ELECTRONIC DEFENSE GROUP
THE UNIVERSITY OF MICHIGAN

ERRATA SHEET
Technical Memorandum No. 48
2262-167-T

Page 17 Sketches accompanying photographs, Figures 18 and 19, should be transposed.

ENGINEERING RESEARCH INSTITUTE
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THE DESIGN AND MEASURED CHARACTERISTICS OF 450 MC POWER DISTRIBUTED AMPLIFIERS

Technical Memorandum No. 48

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Project. 2262

TASK ORDER NO. EDG-1
CONTRACT NO. DA-36-039 sc-63203
SIGNAL CORPS, DEPARTMENT OF THE ARMY
DEPARTMENT OF ARMY PROJECT NO. 3-99-04-042
SIGNAL CORPS PROJECT NO. 194B

July 1957

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ABSTRACT

This report presents the results of an investigation by the Electronic Defense Group into means of increasing the frequency capabilities of power distributed amplifiers. The design, physical construction, and electrical characteristics of a 6-tube 4X150A distributed amplifier and a 6-tube 4X250B distributed amplifier are described. These amplifiers demonstrate experimentally the validity of the theory of distributed amplifiers using dummy constant-k line sections between tubes. The amplifiers have upper cutoff frequencies in the neighborhood of 450 mc and useful output power capabilities. The output power capability is, however, a function of the duty cycle at which the amplifier is operated.

THE DESIGN AND MEASURED CHARACTERISTICS OF 450 MC POWER DISTRIBUTED AMPLIFIERS

1. INTRODUCTION

Power amplification in the frequency range above that in which conventional power amplifiers are able to operate is a subject of continuing interest in the countermeasures research area. Conventional distributed amplifiers using presently available tube types are limited to upper cut-off frequencies in the neighborhood of 300 mc. A novel method of overcoming the upper cut-off frequency limitations of conventional distributed amplifier circuits through the use of dummy grid and plate line sections was investigated theoretically by Dr. P. H. Rogers shortly before he terminated his EDG activities. The present paper gives the design and operating characteristics of a 4X150A distributed amplifier and a 4X250B distributed amplifier which were designed using the principles outlined in Reference 1.

2. GRID AND PLATE LINE CONSIDERATIONS

The problem of raising the upper cut-off frequency of a distributed amplifier resolves itself into that of raising the upper cut-off frequency of the grid and plate lines with fixed tube capacitances and inductances appearing as elements of the lines. The plate lead inductance of the tubes discussed in this report (4X150A and 4X250B) is sufficiently low so that in the operating frequency range it can be assumed that the tubes present to the plate line only shunt capacities equal to the output capacities of the tubes. These tubes present to the grid line a shunt reactance which can be satisfactorily approximated over the operating frequency range with a circuit made up of the series combination of grid lead inductance and input capacitance. The characteristics of the m-derived lumped-constant lines used in the grid circuit of the amplifiers to be described, and in which the fixed tube constants described above appear, are analyzed in Reference 1. The analysis suggests that one should use negative mutual coils in the grid line to cancel or, if it were possible, to even overcompensate for the grid lead inductance. Actually, with maximum attainable coefficients of coupling (approximately 0.6) for the small air core coils used, the maximum bandwidth is obtained by just cancelling the grid lead inductance. This cancellation would result in a constant-k line such as is shown in Figure 1. In this diagram, C_t is the tube input

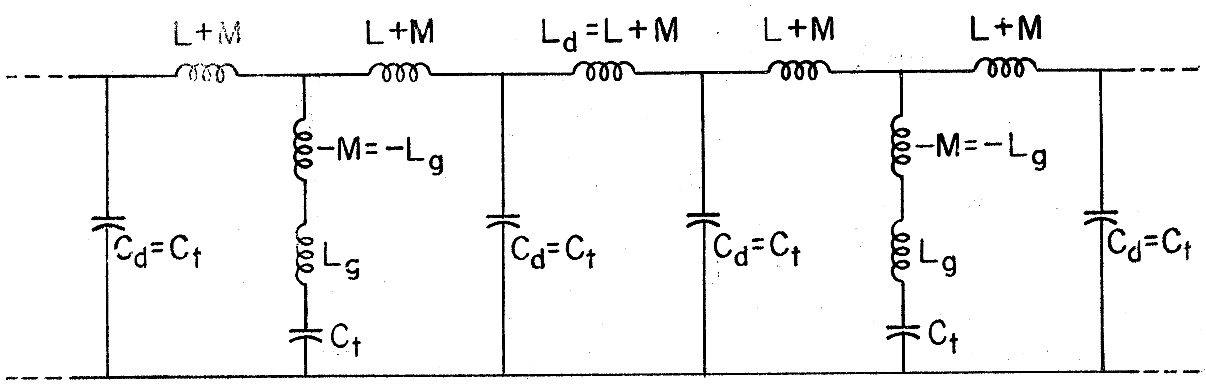

Fig. 1 Constant-k Line

capacitance, L_g is the grid lead inductance, L is the self-inductance of the coils which are coupled so as to reflect a negative mutual inductance equal in magnitude to L_g into the grid lead, C_d is the capacitance of the dummy constant-k sections, and L_d is the inductance of the dummy constant-k sections. If the dummy sections were not present the capacitance per section would be C_t and the inductance per section would be 2(L + M), resulting in a cut-off frequency of

$$\omega_c = \frac{2}{\sqrt{2(L + M)C_t}} \quad (1)$$

For the circuit of Fig. 1 where dummy sections are used, however, the inductance per section is L + M and the cut-off frequency becomes

$$\omega_c \quad \frac{2}{\sqrt{(L + M)C_t}} \qquad (2)$$

Thus, through the use of dummy sections one can increase the upper cut-off frequency by a factor of $\sqrt{2}$ for a fixed magnitude of the shunt capacitances. The grid lead inductance L_g of either the 4X150A or 4X250B tubes is approximately 0.007 microhenries. With a coefficient of coupling between the L's of 0.6, then

$$L = \frac{M}{k} \cong \frac{L_g}{k} = 0.012 \text{ microhenries} \qquad (3)$$

The input capacitance of either a 4X150A or 4X250B tube with a hot filament is in the neighborhood of approximately 20 micromicrofarads. The maximum realizable cut-off frequency with these tube parameters is approximately 515 mc. The amplifiers described later were constructed using the above values as starting points, giving for the grid lines a nominal characteristic impedance of 30 Ω.

In the plate line there is no problem of cancelling lead inductance for the bandwidths achieved, and the realization of this line is simple. The main requirement for the plate line is that for a given grid line the phase shift between plates be the same as the phase shift between respective grids. This means that the cut-off frequency of the plate line should equal the cut-off frequency of the grid line, and, in addition, the number of constant-k sections between tubes should be the same in both the grid and plate lines.

The output capacity of either the 4X150A or 4X250B tubes with shielding is approximately 10 micromicrofarads. The cut-off frequency of the plate line is given by

$$\omega_c = \frac{2}{\sqrt{L_p C_o}} \qquad (4)$$

where L_p is the inductance of a plate line section and C_o is the output capacity of the tube. For a cut-off frequency of 515 mc and an output capacity of 10 micromicrofarads one finds that

$$L_p \cong 0.0382 \text{ microhenries} \tag{5}$$

Again, the amplifiers described later were constructed using these values as starting points, giving for the plate lines a nominal characteristic impedance of 60 Ω.

2.1 Number of Tubes for a Flat Gain Characteristic

P. H. Rogers has shown[2] that by the proper choice in the number of tubes, grid line losses due to tube loading can be made to compensate for the rising impedance characteristic of the mid-shunt grid and plate line sections so as to result in a flat over-all gain characteristic for an amplifier of a given bandwidth. This proper choice is found from Eq 6.

$$n\omega_c = \frac{\omega^2 C_g}{G_{in}} \tag{6}$$

where n is the number of tubes for a flat gain characteristic, ω_c is the cut-off frequency of the amplifier, C_g is the input capacity of the tubes, and G_{in} is the conductive component of input admittance of the tubes. For the 4X150A, G_{in} is determined from Figure 2. Using $G_{in} = f^2/2260$ and $C_g = 20$ micromicrofarads, one finds that for $\omega_c = 515$ mc, n = 5.5. It was decided to use 6 tubes in the 4X150A amplifier to be fabricated. Because of the similarity in input admittance characteristics between 4X150A and 4X250B tubes, 6 tubes were also planned for a 4X250B distributed amplifier.

2.2 Terminating Networks

m-derived half-sections were used to match the constant-k lines to the terminating loads. The resulting circuit is equivalent to Figure 3.

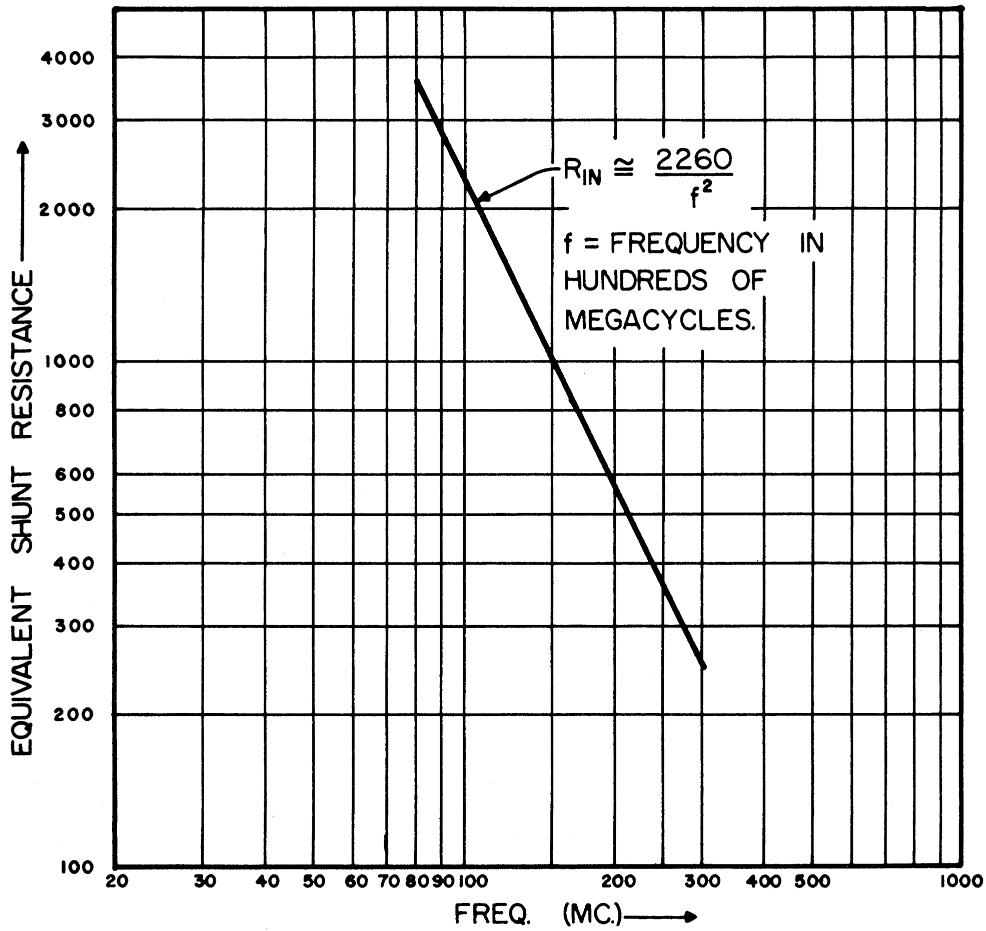

FIG. 2. VARIATION OF EQUIVALENT SHUNT RESISTANCE OF A 4X150A CAUSED BY LEAD INDUCTANCE AND TRANSIENT TIME.

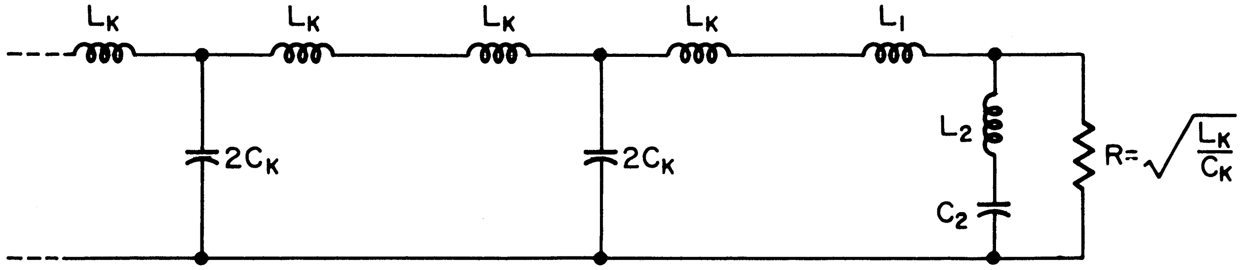

FIG. 3. CONSTANT-K PROTOTYPE AND M-DERIVED TERMINATING SECTIONS.

The elements of the m-derived section are determined by the elements of the constant-k prototype;

$$L_1 = mL_k \tag{7}$$

$$L_2 = \frac{(1 - m^2)L_k}{m} \tag{8}$$

$$C_2 = mC_k \tag{9}$$

A value for m of 0.6 was chosen for these terminal half-sections, which results for the grid line in the element values of Fig. 4.

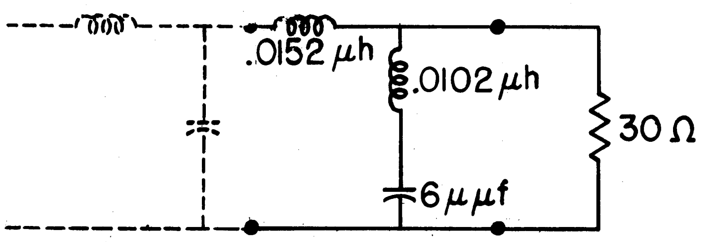

Fig. 4 Grid Line m-derived Terminating Section

For the plate line, the terminating half-section of Fig. 5 results.

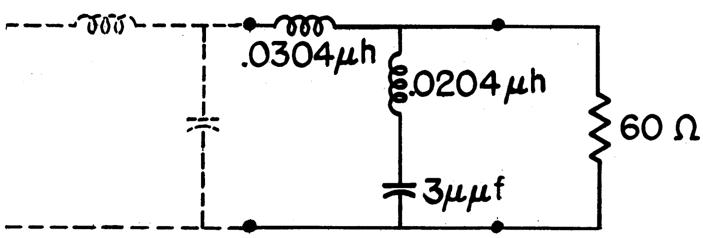

Fig. 5 Plate Line m-derived Terminating Section

The basic design was modified to facilitate the solution of two practical problems. The first of these problems is associated with supplying dc power to the plates and grids of the tubes. The very desirable shunt feeding of these voltages is best accomplished if a shunt inductance is present in the lines. A second problem results from the undesirability of the magnitude of the grid line terminations (30 ohms) which resulted for the experimental amplifier. It is often desirable, both for experimental work and subsequent applications, to be able to use commercially available 50 ohm power terminations and measuring equipment.

It is possible to solve both of the above problems over a bandpass frequency range by insertion of suitable bandpass matching networks between the plate and grid lines, and their several terminations. Since the unique feature of the amplifiers under consideration is their ability to operate in the frequency range 300-500 mc, this frequency range was singled out for experimental investigation. Bandpass matching networks were therefore chosen with 3 db points at 100 mc and 600 mc, resulting in very moderate mismatch in the 300-500 mc range. The mean frequency of the 100-600 mc band is approximately 245 mc, and is therefore the "center frequency" of the networks.

Background material necessary for the choice of suitable networks is widely available in the literature of modern network synthesis, and will not be presented here. However, the generation of the specific networks will be exemplified. Suitable bandpass networks can be derived from the low pass prototype network of Fig. 6. This three-pole one ohm-to-one-ohm matching network has a maximally-flat transmission characteristic, and a 3 db bandwidth of one radian per sec. A suitable network is obtained by performing impedance level, bandwidth, and lowpass to bandpass transformations on this prototype[3].

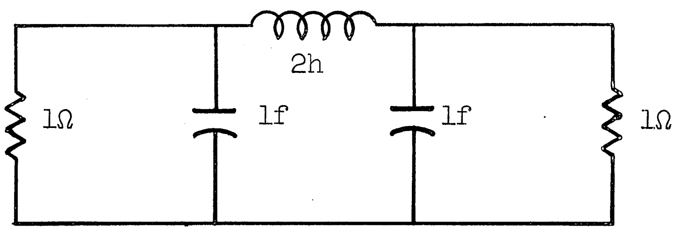

Fig. 6 Maximally Flat, Low Pass, One Ohm-to-One Ohm Matching Network with a 1 rad/sec Bandwidth.

Raising the impedance level of this circuit to 50 ohms yields the circuit of Fig. 7. This is accomplished by increasing all impedances by a factor of 50 at a fixed frequency.

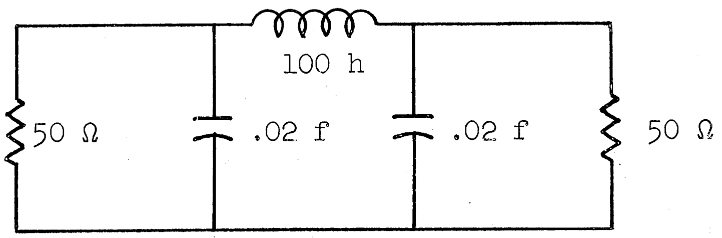

Fig. 7 Maximally Flat, Low Pass, 50 Ohm-to-50 Ohm Matching Network with a 1 rad/sec Bandwidth.

Increasing the bandwidth of the network of Fig. 7 from 1 rad/sec to 500 mc by dividing all reactive elements by $2\pi \times 500 \times 10^6$ results in the circuit of Fig. 8.

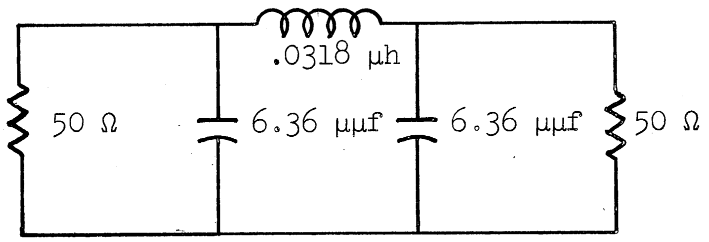

Fig. 8 Maximally Flat, Low Pass 50 hm-to-50 Ohm Matching Network with a 500 mc Bandwidth.

The required bandpass equivalent of the circuit of Fig. 8 with the same 3 db response bandwidth is determined by parallel-resonating all capacitors and series-resonating all inductances at 245 mc. This results in the circuit of Fig. 9.

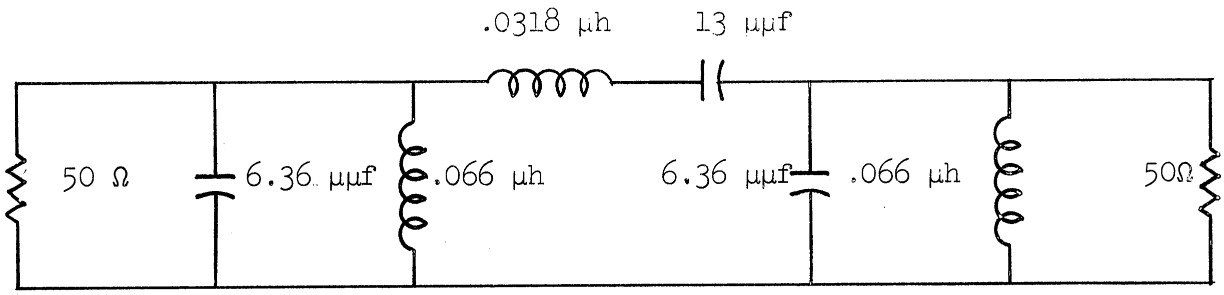

Fig. 9 Maximally Flat, Bandpass, 50 Ohm-to-50 Ohm Matching Network with a 500 mc Bandwidth.

Finally, for the plate line where the characteristic impedance is 60 ohms, the network should provide an impedance transformation between the 60 ohms and the desired 50 ohm impedance level of the termination. This is accomplished by inserting an ideal transformer into the network in accordance with the principles of Ref. 3. It can be shown that the desired ideal transformer should have a turns ratio equal to the square root of the desired impedance transformation, or $\sqrt{60/50}$. The resulting network is shown in Fig. 10a, which has an alternative realization shown in Fig. 10b.

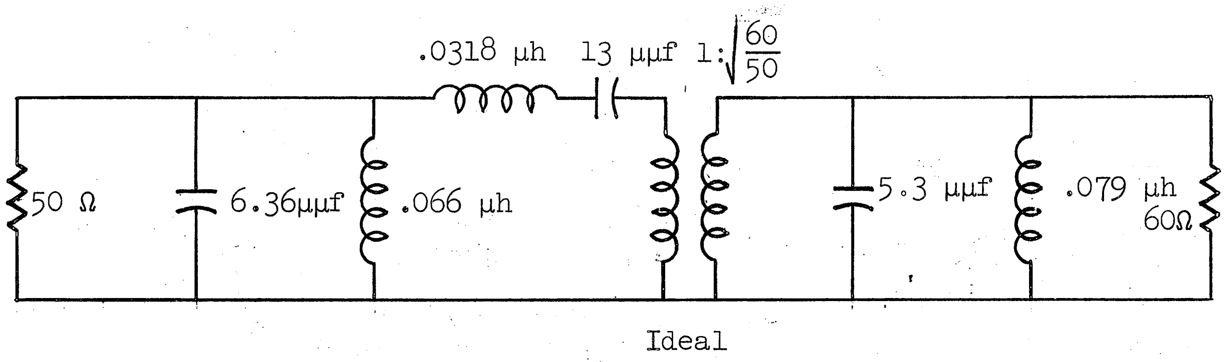

Fig. 10a

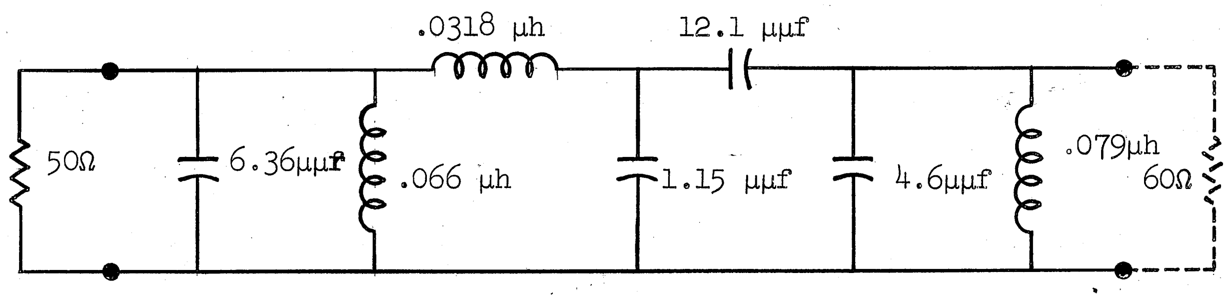

Fig. 10b

Fig. 10 Alternate Forms of a Maximally Flat, Bandpass, 50 Ohm-to-60 Ohm Network with a 500 Mc Bandwidth.

Now, the lower end of the 0.079 microhenry coil is by-passed to ground with a feed-through capacitor and B+ fed to the plate line through this coil.

A similar design procedure was used for the grid line, except that here the grid line characteristic impedance is approximately 30 ohms so that the terminating network in this case is designed to match from this impedance to a 50 ohm input cable. The circuit diagram of the grid line matching network is shown in Fig. 11.

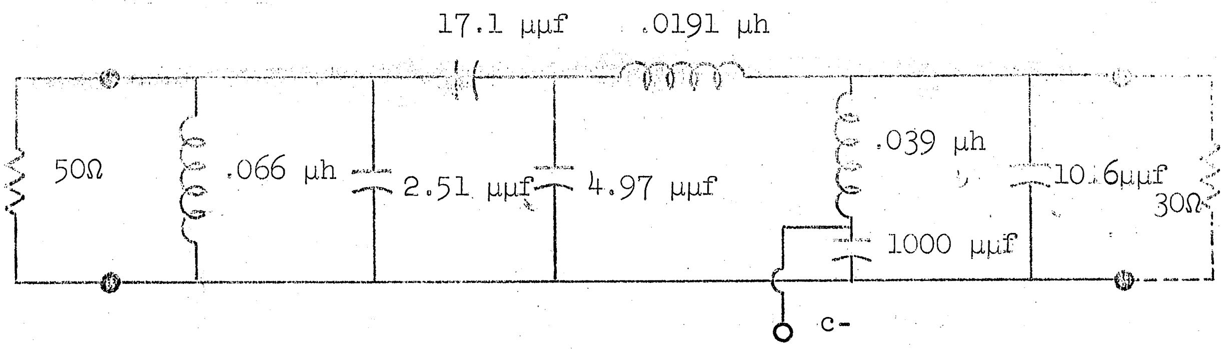

Fig. 11 Maximally Flat, Bandpass, 50 Ohm-to-30 Ohm Matching Network with a 500 mc Bandwidth.

The above described grid line matching networks were used in both the 4X150A and 4X250B distributed amplifiers. However, the above plate line matching network was used in only the 4X150A distributed amplifier. The mismatch loss between a 60 ohm line and a 50 ohm load is only 0.04 db, and is negligible. The 4X250B plates were shunt-fed through an inductance across the reverse termination, the low RF voltage end being bypassed with 1000 µµf. The inductance was chosen to resonate at 100 mc with the stray capacitance present at the 50 ohm reverse termination. Satisfactory frequency characteristics were realized with both types of feed.

2.3 Some Notes on the Physical Layout of the Amplifiers

In the construction of the amplifiers based upon the above considerations, preliminary models of grid lines fell far short of realizing the theoretical cut-off frequency. After a large number of possible difficulties were investigated, with no appreciable success, it was finally hypothesized that perhaps the chassis itself could not be considered a zero impedance structure and that the line currents returning through the chassis inductance could cause sufficiently large voltage drops to affect the behavior of the line. To test this hypothesis, a six tube line was constructed with four dummy sections per tube (so as to make the chassis inductance per section very small). In addition, the line was built circular so as to bring forward and reverse terminations in juxtaposition and located in the center of the ring. Circular construction resulted in a short chassis path through which line currents flowed back to the input, and thereby minimized the return impedance for line currents. The circular construction with a relatively large number of dummy sections resulted in frequency characteristics not far removed from the theoretical. Photographs of the physical construction are shown in Figs. 12-15. These photographs were made of the 4X150A amplifier. However, the 4X250B amplifier is almost physically identical.

The unique tube socket arrangement might be noted from Fig. 15. This arrangement was used to decrease the lead inductance and stray capacitance below that realizable with conventional tube sockets. All grounded pin receptacles were soldered directly to the chassis.

2.4 Tuning Procedure

Theoretically, if one could fabricate all the elements of the grid and plate lines and the terminating networks so as to be pure capacitances and pure inductances with the designed values then, by definition, no adjustment of the elements would be necessary. However, of course, this is not possible, and with the large number of constant-k sections resulting from the use of the dummy sections and the requirment that the signals arrive in phase at the

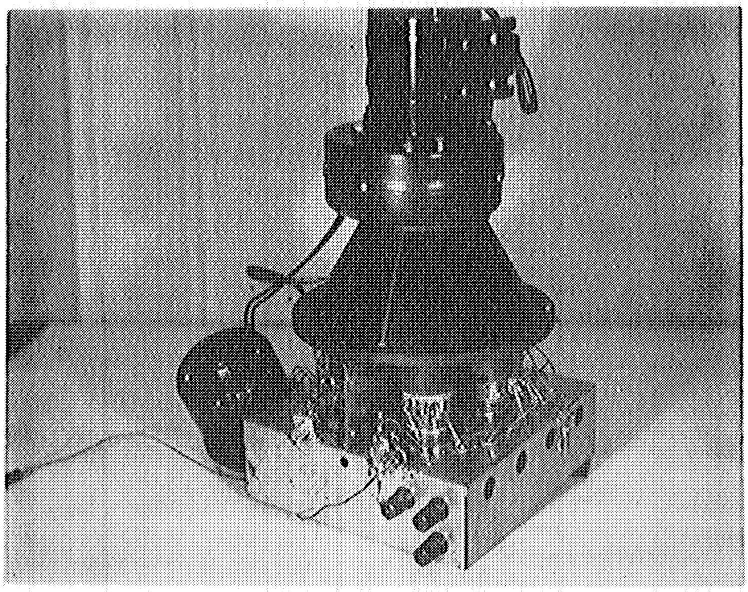

FIG. 12. PHOTOGRAPH OF 4X150A DISTRIBUTED AMPLIFIER. THE STRUCTURE MOUNTED ABOVE THE TUBE IS AN EXHAUST TYPE BLOWER SYSTEM. THE GRID LINE IS ON THE UNDER-SIDE OF THE CHASSIS, WHILE THE PLATE LINE IS VISIBLE ON TOP OF THE CHASSIS.

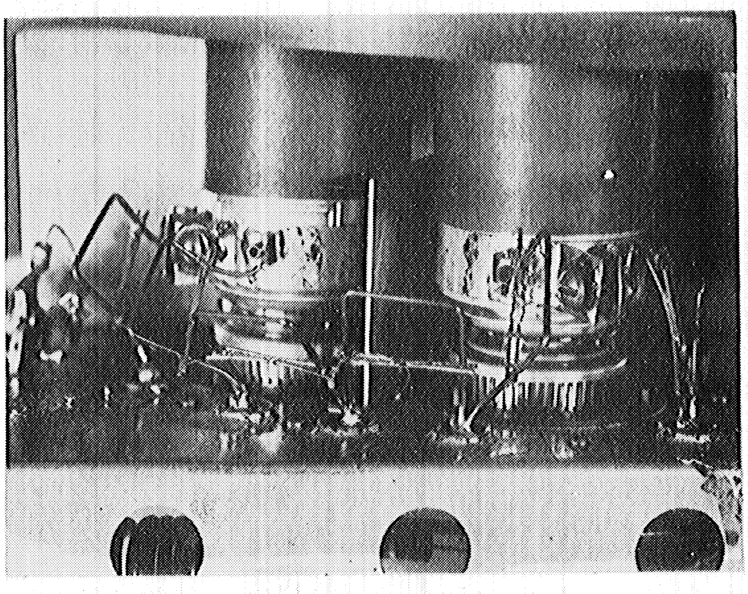

FIG. 13. CLOSE-UP PHOTOGRAPH OF A PORTION OF THE PLATE LINE.

FIG. 14. PHOTOGRAPH OF UNDERSIDE OF AMPLIFIER CHASSIS, SHOWING GRID, FILAMENT, AND SCREEN LINES.

FIG. 15. CLOSE-UP PHOTOGRAPH OF A PORTION OF THE GRID LINE.

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plate of each tube so as to reinforce, it is necessary that the relative phase difference between respective points on the grid and plate lines be very small. If this is not true, then gain characteristics with extremely large ripple result. Therefore, it was found necessary after final assembly to trim the plate line so as to cause this line to have the same phase characteristics as the grid line. This trimming results in a smoothing of the gain characteristic.

Trimming was accomplished using the block diagram shown in Fig. 16. The procedure was as follows:

1. Disconnect all but the screen of tube number 1 and connect the plate line termination to the plate of this tube. Trim the tube No. 1 plate line constant-k inductances by moving the shorting bars shown in Fig. 13 so as to produce a smooth one tube gain characteristic. Since only one tube is present, grid line losses will not now compensate for the rising mid shunt impedance characteristic at the high frequency end. Hence, a rising gain characteristic should result with one tube.
2. Connect the screen of tube No. 2 and move the plate line termination to the plate of tube No. 2. Repeat the above procedure, trimming now only the plate line constant-k inductances between tubes 1 and 2.
3. Continue the above procedure until the complete plate line is adjusted. Note that as more and more tubes are added, the gain characteristic will flatten at the high end.

The above procedure has been used successfully on both amplifiers. It has been our experience that indiscriminate adjustment is not a convergent process. However, minor judicious trimming by an experienced person after

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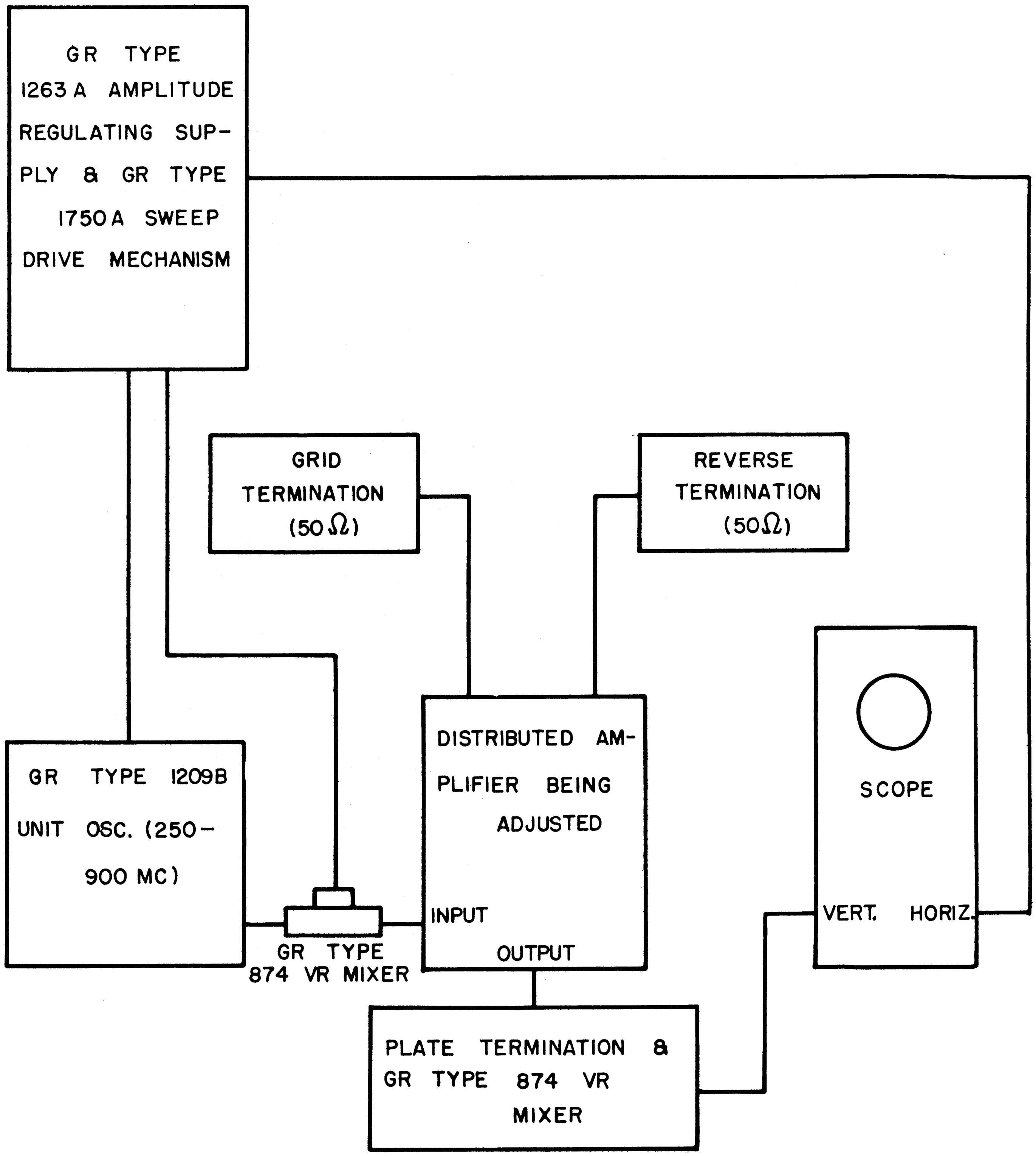

FIG. 16 BLOCK DIAGRAM USED IN PLATE LINE TRIMMING

using the above procedure can further serve to reduce remaining ripple. Photographs of final low-level power gain characteristics for the 4X150A and 4X250B distributed amplifiers are shown respectively as Figs. 18 and 19. From Fig. 18 it can be seen that the 4X150A amplifier has usable gain to above 450 mc (reasonably close to the theoretical). However, from Fig. 19 it can be seen that the 4X250B amplifier has usable gain to only 420 mc. This resulted because the 4X250B tubes available at the time of construction had 20 percent higher input capacitance than the 4X150A tubes. Therefore one would expect an appreciable improvement through the use of presently available low capacity 4X250B tubes.

2.5 Power Measurements

The power characteristics of the two amplifiers described were obtained using the block diagram shown in Fig. 17.

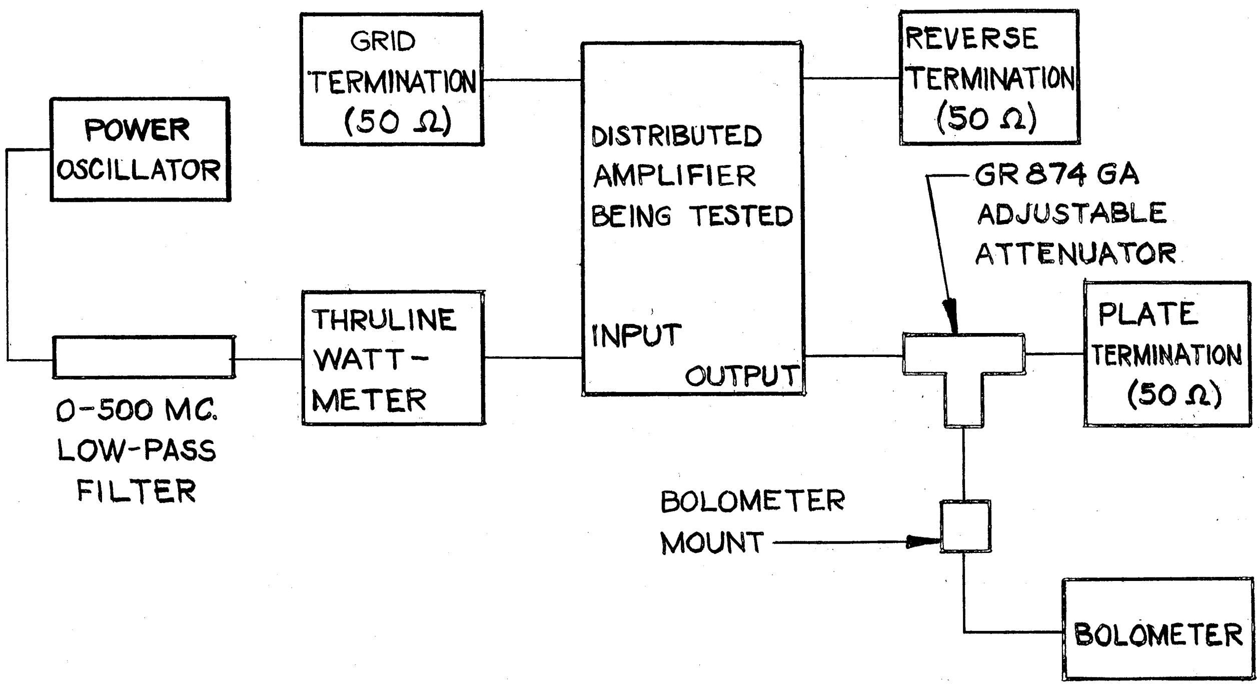

Fig. 17 Block Diagram Used in Power Measurements.

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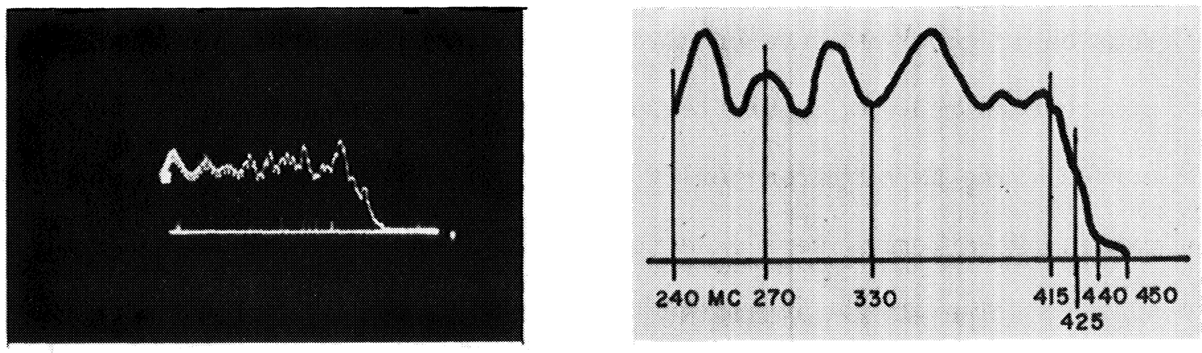

FIG. 18. HIGH FREQUENCY PORTION OF LOW LEVEL GAIN VS FREQUENCY CHARACTERISTIC OF 4X150A DISTRIBUTED AMPLIFIER.

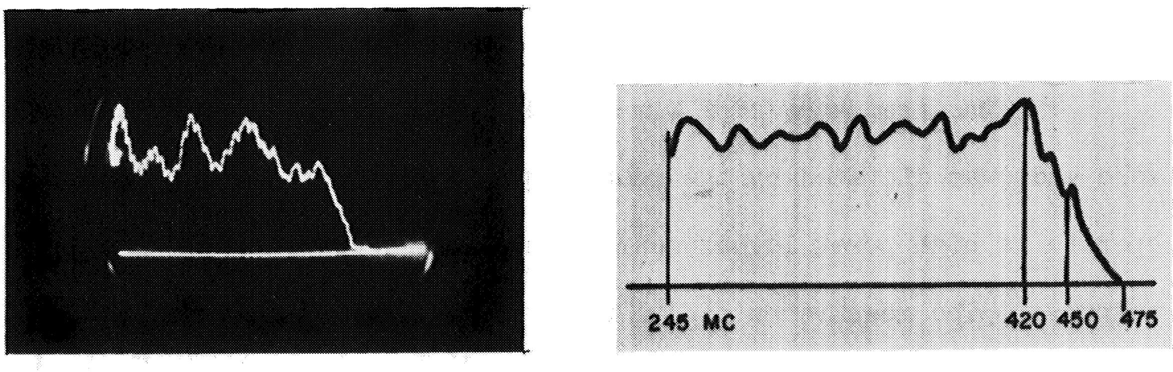

FIG. 19. HIGH FREQUENCY PORTION OF LOW LEVEL GAIN VS FREQUENCY CHARACTERISTICS OF 4X250B DISTRIBUTED AMPLIFIER.

One would not expect the power gain versus frequency characteristic to differ appreciably from the low-level gain vs frequency characteristic. Thus basic power measurements were planned at one convenient frequency with spot checks made at other frequencies to test agreement with the low-level curves. The major parameter of interest in the power measurements was the duty cycle. No attempts were made to operate CW.

The 4X150A amplifier was operated with 600 volts on the plates, sufficient screen voltage as a function of driving power to result in rated dissipation, and a grid gate voltage swing from -80 volts to -20 volts. Previous experience has indicated that these conditions are near optimum. The 4X250B amplifier was operated with 750 volts on the plates, sufficient screen voltage as a function of driving power to result in rated dissipation, and the same gating voltages as used with the 4X150A amplifier. It is felt that these operating conditions were again near optimum. Figures 20 and 21 are the measured power characteristics of the 4X150A amplifier. Figures 22 and 23 are the measured power characteristics of the 4X250B amplifier. The aforementioned frequency spot checks are shown as partial curves in the above mentioned figures. If one correlates these curves with the low-level gain characteristic, one finds good agreement.

The frequency of 270 mc at which the extensive power measurements were made was dictated by the inability of available driving oscillator to operate at high power levels near the upper frequency end of the amplifier response. The measurements at 270 mc on the 4X250B amplifier occurred near a peak of the gain curve, whereas the measurements at 270 mc on the 4X150 amplifier occurred at a mean point on its gain curve. It is estimated from the power curves that the 4X250B has a mean gain approximately 3 db greater than the 4X150A amplifier, due to its ability to operate within rated dissipation at higher operating voltages. Due, then, to a peak of the 4X250B response at

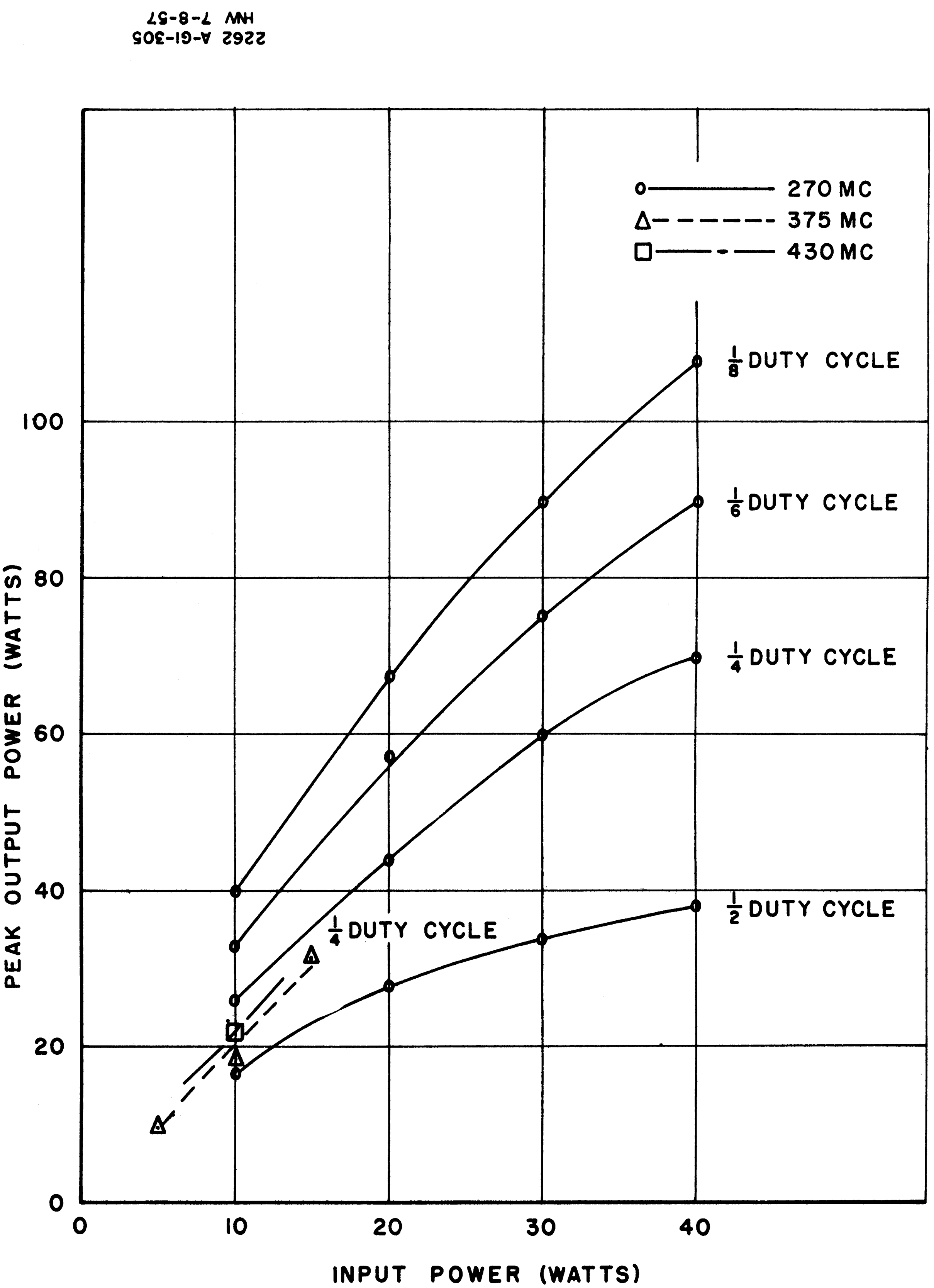

FIG. 20 PEAK OUTPUT POWER vs. INPUT POWER FOR 4X150A DISTRIBUTED AMPLIFIER WITH DUTY CYCLE AS A PARAMETER

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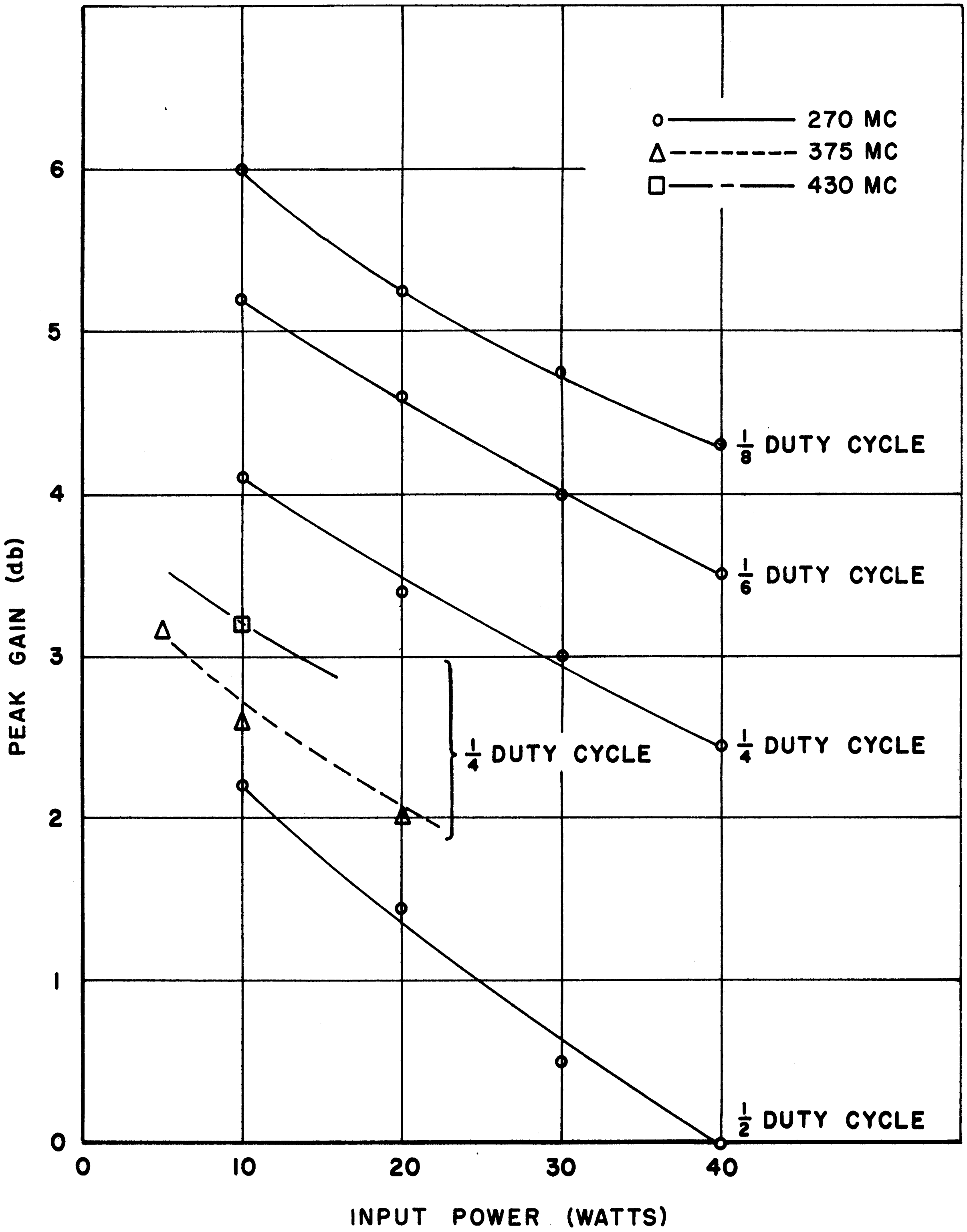

FIG. 21 PEAK POWER GAIN vs. INPUT POWER FOR 4x150A DISTRIBUTED AMPLIFIER WITH DUTY CYCLE AS PARAMETER

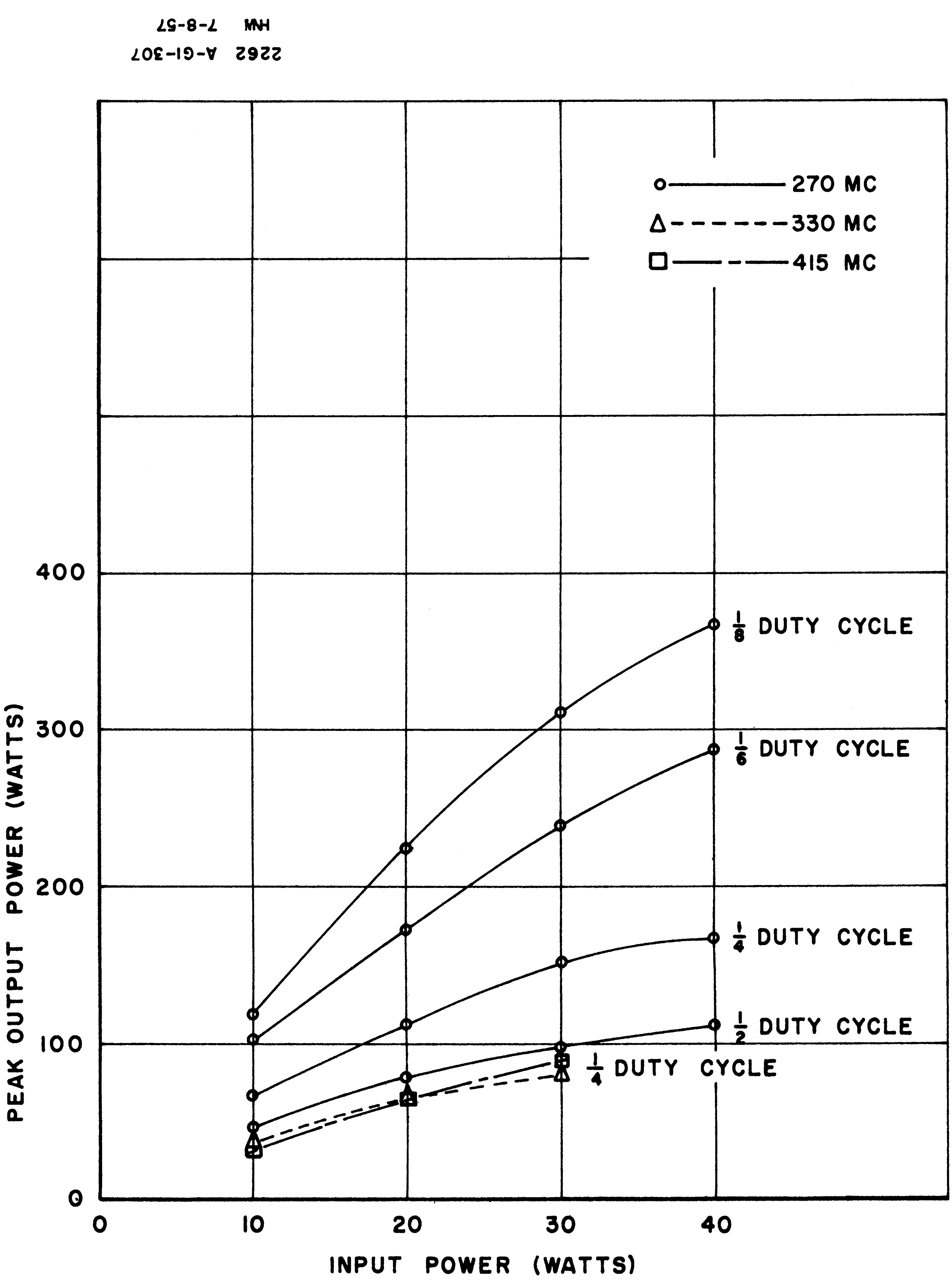

FIG. 22 PEAK OUTPUT POWER vs. INPUT POWER FOR 4 x 250B DISTRIBUTED AMPLIFIER WITH DUTY CYCLE AS PARAMETER

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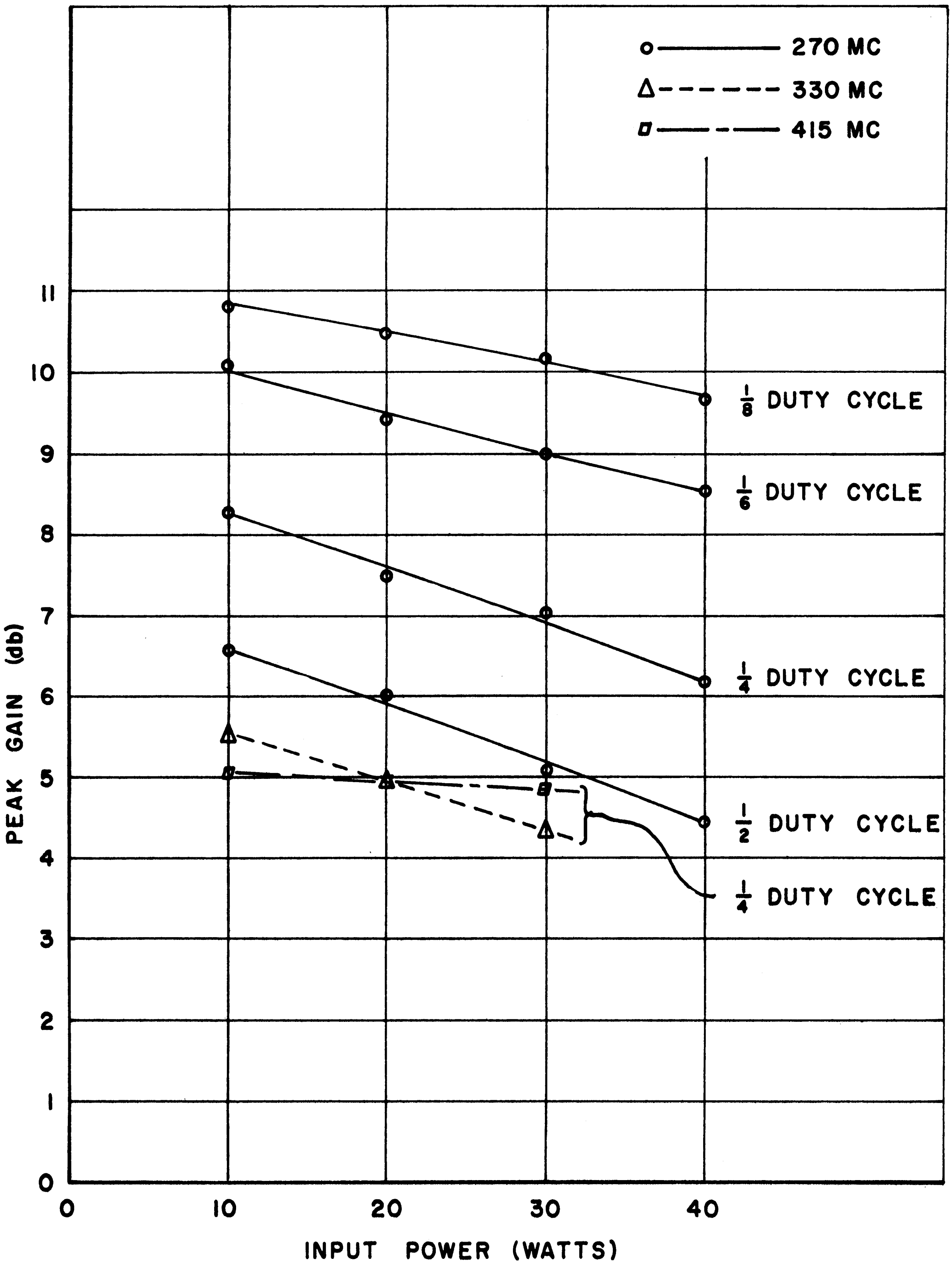

FIG. 23 PEAK POWER GAIN vs. INPUT POWER FOR
4x250B DISTRIBUTED AMPLIFIER WITH DUTY CYCLE AS PARAMETER

270 mc, the power gain at 270 mc can be seen from the curves to be substantially above the power gain at the other frequencies checked. It will be noted that the variation in power gain with frequency at 1/4 duty cycle is much less for the 4X150A amplifier than for the 4X250B amplifier, as would be expected from comparing the low level gain characteristics.

In equipment applications it might not be feasible to adjust the screen voltage so as to maintain rated tube dissipation as the input power is varied, and thus a power gain curve was obtained for each amplifier using fixed screen voltage with rated dissipation occuring at maximum drive available. These curves are shown plotted in Figs. 24 and 25. A complete schematic diagram of the high frequency distributed amplifier is shown in Fig. 26.

3. CONCLUSIONS

The amplifiers described in this paper are seen to have usable gain and power characteristics, and in addition possess bandwidths much superior to the bandwidths of conventional distributed amplifiers. The wider bandwidth obtained required lower impedance levels in both the grid and plate lines, and thus the gain and power characteristics are inferior to those of lower frequency models. This is especially true with the 450 mc 4X150A amplifier, and at low duty cycles there might even be some question of the usability of this amplifier. The usability of the 4X250B amplifier, however, is not so questionable, because of its ability to operate at higher voltages and currents with a corresponding increase in gain due to increased g_m.

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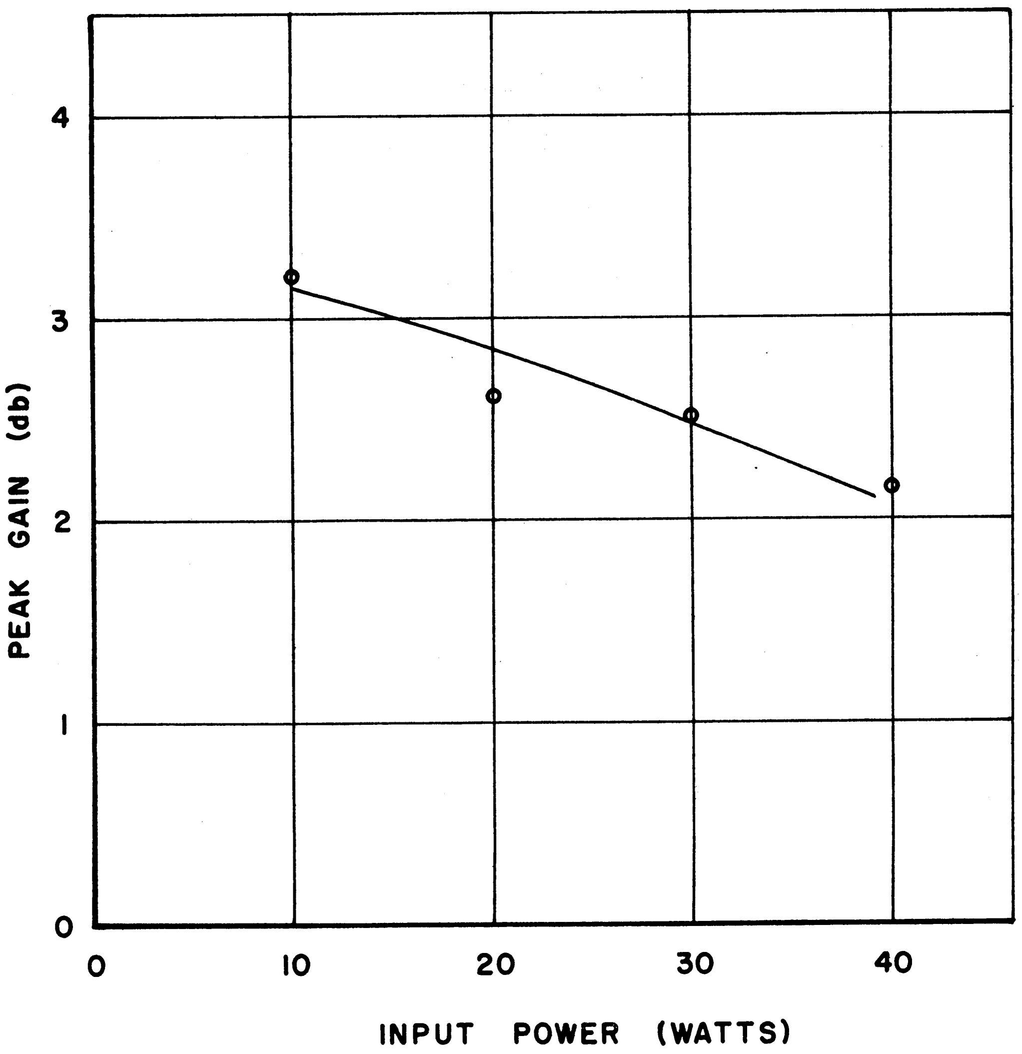

FIG. 24. PEAK POWER GAIN vs. INPUT POWER FOR 4 x 150B DISTRIBUTED AMPLIFIER AT 270 MC WITH FIXED SCREEN VOLTAGE AND $\frac{1}{4}$ DUTY CYCLE

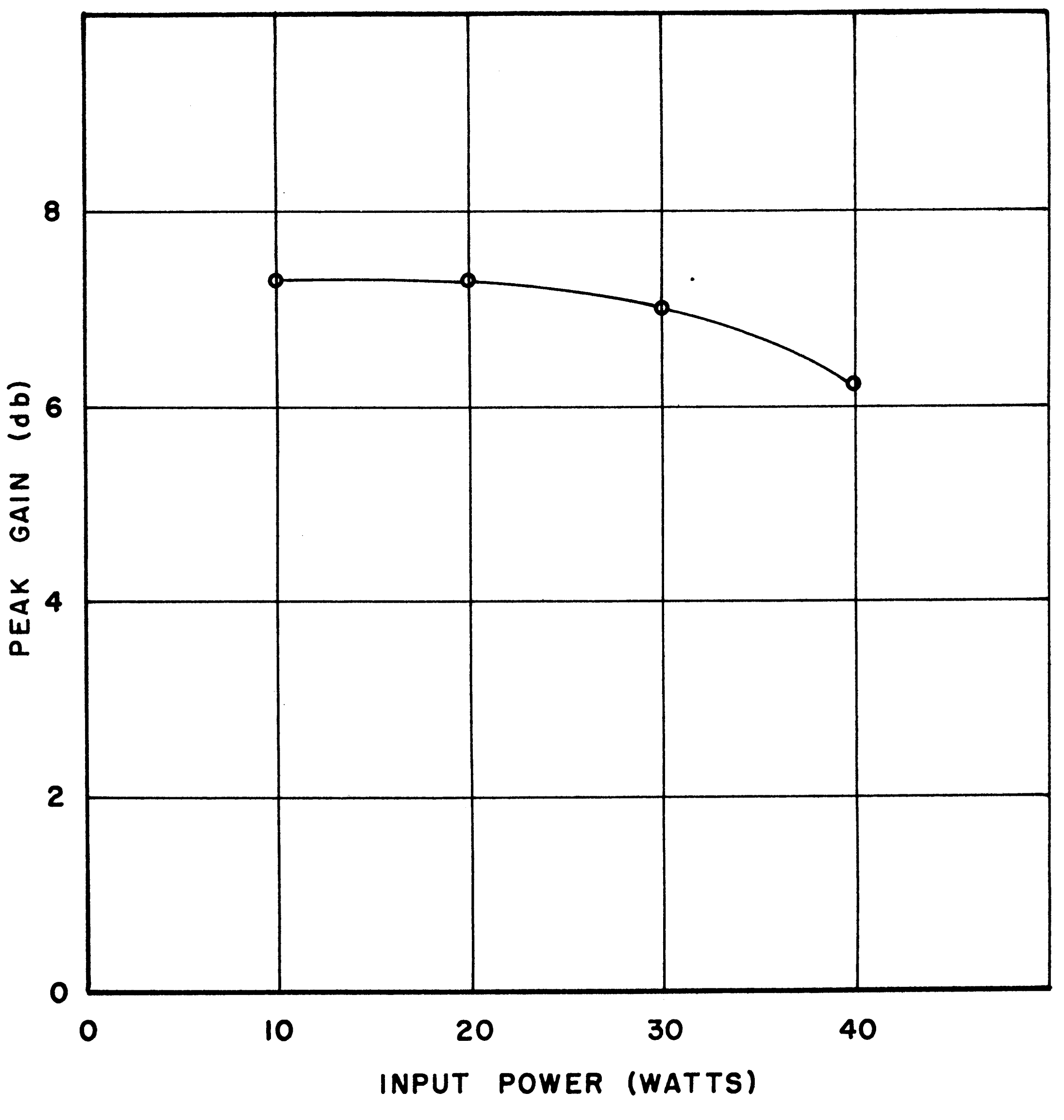

FIG. 25 PEAK POWER GAIN vs. INPUT POWER FOR 4 x 250A DISTRIBUTED AMPLIFIER AT 270 MC WITH FIXED SCREEN VOLTAGE AND DUTY CYCLE

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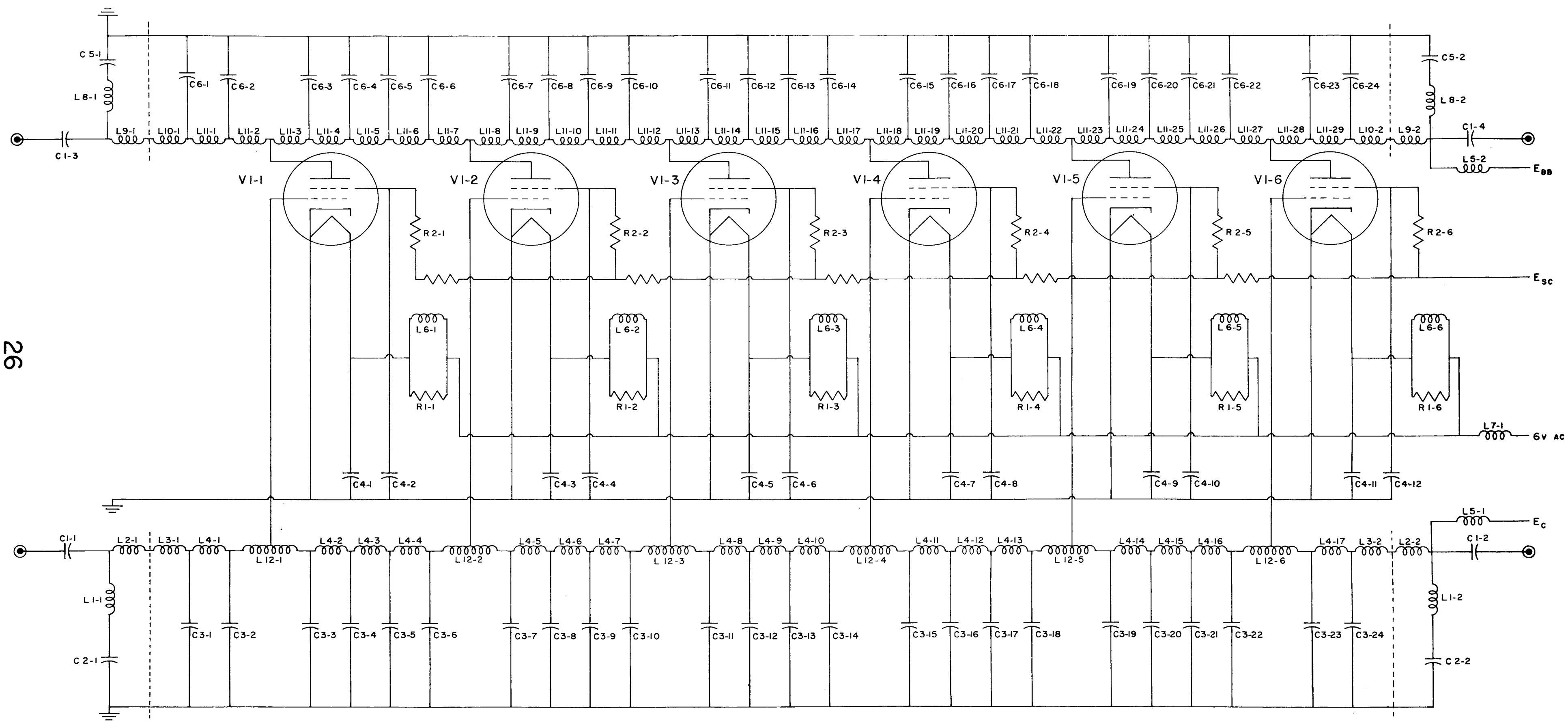

FIG. 26. HIGH FREQUENCY DISTRIBUTED AMPLIFIER

C1- 1000 μμf, ERIE CB
C2- 6 μμf, CERAMIC TRIMMER, CENTRALAB
C3- 19 μμf, 15 μμf ERIE CB PADDED WITH 3 μμf CENTRALAB
C4- 1000 μμf, CENTRALAB STANDOFF
C5- 3.15 μμf, CERAMIC TRIMMER, CENTRALAB
C6- 11 μμf, 10 μμf NOMINAL ERIE CB

R1- 22 Ω, 2 W, ALLEN BRADLEY
R2- 470 Ω, 2 W, ALLEN BRADLEY
R3- 10 Ω, 2 W, ALLEN BRADLEY

V1- 4X150A, EIMAC

L1- 0.01015 μh COIL
L2- 0.0057 μh COIL
L3- 0.0095 μh COIL
L4- 0.019 μh COIL
L5- BROAD BAND RF CHOKE: 5 feet No. 28 GAGE WIRE LOOSELY WOUND TO RESONATE ABOVE 500 MC
L6- RFC
L7- RFC
L8- 0.019 μh COIL
L9- 0.0095 μh COIL
L10- 0.016 μh COIL
L11- 0.032 μh COIL
L12- CENTER TAPPED 0.038 μh COIL. COEFFICIENT OF COUPLING = 0.6
0.007 μh NEGATIVE MUTUAL REFLECTED INTO CENTER TAP

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