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NAVAL RESEARCH LABORATORY REPORT

1 December 1946

R. F. ANTENNA FILTERS FOR PROJECT CADILLAC

By
D. E. Mode
L. W. Nosker

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NAVAL RESEARCH LABORATORY FIELD STATION

1 December 1946

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By D. E. Mode and L. W. Mosker

- Report R-2971 -

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Preliminary Pages a-9
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Figures 25

NOTE CONCERNING THE CREDIT FOR THIS REPORT

The experimental work that formed the basis for this report was done by the Cadillac Group at the Radiation Laboratory of the Massachusetts Institute of Technology. The original plans called for this report to be issued as Radiation Laboratory Report 982. It was not possible to complete the preparation until too late for publication by that agency.

In view of the value of the information to the Cadillac Project, permission was obtained to have the report published by the Naval Research Laboratory Field Station, Boston, Mass. The authors of the report are no longer with the project; Mr. E. P. Steele of this Station is following this work.

Attention is called to the work in the field of distributed constant filters by the Systems Engineering Section Staff of the Airborne Radio Division, Naval Research Laboratory, Washington, D. C. (4-7). This Naval Research Laboratory Group headed by Dr. N. K. Goldstein indoctrinated the authors in distributed constant filter techniques.

The following references are added though some of them were published since the writing of this paper.

REFERENCES

1. W. P. Mason and R. A. Sykes, "The Use of Coaxial and Balanced Transmission Lines in Filters and Wide Band Transformers for High Radio Frequencies (P.S.T.J. 16, 275-302, 1937).
2. H. Salinger, "A Coaxial Filter for Vestigial Side-Band Transmission in Television," Proc. I.R.E. 29, pp.315-20, 1941.
3. P. Richards, "Application of Matrix Algebra to Filter Theory" Proc. I.R.E. 34, 3; p.145, 1946.
4. NRL confidential report No.R-2767 29 March 1946
"AW Interference Report B, Shipboard Problem."
5. NRL confidential report No.R-2768, 1 April 1946
"Antenna Network Correctives for VHF-IF Interference."
6. NRL confidential Report No.R-2766, 30 April 1946
"AW Interference Report, Airborne Problem."
7. NRL Report No.R-2770, 1 Sept. 1946, "Practical Design of Transmission - Line Networks for Broad Band Filter Applications."

ABSTRACT

The design equations for several new type filters employing coaxial lines as elements are presented. These equations are then used in the design of seven R. F. Filters viz., ARC-1, APX-13, ARV, APN-1, ARR-2, and Block III antenna filters. Mechanical design and electrical performance data are included.

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I. INTRODUCTION

The electronic equipments involved in the Cadillac system installations are many, and interferences between them are to be anticipated. An investigation, summed up in a paper by A. Westcott (8/14/45), has indicated the troublesome interferences that must be eliminated by the use of R. F. filters.

This report of the work done at Radiation Laboratory to provide such filters is in three parts as follows:

- (1) A discussion of the types of R. F. filters, both those well known and the new types developed at the Radiation Laboratory by Project Cadillac personnel.
- (2) A summary of the design equations for the new type filters, with a few pertinent design curves.
- (3) A description of the filters actually built and tested, including their requirements, mechanical details, photographs, and experimental and theoretical performance curves.

Due to the hurried nature of the work, for obvious war-time reasons, no claim is made that the filters discussed in this report are the optimum designs. Development work on a particular filter was suspended as soon as a design satisfying the minimum requirements was found.

II TYPES OF H. F. FILTERS

A. Filters Using Coils and Condensers as Elements

The theory of lumped constant filters employing ordinary coils and condensers as elements is well known and need not be discussed here. Filters of this type prove very satisfactory for frequencies up to about 150 megacycles per second. For higher frequencies, the coils become vanishingly small; sometimes the connecting leads alone possess too large an inductance. The effect of distributed capacitance becomes increasingly important, too.

In order to obtain sharp cutoffs, several "m" derived sections are most often desirable. Although small "m" values give much sharper cutoffs than large "m" values, they do not provide sufficient attenuation at frequencies far removed from the pass band and also tend to have "holes" in the attenuation characteristic near cutoff. Another difficulty with the filter sections based on small "m" values is in production, where the tuning becomes critical and hence difficult.

The filters of this type built for the Cadillac system were designed with the above factors in mind.

A brief outline of the mathematical approach to the theory of filters employing coaxial lines as elements will first be presented. Since coaxial lines (most transmission lines for that matter) are linear circuit elements, all the equations of conventional filter theory may be applied. However, when the tangent and cotangent functions defining the line impedances are injected into these filter equations, the result is transcendental. Graphical means must therefore be employed in the prediction of the performance of any given combination of these circuit elements.

Two criteria must be investigated.

- (1) The insertion loss of the filter section out of the pass band and,
- (2) The insertion loss of the filter section in the pass band. The first of these should be large and the second small. The requirement for large attenuation outside the pass band can be satisfied by using enough filter sections, but the necessity of keeping the loss to a minimum in the pass band can only be met by utilizing sections which have a fairly constant image impedance throughout the pass band. Hence the development of usable coaxial line element filter sections consists of a tedious search by graphical methods for filter sections having reasonably flat impedance characteristics in the pass bands. A family of image impedance curves is plotted for each type of filter having the desired low or band-pass (see below) characteristics, and if a sufficiently flat curve is found, it is made the basis for an actual design.

All filters using coaxial line elements are either multiple band-pass or low pass and multiple band-pass. This is so because of the repetitive nature of the impedance-frequency characteristic of a line. It follows, therefore, that in the design of filters using coaxial line elements, careful attention must be paid to the

1

For instance, see "Communication Networks" by Vannevar Bush and Leonard D. Terrell.

superfluous pass bands which occur in the filter attenuation characteristic. By manipulation of the filter design constants these superfluous bands may be shifted in such a way as to meet most design requirements. Occasionally, networks must be placed in tandem resulting in the superfluous band of one being suppressed by the attenuation of another.

Special line configurations such as folded lines may be used for applications where the lines would otherwise be physically too long. For instance, in one experimental low pass filter design the length of line necessary is reduced by a factor of almost four through use of a folded section.

It will be noted that the filters described in this report use mid-shunt termination. Graphical data has shown that for all of the filters investigated, the mid-shunt terminated filter gives the flattest impedance characteristic. However, as there must always be some lead inductance between the end coaxial line filter element and the input or output terminal to the filter, an approximation is introduced which leads to slight differences between observed and predicted losses in the pass band.

The frequencies involved in Cadillac interference problems have all been low enough so that apparatus dimensions are small compared to a wavelength. For this reason it is sufficiently valid to treat the filters as lumped circuits. They would be unmanageably complicated if they had to be worked out as true field or boundary value problems.

Although a certain amount of dissipation is always present in any realizable circuit, no account of this has been taken in the analysis. This practice is justifiable because the "Q" values of the elements involved are so high that any correction for dissipation would result in a negligible modification of the results.

MATHEMATICAL DATA FOR SEVERAL NEW TYPE COAXIAL LINE FILTERS

A. Table of Symbols

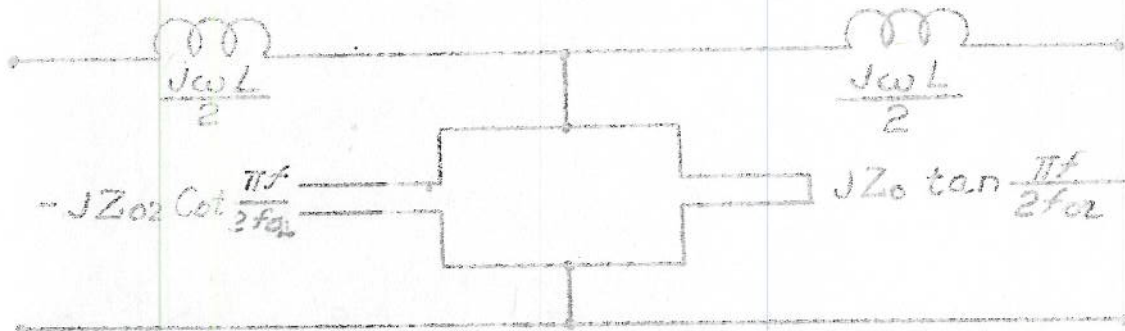
In the mathematical summary of each filter section the following symbols with their attached definitions are used:

Z_1	.....	Total series impedance of a section.
Z_2	.....	Total shunt impedance of a section.
Z_{or}	.....	Image impedance of a "pi" section.
Z_{ot}	.....	Image impedance of a "T" section.
Z_o	.....	Iterative impedance of a coaxial line.
Z_{oj}	.....	Iterative impedance of the j'th coaxial line.
f_o	.....	Frequency at which a coaxial line is quarter-wave resonant.
f_{oj}	.....	Frequency at which the j'th coaxial line is quarter-wave resonant.
f_o'	.....	Frequency at which a coaxial is half-wave resonant.
f_c	.....	Cutoff frequency of a section.
Γ	.....	Coaxial line open at far end.
\square	.....	Coaxial line short-circuited at far end.
α'	.....	Attenuation in decibels.
ρ$	.....	\frac{Z_1}{4Z_2}$



B. "B" Type Band-Pass Filter

This is a filter having a band-pass characteristic without the common superfluous low pass band. No series arm condensers are used with their attendant low power handling capacity.



Typical Section

$$Z_1 = j\omega L$$

$$Z_2 = \frac{jZ_{01}R}{\operatorname{Reot} \frac{\pi f}{2f_{01}} - \tan \frac{\pi f}{2f_{02}}}$$

$$Z_{0T} = \frac{2Z_{01}}{\left[\operatorname{Reot} \frac{\theta_1 f}{f_c} - \tan \frac{\theta_2 f}{f_c} \right] \sqrt{\frac{f}{f_c} \left[\tan \frac{\theta_2 f}{f_c} - \operatorname{Reot} \frac{\theta_1 f}{f_c} \right]} - 1}$$

wherein:

$$R = Z_{02}/Z_{01} \quad \text{subject to } \operatorname{Reot} \theta_1 = \tan \theta_2$$

$$\theta_1 = \frac{\pi f_c}{2f_{01}}$$

$$\theta_2 = \frac{\pi f_c}{2f_{02}}$$

$$R = \frac{4Z_{01}^2}{Z_{02}^2}$$

A curve of attenuation vs. frequency for four of these sections in tandem is shown in Figure 20. A single section would have one-fourth of the indicated attenuation.

The attenuation may be computed from the relations:

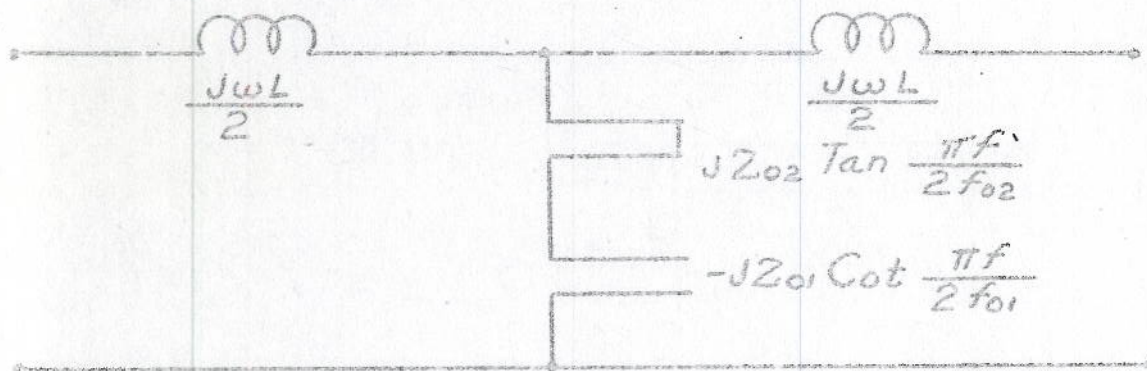
$$\alpha = 17.35 \sinh^{-1} \sqrt{-1-\rho} \text{ for } \rho < -1$$

$$= 17.35 \sinh^{-1} \sqrt{\rho} \text{ for } \rho > 0$$

$$\text{where } \rho = \frac{f}{f_c B} \left[\operatorname{Re} \frac{\theta_1 f}{f_c} - \frac{\tan \theta_2 f}{f_c} \right]$$

C. "R" Type Low Pass Filter

This is a filter having a low-pass characteristic with a wide attenuation band. It is particularly suited for comparatively low frequency work where other types would require lines of too great length.



Typical Section

$$Z_1 = j\omega L$$

$$Z_2 = jZ_{02} \tan \frac{\pi f}{2f_{02}} - jZ_{01} \cot \frac{\pi f}{2f_{01}}$$

$$Z_{or} = \frac{2Z_{o1} \left[\cot \frac{\theta_1 f}{f_c} - R \tan \frac{\theta_2 f}{f_c} \right]}{\sqrt{\frac{bf_c}{f} \left[\cot \frac{\theta_1 f}{f_c} - R \tan \frac{\theta_2 f}{f_c} \right]} - 1}$$

Wherein:

$$b = \frac{4Z_{o1}}{w_c l}$$

$$R = Z_{o2}/Z_{o1}$$

$$\theta_1 = \frac{\pi f_c}{2f_{o1}}$$

$$\theta_2 = \frac{\pi f_c}{2f_{o2}}$$

subject to $b = 2\cot\theta_1 - 2R\tan\theta_2$

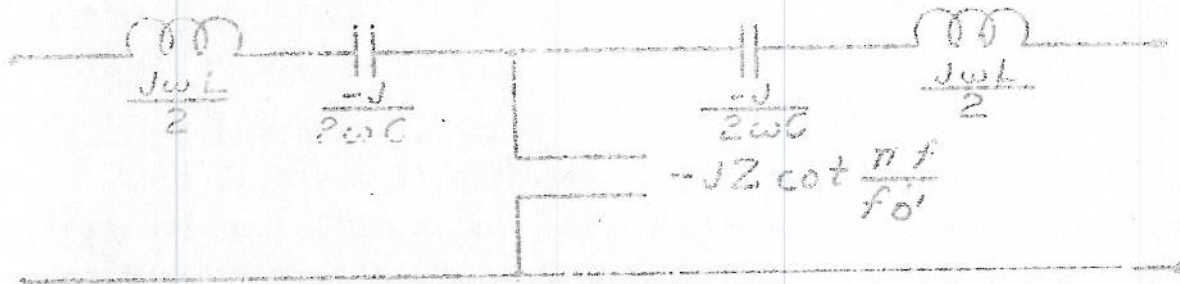
The attenuation in the first stop band is computed from the relation:

$$\alpha = 17.35 \sinh^{-1} \sqrt{\frac{\frac{f}{f_c b}}{\left[\frac{R \tan \theta_2 f}{f_c} - \frac{\cot \theta_1 f}{f_c} \right]}}$$

Attenuation and impedance curves are shown in Figs. 1 and 2.

D. "D" Type Band-Pass Filter

This is a filter having a fairly good band-pass characteristic, no superfluous low-pass band, and a physically long coaxial shunt line element thus making it particularly adaptable to the higher frequency bands.



Typical Section

$$Z_1 = j\omega L - \frac{1}{\omega C}$$

$$Z_2 = -jZ_0 \cot \frac{\pi f}{f_0'}$$

$$Z_{in} = 2Z_0 \cot \theta \sqrt{\frac{1 - \left(\frac{f}{f_0'}\right)^2}{\left(\frac{f}{f_0'}\right)^2 - 1 - \frac{4Df \cot \theta}{f_0'}}$$

Wherein:

$$\theta = \frac{\pi f}{f_0'}$$

$$D = \omega_0' C Z_0 \quad \text{Subject to } \omega_0'^2 LC = 1$$

The attenuation may be computed from:

$$\alpha = 17.35 \sinh^{-1} \sqrt{\rho} \quad \text{for } \rho > 0$$

$$\alpha = 17.35 \sinh^{-1} \sqrt{-1-\rho} \quad \text{for } \rho < -1$$

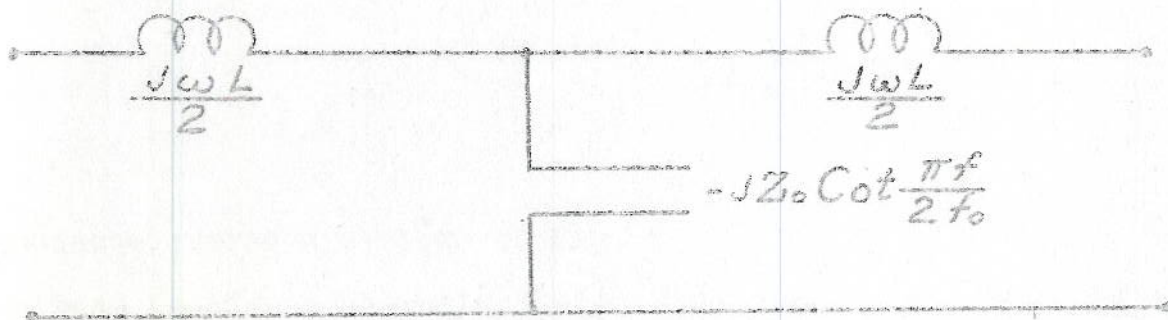
where

$$f = \frac{f_{01} - f_{01} \omega^2 LC}{4fD \cot \theta}$$

Attenuation and impedance curves are shown on Figs. 3 and 4, respectively.

E. "y" Type Low Pass Filter

This filter was developed by NRL. It is perhaps the simplest low pass filter, but uses sections about four times as long as the "R" type filter. The equations expressing the filter performance may be written in terms of different constants, a "y" constant and a "b" constant.



Typical Section

$$Z_1 = j\omega L$$

$$Z_2 = -jZ_0 \cot \frac{\pi f}{2f_0}$$

Using the "y" constant, the equations are:

$$Z_{or} = 2Z_0 \cot \frac{\pi f}{2f_0} \sqrt{\frac{f}{4y Z_0 \cot \frac{\pi f}{2f_0} - 1}}$$

wherein:

$$y = \frac{Z_0}{\omega L}$$

Using the "b" constant, the equations become:

$$Z_{0n} = \frac{2Z_0 \cot \frac{\theta f}{f_0}}{\sqrt{\frac{4f_c}{bf} \cot \frac{\theta f}{f_0} - 1}}$$

wherein:

$$b = \frac{\omega_c L}{Z_0}$$

$$\theta = \frac{\pi f_c}{2f_0}$$

The attenuation may be computed from the equation:

$$a = 17.35 \sinh^{-1} \sqrt{\frac{-bf}{4f_c \cot \frac{\theta f}{f_0}}}$$

Impedance curves are shown on Fig. 8.

The best impedance characteristic is obtained for a value of $b = 0.6$

The attenuation may be computed from the relation:

$$a = 17.35 \sinh^{-1} \sqrt{-\frac{r}{f_0 y \cot \frac{\pi f}{2f_0}}}$$

The best impedance characteristic is obtained for a value of $y = 1.5$. An attenuation curve is shown in Fig. 5 and impedance curves appear in Figs. 6 and 7.

F. "m" Derived "y" Type Low-Pass Filters.

Since the lead to the open line forming the shunt element in the "y" type filter has some inductance, it follows that all "y" type filters are in reality "m" derived. Although no samples of the "m" derived sorts have been tested the following theoretical observations may be of some enlightenment:

The value of $b = 0.6$ in the simple "y" type filter ($m = 1$) gives a flat impedance characteristic, and values of b either larger or smaller cause the curve to rise or fall. However, for the larger values of "b", the impedance characteristic can be flattened out by choosing the proper value for "m". This can be seen from inspection of the equation for the mid-shunt image impedance of the "m" derived "y" type filter as follows:

$$Z_{Omm} = \frac{Z_0 \left[(m^2 - 1) b \frac{f}{f_c} + 2 \cot \theta \frac{f}{f_c} \right]}{\sqrt{\frac{4f}{bf} \cot \theta \frac{f}{f_c} + m^2 - 2}}$$

wherein Z_{O1} is the usual image impedance of the "b" type section ($m = 1$) and Z_{Omm} is the image impedance of the mid-shunt derived "m" section. The curve on Fig. 9 illustrates such an image impedance correction.

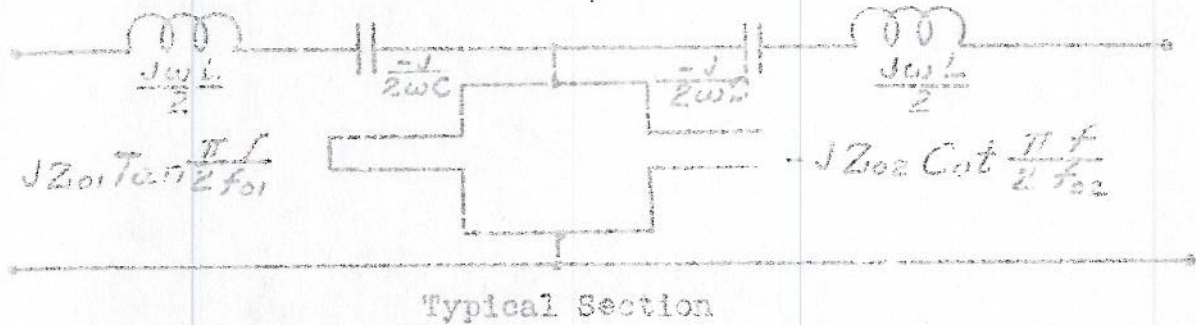
The practical use of these "m" derived sections is in their control over the attenuation bandwidth. The procedure in design would be as follows:

- 1) Choose a value of "b" giving the required attenuation bandwidth.
- 2) Use enough "T" sections having this "b" value to give the required attenuation and then terminate each end of the filter with an "m" derived section having a value of "m" which corrects the image impedance curve at about a value of $f/f_c = 0.7$ (empirical).

It is to be noted that different "b" values could be used in the various sections so long as the impedance of all the sections is kept matched over the pass band.

G. ψ Type Band-Pass Filter

Development work on this filter was stopped before its characteristics had been investigated. The equations are presented for those interested.



$$Z_1 = j \left[\omega L - \frac{1}{\omega C} \right]$$

$$Z_2 = \frac{jRZ_{01}}{R \cot \frac{\pi f}{2f_{01}} - \tan \frac{\pi f}{2f_{02}}}$$

$$Z_{0T} = \frac{2RZ_{01}}{\left[R \cot \frac{\theta_1 f}{f_1} - \tan \frac{\theta_2 f}{f_1} \right] \sqrt{\left(\frac{f_1}{f} - \frac{f}{f_1} \right) \left[R \cot \frac{\theta_1 f}{f_1} - \tan \frac{\theta_2 f}{f_1} \right]}}$$

wherein:

$$f_1 \text{ is defined by } f_1 = \frac{1}{2\pi\sqrt{LC}}$$

$$\theta_1 = \frac{\pi f_1}{2f_{01}} \text{ and } \theta_2 = \frac{\pi f_1}{2f_{02}}$$

$$R = \frac{Z_{02}}{Z_{01}} \text{ subject to } R \cot \theta_1 = \tan \theta_2$$

$$\psi = \frac{4RZ_{01}}{L\omega_1}$$

The attenuation is computed from the equations:

$$\alpha = 17.35 \sinh^{-1} \sqrt{1-\rho} \text{ for } \rho < -1$$

$$\alpha = 17.35 \sinh^{-1} \sqrt{\rho} \text{ for } \rho > 0$$

where

$$\rho = \frac{\left[\frac{f}{f_1} - \frac{f_1}{f} \right] \left[\operatorname{Re} \cot \frac{\theta_1 f}{f_1} - \tan \frac{\theta_2 f}{f_1} \right]}{\psi}$$

IV DESIGN AND PERFORMANCE DATA OF FILTERS BUILT FOR PROJECT CADILLAC

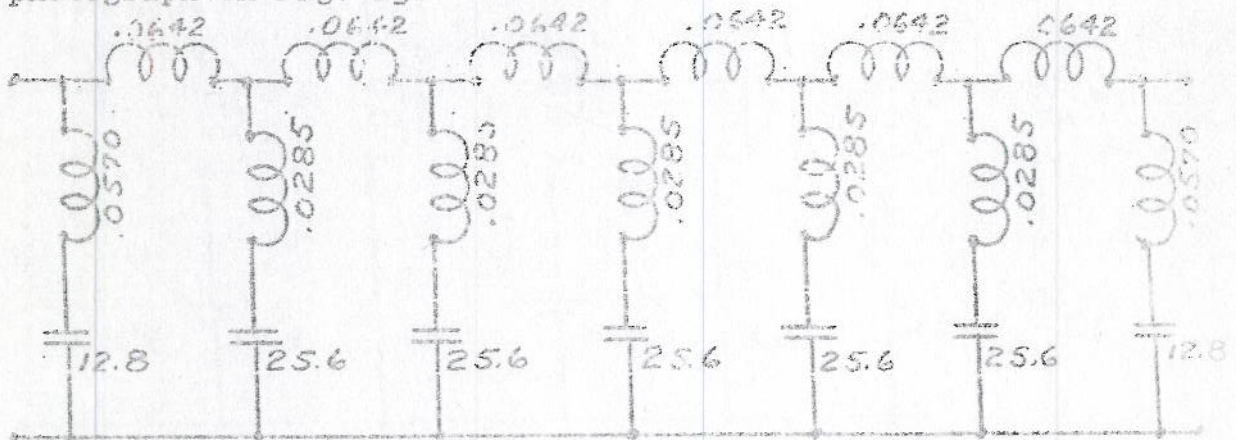
A. Low Pass Filter for the ARC-1.

1. Design Requirements.

Symmetrical low-pass filter having a 50 ohm image impedance, cutoff at 149 megacycles (insertion loss 3 db or less) with an insertion loss of 60 db or more at 165 megacycles. Loss in pass band not to exceed 2 db.

2. Electrical Design.

Conventional type,² the schematic of which is shown below. It consists of five full "T" sections and two 1/2 sections providing mid-shunt termination at each end. The "m" value for all sections is 0.6 and the frequency to which the shunt resonant circuits are tuned is 187 megacycles. Inductances are in microhenries and capacitances in micromicrofarads. An attenuation curve obtained from the sample is shown on Fig. 10, and a photograph on Fig. 13.



²Reference: Communications Circuits, Ware and Reed

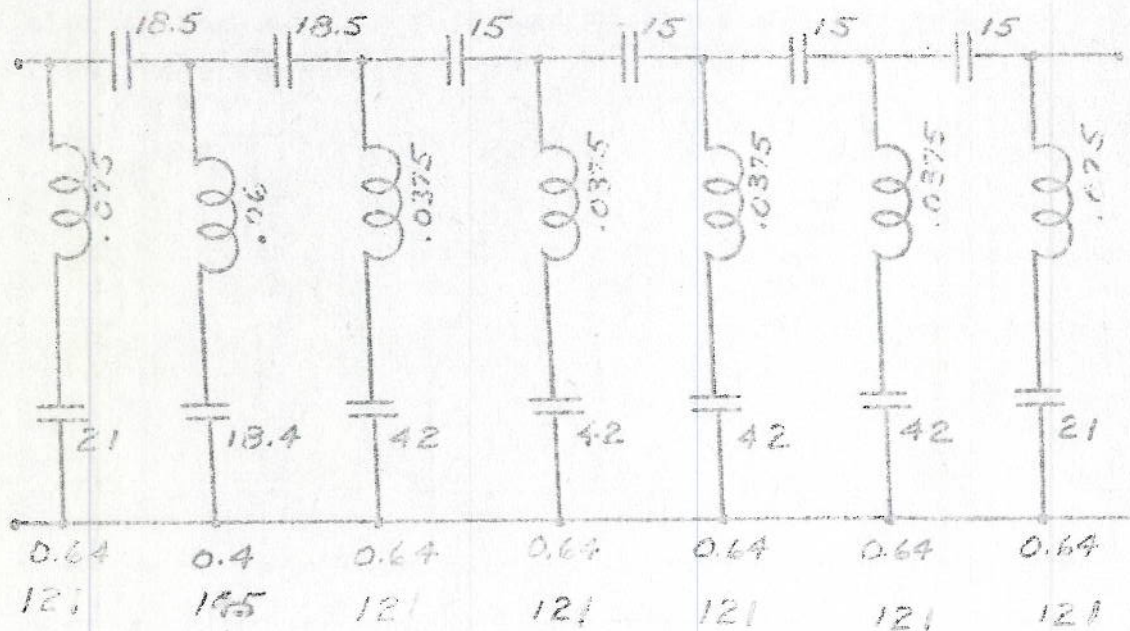
B. High Pass Filter for the APX-1 and APX-13.

1. Design Requirements.

Symmetrical high-pass filter having a 50 ohm image impedance, cutoff at 153 megacycles (insertion loss 3 db or less) with an insertion loss of 60 db or more at 150 megacycles. Loss in pass band not to exceed 2 db.

2. Electrical Design.

Conventional type,³ the schematic of which is shown below. It consists of five full "π" sections and two 1/2 sections providing mid-shunt termination at each end. The numbers below each section indicate the "m" value for the section and the frequency in megacycles to which the shunt resonant circuit is tuned. Inductances are in microhenries and capacitances in micromicrofarads. An attenuation curve obtained from the sample is shown on Fig. 11, and a photograph on Fig. 13.



³Reference: "Communications Circuits", Ware and Reed.

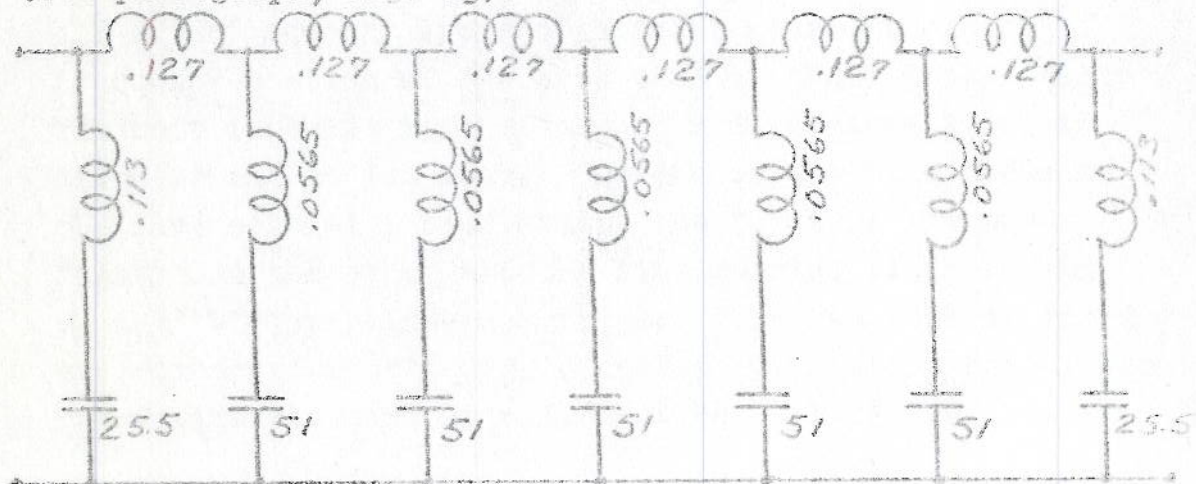
C. Low Pass Filter for the ARV.

1. Design Requirements.

Symmetrical low-pass filter having a 50 ohm image impedance, cutoff at 75 megacycles (insertion loss 3 db or less) with an insertion loss of 60 db or more at 85 megacycles. Loss in pass band not to exceed 2 db. To handle 250 watts C.W.

2. Electrical Design.

Conventional type,⁴ the schematic of which is shown below. It consists of five full "T" sections and two 1/2 sections providing mid-shunt termination at each end. The "m" value for all sections is 0.6 and the frequency to which the shunt resonant circuits are tuned is 94 megacycles. Inductances are in microhenries and capacitances in micromicrofarads. An attenuation curve obtained from the sample is shown on Fig. 12. Construction is the same as for the ARC-1 low-pass filter. (See photograph, Fig. 13).



⁴Reference: "Communications Circuits", Ware and Reed.

D. Band-Pass Filter for the ARR-2.

1. Design Requirements.

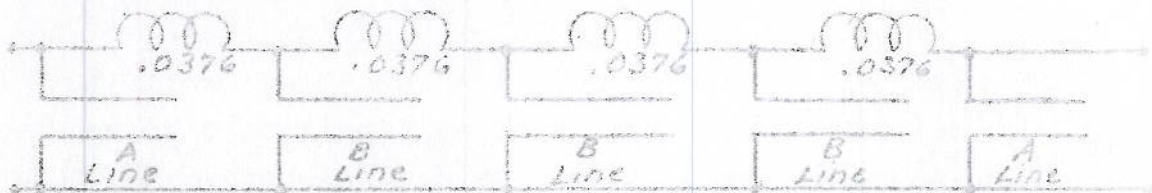
Symmetrical band-pass filter having a 50 ohm image impedance; insertion loss as low as practicable from 220-260 megacycles, rejection bands from 165-215 megacycles and from 275-375 megacycles.

2. Electrical Design.

A "y" type low-pass filter in tandem with a "D" type band-pass filter is used to obtain the required overall characteristic. The "B" type design might be adaptable to this application, and if so the construction would be considerably simplified. At the time this filter was designed, the "B" type had not yet been investigated. The impedance characteristic of the "D" type filter is poor at the upper end of its pass band and its band width is too great. Hence a sharp cut off "y" type low-pass filter is placed in tandem with the "D" type band-pass filter, the low-pass filter cutting off at a frequency low enough to eliminate the high frequency portion of the pass band of the "D" type filter. The unit is built in the form of a large tube 3 in. in diameter and 21 in. long. One end of the tube contains the five coaxial lines forming the "y" type low-pass filter and the other end the five coaxial lines making up the "D" type band-pass filter. The two sets of lines are connected together by a centrally located coaxial line. The design constants $y = 1.5$ and $"D" = 1.15$ are used.

1. Low-Pass Unit.

The schematic is shown below:



A Line:

$Z_0 = 111$ ohms. This is obtained with a pipe of $3/8$ in. inside diameter and inner rod $1/16$ in. in diameter, inner rod

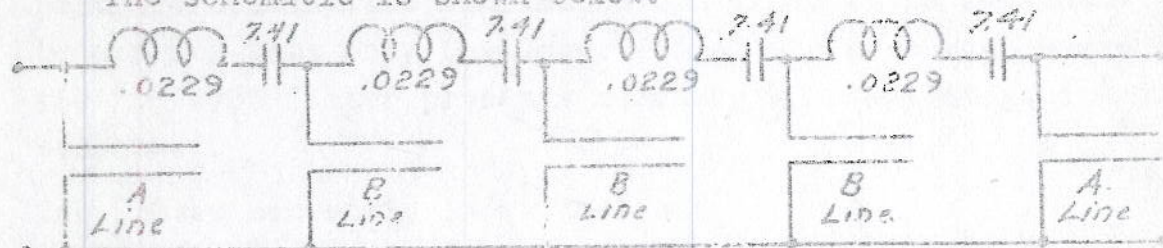
length 8 in.

B Line:

$Z_0 = 55.5$ ohms. This is obtained with a pipe having an inside diameter of $3/8$ in. and inner rod of $5/32$ in. diameter, inner rod length 8 in.

2. Band-Pass Unit.

The schematic is shown below:



A Line:

$Z_0 = 139$. This is obtained with a pipe of $5/16$ in. inside diameter and an inner rod $1/32$ in. in diameter, length $13-13/16$ in.

B Line:

$Z_0 = 69.5$. This is obtained with a pipe of $7/16$ in. inside diameter and an inner rod $1/8$ in. in diameter, length $13-13/16$ in. The theoretical and experimental attenuation curves for this filter are shown on Fig. 14. Photographs of the unit appear on Figs. 15 and 16.

B. Band-Pass Filter for the APN-1

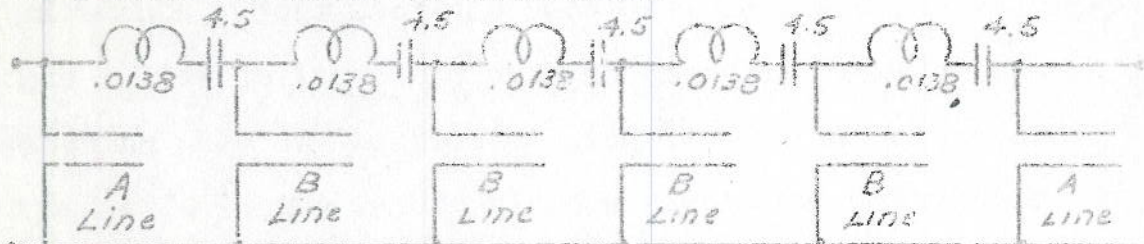
1. Design Requirements

Symmetrical band-pass filter having a 50 ohm image impedance; insertion loss less than 2 db in the band 400-460 megacycles; to reject the band 100-250 megacycles with a strong spot reject at 320 megacycles.

2. Electrical Design

A "D" type filter having the constant $D = 1.15$ is used for this duty, four full "T" sections plus the usual two 1/2 mid-shunt terminating sections being employed. This filter type is simple to construct and can be adapted ideally to the design requirements of infinite attenuation at a given frequency as well as a rejection band. The "B" type filter can not do this. The poor impedance characteristic of the "D" type filter in the higher frequency portion of its pass band is here of no importance because the equipment with which it is designed to operate uses only the lower end of the pass band where the "D" type filter presents a fairly constant image impedance.

The filter schematic is as follows:



A Line:

$Z_0 = 139$. This is obtained with a pipe of 5/16 in. inside diameter and inner rod 1/32 in. in diameter, length 8-3/8 in.

B Line:

$Z_0 = 69.5$. This is obtained with a pipe of 7/16 in. inside diameter and inner rod of 1/8 in. diameter, length 8-3/8 in.

The theoretical and experimental attenuation curves are shown in Fig. 17. Photographs of the unit appear on Figs. 18 and 19.

F. Band-Pass Filter for the Block III Transmitter

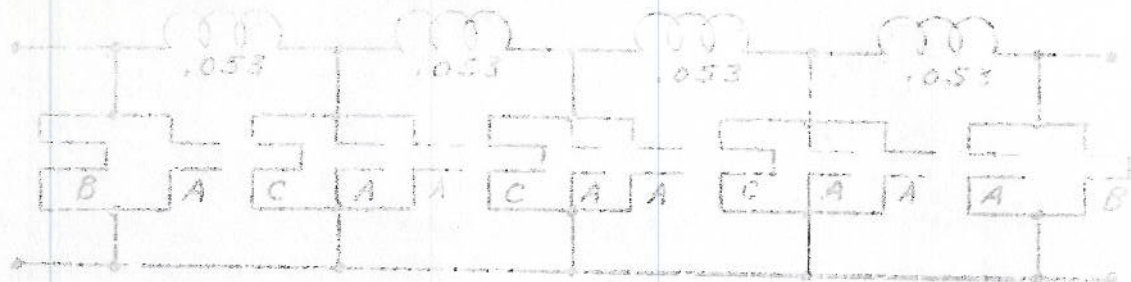
1. Design Requirements

Symmetrical band-pass filter having a 50 ohm image impedance; insertion loss less than 2 db in the band 299-320 megacycles, over 40 db below 260 megacycles and above 360 megacycles.

2. Electrical Design

A "D" type filter section having the constants $R = 1/4$; $f = 1/2$; $\theta_2 = 16.6^\circ$ and $\theta_1 = 40^\circ$ was selected in that it gave a satisfactory bandwidth and impedance characteristic. It is the simplest filter type that we know of to meet these requirements. Four sections were used in the first and only sample filter built. A 10 percent empirical correction shortening made in the coaxial line lengths to compensate for end effects was apparently too great, for the cutoff frequencies of the sample were a little high. A correction of about 5 percent should give cutoff frequencies closer to the theoretical value.

The circuit schematic is shown below:



The use of two A sections in parallel for the "T" sections is due to the mechanical difficulty of getting a single line with a low enough L_0 . Two sections in parallel each have twice the value of L_0 given by their combinations.

A Line:

$Z_0 = 21.6$, $f_0 = 1485$ mc/cycles; these values are obtained with a pipe of $7/64$ in. inside diameter and inner rod of $5/64$ in. diameter. Length of inner rod is $1-13/16$ in.

B Line:

$Z_0 = 86.8$, $f_0 = 615$ mc/cycles; these values are obtained with a pipe of $17/64$ in. inside diameter and inner rod of $1/16$ in. diameter. Length of inner rod is $4-3/8$ in.

C Line:

$Z_0 = 43.4$, $f_0 = 615$ mc/cycles; these values are obtained with a pipe of $1/4$ in. inside diameter and inner rod of $1/8$ in. diameter. Length of inner rod is $4-3/8$ in.

The theoretical and observed attenuation curves are shown on Fig. 20. Photographs of the units appear on Figs. 21 and 22.



G. Experimental Low-Pass Filter

1. Design Requirements

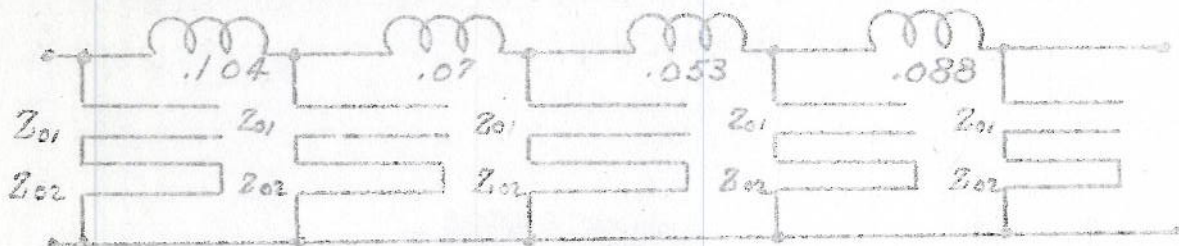
Symmetrical low-pass filter having a 50 ohm image impedance; insertion loss less than 2 db up to 75 megacycles; to reject frequencies in the band 100-350 megacycles.

2. Electrical Design

An "R" type filter was used in this design because the line lengths required for this type of filter are not prohibitively long, even for as low a cutoff frequency as 75 megacycles. The design constants $R = 4$; $b = 2$; $\theta_1 = \theta_2 = 21.3^\circ$ were selected because they afford a fairly good impedance characteristic. However, in order to stretch out the attenuation band, the filter was built in four sections, each section having a different cutoff frequency, viz., 90, 100, 150, and 240 megacycles. The line lengths were built 10 percent shorter than theoretical in an attempt to correct for end effects.

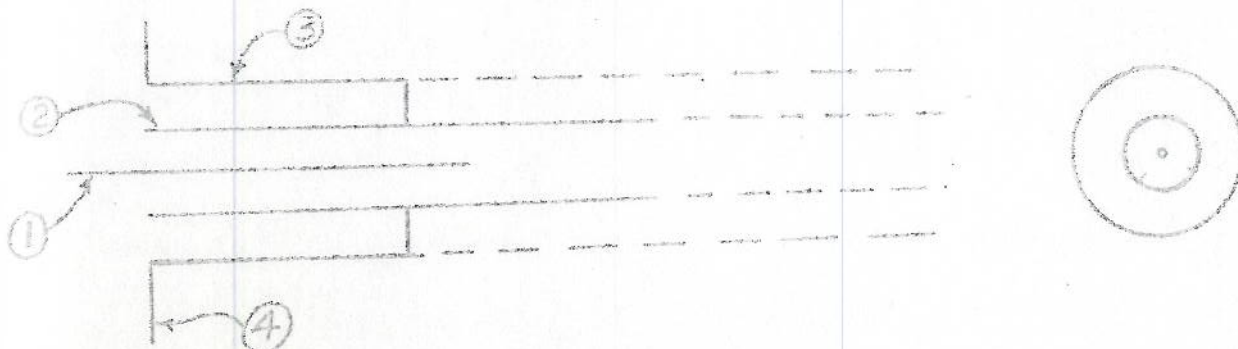
Originally, this filter was intended for the ARW, but a compact, lumped constant design was later worked out which was superior in many ways. For the record, it should be pointed out that this filter was the first sample constructed by the Project Cadillac group, and that further design experience showed that its size could be cut down by a factor of four, viz., the 3 in. diameter pipes could be made 3/4 in. diameter without affecting the performance of the unit, etc.

The filter schematic is shown below:



The inductances, as usual, are in microhenries.

The shunt line sections are of a special type tentatively called a "folded section" in that the line is more or less folded upon itself. The rough sketch below illustrates the construction:



where:

- (1) is the inner rod for the first coaxial line,
- (2) is a brass tube whose inside surface forms the outer conductor for the first coaxial line, and whose outer surface becomes the inner conductor for the second coaxial line.
- (3) is another brass tube whose inner surface forms the outside conductor of the second coaxial line.
- (4) is the chassis on which the element is mounted.

It can be seen that the first coaxial line is open and the second short-circuited. The outer conductor of the first coaxial line is carried on beyond where the inner conductor ends in order to confine the stray fields. The design data for the four sections is as follows:

Line A

Half section for mid-shunt termination $Z_{01} = 31$; $Z_{02} = 124$;
 $l = 7.8$ in.; tuned quarter wave at 379 megacycles. The above is accomplished by using an inner rod of diameter 0.375 in., inner pipe having inside diameter 1/4 in. and outside diameter 0.375 in., outer pipe with inside diameter 2.875 in.

Line B

Full section. $Z_{01} = 15.5$; $Z_{02} = 62$; $l = 7.0$ in.; tuned quarter wave at 421 megacycles. The above is accomplished by using an inner rod of 0.48 in. diameter, an inner pipe having an inside diameter of 0.625 in. and outside diameter of 0.750 in., outer pipe with an inside diameter of 2.125 in.

Line C

Same as line B except length is 2.9 in. and quarter wave frequency 1010 megacycles.

Line D

Same as line B except length is 4.6 in. and quarter wave frequency 632 megacycles.

The theoretical and experimental attenuation curves are shown on Fig. 23. Photographs of the unit appear on Figs. 24 and 25.

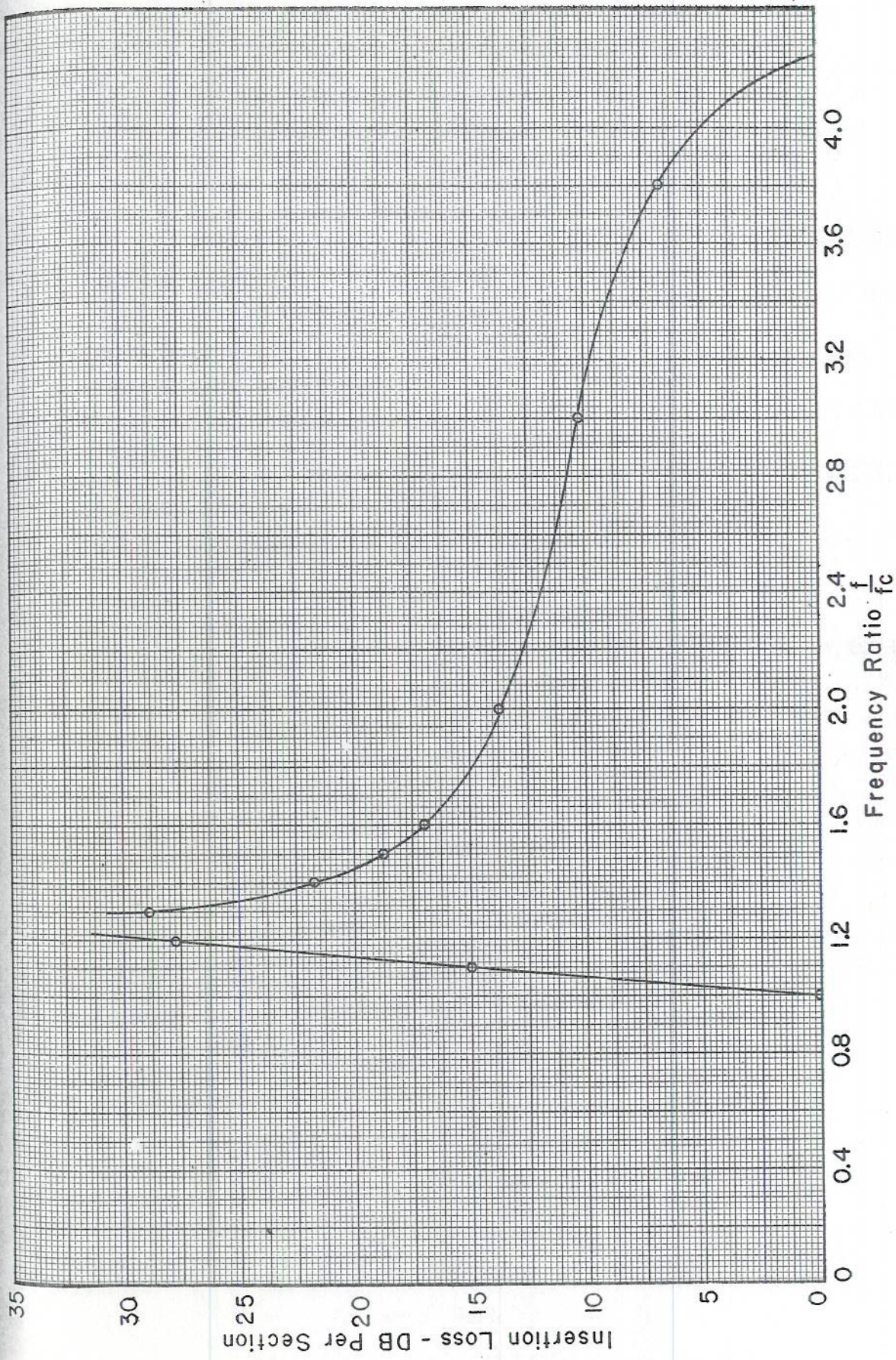
REVIEWER'S POSTSCRIPT

Attention is called to the work in the field of distributed constant filters by the Systems Engineering Section Staff of the Airborne Radio Division, Naval Research Laboratory, Washington, D. C. (4-7). This Naval Research Laboratory Group headed by Dr. H. K. Goldstein indoctrinated the authors in distributed constant filter techniques.

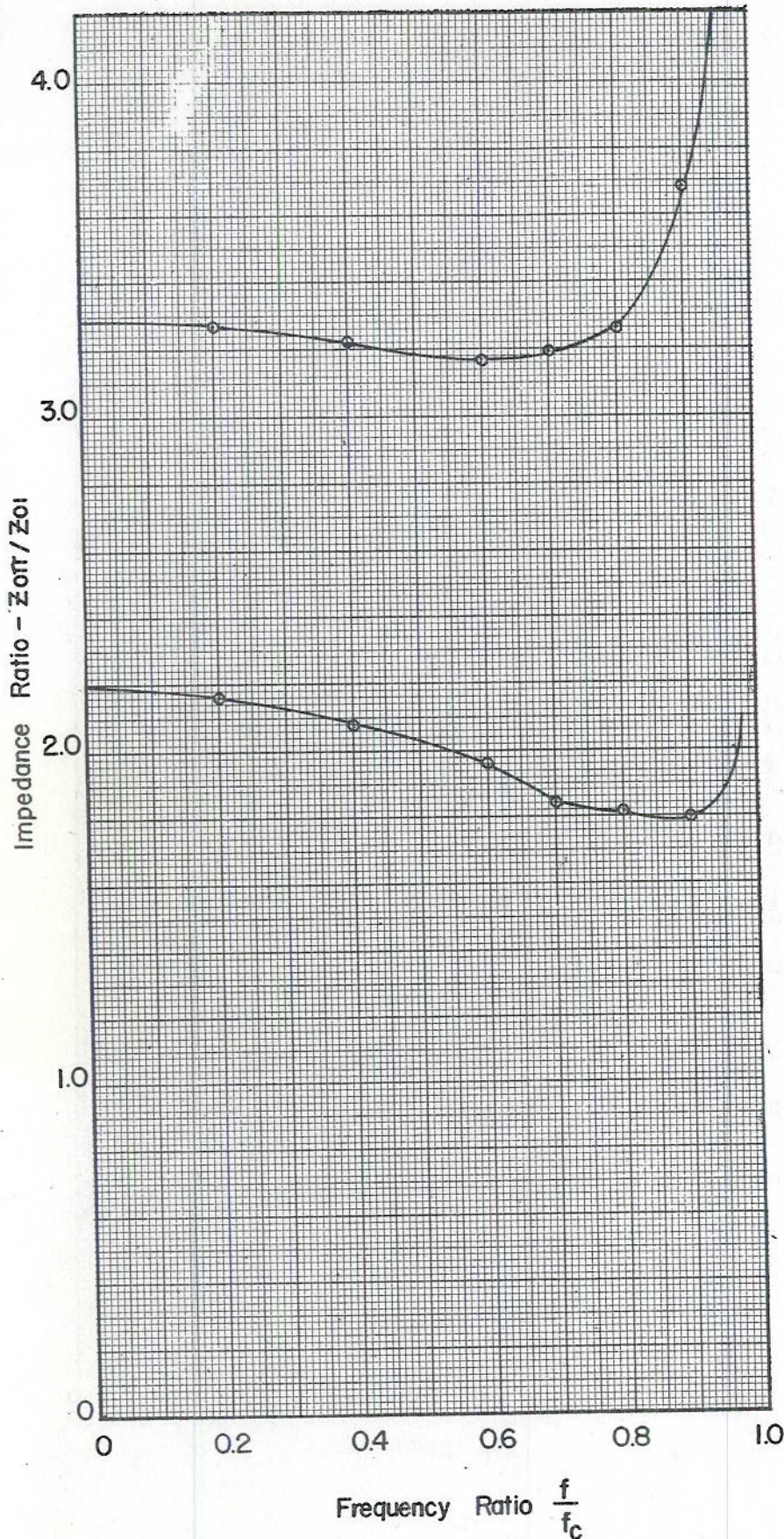
The following references are added though some of them were published since the writing of this paper.

REFERENCES

1. W. P. Mason and R. A. Sykes, "The Use of Coaxial and Balanced Transmission Lines in Filters and Wide Band Transformers for High Radio Frequencies (B.S.T.J. 16, 275-302, 1937).
2. H. Salinger, "A Coaxial Filter for Vestigial Side-Band Transmission in Television", Proc. I.R.E. 29, pp. 115-20, 1941.
3. P. Richards, "Application of Matrix Algebra to Filter Theory" Proc. I.R.E. 34, 3; p. 145, 1946.
4. NRL confidential report No. R-2767 29 March 1946 "AEW Interference Report B, Shipboard Problem."
5. NRL confidential report No. R-2769, 1 April 1946 "Antenna Network Correctives for VHF-IF Interference."
6. NRL confidential Report No. R-2766, 30 April 1946 "AEW Interference Report, Airborne Problem."
7. NRL Report No. R-2770, 1 Sept. 1946, "Practical Design of Transmission - Line Networks for Broad Band Filter Applications."



CALCULATED INSERTION LOSS OF SINGLE FOLDED SECTION HAVING CONSTANTS $R=4$, $b=2$, $\theta_1=\theta_2=21.35^\circ$
 FIGURE 1 - "R" FILTER \propto CURVE



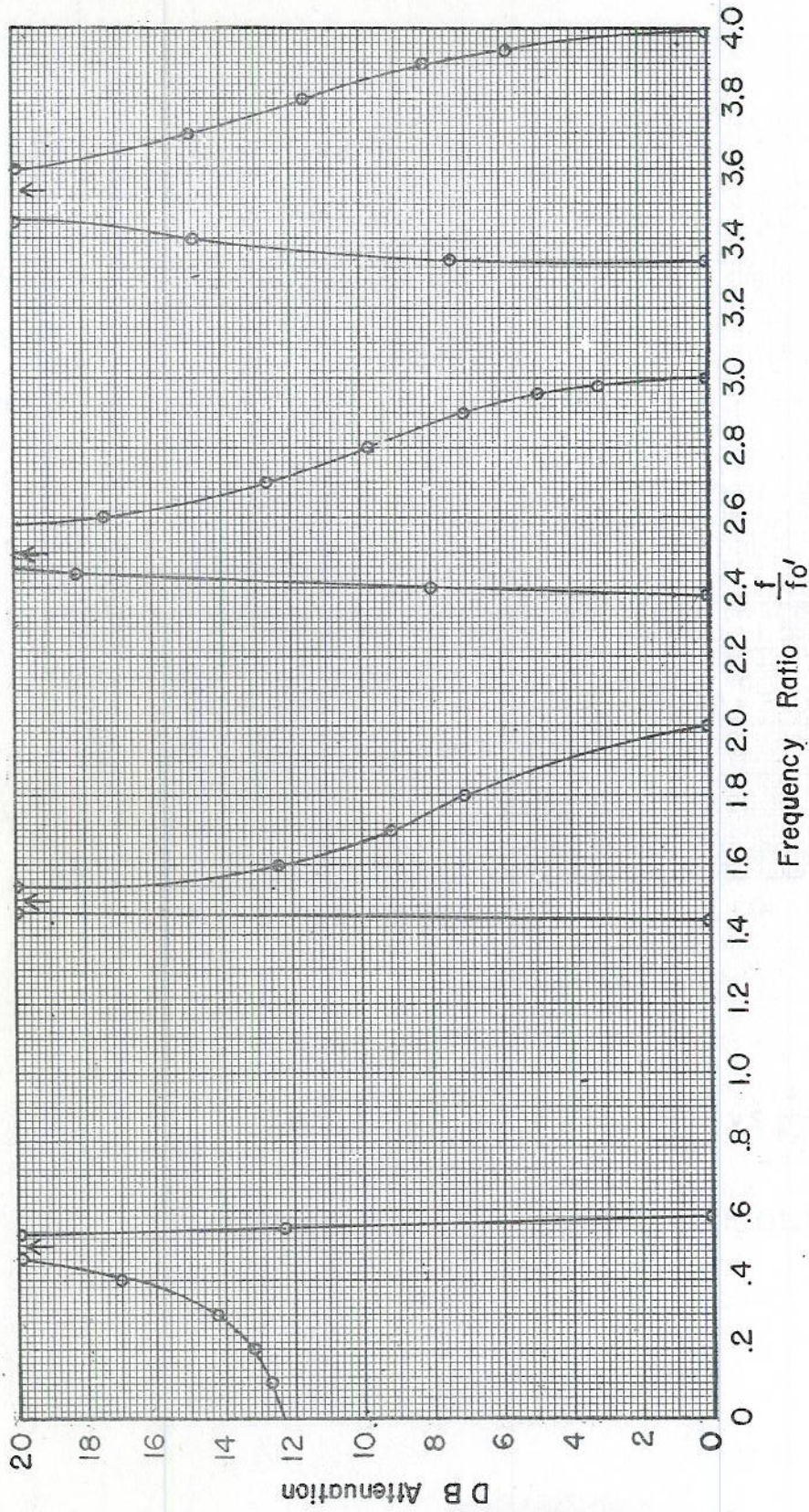
$$R=4, b=2, \theta_1=\theta_2=21.35^\circ$$

"R" TYPE
 FOLDED SECTION
 LOW-PASS FILTER
 IMPEDANCE
 CHARACTERISTIC

$$R=4, b=1, \theta_1=\theta_2=24^\circ$$

FIGURE 2 — "R" FILTER $Z_{0\pi}$ CURVE

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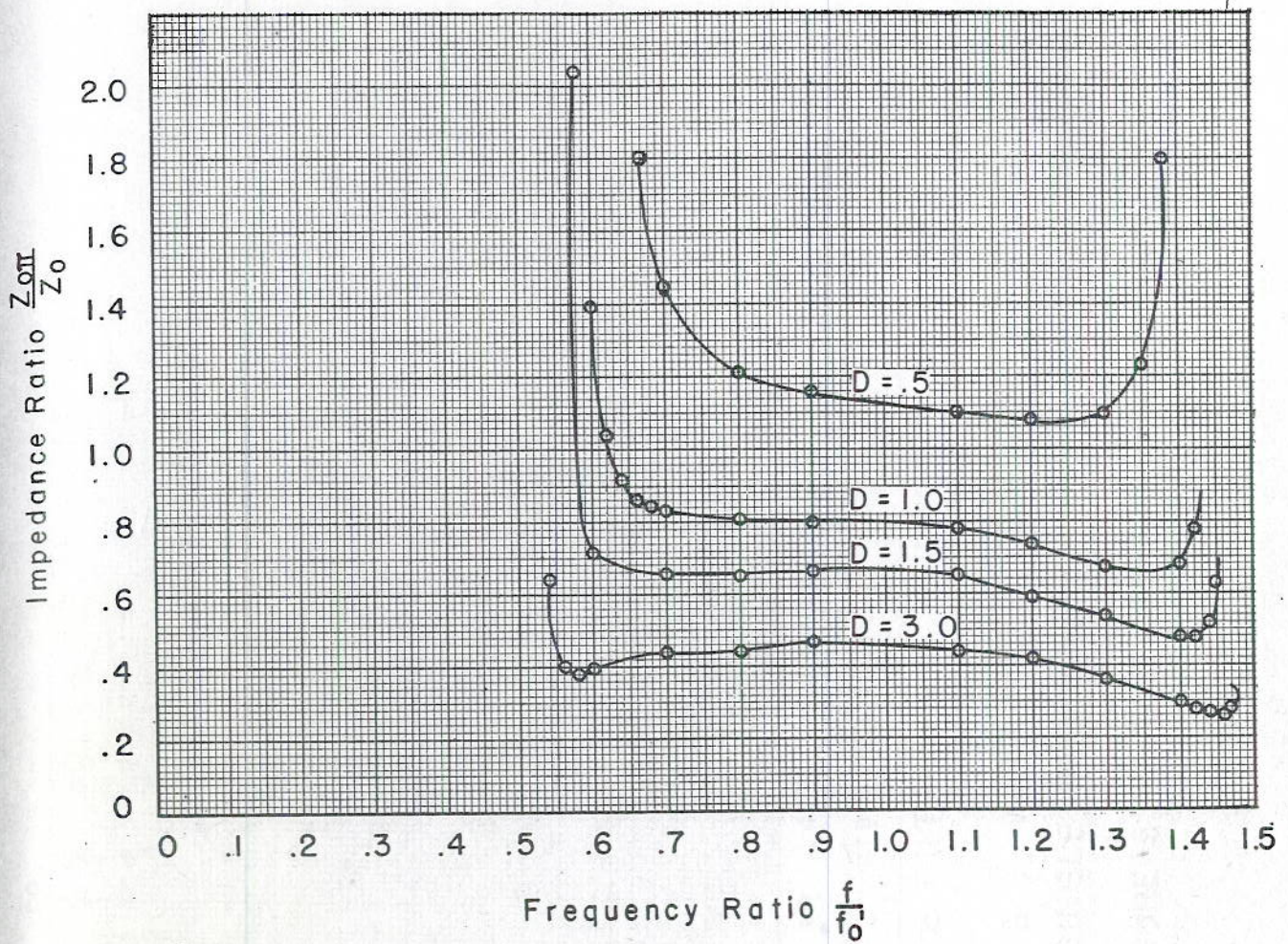
"D" TYPE FILTER. $D=1.25$ LOSS vs $\frac{f}{f_0}$ WHEN TERM.

IN IMAGE IMPEDANCE SINGLE SECTION

FIGURE 3 - "D" FILTER \propto CURVE

CONFIDENTIAL

FIGURE 3

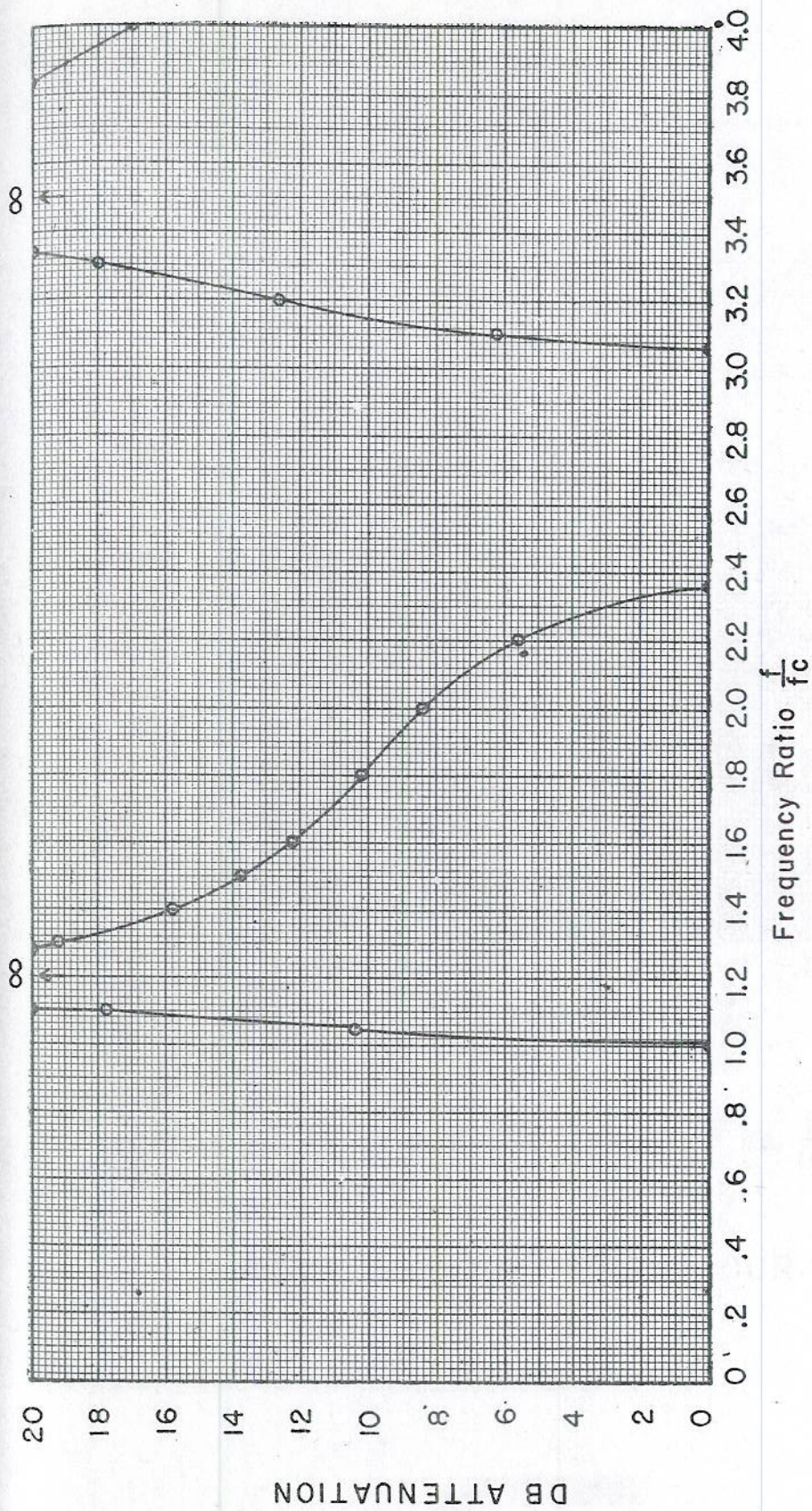


"D" TYPE FILTER. $\frac{Z_{0\pi}}{Z_0}$ vs $\frac{f}{f_0}$

FIGURE 4 — "D" FILTER $Z_{0\pi}$ CURVE

CONFIDENTIAL

FIGURE 4

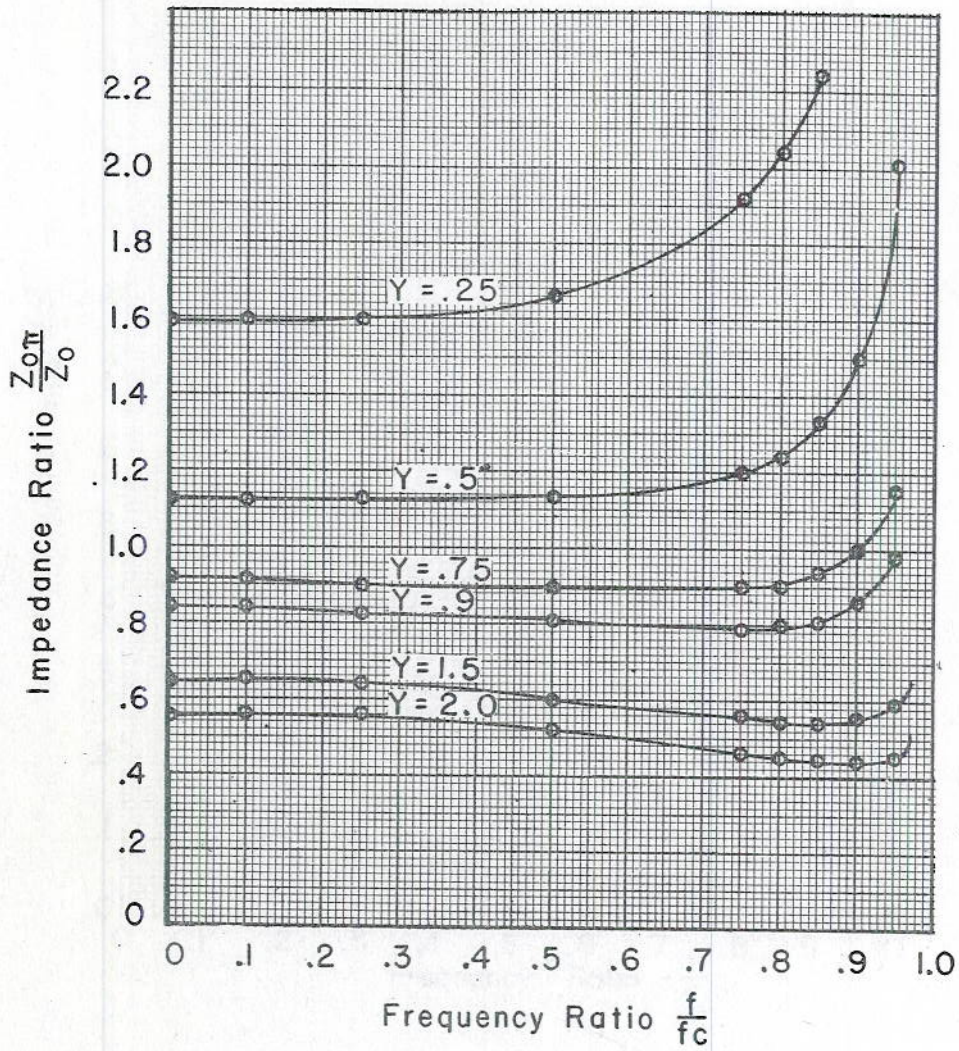


"Y" TYPE FILTER
 $Y = 1.8$
 LOSS VS $\frac{f}{f_c}$ WHEN TERM. IN IMAGE IMPED-
 ANCE SINGLE SECTION.

FIGURE 5 — "Y" FILTER α CURVE

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FIGURE 5

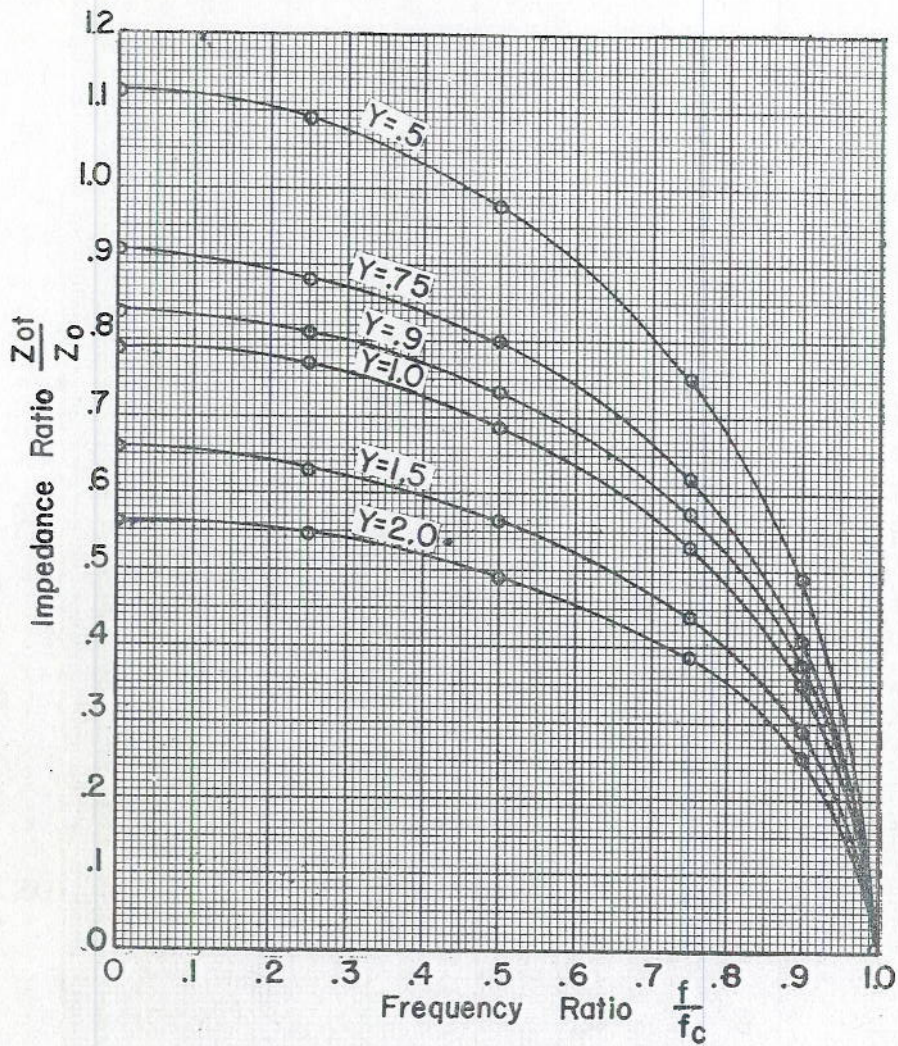


"Y" TYPE FILTER . $\frac{Z_{0\pi}}{Z_0}$ vs $\frac{f}{f_c}$

FIGURE 6 —"Y" FILTER $Z_{0\pi}$ CURVE

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FIGURE 6

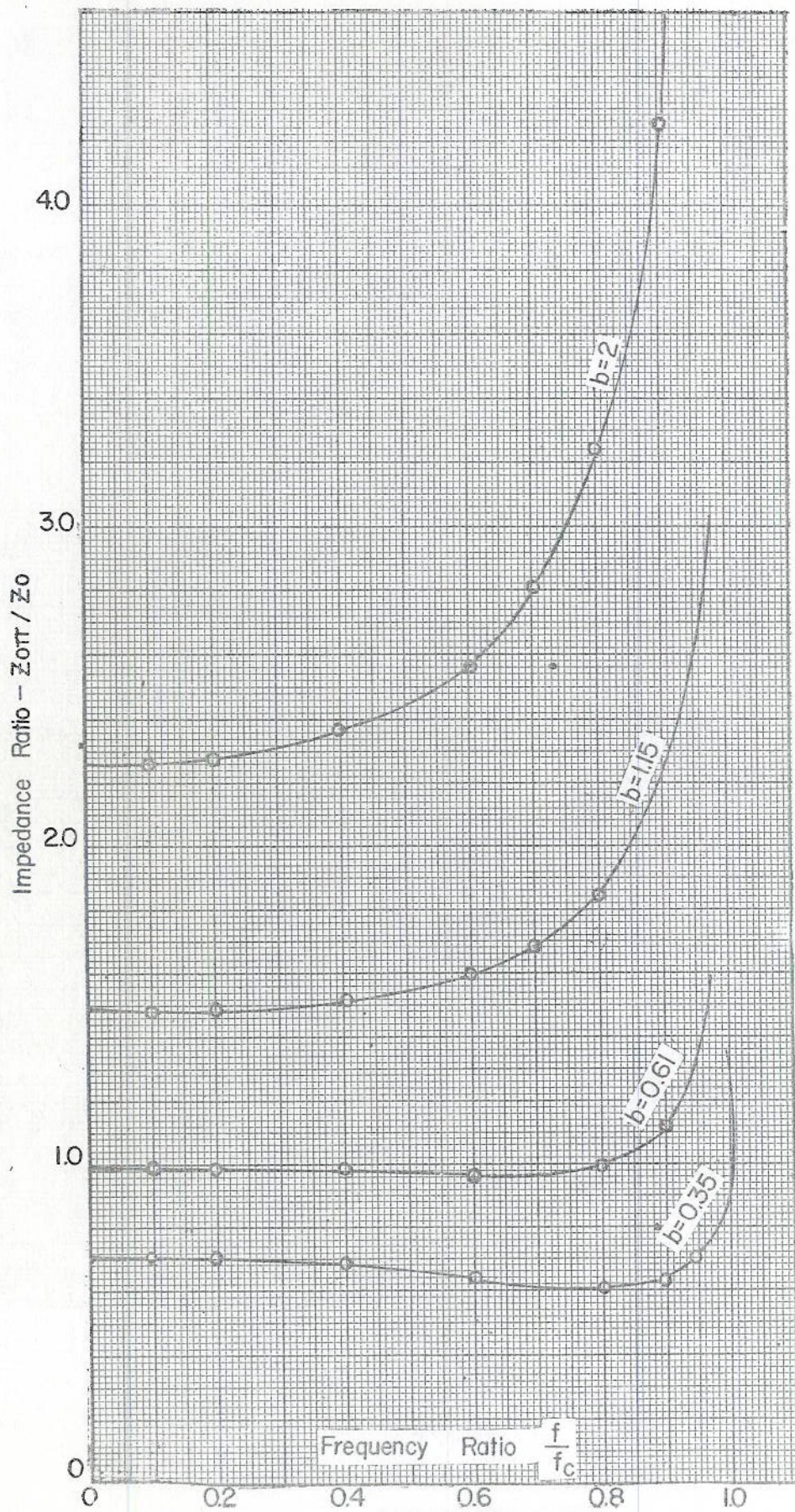


"Y" TYPE FILTER. $\frac{Z_{ot}}{Z_o}$ vs $\frac{f}{f_c}$

FIGURE 7.— "Y" FILTER Z_{ot} CURVE

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FIGURE 7



IMPEDANCE
RATIO DATA
FOR "b" TYPE
LOW-PASS FILTERS.

FIGURE 8
"b" FILTER Z_{0T}
CURVE.

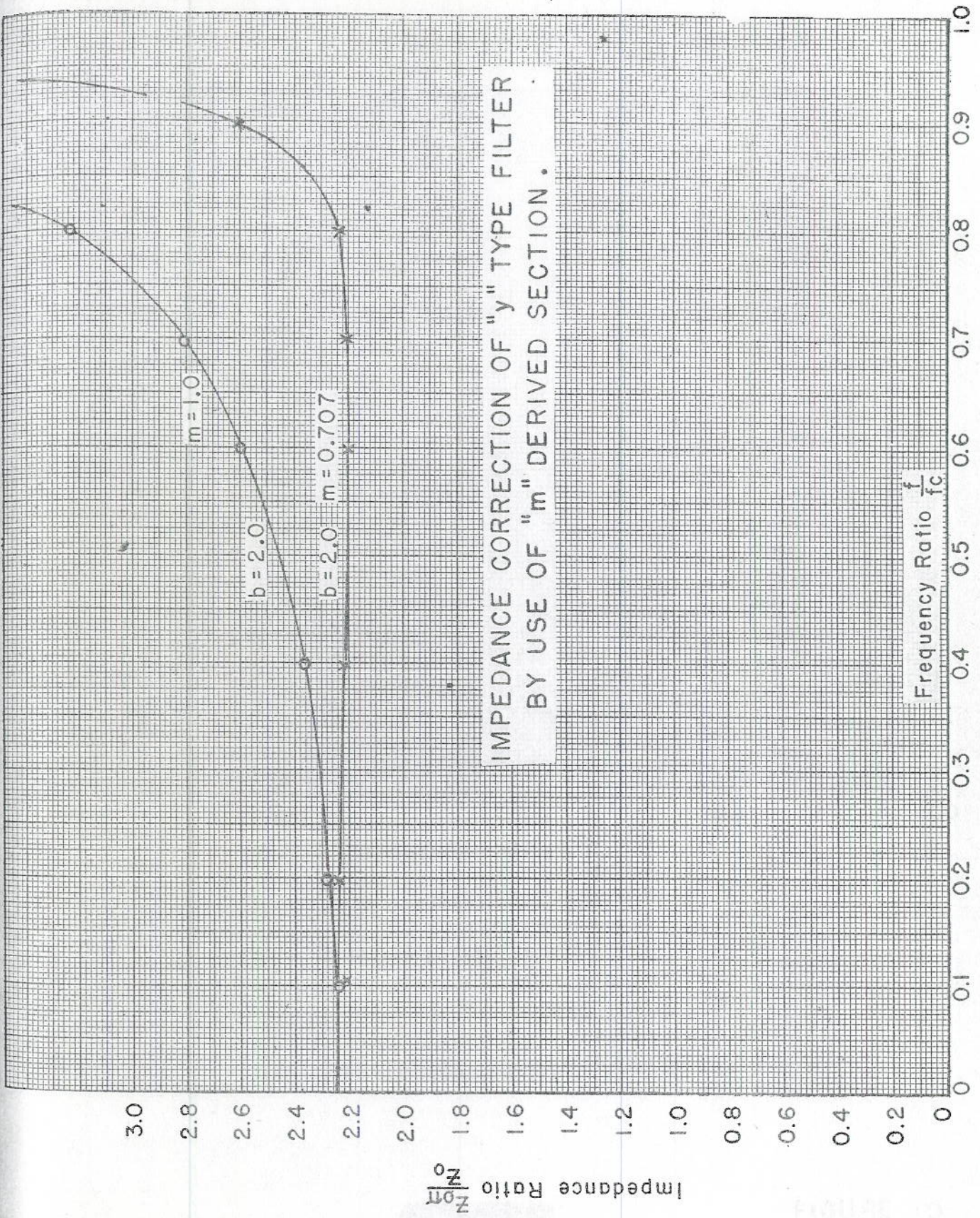


FIGURE 9 - "Y" FILTER "M" DERIVED

FIGURE 9

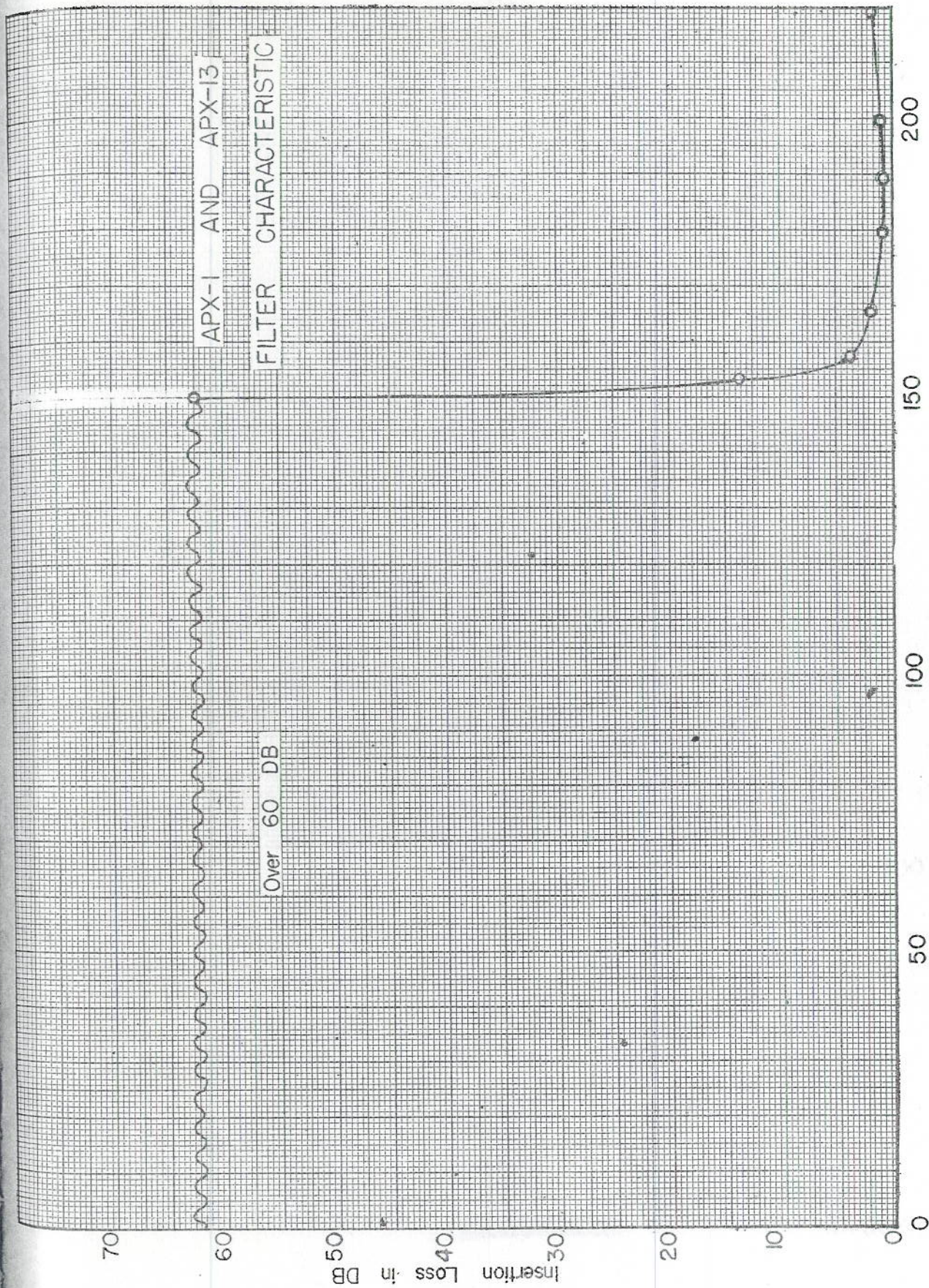
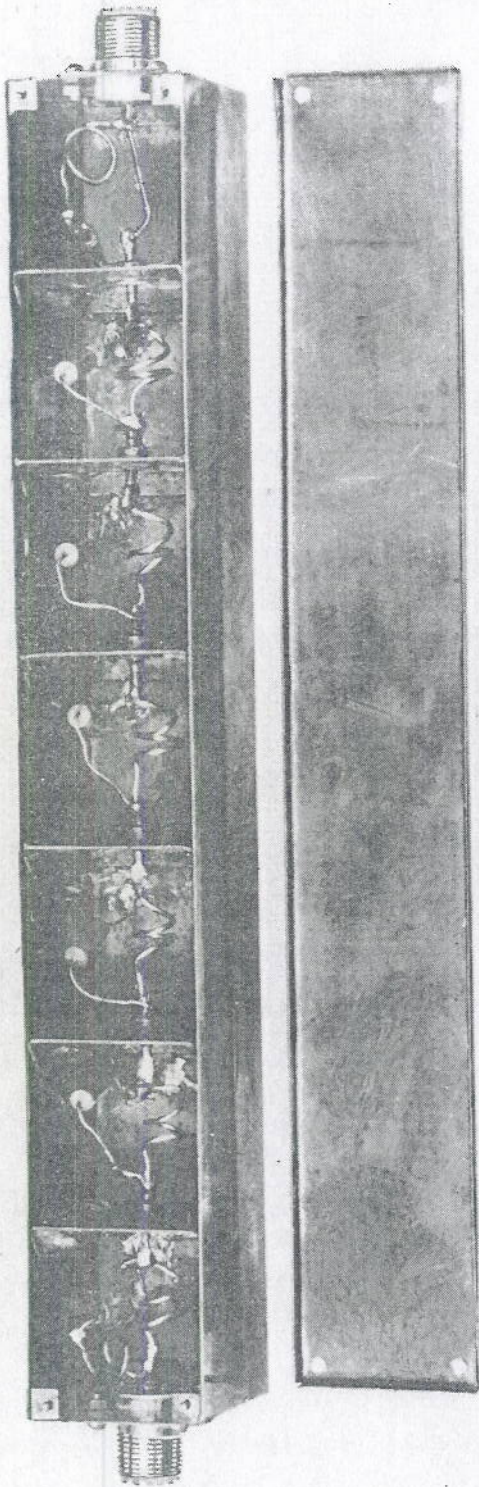
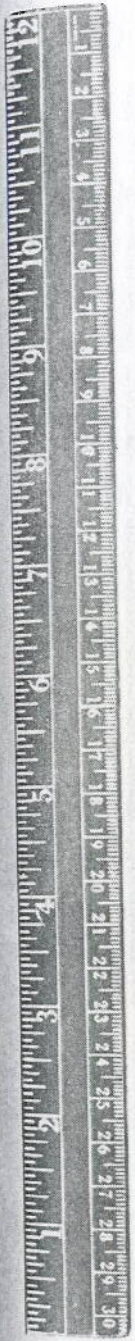
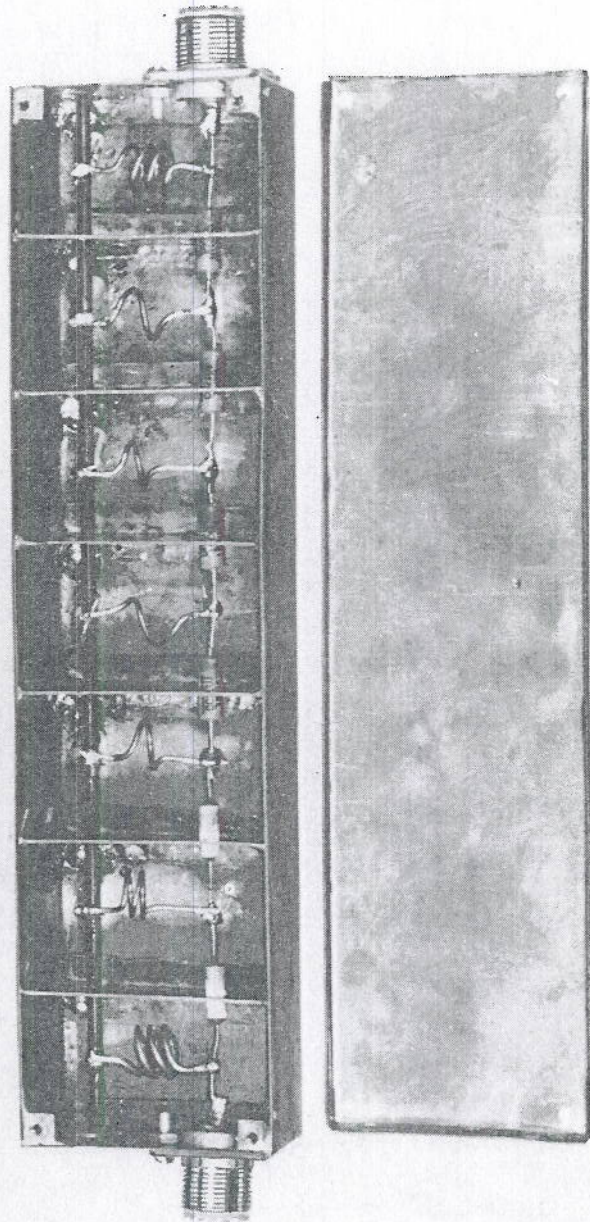


FIGURE 11 - APX-1 AND APX-13 "α" CURVE

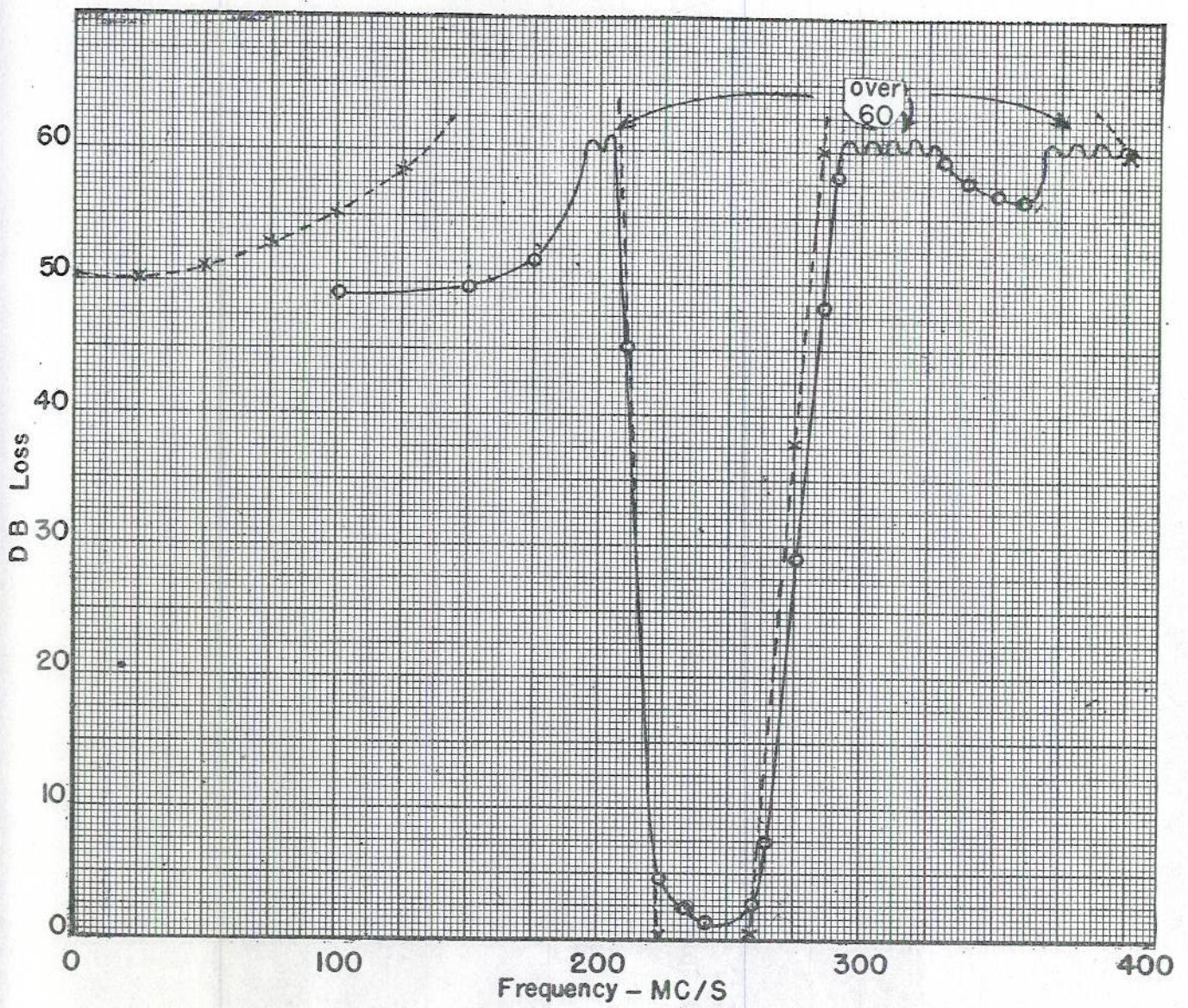


ARC-1



APX-1
APX-13

FIGURE 13 - PHOTOGRAPH OF ARC-1, APX, ARW FILTERS



ARR2 FILTER.

---x---x---x--- Theoretical

—o—o—o— Measured

FIGURE 14 - ARR-2 "α" CURVES

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FIGURE 14

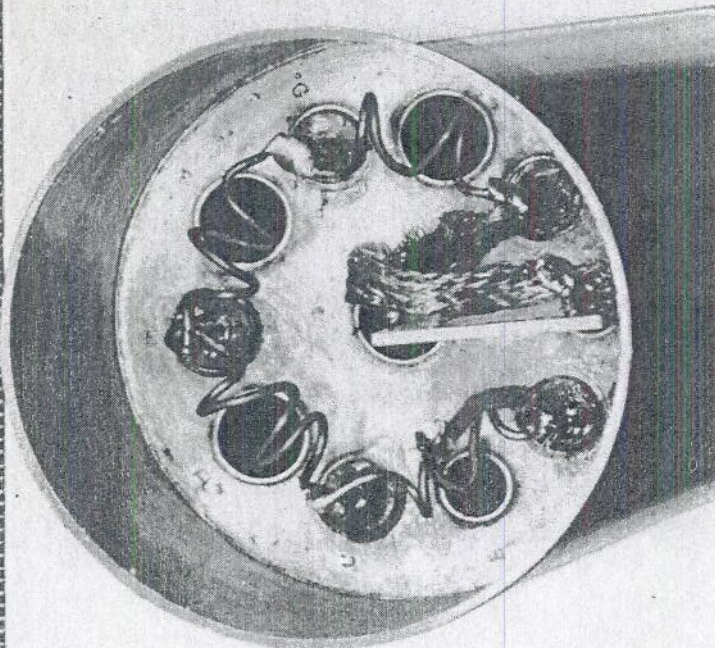
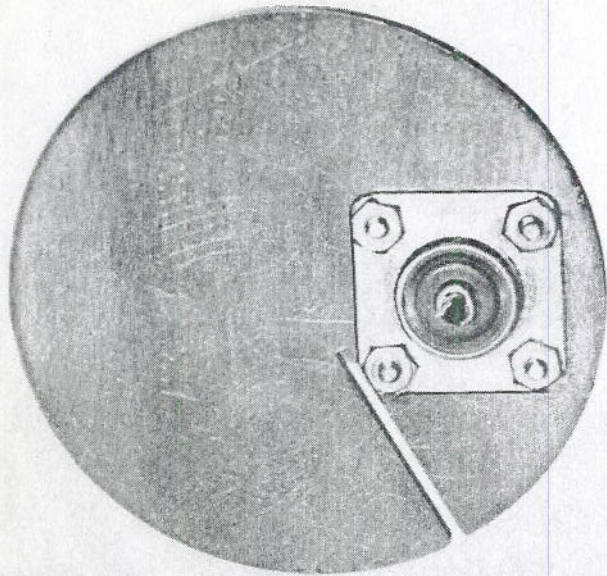


FIGURE 15 - PHOTOGRAPH OF ARR-2
FILTER, END VIEWS

CONFIDENTIAL

FIGURE 15

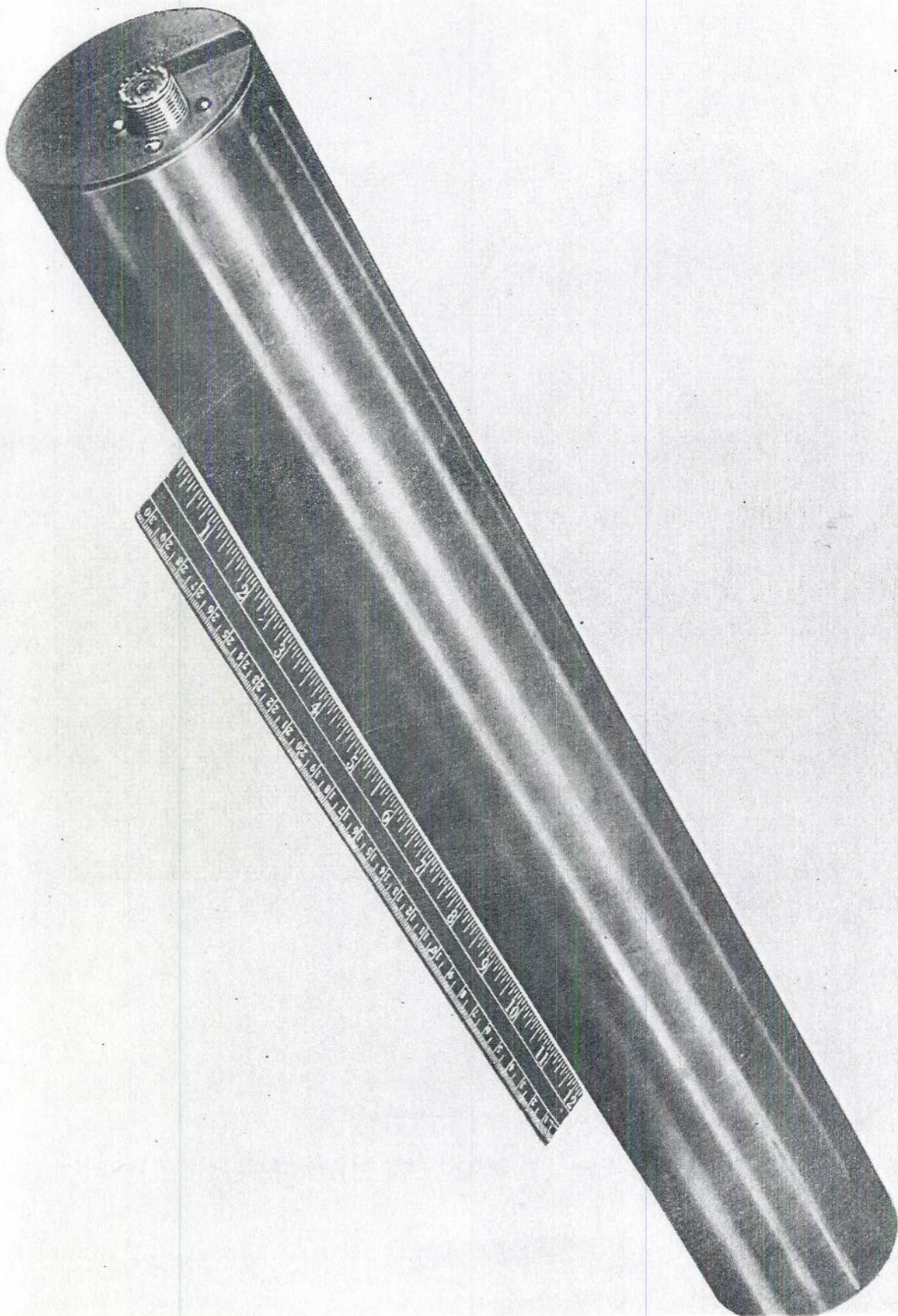
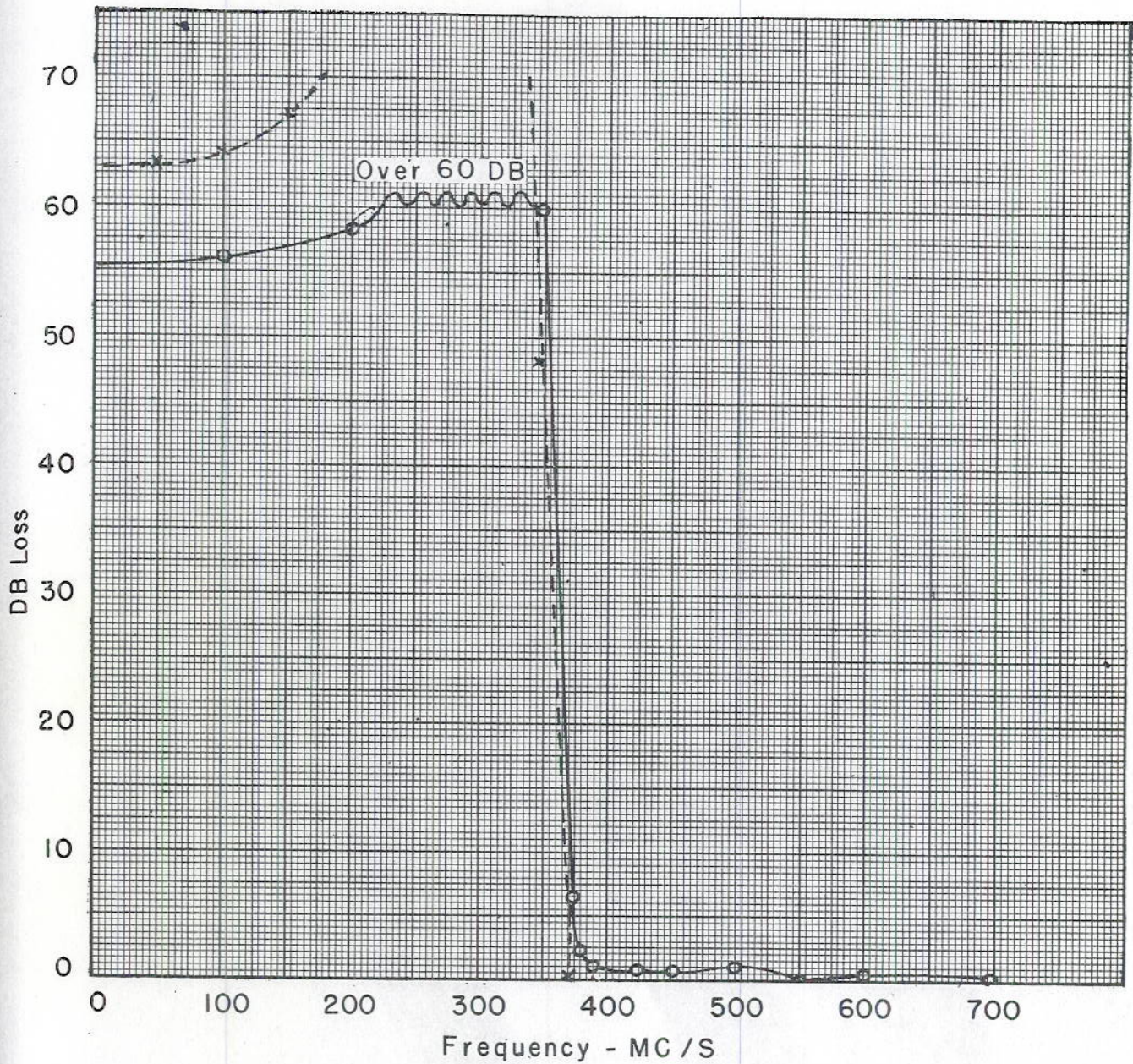


FIGURE 16 - PHOTOGRAPH OF ARR -2 FILTER, SIDE VIEW



APN-1 FILTER
 x--x--x--x Theoretical
 o--o--o--o Measured

FIGURE 17- APN-1 "α" CURVE

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FIGURE 17

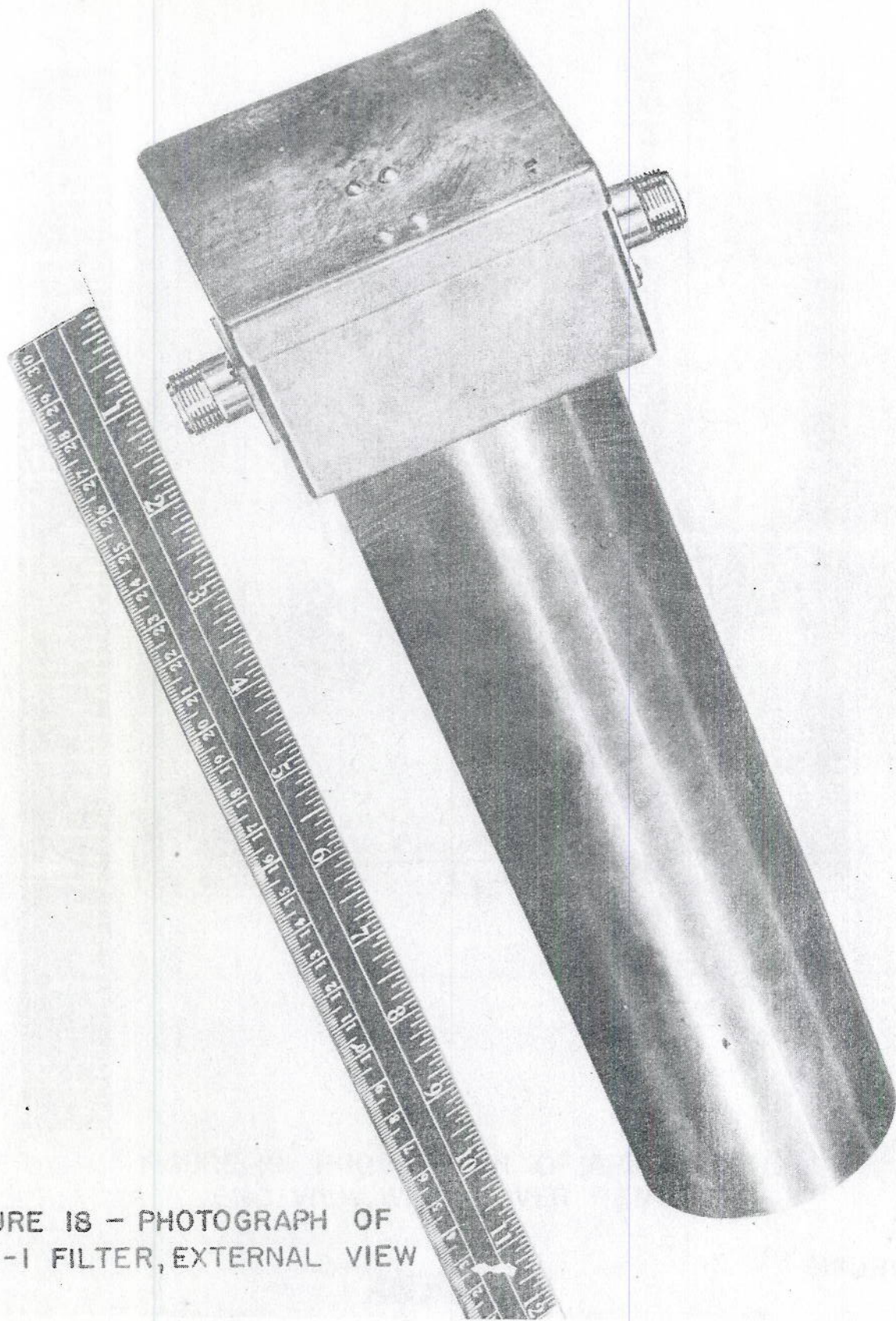


FIGURE 18 - PHOTOGRAPH OF
APN-1 FILTER, EXTERNAL VIEW

FIGURE 18

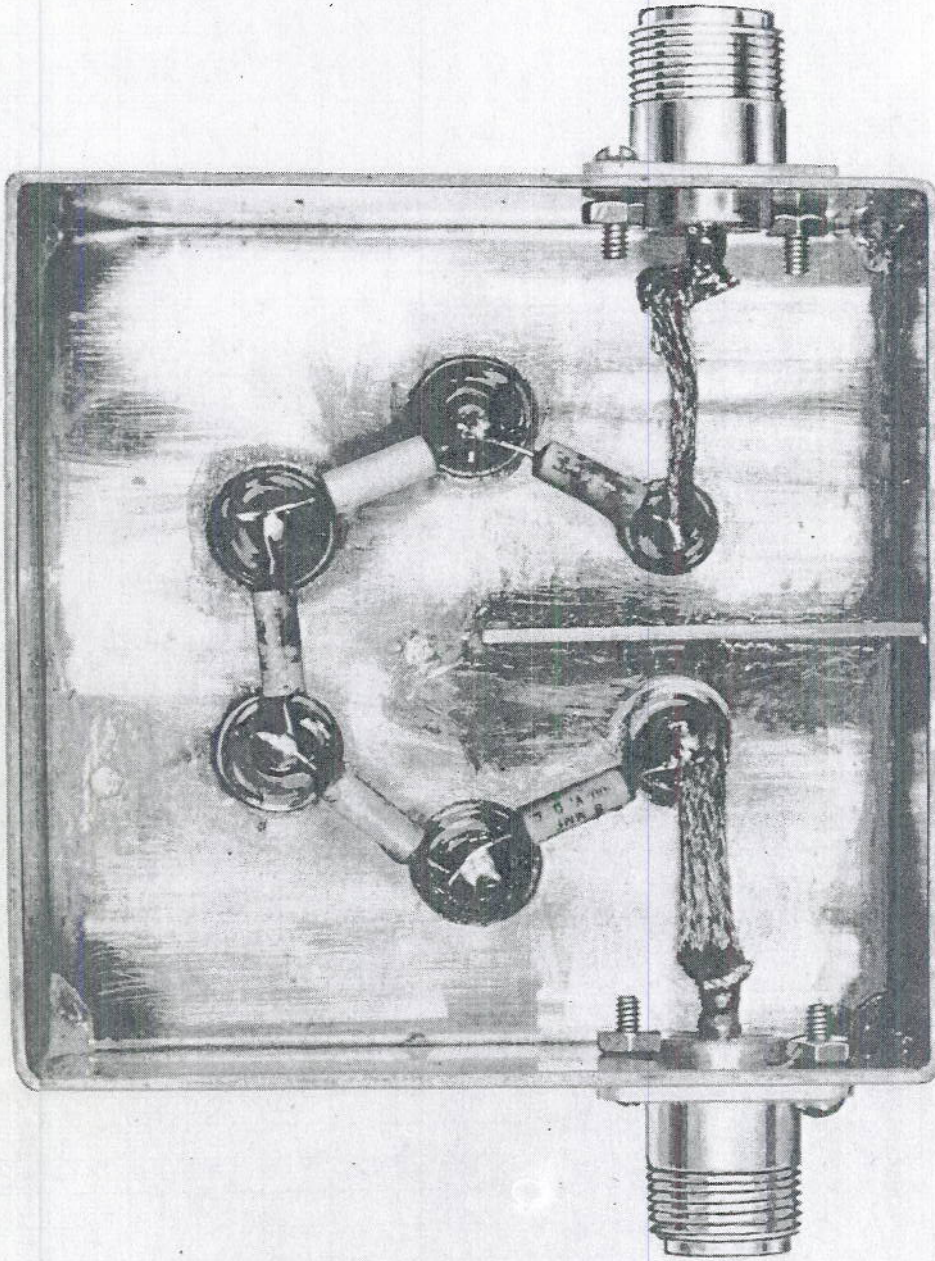


FIGURE 19 PHOTOGRAPH OF APN-1 FILTER.
END VIEW WITH COVER REMOVED.

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FIGURE 19

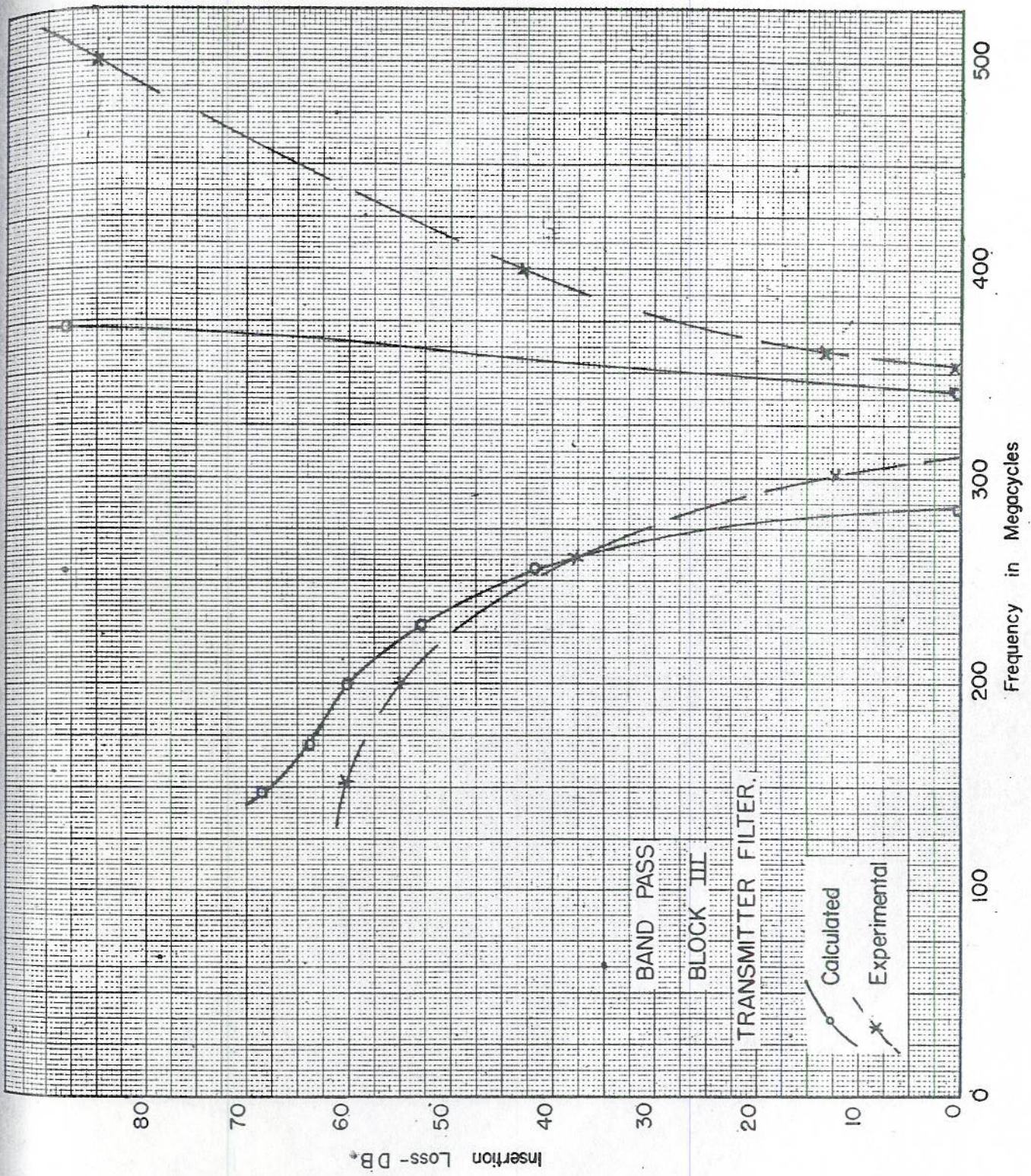


FIGURE 20 - BLOCK III "∞" CURVE

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FIGURE 20

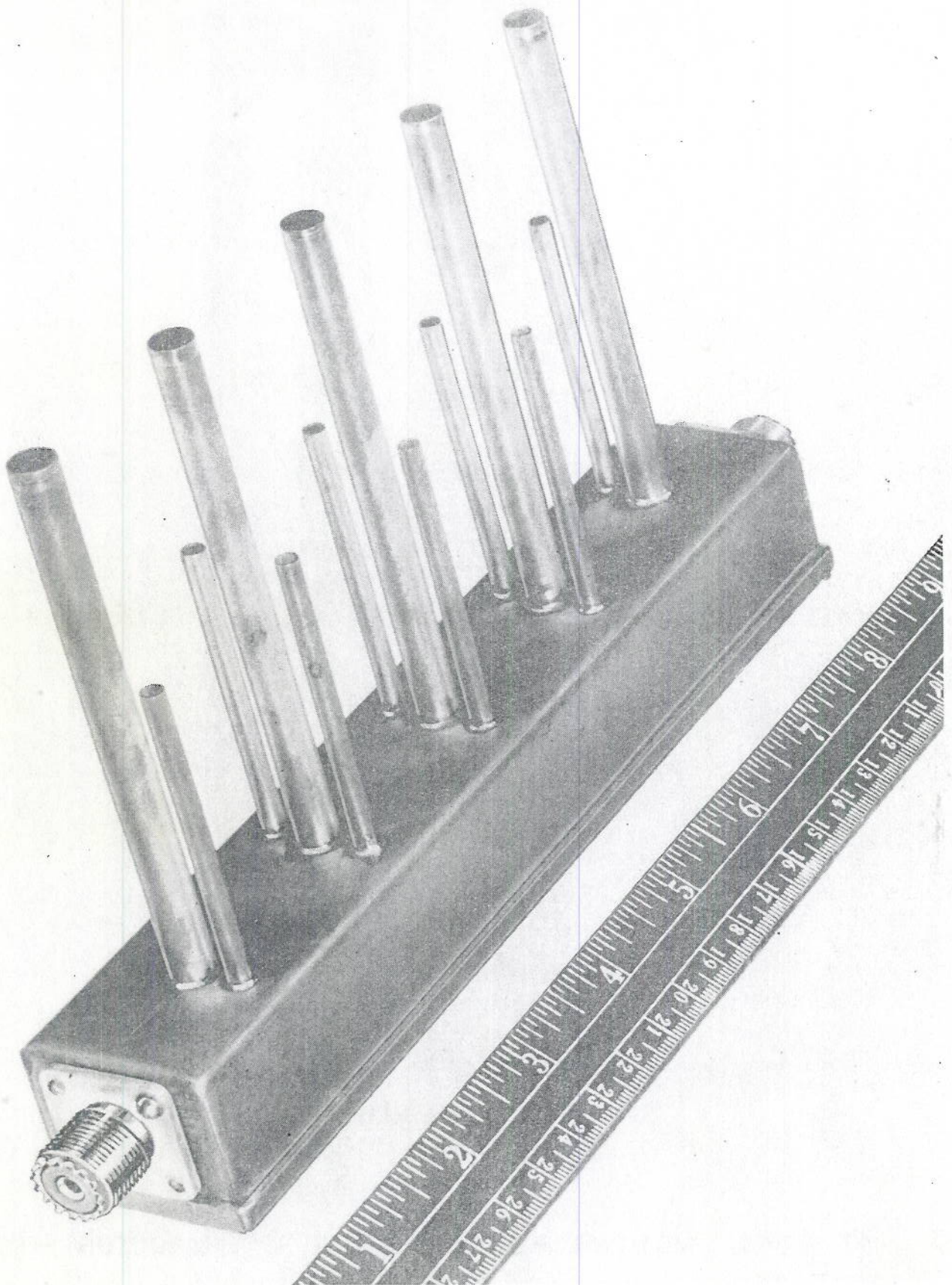


FIGURE 21 - PHOTOGRAPH OF BLOCK III FILTER - EXTERNAL VIEW



FIGURE 21

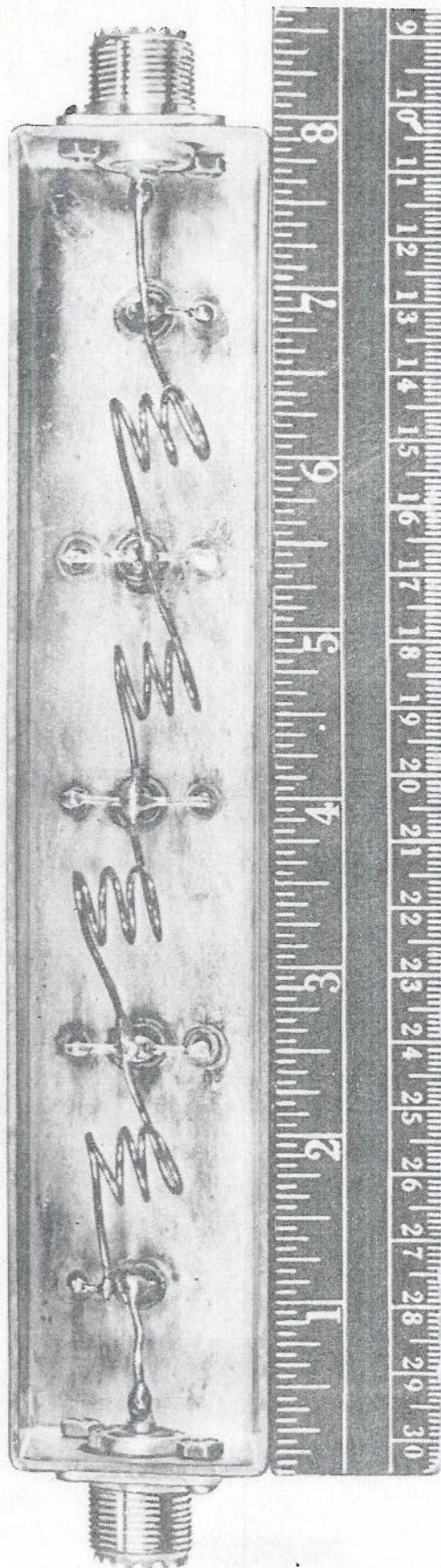
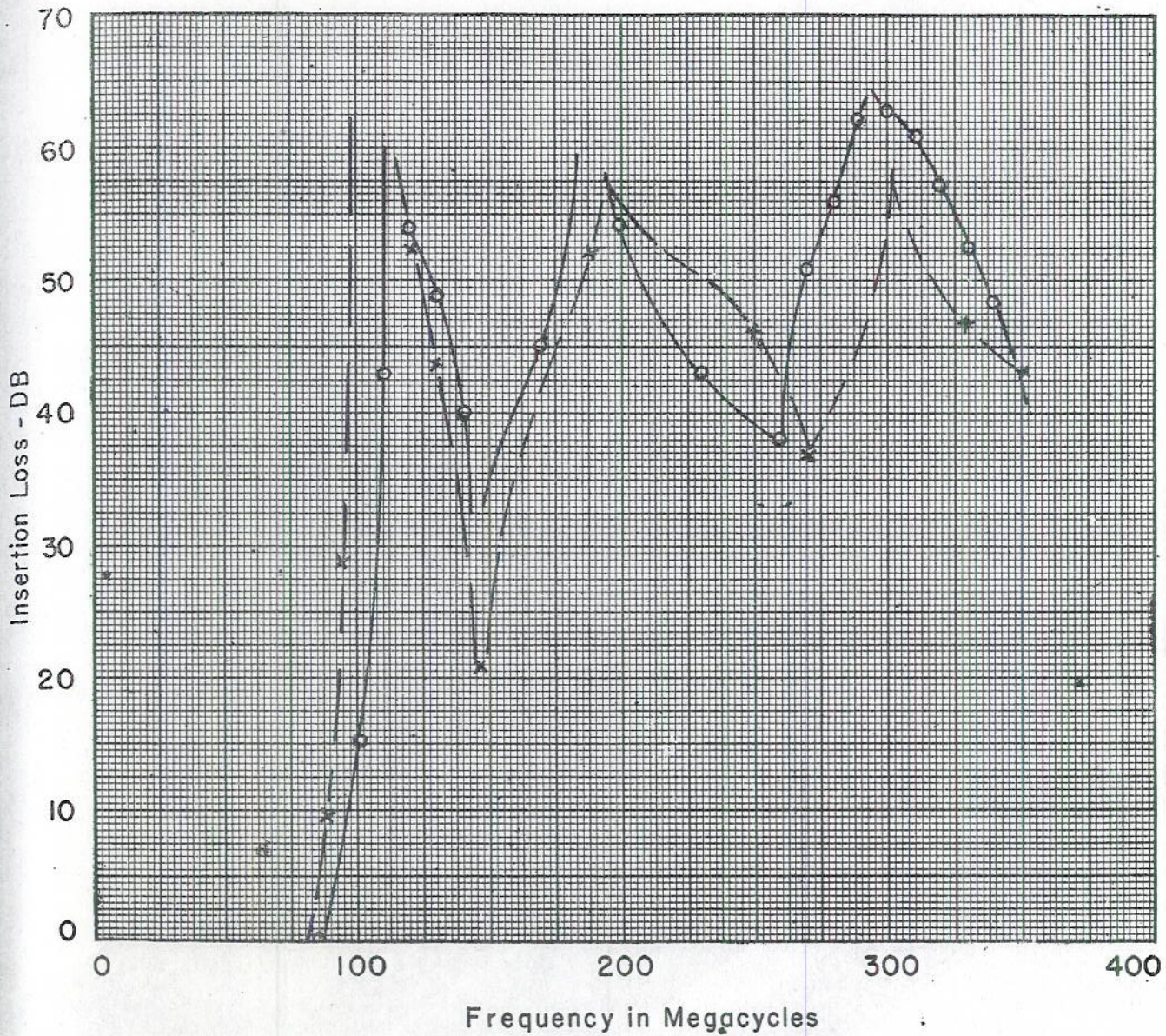


FIGURE 22 -- PHOTOGRAPH OF BLK. III FILTER -- BOTTOM COVER REMOVED

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FIGURE 22



COMPOSITE FOUR SECTION LOW-PASS FOLDED SECTION FILTER ATTENUATION DATA



 Calculated
 Observed

FIGURE 23 - "R" FILTER " α " CURVE

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FIGURE 23

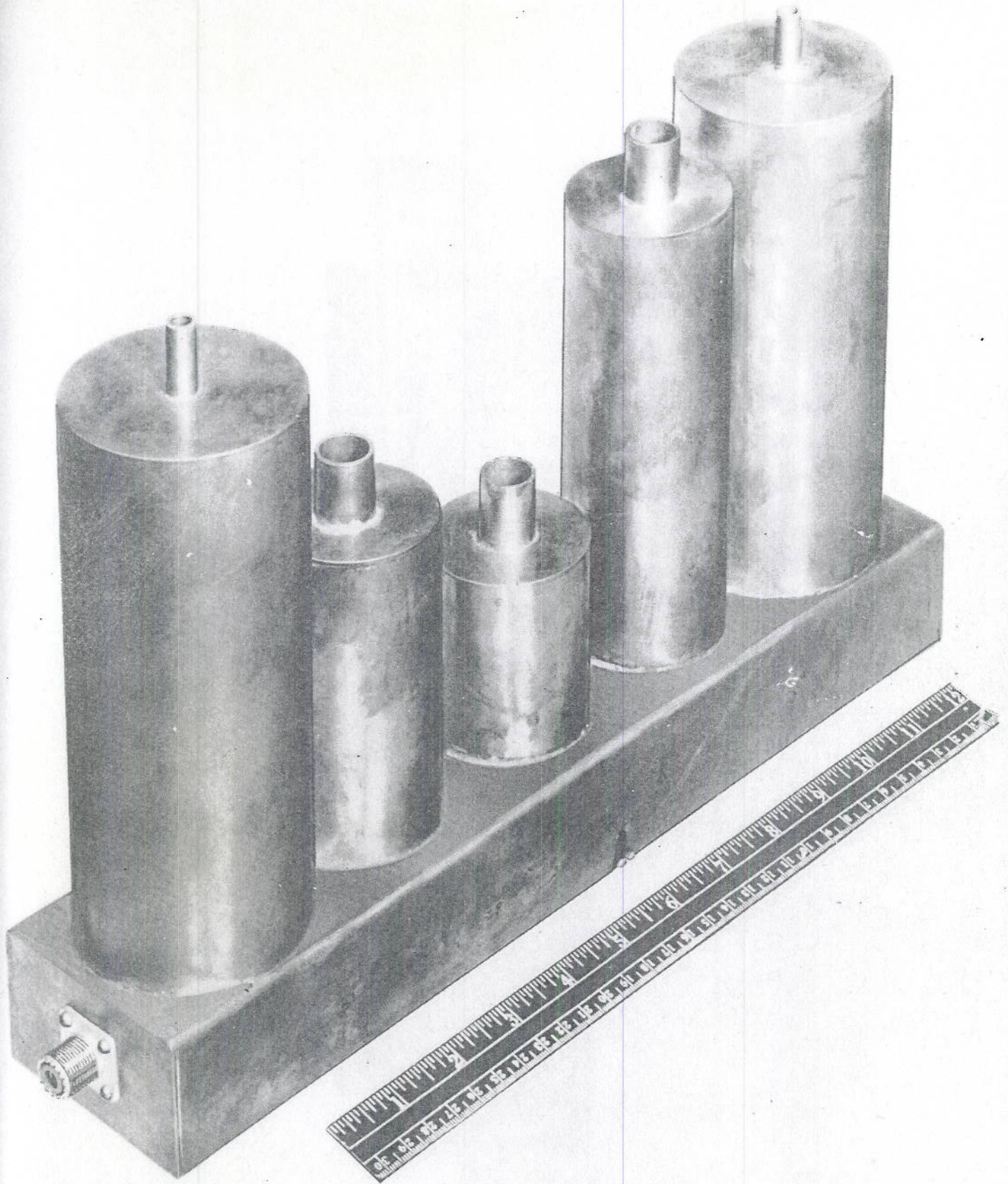


FIGURE 24 PHOTOGRAPH OF "R" FILTER, EXTERNAL VIEW.

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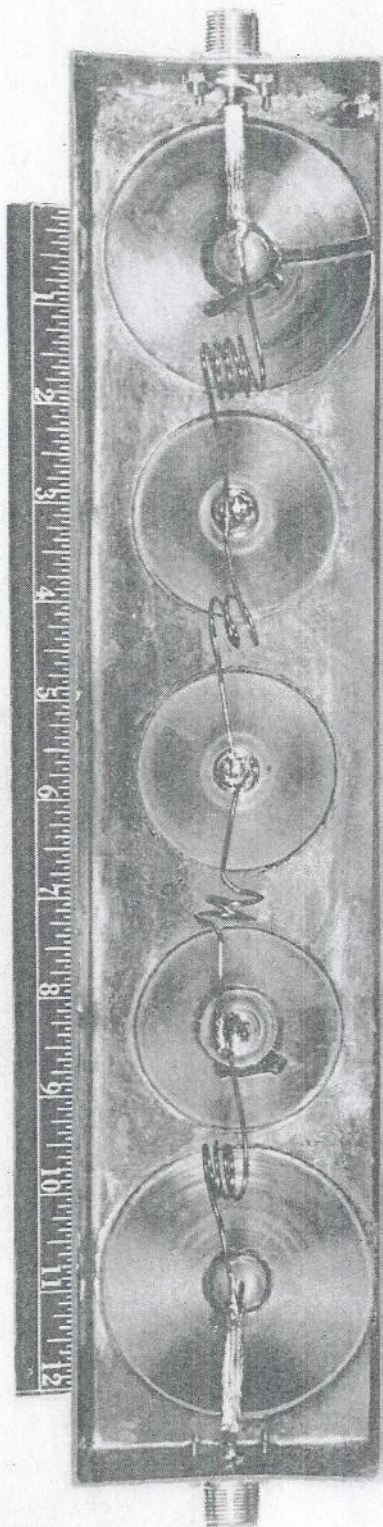


FIGURE 25 PHOTOGRAPH OF "R" FILTER - BOTTOM COVER REMOVED.

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