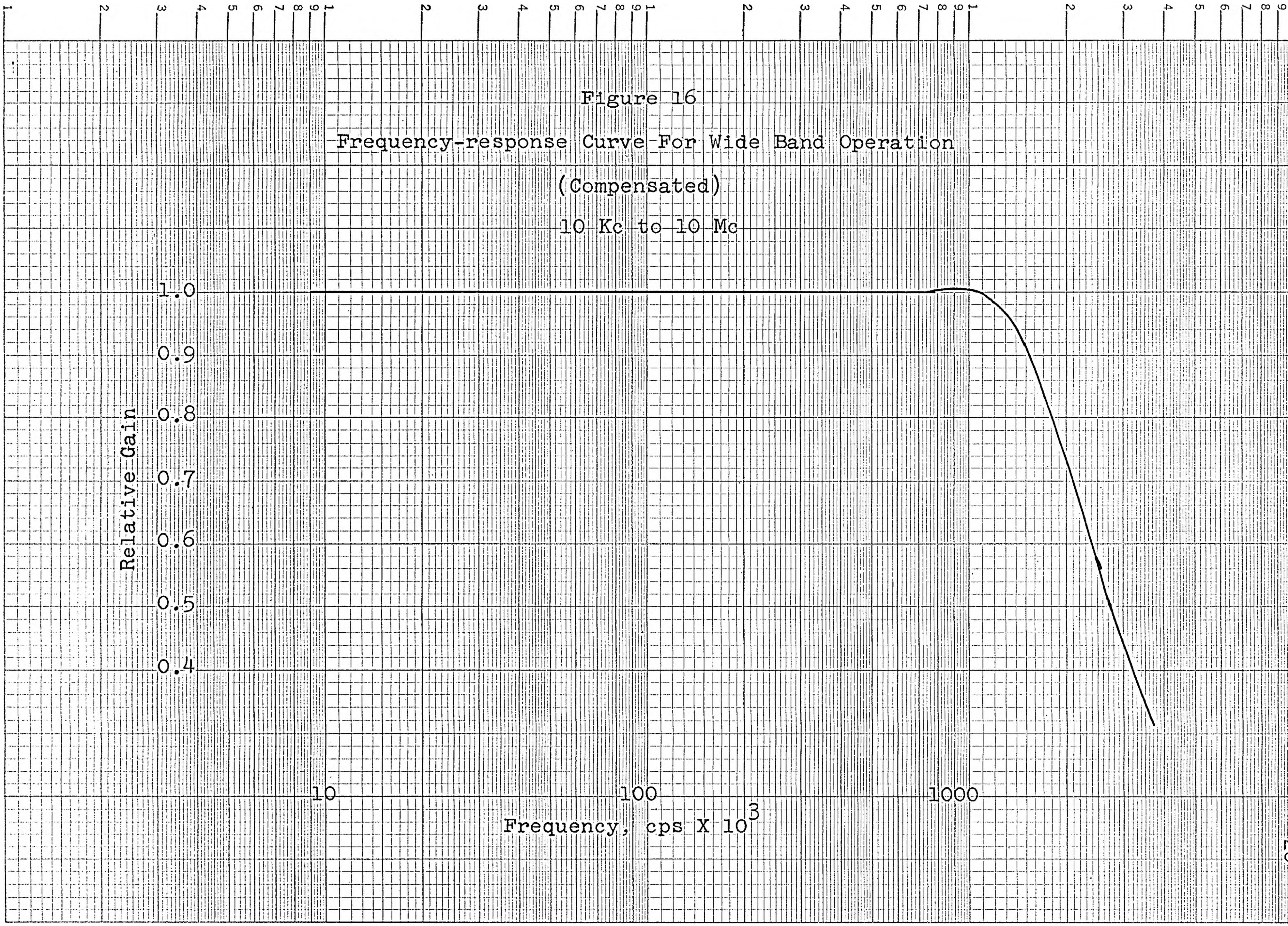


Figure 16

Frequency-response Curve For Wide Band Operation

(Compensated)

10 Kc to 10 Mc

IV. CONCLUSIONS

While operating in the uncompensated wide band mode the amplifier has a flat response from 100 cps to 700 Kc. Mid-band gain is 3640 and drops to its half-gain value at 3.8 Mc. The response curve remains flat to 1.2 Mc and drops to its half-gain value at 2.7 Mc while in the compensated wide band mode. Peaking coils placed in series with the signal path between the stages account for this increase but produce a sharper cutoff in the frequency-response curve. Resonant plate circuits may be incorporated in the fourth and fifth stages. The amplifier in this mode has a larger gain but correspondingly narrower bandwidth. If losses in gain are tolerable, the amplifier may be used to approximately 5 Mc by this method. A gain of 63,000 at 1 Mc was achieved by a pair of resonant plate circuits and can be increased if the Q values of the resonant circuits are made larger. If larger Q values are desired high loss components such as mica capacitors and ferrite inductor cores should be avoided.

The sensitivity was found to be 6 micro-volts in the wide band mode.

For various pulse widths from 10 μsec to 50 μsec in length the rise time and recovery time remain constant at 30 μsec and 80 μsec, respectively. The rise time is defined here as the time required to move from the leading edge to the top of the pulse, and the recovery time from the top to the position where the trailing edge of the pulse has been damped completely.

The clipping level can be varied by adjusting the impedance control at the grid of the first stage. This control also prevents damage to the first stage by attenuating large pulses and thereby limits the grid current on the positive half cycles of large amplitude input pulses. The large direct pulses from the ultrasonic pulsing unit are attenuated, and the micro-volt echo pulses are detected immediately following due to the 80 usec recovery time.

This amplifier can be used more effectively for pulse-echo techniques if operated in the tuned plate circuit mode because of the extreme gain needed. In this mode the frequency must remain constant or suffer a large variation in gain. The relative half-gain bandwidth for Q = 110 at a resonant frequency of 1 Mc shown in Figure 11 is 0.1 Mc. If the investigation requires a frequency dependent study in this mode of operation the amplifier can be used as the intermediate frequency amplifier of a superheterodyne unit.

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VITA

The author was born on December 5, 1935, in St. Louis, Missouri. His grade school and high school education was received in that city. Upon completion of his high school education in 1953 he enrolled at Harris Teachers College. In 1954, he enrolled at Parks College of Aeronautical Technology of St. Louis University where he received a Bachelor of Science in Aeronautical Engineering in April, 1957. From September, 1957 until September, 1959, he served in the United States Army. He enrolled at the Missouri School of Mines and Metallurgy in January, 1960, and received a Bachelor of Science, physics major in May, 1961.

He was married to the former Shirley Arlene Saum of Villa Ridge, Missouri, on June 4, 1961.