THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE
ANN ARBOR, MICHIGAN

HIGH-POWER COUPLED-HELIX ATTENUATORS

TECHNICAL REPORT NO. 36

Electron Physics Laboratory
Department of Electrical Engineering

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Project 2750

CONTRACT NO. AF30(602)-1845
DEPARTMENT OF THE AIR FORCE
PROJECT NO. 5573, TASK NO. 55253
PLACED BY: THE ROME AIR DEVELOPMENT CENTER
GRIFFISS AIR FORCE BASE, NEW YORK

March, 1960

ABSTRACT

A high-power high-attenuation coupled-helix attenuator has been developed using a multifilar coupled helix embedded in a lossy ceramic. The lossy material is made from a mixture of hydrostone and lampblack in which the multifilar coupled helix is embedded. Attenuation values near 20 db/inch have been obtained at S-band with an average power-handling capacity of 100 watts. The attenuator is light and rugged and has an excellent VSWR characteristic.

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INTRODUCTION

Coupled helices have been used extensively in broadband traveling-wave amplifiers both as couplers and as attenuators. When used as a coupling transducer between a helical r-f structure and a coaxial line the coupled helix is usually made of low-loss wire and wound in a single filar form. In low-power amplifiers coupled-helix attenuators have been used outside the vacuum envelope to obtain octave-bandwidth attenuators which may be optimized after the tube is assembled. These attenuators are frequently made in multifilar form out of lossy wire and embedded in teflon forms. In order to achieve relatively constant attenuation over a broad frequency bandwidth it is known that the ratio of the coupled helix radius to the inner helix radius should be kept less than 1.6-1.7. Also these attenuators are limited in power-handling capacity due to the temperature limitations of the teflon.

In high-power tubes it is desirable that the attenuator be capable of dissipating the full output of the tube in order that it be short-circuit stable. Aquadag and ceramic embedded with graphite are frequently used as attenuators for high-power tubes. These, however, have the disadvantage that they must be located inside the vacuum envelope and hence must be optimized before the tube is constructed. Also, they cannot be effectively cooled. Clearly coupled-helix attenuators located outside the vacuum envelope and capable of dissipating high average powers would be preferable.

The work reported on in this paper concerns the development of a coupled-helix attenuator for high-power amplifiers which is capable of dissipating over 100 watts of cw power. High values of attenuation are obtained by embedding the coupled helix in a lossy dielectric.

The general analysis of coupled helices has been developed by several authors[1,2] and these analyses were used as the basis of the general design for the attenuators. However, since the coupled helices were embedded in a very lossy dielectric the design had to be modified to account for the consequent slowing of the r-f wave in addition to the slowing caused by the dielectric region separating the two helices.

The ceramic material used for support of the coupled helices is known as hydrostone; it is a commercially available industrial casting cement. To obtain high loss it is mixed with lampblack. Water is added and then the entire structure including the helix is placed in a mold. The level of attenuation generally achievable is dependent upon many parameters which necessarily must be studied for a general evaluation of its capabilities. These factors are: 1) length, 2) helix pitch, 3) ratio of helix radii, 4) lampblack concentration, 5) wire size and 6) number of files in the coupled helix. Embedding the helix in the lossy hydrostone aids in obtaining a good impedance match to the coupled helix since energy is absorbed by the lossy material.

This type of attenuator has many advantages when used in a high-power tube since it is located on the outside of the vacuum envelope, where optimum positioning may readily be achieved in addition to facility of cooling with either forced air or through the use of a circulating coolant such as water or one of the many fluorocarbons. Fabrication of these units is quite simple and they are relatively small in size as well as light.

The evaluation of carbon-impregnated hydrostone presented in this report concerns principally its use with coupled helices. It may, however, be utilized in severed-circuit amplifiers, where periodically loaded waveguide circuits with lossy ceramic sections between the circuit sections are used. The only limitations on temperature of operation in a vacuum would be the temperature at which there was a chemical reaction between the ceramic and the lampblack or the temperature at which the carbon melts (> 3500°C). Since both of these temperatures are extremely high no significant limitation is seen.

Generally the length of a coupled-helix coupler is taken as $\lambda_c/2$, where λ_c is the coupling wavelength and is defined by $\lambda_c = |2\pi/\beta_c|$. The coupling phase constant β_c is obtained from a graph[2] of $\beta_c a$ vs. β_a for particular values of r_o/r_i, the ratio of radii of the coupled helix and the inner helix. The presence of dielectric material between the coupled helices increases the coupling wavelength, and an outer metallic shield around the outer helix reduces the inner helix impedance as well as affecting the impedance match into the inner helix.

The pitch of either couplers or attenuators is generally related to the pitch of the inner helix through the following well-known relationship.

$$(\mathrm{TPI})_o r_o = (\mathrm{TPI})_i r_i \quad ,$$

where the subscripts "o" and "i" indicate the outer and inner helices respectively. Since the loss per unit length is of principal concern in coupled-helix attenuators, the design length is not as critical as in the case of the coupler and the coupling wavelength is hence not as important. The optimum pitch of the coupled-helix attenuator in the presence of a dielectric with $\epsilon_r = 5.7$ and a loss of 20 db/inch is increased over the value given by the above relation by some 25 percent.

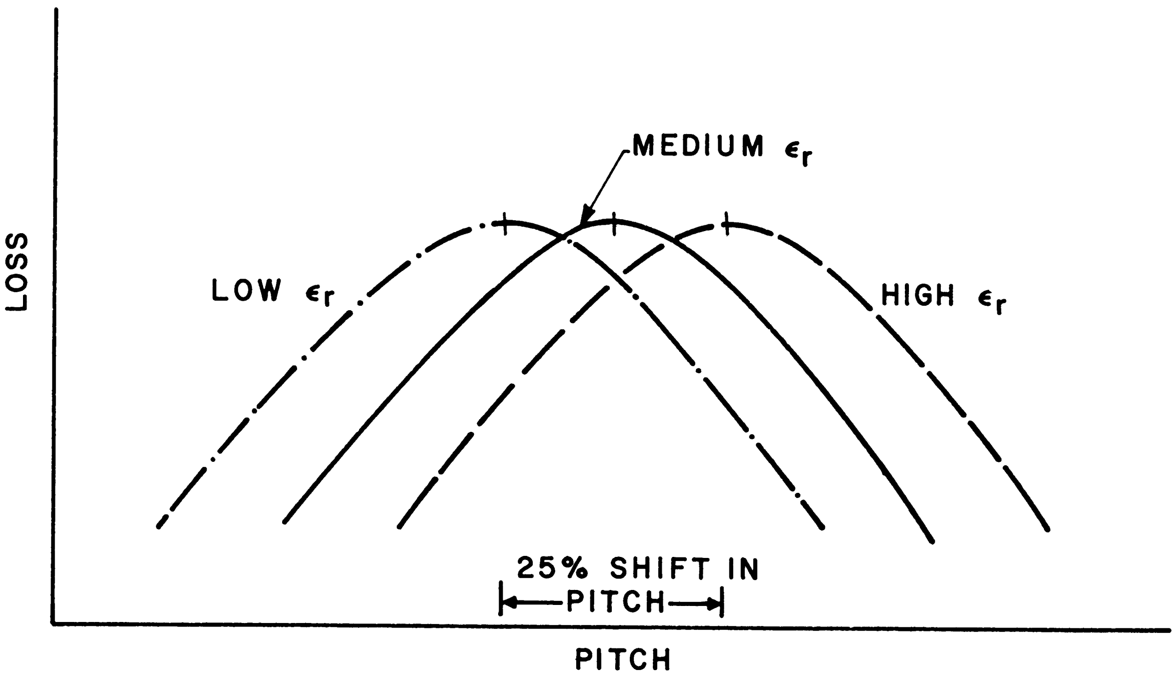
Generally an improvement in performance of the coupled-helix attenuator can be achieved by using a multifilar helix. The loss per unit length can usually be raised in this way and the attenuation vs. frequency curve can be reshaped. Lossy material and high dielectric constants increase the desired pitch and hence a greater number of files can be used. The effect of dielectric constant and of the number of files on coupled-helix attenuator performance is shown qualitatively in Fig. 1.

The following sections of this report are devoted to a discussion of the fabrication, principal characteristics and experimental results on various high-power coupled-helix attenuators.

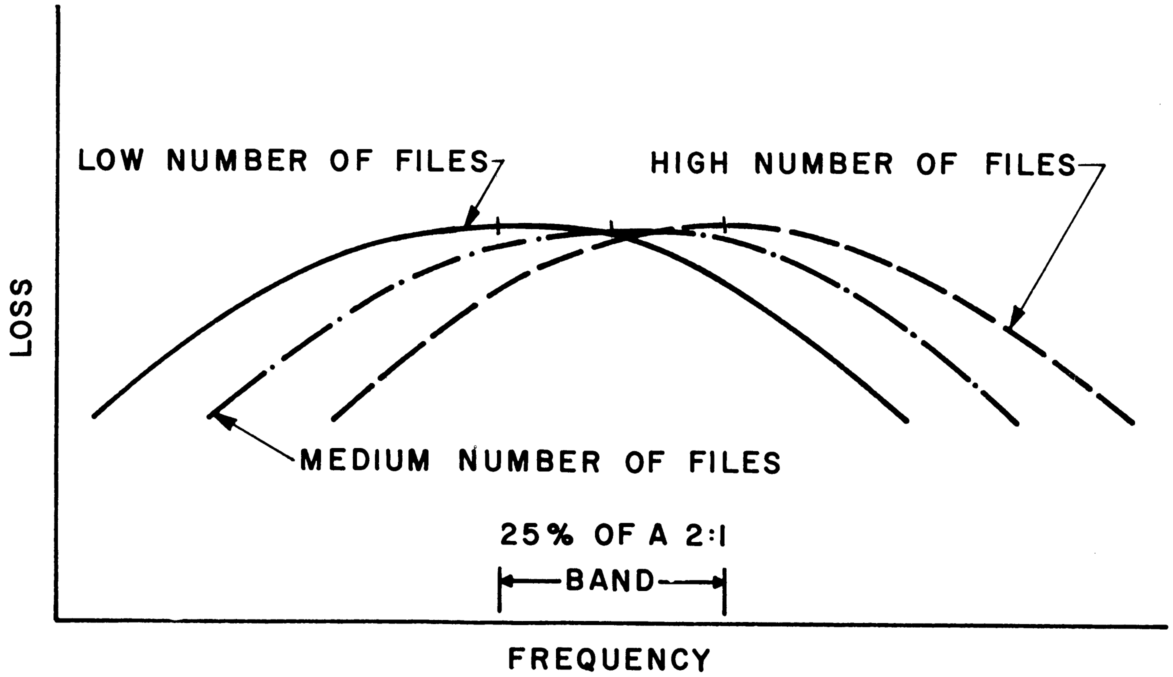
DESIGN OF HIGH-POWER ATTENUATORS

It is well known that the coupled helix is basically a broadband coupling device in which the performance is dependent upon the constancy of the coupling wavelength. A generally satisfactory coupler design can be evolved rapidly although the specific results are dependent upon a great many variables. A general study of all these parameters reveals that may parameters have a secondary effect on the final performance and hence need not be optimized.

The most important consideration is that of obtaining good coupling over a broad band of frequencies. This is accomplished by making the phase velocities of r-f waves on both the outer and inner helices equal. Generally the greater the coupling the better the performance in terms of wide bandwidths and high values of attenuation along with a relatively constant level of attenuation over the frequency range. As pointed out previously, the presence of dielectric material around the coupling helix tends to reduce its phase velocity and hence requires that the pitch be increased. Experiment indicates that the pitch



1a. LOSS vs. PITCH AND ϵ_r



1b. LOSS vs. FREQUENCY AND NUMBER OF FILES

FIG. 1 DEPENDENCE OF COUPLED-HELIX ATTENUATION ON DIELECTRIC CONSTANT AND NUMBER OF FILES.

parameter and the loss parameter may be optimized independently.

The loss parameter of the coupled-helix unit is determined both by the loss of the coupled-helix wire and by the resistivity of the impregnated ceramic in which the coupled helix is embedded. The wire size, resistivity and thermal conducting properties of the impregnated ceramic also determine the power-handling ability of the unit. In general the unit will absorb 90 percent of the coupled energy in the dielectric material and the other 10 percent will be carried by the helix wire itself. The amount of power that it is capable of dissipating at any given temperature will be determined partially by the wire diameter. Multifilar helices have an increased power-handling capability over the single-filar version.

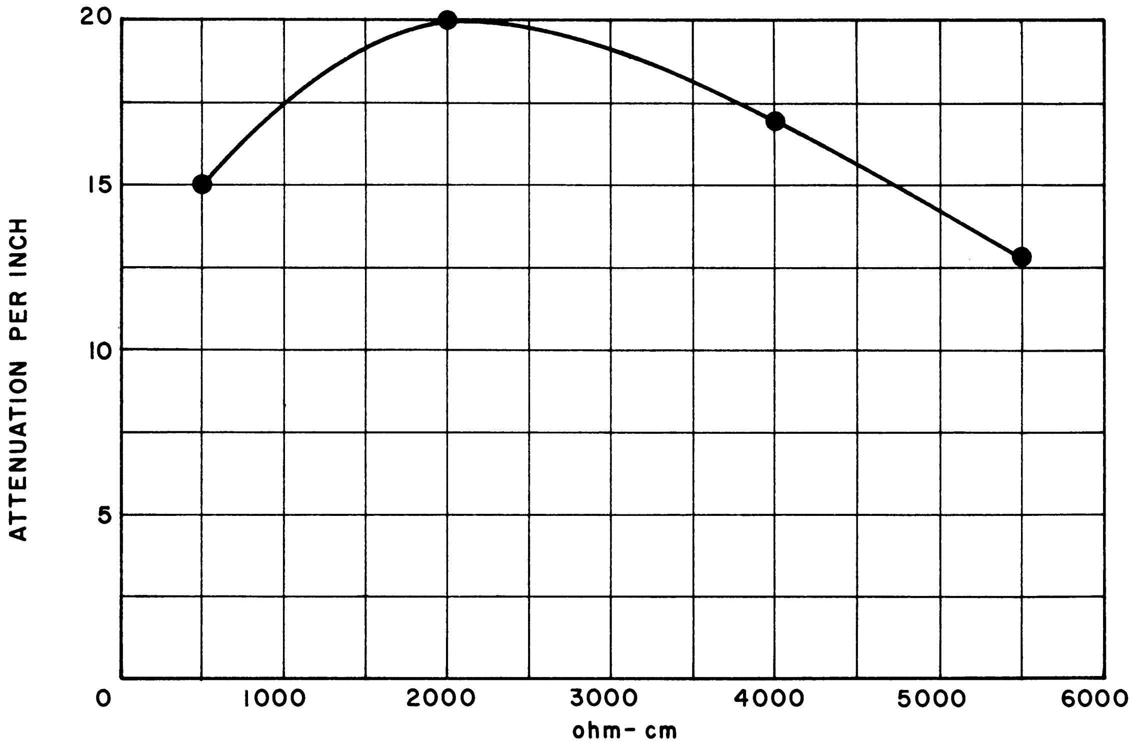
As expected, the level of attenuation decreases with frequency for any given attenuator due to the fact that the r-f fields fall off exponentially with wavelength in the radial direction away from the helix wire. This effect can be reduced principally through an increased coupling by reducing the radii ratio between the two helices. Another way in which the high-frequency level of attenuation can be increased is through increasing the number of files. This has a pronounced effect up to four files and in some cases there are advantages to be obtained in going to eight files. The general results obtained with an increase in the number of files are 1) an increased attenuation, 2) smoother response, 3) a shift in the response to higher frequencies, and 4) an increase in the power-handling capability of the attenuator. Improved shaping of the attenuation vs. frequency curve can also be achieved by adding files to the coupled helix.

Dielectric loading of the system provided by the lampblack-impregnated hydrostone reduces the phase velocity of the r-f wave and can effect a reduction in the dispersion, resulting in a broadening of the bandwidth. This dielectric loading also produces a shift in the response.

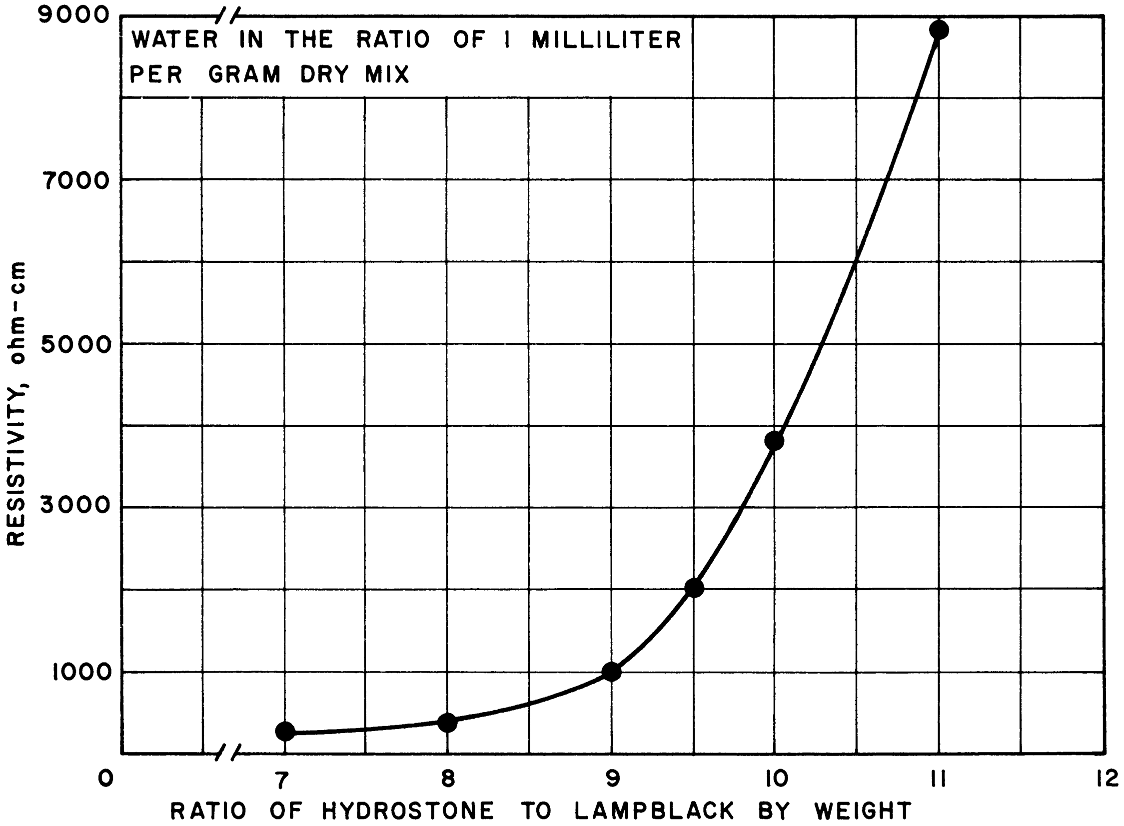
In the case of aquadag attenuators and teflon-embedded coupled-helix attenuators it is sometimes difficult to obtain a good r-f impedance match when viewed from either end of the attenuator. This is usually solved by tapering the loss into the coupled helix. In the case of the ceramic-loaded attenuator discussed here, this problem is minimized due to the fact that the lossy ceramic absorbs the waves rather than tending to reflect them. From the standpoint of obtaining a low VSWR into the coupler, lossy materials with a resistivity of approximately 2000 ohm-cm are found to be near optimum for low reflections. The resistivity as a function of the percentage of lampblack in hydrostone and the level of attenuation vs. resistivity are shown in Fig. 2.

EFFECT OF MAGNETIC FIELDS

It has been reported in the literature[3] that coupled helices made with small-diameter magnetic kanthal wire exhibit a dependence of attenuation on the strength of the magnetic field. All of the attenuators discussed here have been made with kanthal wire and the following interesting effects have been observed. The effect is more pronounced for wire diameters near 0.001 inch and generally decreases as the wire diameter is increased up to 0.008 inch, usually disappearing with diameters above that level. The attenuation increases with magnetic field up to some 700-800 gauss and generally the effect disappears at higher values of magnetic field and the attenuation then increases linearly with length. The effect of high dielectric loading generally reduces the magnetic field effect and for high dielectric constants it



2 a. LOSS vs. RESISTIVITY


WATER IN THE RATIO OF I MILLILITER PER GRAM DRY MIX

2 b. RESISTIVITY vs. LAMPBLACK CONCENTRATION

FIG.2 COUPLED-HELIX ATTENUATION vs. RESISTIVITY.

may be completely absent.

The change in loss of the attenuators is due to a change in the coupling constant (wavelength) which occurs due to a variation in the magnetic permeability of the kanthal wire. This effect can result in a significant shift of the attenuation vs. frequency characteristic of the attenuator. The change in the level of attenuation and the shift in the attenuation vs. frequency characteristics for two typical coupled-helix attenuators are shown in Figs. 3 and 4. The effect of this change in coupling wavelength on the attenuation vs. length at various magnetic field values is indicated in Fig. 5.

FABRICATION OF A HIGH-POWER COUPLED-HELIX ATTENUATOR

As discussed earlier in this report, the high-power attenuator is made by embedding a multifilar-helix kanthal attenuator with small wire size in a mold of hydrostone and lampblack. The kanthal wire is wound on a cellophane tape form for support throughout the molding process. The hydrostone and lampblack are dry-mixed in a weight ratio of 9.5 units of hydrostone to 1 unit of lampblack. Hot water is then added in a proportion of 1 milliliter to 1 gram of the dry mix. The mixture is then poured into a glass tube mold, the inside surface of which has been coated with wax that can be heated later to aid in removing the attenuator from the mold. When a proper amount of water is used the mixture will set in approximately one-half hour, after which the mandrel and tape are removed. The attenuator is then oven-dried at a temperature less than 100°C for two or three hours until all the excess moisture is removed.

The lampblack is used to reduce the resistance of the ceramic material by creating high conducting paths through the material due

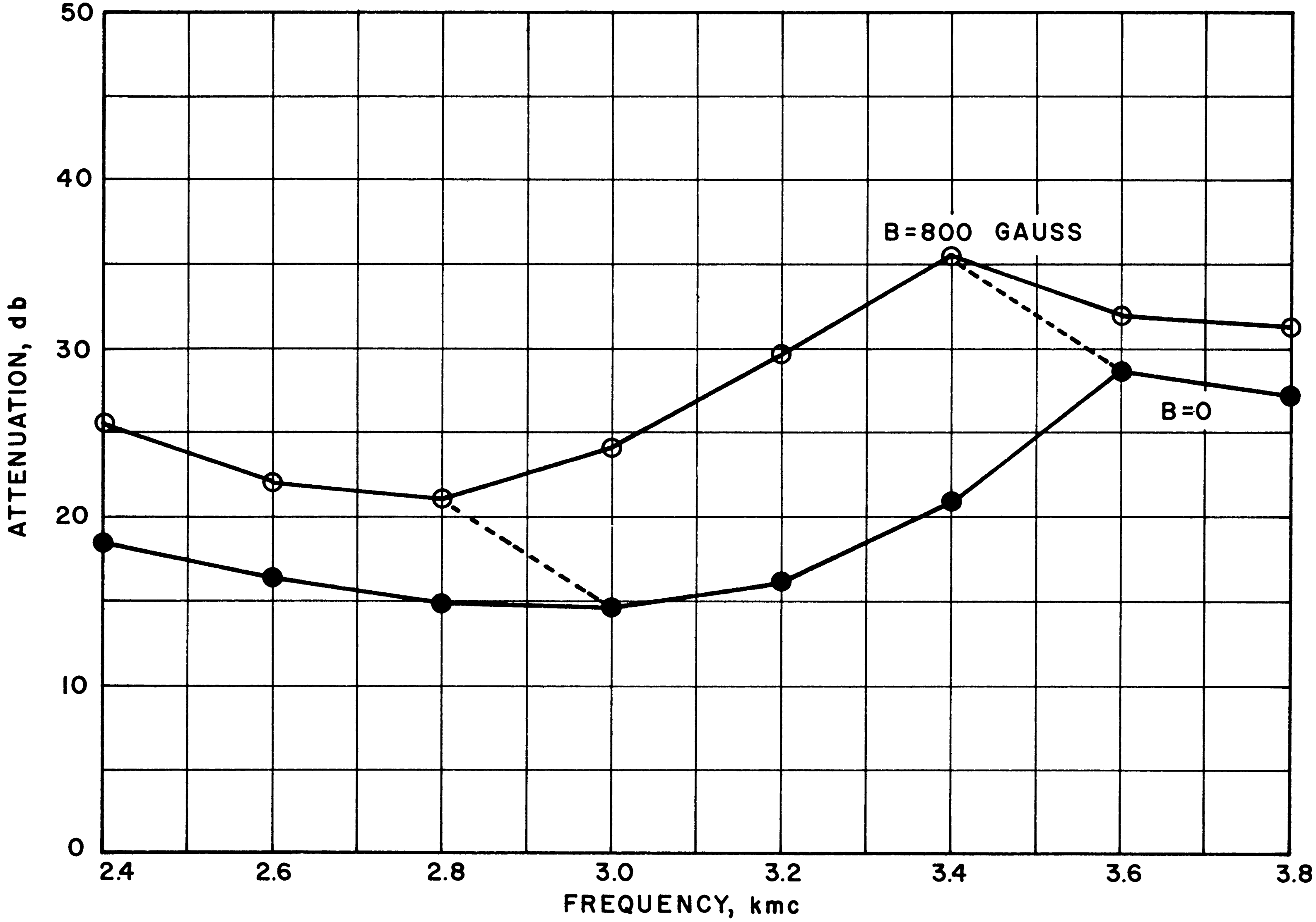


FIG. 3 ATTENUATION vs. FREQUENCY FOR AN 8-FILAR COUPLED HELIX. (TPI = 4.2, L=2 INCHES, WIRE DIAMETER = 0.002 INCH)

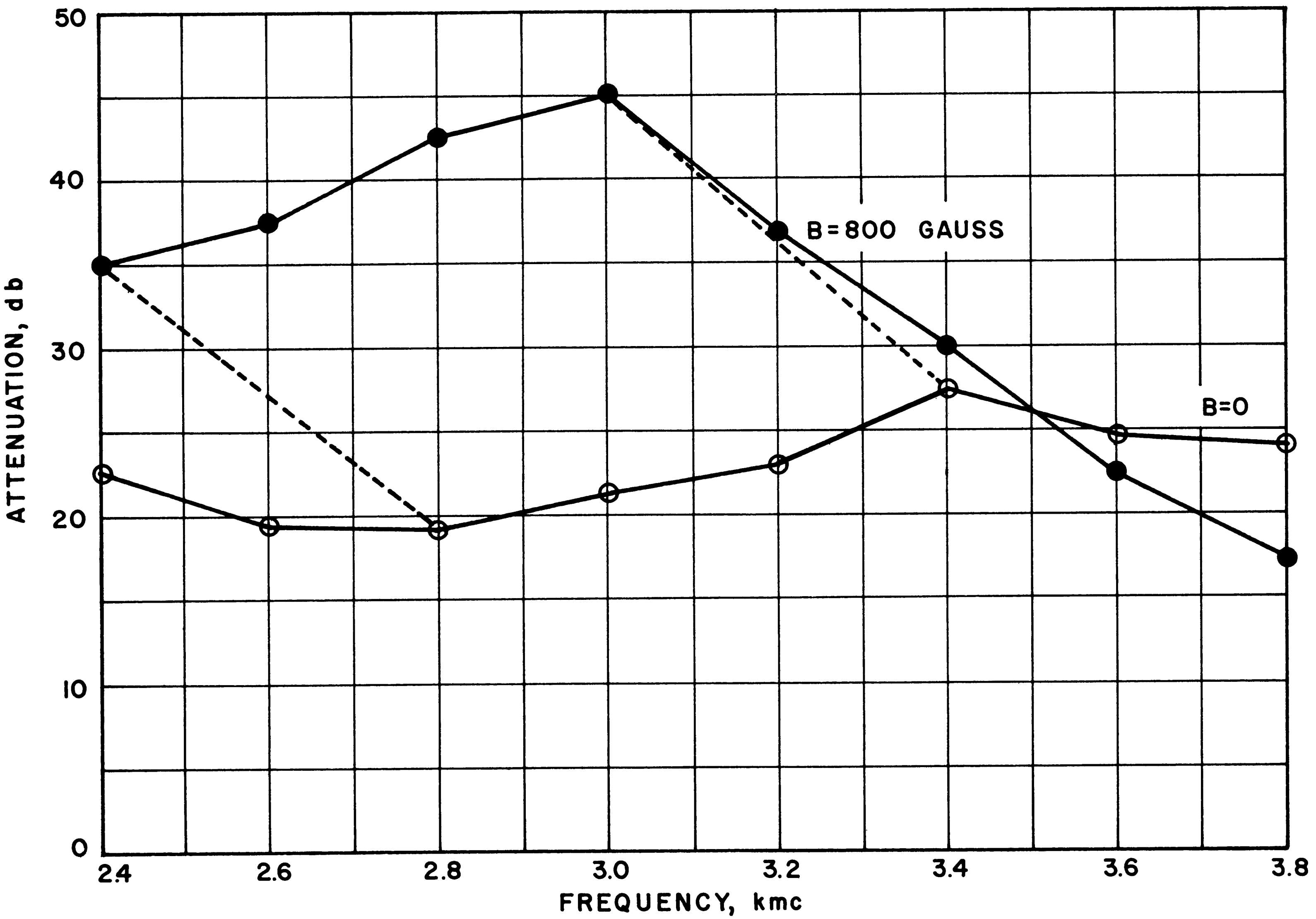


FIG. 4 ATTENUATION vs. FREQUENCY FOR A 6-FILAR COUPLED HELIX. (TPI=3.8, L=2 INCHES, WIRE DIAMETER=0.001 INCH)

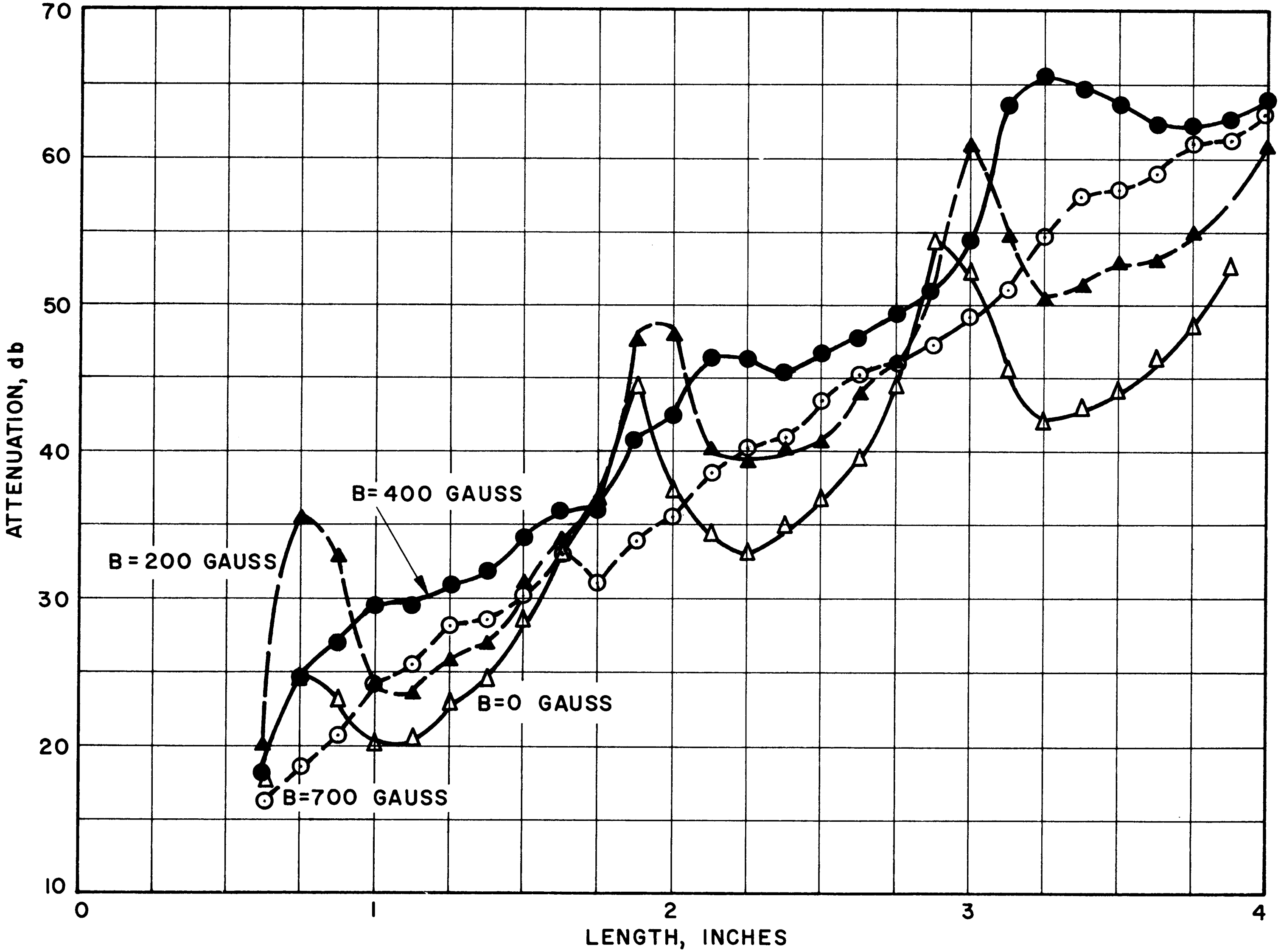


FIG. 5 DEPENDENCE OF COUPLED-HELIX ATTENUATION ON LENGTH AND MAGNETIC FIELD. (TPI=3.5, 3-FILAR, WIRE DIAMETER=0.003 INCH)

to point-to-point contact between the particles of lampblack. The amount of water added will affect the final resistance and if too much water is used the attenuator will be porous and weak. Also, excess moisture lengthens the setting time appreciably.

The optimum value of resistivity is near 2000 ohm-cm for maximum attenuation per inch. The dielectric constant of hydrostone is $\epsilon_r = 5.66$ at 10 kilocycles.

EXPERIMENTAL RESULTS

High-power attenuators of the type described in the preceding sections of this paper have been made and studied experimentally in both the S- and X-band frequency ranges. The objective for the S-band attenuator was to obtain at least 40 db of attenuation in a 2-inch length to operate over the entire S-band region with an average power-handling capability of at least 100 watts. The high-power characteristic was not sought in the X-band attenuator; rather it was desired to achieve 35 db of attenuation in as short a length as possible, over the frequency range from 8.0 to 12.4 kmc. The requirement of a short length is a result of a desire to obtain the highest efficiency possible in the tubes under study. The effect of length on saturation efficiency has been studied by Rowe and Sobol[4], who determined that an attenuator length of 5 or fewer retarded wavelengths is desirable.

Attenuation, impedance matching and power-handling capability were all studied experimentally. High-power measurements were limited due to the lack of a higher power source. Water was circulated in a metal water jacket around the attenuator and the temperature was measured with a thermocouple placed on the inside incident face at the helix radius. Air was circulated within the inner helix to keep both its loss and temperature as low as possible.

The results for the S-band attenuator are shown in Fig. 6 for two different TPI values with four-filar helices. The VSWR match for a typical S-band attenuator is shown in Fig. 7. The slight change in slope of the attenuation curve at the high-frequency end of the band is a result of the slight variation in pitch of the attenuator. As is seen from Fig. 7, the VSWR match looking into either end of these attenuators is excellent. This is due to the fact that the lossy ceramic absorbs the microwave energy rather than reflecting it.

The experimental results on the X-band attenuator are shown in Figs. 8 and 9. The higher attenuation curve in Fig. 8 indicates the effect mentioned earlier of varying the spacing between files of the multifilar helix. The doubly peaked response and higher attenuation are the results. The VSWR match obtained in this case is also good and as in the S-band attenuator case the VSWR tends to decrease with increasing frequency. The effect of increasing length from the minimum usable value is shown in Fig. 10. For very short lengths (a few coupling wavelengths) the response is peaked at low frequencies and falls off rapidly at high frequencies. As the attenuator length is increased the response flattens out and high attenuation values per unit length are obtained.

The effect of wire size on the loss of plain coupled helices not embedded in lossy ceramics is shown in Fig. 11. In general the level of attenuation decreases with increasing wire size and also the response peak is shifted to higher frequencies. This change in wire size can be used to offset the effect of a dielectric which tends to shift the response to lower frequencies. The wall thickness of the lossy ceramic also has an effect on the attenuation per unit length. The effects of

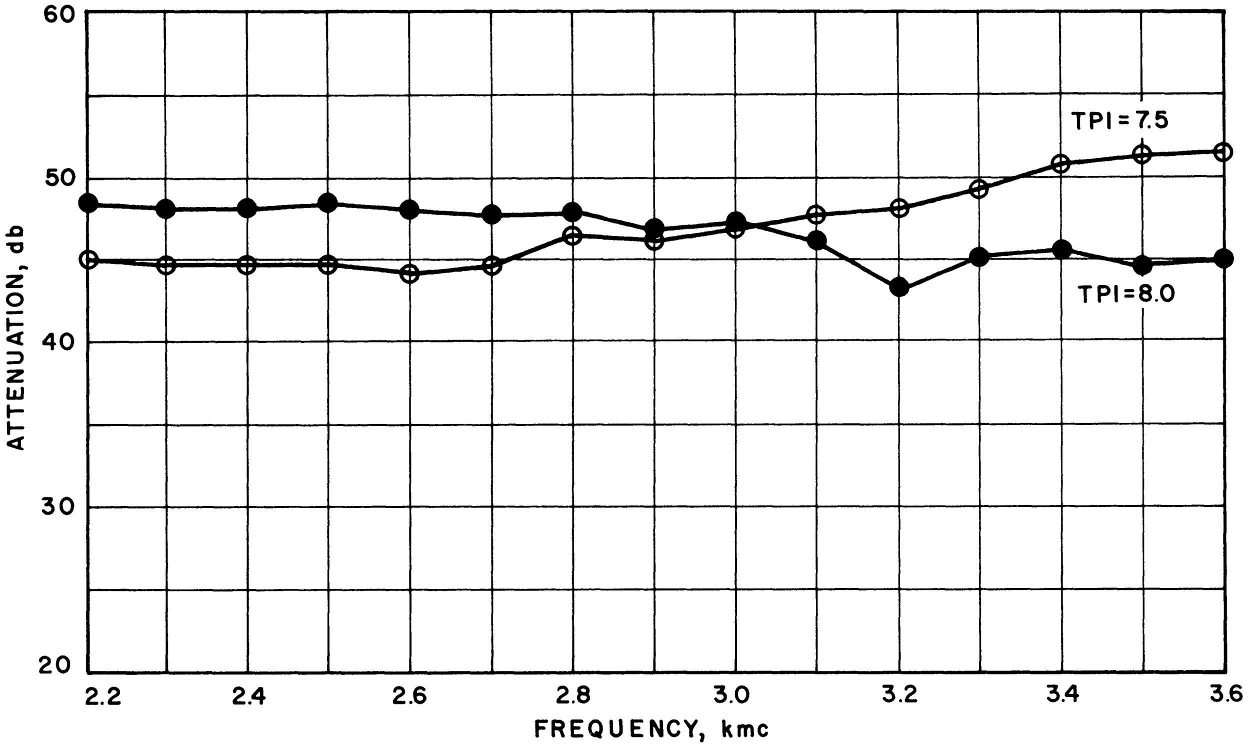


FIG. 6 HIGH-POWER ATTENUATOR LOSS vs. FREQUENCY. (L=2 INCHES, 4-FILAR, WIRE DIAMETER = 0.005 INCH)

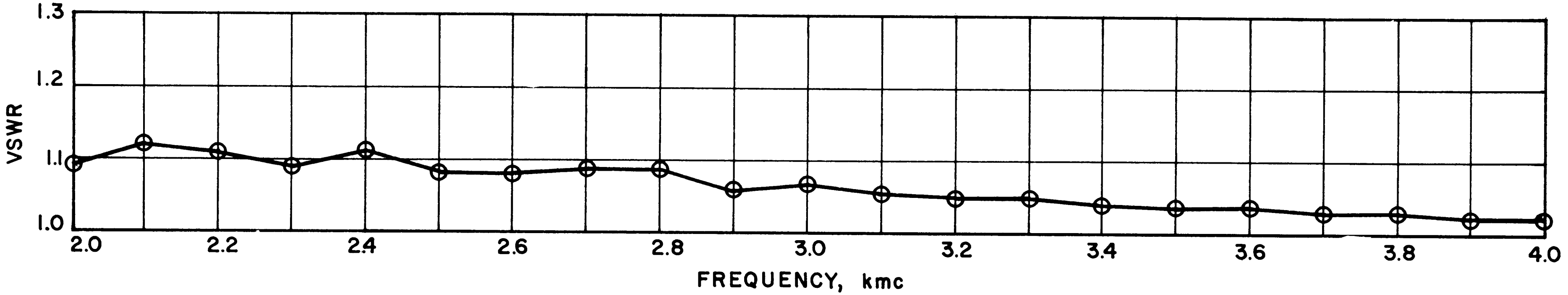


FIG.7 VSWR vs. FREQUENCY FOR 7.5-TPI ATTENUATOR SHOWN IN FIG.6 WITH L=1-7/16 INCHES.

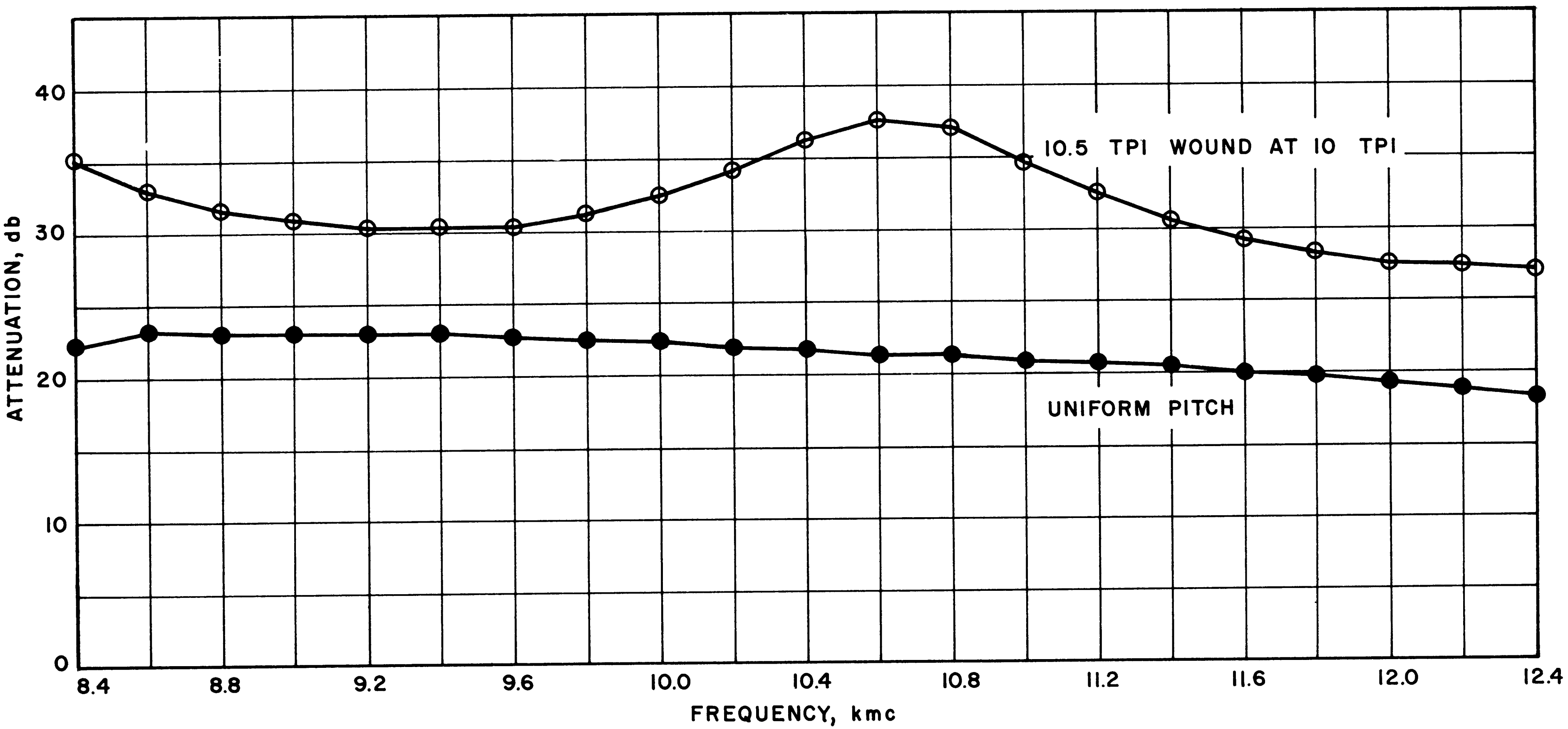


FIG. 8 HIGH-POWER ATTENUATOR LOSS vs. FREQUENCY. (L=1.5 INCHES, 4-FILAR, WIRE DIAMETER = 0.003 INCH)

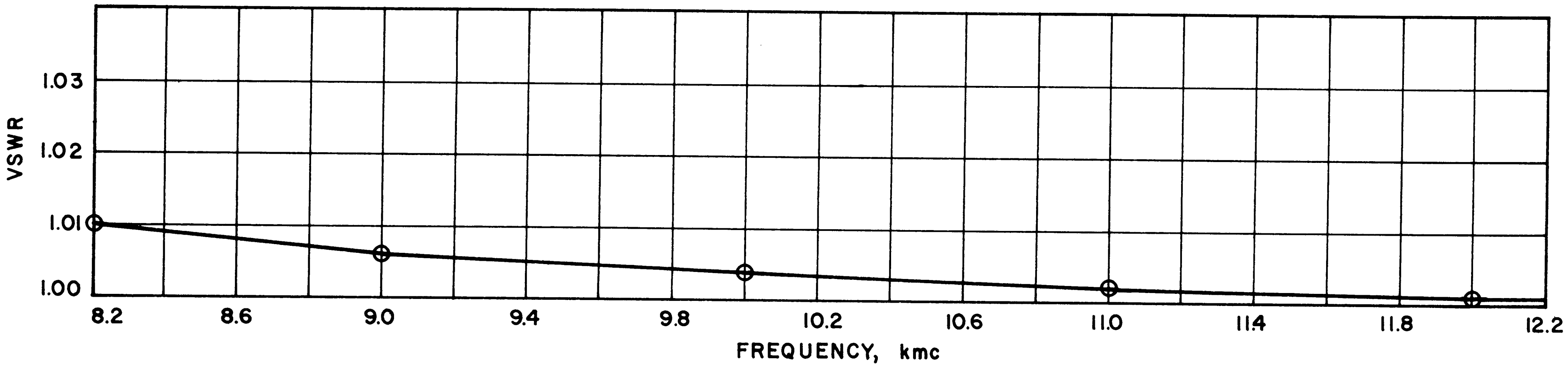


FIG.9 VSWR vs. FREQUENCY FOR UNIFORM-PITCH ATTENUATOR SHOWN IN FIG. 8.

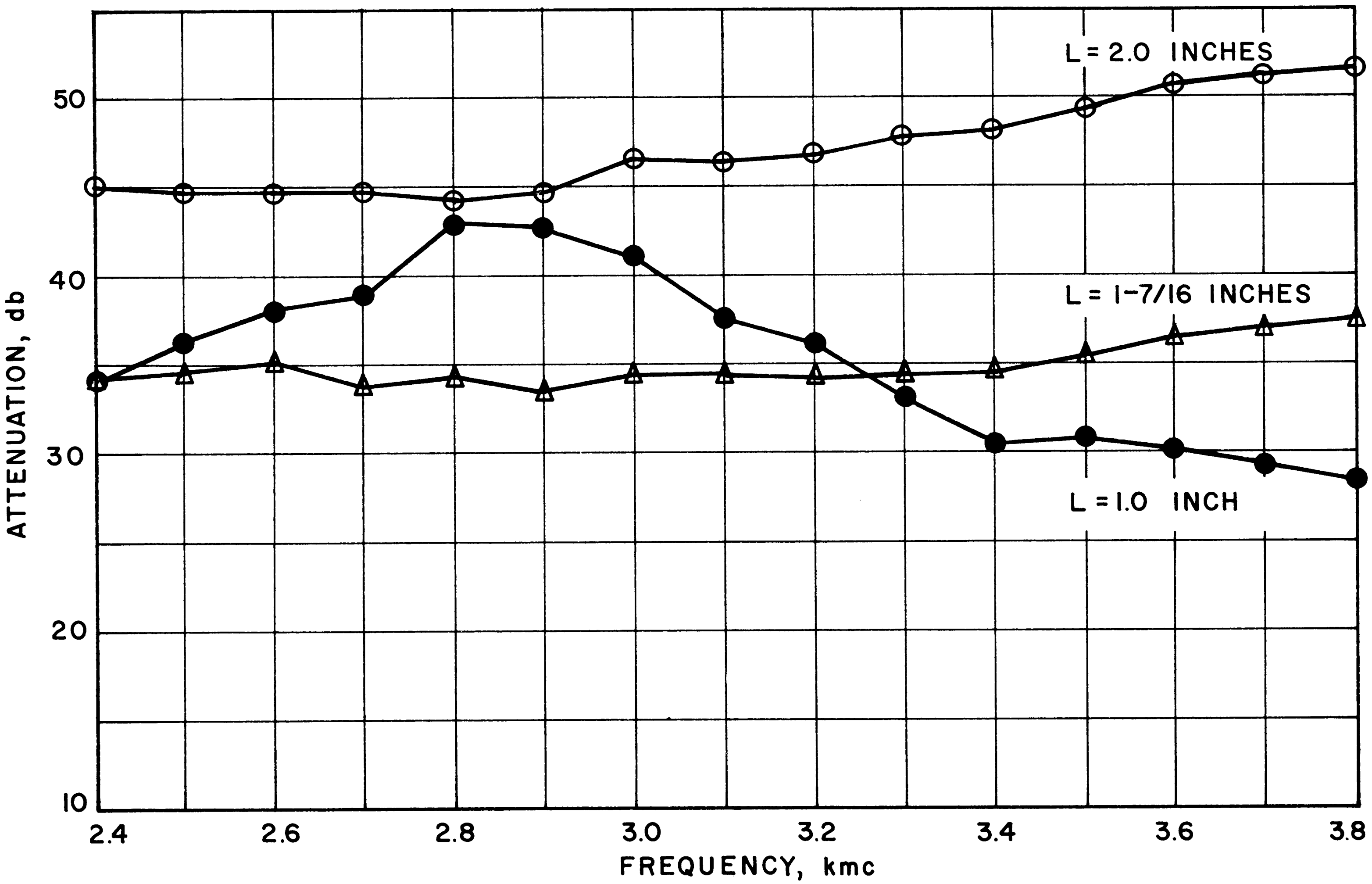


FIG. 10 RESPONSE CURVE AS A FUNCTION OF LENGTH. (TPI=7.5, 4-FILAR, WIRE DIAMETER=0.005 INCH)

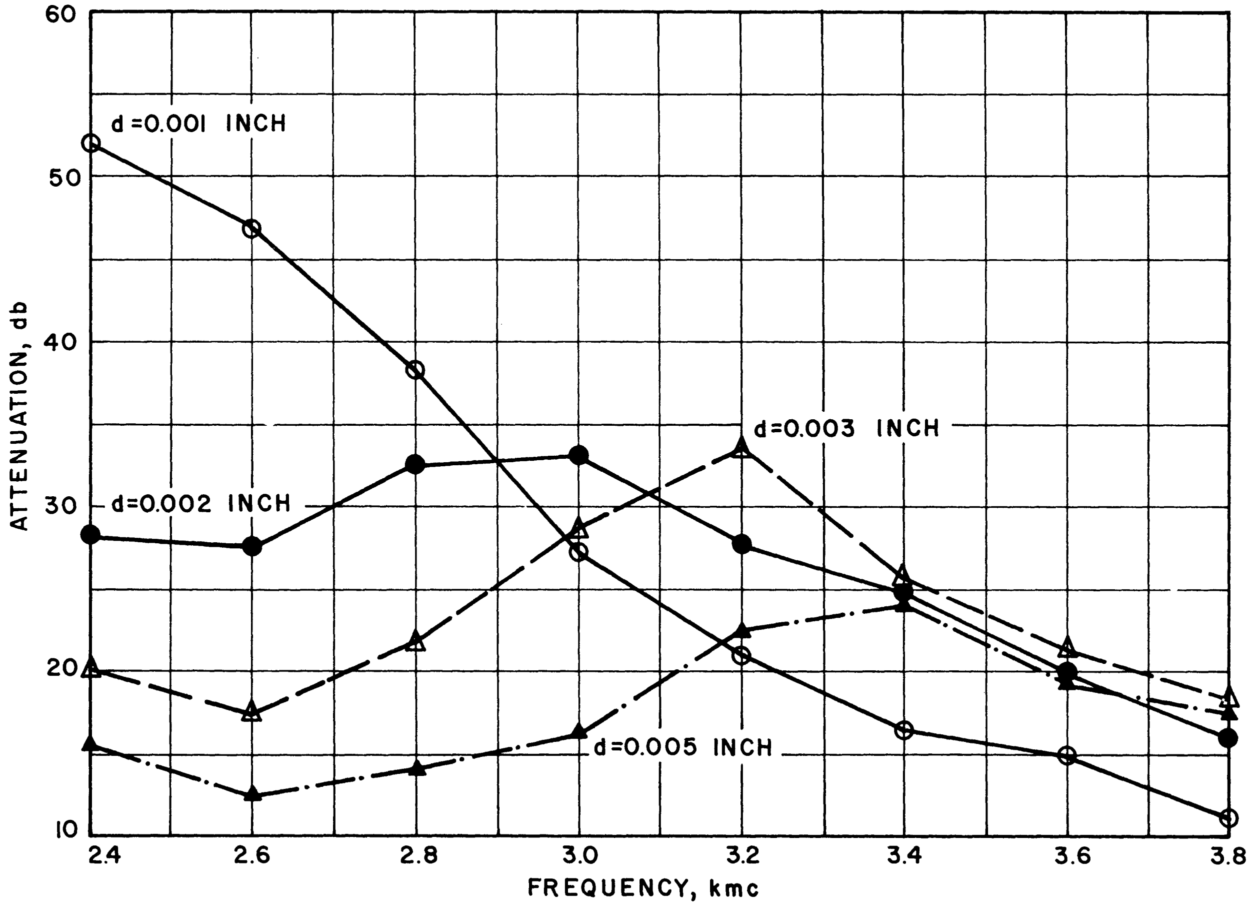


FIG. 11 RESPONSE CURVE AS A FUNCTION OF WIRE DIAMETER. (TPI=4.2, L=2 INCHES, 3-FILAR)

both wire size and shell thickness on loss per unit length are summarized qualitatively in Fig. 12. This effect was anticipated, since it is volume resistivity in the lossy ceramic which is utilized.

R-F POWER HANDLING CAPACITY

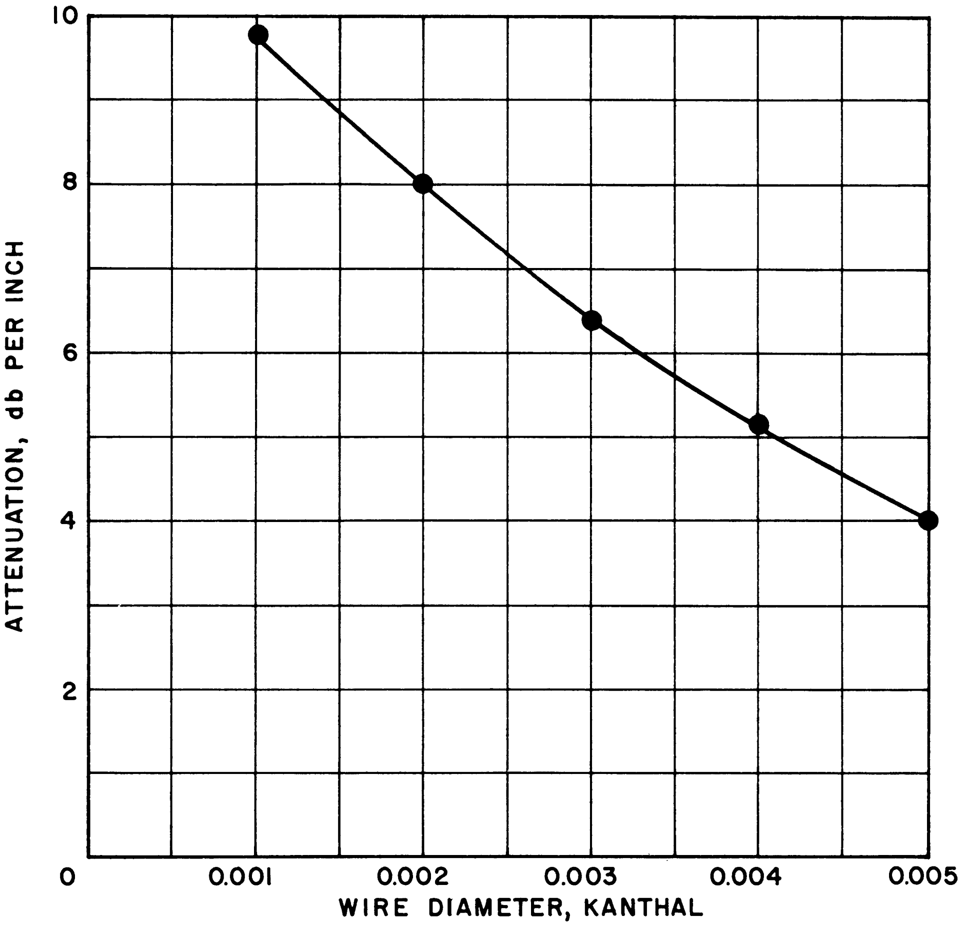
When used external to a glass vacuum envelope of a tube, the maximum power-handling capacity of these attenuators will be determined primarily by the maximum temperature tolerable between the attenuator and the glass envelope. Another significant limitation is of course the temperature at which the lampblack will turn to CO_2, which is approximately 350°C.

A simple metallic sheet wrapped around the attenuator with a cooling coil attached through which water was passed served as an easy means of effective cooling. An inner finned metallic case embedded in the lossy ceramic was also used for cooling. With this arrangement a water-cooled attenuator can safely dissipate 100 watts at a temperature of 100°C. With forced-air cooling alone, 15 watts can be effectively dissipated. Even greater amounts of power can be dissipated by reducing the shell thickness and designing the finned cooling cylinder carefully.

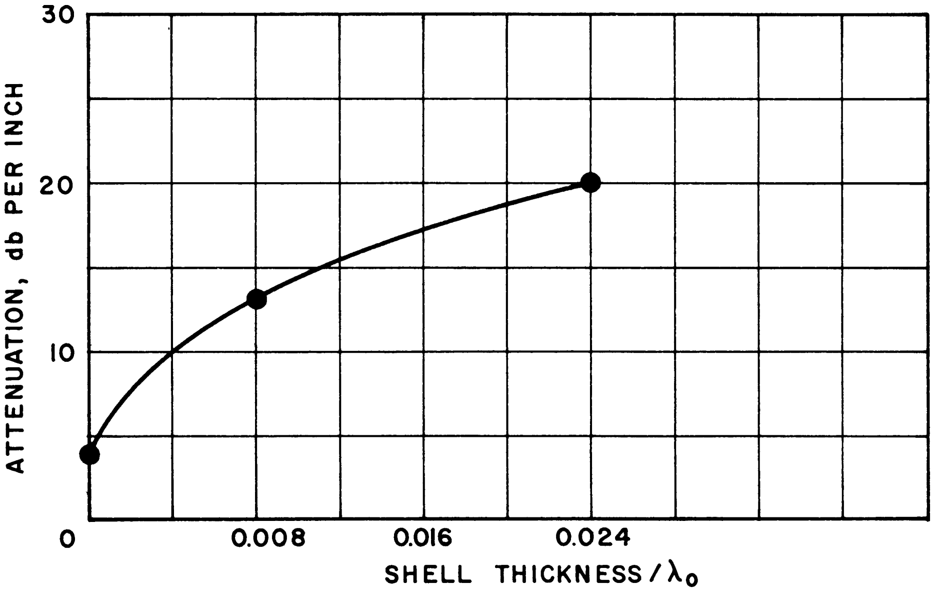
It should be remembered that the attenuators studied have a high loss and hence most of the power is dissipated in a short distance. This can be improved by constructing a short 10-db attenuator to handle this high power and then a separate section to provide the additional attenuation. In the S-band attenuator approximately 90-95 percent of the loss is provided by the lossy ceramic and the rest by the kanthal wire.

The attenuator dimensions are tabulated below.

Length = 1.5 inches



12a. LOSS vs. WIRE DIAMETER



12 b. LOSS vs. CERAMIC SHELL THICKNESS

FIG. 12 ATTENUATION PER INCH vs. WIRE DIAMETER AND CERAMIC SHELL THICKNESS FOR $L \geq 1.25$ INCHES.

Inside dia. = 0.278 inch

Outside water jacket dia. = 0.700 inch

Metal cooling coil = 1.5 inches long

= 0.140 inch thick

Attenuation > 20 db

The temperature of the attenuator as a function of the power level is shown in Fig. 13.

CONCLUSIONS

A new material for making high-power coupled-helix attenuators has been investigated experimentally and an S-band coupled-helix attenuator with high attenuation, broad bandwidth and a power-handling capacity of 100 watts average power has been developed. The material used is a ceramic called hydrostone with lampblack embedded in it to obtain volume loss. The design and construction of these attenuators has been discussed and the influence of all the design parameters on both the level and the shape of the attenuation curve examined. Short-length attenuators for the X-band frequency range are also discussed.

The advantages of the hydrostone-lampblack combination for use in attenuators are many. The final form of the attenuator is one which is strong, light in weight, and capable of dissipating high average powers. Attenuators have been made with up to 45 db per inch of attenuation. Power capabilities up to 100 watts have been achieved and it is predicted that values up to 300 watts cw are achievable with optimum design of both the attenuator and the cooling shell.

ACKNOWLEDGMENTS

The author acknowledges the contributions and guidance of Professor J. E. Rowe during the course of this work.

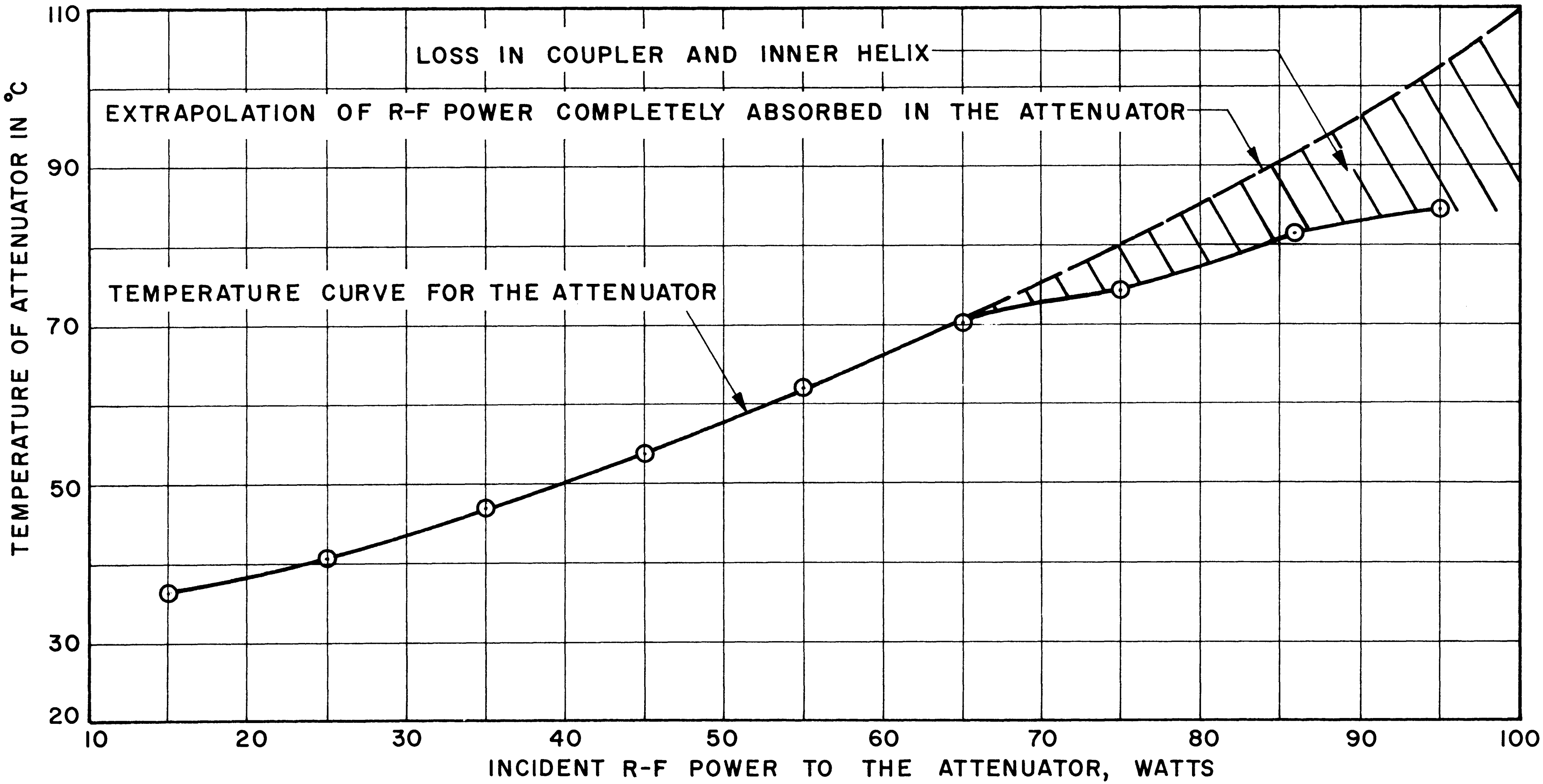


FIG. 13 POWER-HANDLING CAPACITY OF S-BAND ATTENUATOR WITH 1 LITER/MINUTE OF H_2O COOLING.

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University of Michigan, Electron Physics Laboratory, Ann Arbor, Michigan. HIGH-POWER COUPLED-HELIX ATTENUATORS, by H. W. Krage. March, 1960, 24 pp. incl. illus. (Proj. No. 5573, Task No. 55253) Unclassified Report.

A high-power high-attenuation coupled-helix attenuator has been developed using a multifilar coupled helix embedded in a lossy ceramic. The lossy material is made from a mixture of hydrostone and lampblack in which the multifilar coupled helix is embedded. Attenuation values near 20 db/inch have been obtained at S-band with an average power-handling capacity of 100 watts. The attenuator is light and rugged and has an excellent VSWR characteristic.

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2. Effect of Magnetic Fields
3. Fabrication of a High-Power Coupled-Helix Attenuator
4. Experimental Results
5. R-f Power-Handling Capacity

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