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Echo Box Design Handbook

Theory and Practice of Echo Box Design
Survey of Existing Cavities

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PREPARED FOR

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PREFACE

This is the final report on a study and survey of microwave echo boxes, performed under a subcontract with the Johnson Service Company of Milwaukee, Wisconsin. The work was sponsored by the Bureau of Ships, U. S. Navy, under Contract No. NObsr-57108. The following items of work were called for in the subcontract:

a. Determine the needs of the Navy concerning microwave echo box test equipment . . .

b. Prepare a bibliography and set of abstracts covering the field of echo box development and application...

c. Prepare a design handbook for echo boxes . . .

d. Furnish a tabulation of data on each existing echo box design . . .

e. Prepare a new echo box design...

A survey performed under (a) above disclosed a need for an echo box in the frequency range 3400 - 3700 mcs with longer ringing time than now available. Therefore, a new box meeting these requirements was designed and a prototype built and tested as required under (e) above.

The survey also disclosed that echo boxes are not being used efficiently by most of the radar maintenance personnel interviewed. In a majority of cases this inefficiency was apparently due to inadequate information as to the inherent capabilities and limitations of the echo box as a radar test instrument, and how it compares with other types of test equipment. A discussion of these factors has therefore been included in Chapter II of this report.

The "Design Handbook" makes up the remainder of the report, with the exception of Appendices IV and V, which contain the abstracts and echo box data called for under (b) and (d) of the Work Statement. The bibliography and abstracts sections consist of more than 300 abstracts of patents, books, articles, laboratory reports, and technical manuals dealing with echo box or resonant cavity theory and practice. Data on 69 existing echo boxes have been tabulated.

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ECHO BOX DESIGN HANDBOOK

CHAPTER I

INTRODUCTION AND SUMMARY

The term "echo box" has, by common usage, come to mean a radio-frequency resonant cavity designed specifically to test the over-all performance of a pulsed radar. A cavity so designated is differentiated from other cavities designed primarily to serve as frequency meters, as stabilizers for microwave oscillators, or for other purposes. The particular feature of the echo box which sets it apart from other resonant cavities is the possession of an exceptionally high quality factor, or "Q", analogous to the Q of ordinary tuned resonant circuits. This feature permits electromagnetic energy within the cavity to dissipate very slowly, over a period of time sufficiently long for the stored energy to be used as a signal source of known characteristics with which to measure radar performance. An earlier, and perhaps more descriptive, name applied to the device was "phantom target".

It is believed that the idea for using a cavity in this fashion originated at the MIT Radiation Laboratory fairly early in World War II. The early echo boxes were designed and built hurriedly and to a considerable extent empirically. The results were not particularly satisfactory, and it was then realized that more careful design and construction were necessary. Once this fact was established, the development of more adequate designs proceeded rapidly. Members of both the Radiation Laboratory and the Bell Telephone Laboratories contributed extensively to the theoretical work, and the boxes were built by a number of concerns, notably the Johnson Service Company and the Western Electric Company.

At the present time the design and manufacture of echo boxes involves the use of specialized techniques and processes which have resulted from theoretical and experimental investigation, as well as from the experience obtained in the production of successful (and unsuccessful) past designs. The echo box has evolved into a rugged, simple, relatively light, and highly reliable piece of test equipment, capable of considerable precision when used properly. Unfortunately, it appears to have suffered some neglect and misunderstanding on the part of its users due to the very fact that it is such a simple device. There appears to be a fairly wide-spread feeling among radar maintenance men that, because of its simplicity, the echo box is not capable of furnishing other than relative, qualitative measurements. Therefore, a discussion of the application of the echo box to radar testing has been included in Chapter II. This chapter describes the various tests which can be made with an echo box, their relative accuracy, and the proper ways of performing them. In addition, a comparison is made between the echo box and other types of radar test equipment which can perform similar or duplicate functions. The factors which determine the specific type of echo box required for a particular application, are also discussed, because it has been found in the field that maintenance personnel are sometimes handicapped by having an echo box that will not perform sufficiently well to be useful with a particular radar, or in a particular geographical location.

The remainder of this paper is concerned with the theory, design, manufacture, and testing of echo boxes. Chapter III begins with a discussion of resonant cavities in general, introduces the concept of the mode chart, explains the construction and use of such a chart, and discusses the theory of cavity coupling and the suppression of extraneous modes. Charts and diagrams for various cavity modes are given, and a table of roots of Bessel functions is provided. In addition, three large mode charts are included which incorporate most of the commonly used modes. The factors which influence ringing in an echo box, as well as techniques for providing uniformity of ringing, are discussed. Design of cylindrical, coaxial, and partial coaxial cavities is also discussed, and an example of each type of cavity is given.

Chapter IV is concerned with the manufacture of echo boxes, and Chapter V with design and acceptance tests and testing methods. Chapter VI deals with unusual types of echo boxes or similar devices.

Throughout the paper an attempt has been made to avoid lengthy mathematical or theoretical discussion. Where it was felt that such discussion should be included, it has been relegated to the appendices. No development of the cavity field equations is included, the reader being referred to References 7 and 27 for standard treatments of this subject. The appendices on cavity perturbations and equivalent circuits should not be regarded as extensive discussions of the subjects, but rather as sketches or outlines showing the progress of investigation along these lines, and as indications of the possible usefulness of these concepts.

The handbook attempts to treat echo box design and construction as the state of the art presently stands, and speculations as to future lines of development or investigation are avoided. It is hoped that by doing so, a more practical handbook has resulted.

Material has been borrowed freely from many references in the field, notably the excellent articles (Ref. 6) on resonant cavity design by Messrs. Kinzer, Schramm, and Wilson of the Bell Telephone Laboratories; the Bell Telephone Laboratories have kindly given permission to reproduce their outstanding series of plates depicting cavity fields and wall currents, as well as numerous other figures from Bell Telephone Laboratory reports. Mr. John Martin of the Johnson Service Company supplied considerable information regarding manufacture and testing of echo boxes. To these sources, and to all others who have given permission to use material, thanks are expressed.

In addition to the authors, the following personnel at the Willow Run Research Center have contributed to the technical work required in the preparation of this handbook: J. Wolf, J. Constant, W. Orthwein, H. Weil, L. Roellig, and D. M. Brown.

CHAPTER II

THE ECHO BOX AS A TEST INSTRUMENT

IIA METHODS OF TESTING WITH ECHO BOXES

IIA.1 Radar Performance Measurements

Fundamentally a radar is a rather simple device; radar systems, however, have become increasingly complex in recent years. The growing tendency has been to place more and more dependence on the information provided by radar means. Radar units have become more or less integral parts of complex networks for the gathering and handling of information. The evolution of radar has produced three major maintenance problems: the technical difficulty of maintenance has increased; it is more difficult to schedule sufficient "down-time" for maintenance; it is more important than ever to keep radars in peak operating condition.

In view of these problems, it is essential for maintenance personnel to be especially skillful in the use of those techniques which will enable them to achieve the desired results with a minimum of time and effort, and with an accuracy consistent with the uses for which the radar was intended.

The maintenance of a radar from the point of view of maximizing its performance as a detection device involves determining the sensitivity of the radar receiving system; ascertaining the condition of the transmitting system; localizing defective components; and restoring the equipment to optimum performance if it is found to be defective.

IIA.2 Testing With Echo Boxes

Under the proper conditions, most of the above tasks may be performed with the resonant cavity known as an echo box. This does not mean that the echo box is necessarily the best means for these measurements. The most effective tool must be determined by other considerations including desired accuracy of results, type of radar, and availability of equipment and time. A comparison of echo box techniques with other methods of making radar performance checks is given in Section IIC.

For accurate and reliable measurements to be made with an echo box, the following requirements must be met (Ref. 1):

1. A reliable, well designed, tunable echo box must be provided. This box must have sufficient ringing time, and must be equipped with: an adequate tuning indicator; an accurate, easily readable tuning dial; and a frequency calibration curve (if available). The electrical properties of the box must be known or predictable over the entire tuning range.

2. Simple and reliable means for coupling the echo box to the radar must be provided. The degree of coupling must be known quantitatively.

3. Means must be provided for observing and accurately measuring the echo box ringing time.

4. Means must be provided for predicting the proper ringing time of the echo box for the radar being tested.

In the hands of a technician familiar with the factors affecting the ringing time, these essentials permit the echo box to be used to its maximum accuracy and reliability and the results to be interpreted. It is still possible to use the echo box even if the box itself is not of the best design, if the coupling means to the radar is not known quantitatively, or if a means for predicting ringing time is not available, although results obtained under these circumstances will be of lesser value.

IIA.3 Echo Box Ringing Time

The ringing time is a measure of the over-all radar performance. The ringing time depends on the performance of both the transmitting and receiving systems, and significant defects of either system will, in most cases, be revealed by a decrease in ringing time.

An echo box is essentially a tuned resonant cavity which, for the purposes immediately at hand, may be represented as a simple tuned resonant electrical circuit containing resistance, inductance, and capacitance in series. When in use, this cavity is coupled loosely to the radar so that, during the transmitter pulse, a small portion of the transmitted energy passes through the coupling device and into the resonant cavity. The arrangement is shown schematically in Figure IIA-1. As indicated in

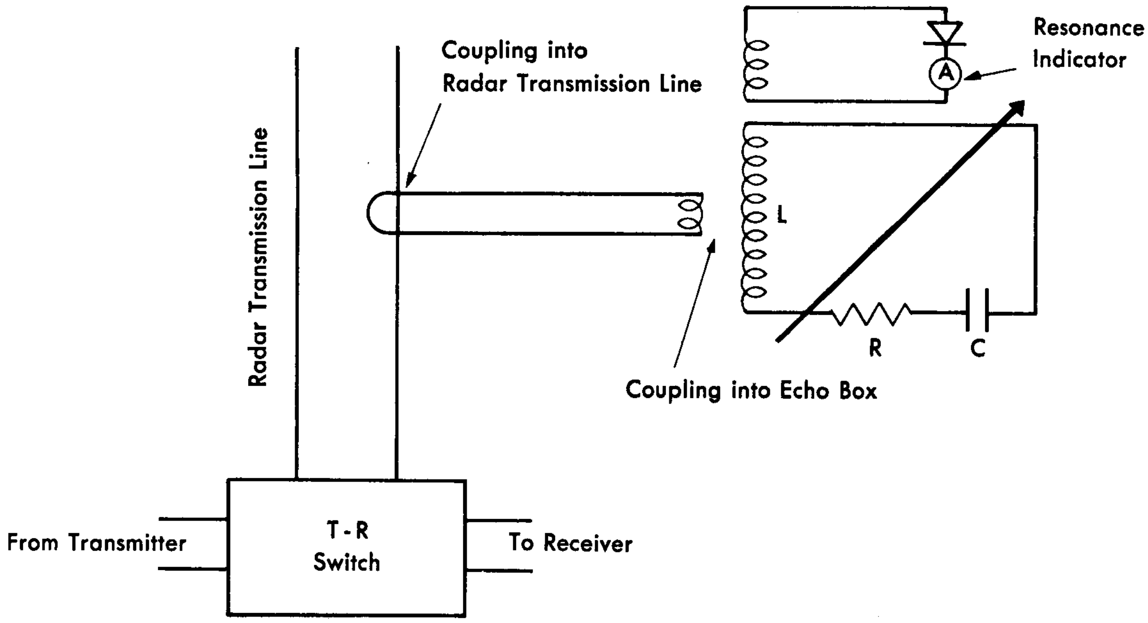


FIG. II A-1 SCHEMATIC REPRESENTATION OF ECHO BOX COUPLED TO RADAR

this figure, there are actually two coupling devices to consider: one from the radar into the line leading to the echo box, and one into the box itself. An indicator is provided to show when the echo box is tuned to the transmitter frequency. Commonly, a small portion of the energy is coupled out of the resonant cavity, rectified by means of a crystal diode, and the resulting direct current indicated on a meter.

An electrical, mechanical, or acoustical resonant circuit possesses the property that, when momentarily disturbed, it may continue to vibrate or oscillate for a period of time after the initial disturbance has ceased. The duration of such an oscillation depends upon the rate at which energy is extracted from the system, regardless of whether the energy is lost as heat, or is deliberately removed for some useful purpose. The usefulness of the echo box as a radar test instrument is directly dependent on this ability to "ring" or oscillate for an extended period following initial excitation. When the transmitter is turned on, the echo box cavity, initially unenergized, receives energy via the coupling device. If the resonant frequency to which the box is tuned corresponds to that which the radar transmitter is generating, electromagnetic oscillations of increasing intensity will be induced in the cavity.

If the transmitter were to be left turned on for an extended period, the oscillations within the cavity would eventually reach a steady amplitude; however, most radar transmitters are pulsed for too short a time for this to happen. Therefore, the amplitude of the oscillations in the cavity is still increasing at the time the transmitter is turned off.

After the transmitter has been turned off, the oscillations in the cavity gradually die away. Most of the stored energy is lost as heat in the resistor R (Fig. IIA-1), which represents the internal losses in the metal walls of the cavity and in the resonance-indicating circuit. Some of the energy, however, will leave the cavity by way of the path along which it entered -- namely, the coupling devices and transmission line leading to the radar. It is this part of the energy which provides a radar performance test, for, as it passes down the radar transmission line and into the receiver, it will be seen on the radar indicator or auxiliary indicator as a signal or "echo" lasting until the strength of the oscillations has diminished to the point at which they are no longer discernible in the "grass" or noise generated in the radar receiver.

Immediately after the transmitter has been turned off, the strength of the signal returned from the echo box is great, in general many times greater than the maximum signal the radar receiver and indicator are designed to handle. Therefore, the indicator will display a maximum or saturating signal which will extend out to that range at which the returned energy is no longer sufficient to saturate the receiving or indicating circuits. Beyond this range, the signal will drop quickly into the noise background. The general appearance of this phenomenon on an A-scope is shown in Figure IIA-2. It should be noted that the ringing time is measured from the beginning of the radar pulse to the range at which the "top" of the noise is no longer above the general level of the rest of the noise. It is not possible to judge ringing time by the range to the end of the saturated portion of the ringing time, nor by the bottom of the noise because

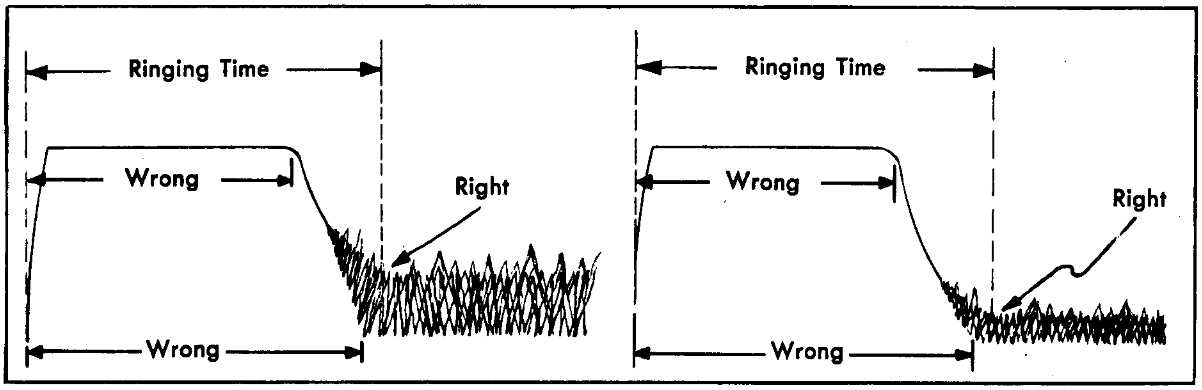


FIG. II A-2 MEASUREMENT OF RINGING TIME ON AN "A" SCOPE

these ranges are affected by receiver gain settings and other factors which tend to make the measurements inaccurate.

The A-scope presentation is the most satisfactory for determining ringing time accurately. If, however, an A-scope is unavailable, other types of scopes may be used. Figure IIA-3 shows ringing time on a PPI, both with the antenna motionless and with the antenna rotating.

The more powerful the radar transmitter, the more energy will be stored in the echo box cavity during the transmitted pulse, and the greater the time after the pulse before the energy dies down to the level at which it can no longer be seen on the indicator. In addition, the ringing time will be longer with a sensitive receiver.

IIA.4 Factors Affecting Ringing Time and the Prediction of Ringing Time

The relation among the several factors affecting ringing time of an echo box is shown in Figure IIA-4. The energy level which exists in the radar transmission line during the transmitted pulse is represented by the horizontal line at the top of the figure. A small amount of this energy is removed from the radar system -- preferably by a directional coupler; otherwise, with a test dipole or horn located in the beam of the antenna --

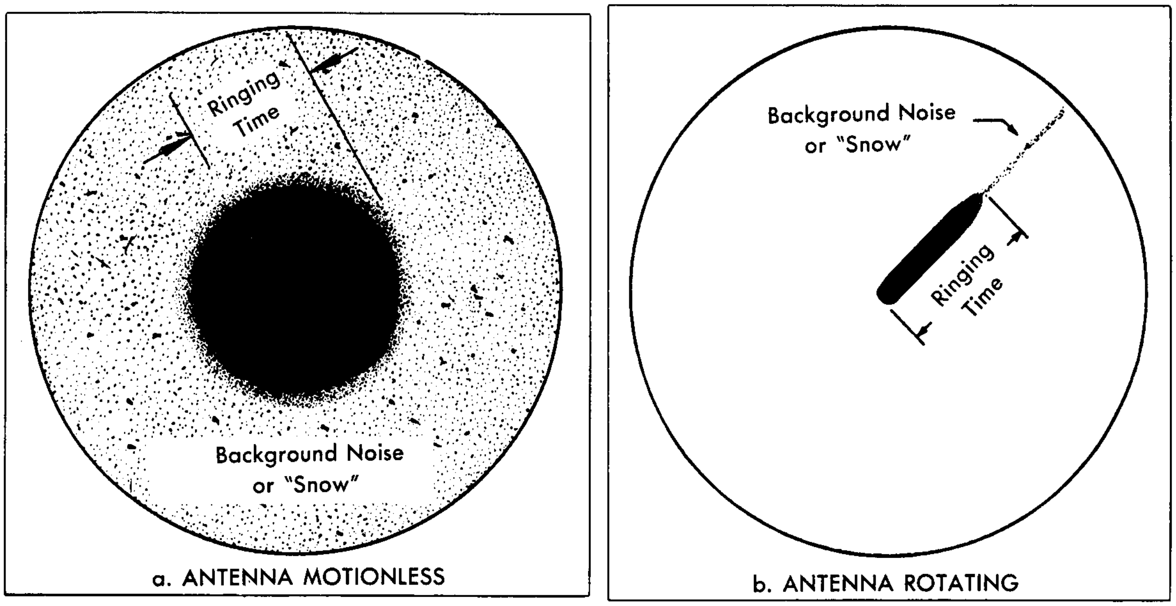


FIG. II A-3 MEASUREMENT OF RINGING TIME ON A PPI SCOPE

and fed into an auxiliary transmission line leading to the echo box. The decrease in energy level associated with this sampling process is indicated by the vertical line marked "Coupling Loss W_1". This loss is generally of the order of 20 to 35 decibels.

There will be a certain amount of energy loss in the radio frequency (RF) transmission line leading from the coupling device to the echo box. This loss is represented in the diagram by the vertical line marked "Line Loss W_2". Because this transmission line is generally made up of a length of flexible coaxial cable such as RG-8/U, it is not desirable to use too long a run, for the attenuation of such a cable is a function of temperature and of the age and general condition of the dielectric. In addition,

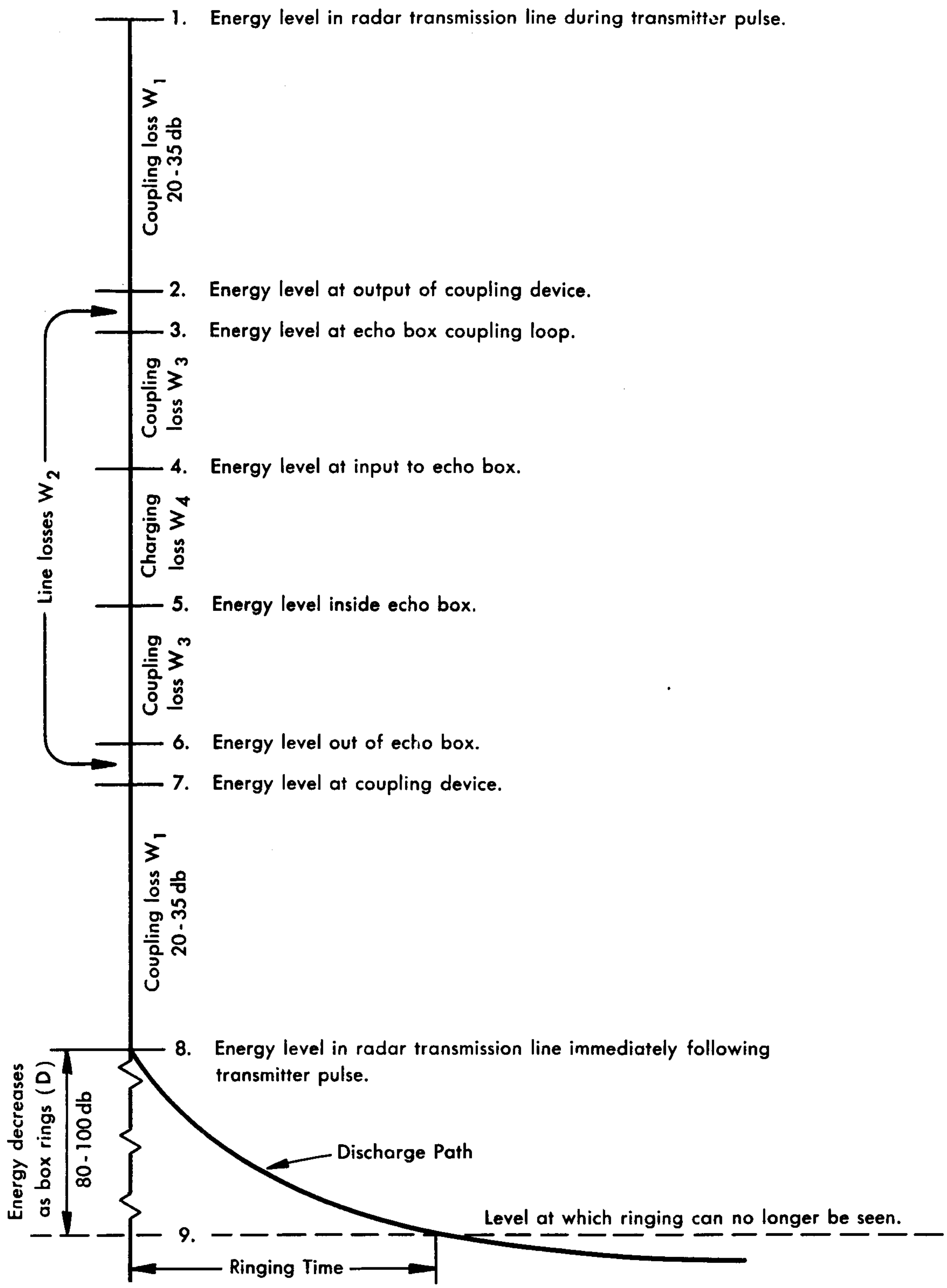


FIG. II A-4 ENERGY LEVELS IN A RADAR-ECHO BOX SYSTEM the attenuation increases rapidly with frequency so that, at the higher radar frequencies, the attenuation of a long cable will be excessive and variable in an unpredictable manner. The attenuation of some commonly used cables is given in Figure IIA-5. On the other hand, a certain amount of attenuation between the coupling device and the echo box is a necessity, due to the mismatch of the impedances at the output of the transmission line from the resonant cavity (see below). This minimum attenuation should be of the order of 3 db. The level of energy in the input coupling device at the echo box is represented by Level 3 in the figure.

For reasons which are discussed in more detail in Section IIID, the impedance match into the echo box itself is necessarily quite poor; a qualitative explanation can be given here. If the transmission line impedance were to be matched at the device coupling energy into the echo box, energy transmission into the box would be at a maximum, and this condition would provide the greatest possible amount of energy storage in the box for a given amount of energy received from the radar pulse. On the other hand, this condition would lead to the most rapid transfer of energy out of the cavity after the end of the transmitted pulse; the stored energy would be dissipated very quickly by coupling back into the radar system; and the ringing time would be very short. This is, of course, undesirable. Conversely, it is obvious that, if the coupling is too loose, little ringing time is obtained because insufficient energy is being transferred into the cavity. The optimum value of coupling at the echo box coupling device will lie somewhere between these two extremes, and an impedance mismatch is presented. In the practical design of echo box cavities, this value is obtained experimentally by varying the coupling until the greatest ringing time is obtained when the box is used with the radar system for which it is designed. This loss, W_3, resulting from the optimum value of mismatch, is usually from 10 to 15 decibels.

It was stated above that the energy in the resonant cavity does not reach a steady level during the transmitted pulse, because the pulse is too short. The energy levels within the cavity are represented in Figure IIA-6. The solid lines represent the actual energy within the cavity, while the broken line represents the manner in which the energy would continue to increase if the radar transmitter were left turned on for a very long time. The difference between the energy in the cavity at the end of the pulse and the energy level that would eventually have been

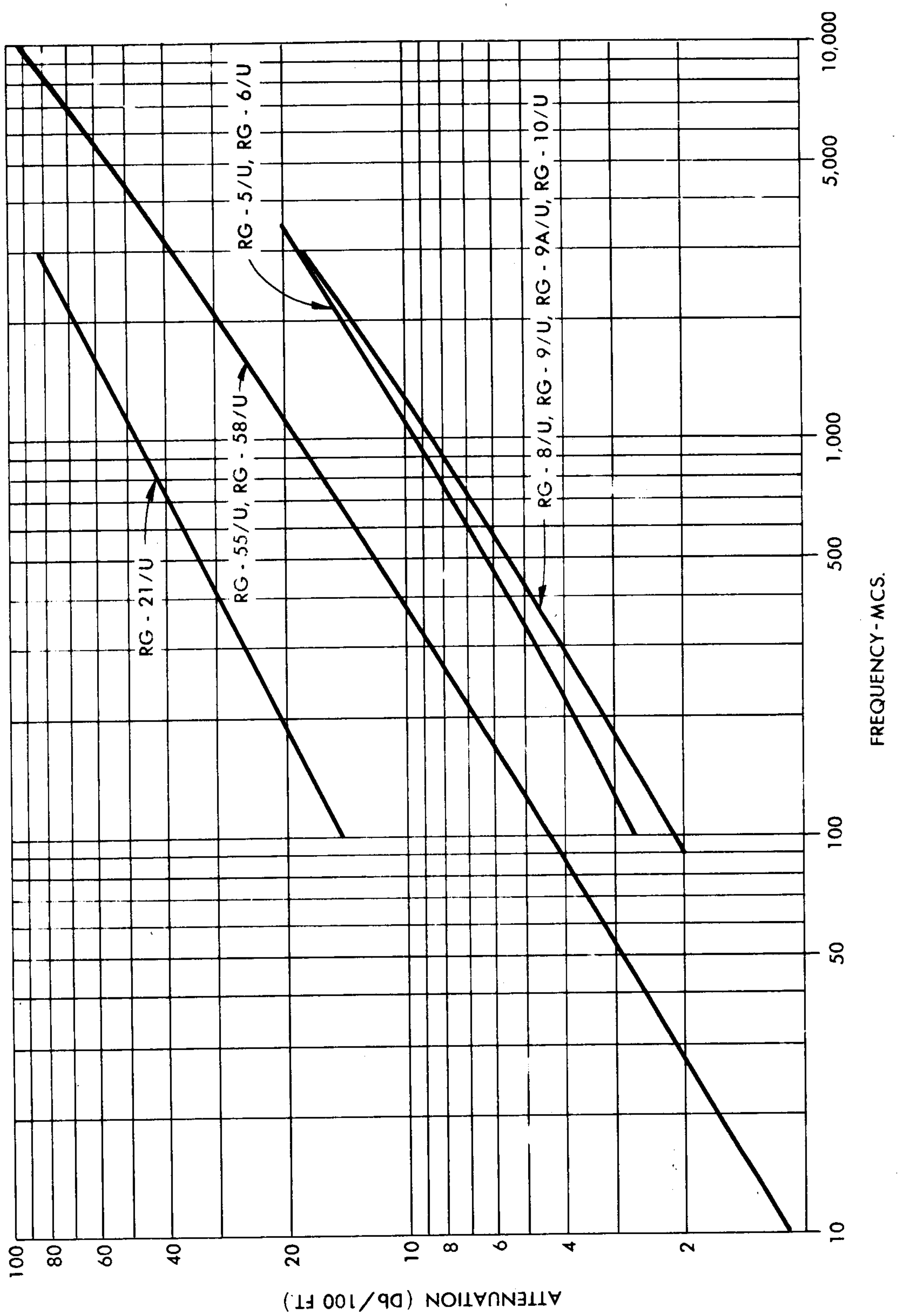


FIG. II A-5 ATTENUATION OF SOME COMMONLY USED RF CABLES

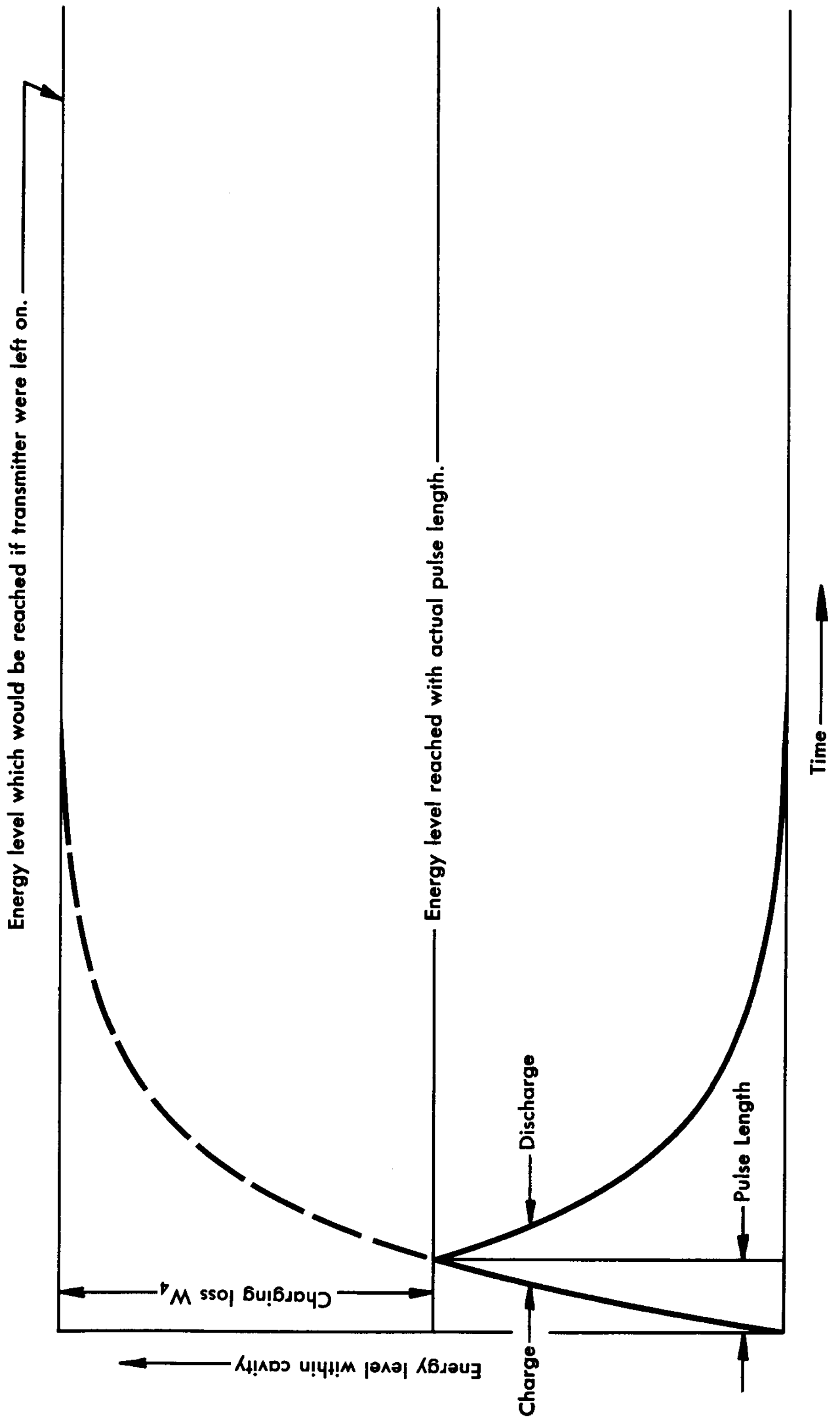


FIG. II A-6 REPRESENTATION OF ENERGY LEVELS WITHIN AN ECHO BOX reached is labeled "Charging Loss W_4". This charging loss is a function not only of the radar pulse length, but also of the quality factor (in this case, the "loaded Q", or Q_L) of the cavity (Sec. IIIA). The charging loss W_4 can be found to within a good approximation from the equation:

$$\text{Charging loss in db} = 20 \log_{10} \left(1 - \exp \frac{-\omega t_1}{2Q_L} \right)$$

where $\omega = 2\pi \times$ the frequency of resonance in megacycles per second, t_1 is the pulse length in microseconds, and Q_L is the quality factor. Charging loss is plotted against the exponential term $\frac{\omega t_1}{2Q_L}$ in Figure IIID-1.

After these losses have been subtracted, the energy level that exists within the echo box at the termination of the transmitted pulse, is obtained (Level 5 on Fig. IIA-4). Since the transmitter is now turned off, energy will be fed out of the resonant cavity and back into the radar system. In its return path, it encounters the losses enumerated previously: coupling loss W_3, line loss W_2, and coupling loss W_1; just after the termination of the transmitted pulse, the energy existing within the radar transmission line as a result of the storage of energy within the echo cavity can thus be represented by Level 8 in Figure IIA-4.

As the energy within the cavity is dissipated, its level at the radar transmission line will decrease along an exponential curve such as that labeled "Discharge Path" in Figure IIA-4. At some later time the signal will no longer be visible in the receiver noise. This time is the ringing time of the echo box, and is so labeled in Figure IIA-4. It should be noted that the ringing time in the figure is measured from the termination of the transmitted pulse; however, in practice, this is not usually done. Instead, the ringing time, like radar ranges, is measured from the beginning of the transmitted pulse, which means that the duration of the transmitted pulse must be added to the ringing time shown in Figure IIA-4.

When all the above factors are known, it is possible to obtain a figure which represents the "expected ringing time" -- that is, the ringing time which is expected when the echo box is being used with the particular radar for which these factors are determined, and under the assumption that the radar is in good condition. In some cases, an equation for predicting the ringing time is given in the instruction manual for the particular box. This equation will contain some of the quantities affecting the ringing time in the form of an empirical constant. When furnished, this equation should be used in preference to other methods of predicting ringing time, since it will produce more accurate results. The authors believe that all specifications for echo boxes should contain a requirement that this equation be determined and included in the instruction manual because, without it, the user of the box finds himself unable to make quantitative measurements of radar performance. In case this equation is not known, it may be possible to measure the radar performance accurately by other means, and then make a measurement of ringing time.

If neither of the above alternatives is possible, estimates of the various quantities contained in the ringing time equation can be made (Sec. IIID).

IIA.5 Interpretation of Ringing Time

A loss in radar performance is commonly measured in terms of decibels below a standard or optimum figure. Such a standard figure can be obtained by determining the peak power output which the transmitter should have, and subtracting from it the power of the minimum signal which the receiver should be able to present as a visible target. Both powers are expressed in decibels relative to an arbitrary reference level such as one watt or one milliwatt.

For example, if a radar has a peak output power of 200 kilowatts, this output can be represented as +53 dbw (plus 53 decibels relative to one watt). With a good radar receiving system, it is usually possible to observe a signal whose power is somewhat (approximately 5 db) below the noise level of the receiver. The noise level of a good receiver is greater than the "theoretical noise" level by 10 to 17 decibels. The difference between actual and theoretical noise levels is the "noise figure" of the receiver. The theoretical noise level is the thermal noise that would be generated in an ideal receiving system having the same bandwidth as the actual one; the noise figure, 10 to 17 decibels, represents the discrepancy between the ideal receiver and a fairly good microwave receiving system. The theoretical noise level is approximately -144 dbw for an ideal receiver with a one-mcs bandwidth. Since noise power is proportional to the receiver bandwidth, an ideal receiver of two-mcs bandwidth would generate, internally, a noise power of -141 dbw. A practical receiver of one-mcs bandwidth would be able to perceive a signal of the order of -144 +10 -5 or -139 dbw. If this receiver were used with the 200 kw transmitter mentioned previously, the radar performance would be +53 -(-139) or 192 db. (Since the final number of 192 represents the ratio of the peak output power to the minimum received signal, it is proper to express this number simply in terms of decibels rather than decibels relative to a certain reference level).

In making radar performance tests with an echo box, the operator does not ordinarily compute the radar performance to be expected, measure the ringing time, deduce the actual performance from the ringing time, and then compare the actual performance with the expected performance. Instead, as a simplification, he computes the ringing time to be expected if the performance of the radar is good, compares the expected ringing time with the measured ringing time, and interprets the difference in ringing times in terms of decibels loss of performance.

A loss of a certain number of decibels in the performance of a radar signifies that the ability of a radar to "see" targets (that is, the probability of detection) has diminished. Unfortunately, the loss in range may be entirely out of proportion to the number of decibels lost. A radar cannot perceive all types of targets equally well. The effect of a loss of radar performance on the range at which a "hard-to-see" target is detected is drastic indeed.

The effect of loss in radar performance on detection range is shown in Figure IIA-7 for three types of targets: large ships, small objects over water, and aircraft. A loss of only 12 db reduces the maximum range at which aircraft can be detected to one-half its normal value, while the loss of an additional 12 db reduces the range by another 25 per cent. In order to detect small targets (such as aircraft, small boats, periscopes and schnorkels) at maximum range, it is of the utmost importance to maintain the radar at peak performance. The first few decibels of lost performance

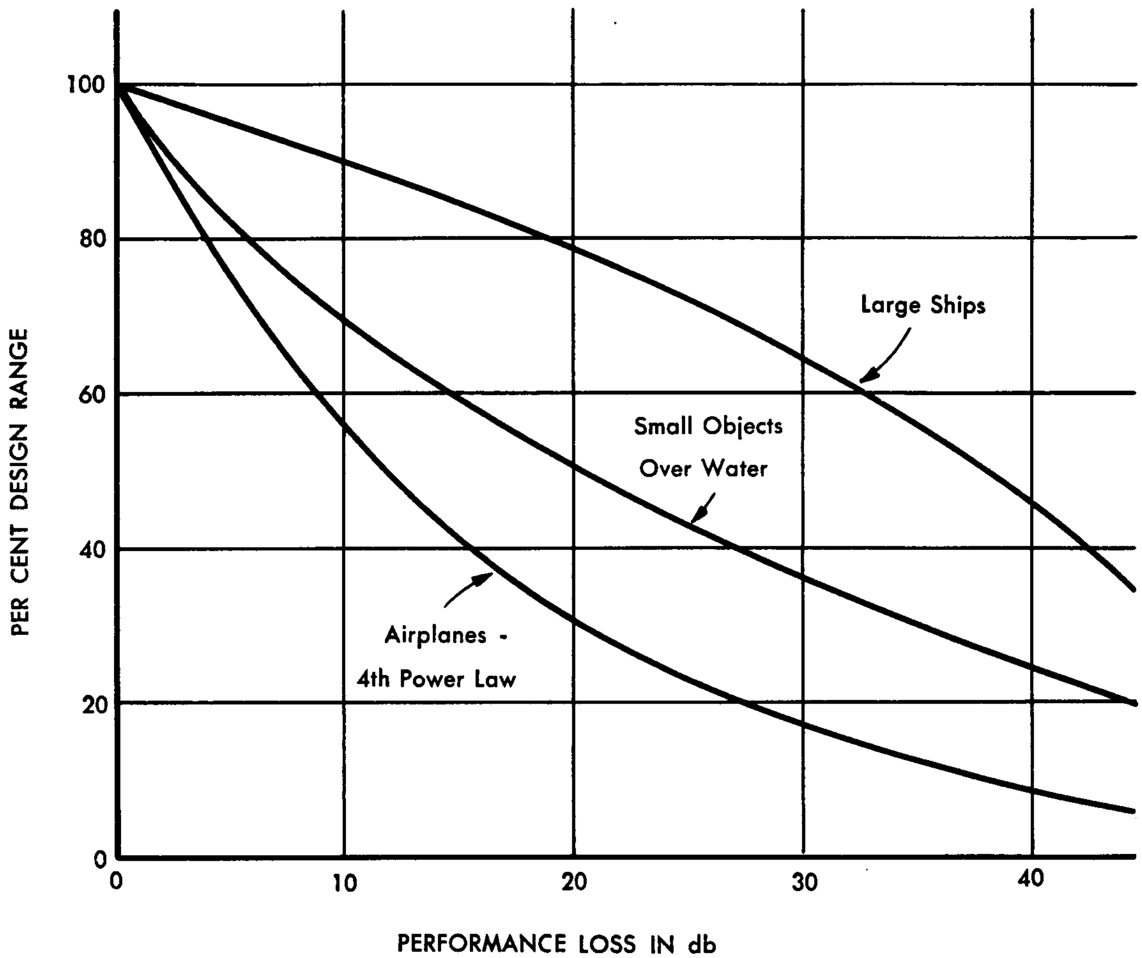


FIG. II A-7 EFFECT OF RADAR PERFORMANCE LOSS ON RADAR RANGE do the greatest amount of damage to a radar's ability to detect these small but important objects. However, easy-to-see radar targets will still be visible, so that the radar seems to the operator to be normal.

In order to translate a decrease in ringing time into a decibel loss in radar performance, a relationship must be established between these two factors. This relationship is commonly called the "sensitivity" of the echo box and is expressed in terms of yards of ringing time lost per decibel lost. (Sometimes the "decrement" is given in db per microsecond). Again, in order to determine this quantity, the characteristics of the echo box must be known. The echo box sensitivity should be stated in the instruction manual for the box being used, although this is not always done. For most boxes it is between 40 and 100 yards per db. A good S-band box such as the TS-270/AP has a sensitivity of about 90 yards per db.

The sensitivity can be measured without too much difficulty by inserting a known attenuator in the cable leading to the echo box. The ringing time is first measured without the attenuator and is then measured with the known attenuator in the line. The second ringing time will be less than the first because of the additional attenuation. Since the RF energy must pass through the attenuator twice -- once entering the echo box and again leaving -- the attenuation used in the calculation must be twice the value marked on the attenuator. The sensitivity of the echo box is the observed change in ringing time divided by twice the value of the attenuator in db. As is the case with all measurements conducted at microwave frequencies, there are pitfalls awaiting the uninitiated. This measurement should be performed only by an experienced microwave technician (Sec. VA-3).

IIA. 6 Other Possible Echo Box Measurements

The prime function of an echo box is the determination of over-all radar performance by means of ringing time measurements. In addition, the device can be used as a diagnostic tool to localize difficulties occurring within the radar system. By proper use of an echo box, it is possible to:

1. Tune the tunable RF components
2. Measure transmitter frequency, spectrum, and pulse length

3. Measure the receiver passband
4. Determine whether the transmitter changes frequency as the antenna is moved ("pulling")
5. Discover erratic operation and, in some cases, discover its cause
6. Obtain a rough indication of transmitter power output
7. Examine the operation of the automatic frequency control
8. Measure the recovery time of the transmit-receive switch (TR box)
9. Determine the recovery time of the receiver
10. Measure the standing wave ratio.

IIA. 6. 1 Tuning RF Components

An echo box is a valuable aid in tuning up a radar. When a radar is grossly out of tune, as is frequently the case after components are replaced, echoes frequently cannot be seen at all. Therefore, there is no criterion for tuning. An echo box provides an echo which is extremely strong, stronger than the echoes from near-by objects. For tuning purposes, the echo box is connected and tuned as for a ringing time test, and then the radar local oscillator is tuned until ringing time is seen. The other adjustments can be almost arbitrarily far from correct tune, yet ringing will still be seen. Once ringing appears, the other adjustments can be set to maximize the ringing.

Echo boxes are of particular value when a radar must be tuned in the absence of an antenna, as in a repair shop, in a submarine, or during radio silence. In some radars, an RF switch is provided so that tune-up can be made on a dummy load; thus, the radar can be put into operation instantly by switching to the antenna. When this is done, it is important to be sure that the transmitter does not shift frequency during the change from the load to the antenna. The best way to overcome this difficulty is to tune up on the load, switch to the antenna, then shift the magnetron tuning as needed to move the transmitter back to the exact frequency on which the tune-up was made. The echo box meter is used as the criterion for setting the magnetron frequency, since the echo box tuning remains set on the original magnetron frequency on which the tune-up was made.

Even when echoes are present, it is quite convenient to tune a radar using an echo box signal. The echo box signal will not fluctuate or flutter as a "natural" echo will, and a better tune-up results.

It is most desirable to use an A-scope to observe the ringing, and it is very helpful to reduce the receiver gain so that noise is eliminated. This procedure improves the accuracy to which the ringing time can be measured. It is also helpful to place a vertical mark on the face of the A-scope with a grease pencil as shown in Figure IIA-8a, so that it cuts

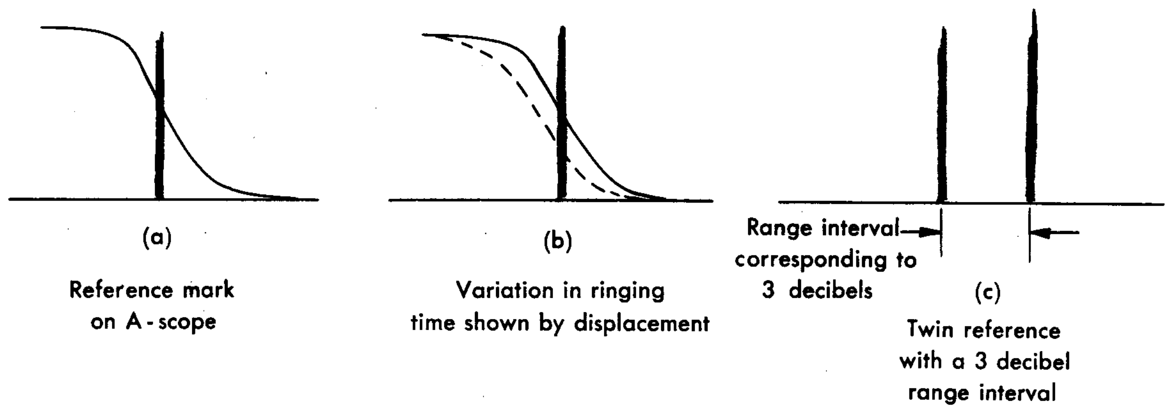


FIG. II A-8 REFERENCE MARKS ON A-SCOPE AS AN AID IN MEASURING RINGING TIME

through the sloping portion of the ringing. Variations in ringing can then be seen easily as a displacement of the point where the ringing cuts the vertical line (Fig. IIA-8b).

If this is not done, and if echoes or range marks are not present, the eyes of the operator tend to follow the ringing decay pattern back and forth in range. Since the shape of the pattern does not change, the result is misleading. Maintenance men sometimes say, "I can tune up better on an echo". This statement is incorrect, and it is the result of not placing a mark on the scope. At each point in the echo box decay signal, the signal moves up and down with tuning exactly as does a target echo. The echo box provides a signal of constant strength which permits more accurate tuning to be made than with a "live" target because there is no flutter or fading.

The major advantage of using an echo box rather than an echo in tuning a radar is that the box is set up as for a ringing time check, so that it is possible to tell in a few seconds by a ringing time check whether or not the radar tuning has accomplished its purpose. In spite of the contrary subjective opinions of some experienced radar maintenance men, such a check simply is not possible on natural target echoes.

Maintenance men sometimes also say, "I get a different tune-up on the echo box than on echoes". This statement is an indication of a very simple mistake: the echo box was not tuned to the radar frequency. What probably happened was that the radar was turned on, the echo box tuned to the transmitter, and the tuning commenced. The transmitter was cold, and it drifted as it warmed up. Hence, maintenance men must be sure to check the echo box tuning.

There is a possibility that, due to feed-back within the IF strip or to misalignment of a "stagger tuned" IF strip, there will be a peak in the IF response near one side of the IF passband. In this case, the local oscillator may be tuned accurately to this peak rather than to the center of the IF passband when an echo box is used. The echo box re-radiates energy in very narrow bandwidth. When tuning the local oscillator by use of an echo box, it is easy to recognize a "flat topped" IF and to tune to the center of it. It is also easy to recognize such a peak in the IF and avoid it. In general, the result of tuning to such a peak is not particularly serious in any case, and no adjustments other than that of the local oscillator are affected. If it is suspected that the IF amplifier has this particular fault, it is possible to check the shape of the IF passband with an echo box, as directed below.

There are three components which must not be tuned by the criterion of maximum ringing time. First, it is not reasonable to tune antenna adjustments, when these are provided, with ringing time as a criterion. These should be adjusted by means of standing wave ratio indicators. The echo box, with an accessory probe and slot, can be used as a detector for this purpose (Sec. IIA. 6. 10).

Second, any other adjustments provided for varying the load impedance seen by the transmitter should not be set by reference to ringing time or by maximizing the transmitter output. Such adjustments are rarely provided in modern equipment. To maximize the transmitter power output in this way is to place the transmitter at its least stable operating point. Rather, maximum power should be avoided and spectrum quality, stability, and lack of pulling should be used as a criterion. All these quantities can be checked by the echo box (Sec. IIA. 6. 2).

Third, the IF stages should not be tuned by use of an echo box signal unless it is known that the IF is not of the "stagger tuned" variety. To do so would reduce the receiver passband and thus improve the ringing time, but it would alter the radar from its design characteristics. The IF passband can be observed with an echo box, as described below.

IIA. 6. 2 Measurement of Transmitter Frequency, Spectrum, and Pulse Length

A radar transmitter can be thought of as an oscillator which is pulsed or turned on periodically for a short time interval. While this description does present a reasonable picture of the operation of a radar transmitter, it may lead to an erroneous concept of the actual character of the transmitter output. When an oscillator is turned on and off periodically, the resulting output is not a single frequency, but in reality is a band, or spectrum, of frequencies. The additional frequencies are side bands resulting from the pulse modulation of the oscillator. If the transmitter is amplitude-modulated by a nearly rectangular pulse, as it should be in the case of a radar transmitter, the spectrum should have roughly the outline of Figure IIA-9a, where the horizontal distance represents relative frequency and the vertical distance represents the relative amount of energy at that particular frequency. The greatest amount of energy in such a spectrum is contained in frequency components located at or near the center frequency.

An echo box can respond only to a relatively narrow range of frequencies. In fact, a typical echo box has a bandwidth of approximately 50 to 100 kc, regardless of the frequency band for which the box was designed. The band of frequencies which the radar generates is generally much wider than 100 kc; for example, the frequency spread of the large center lobe

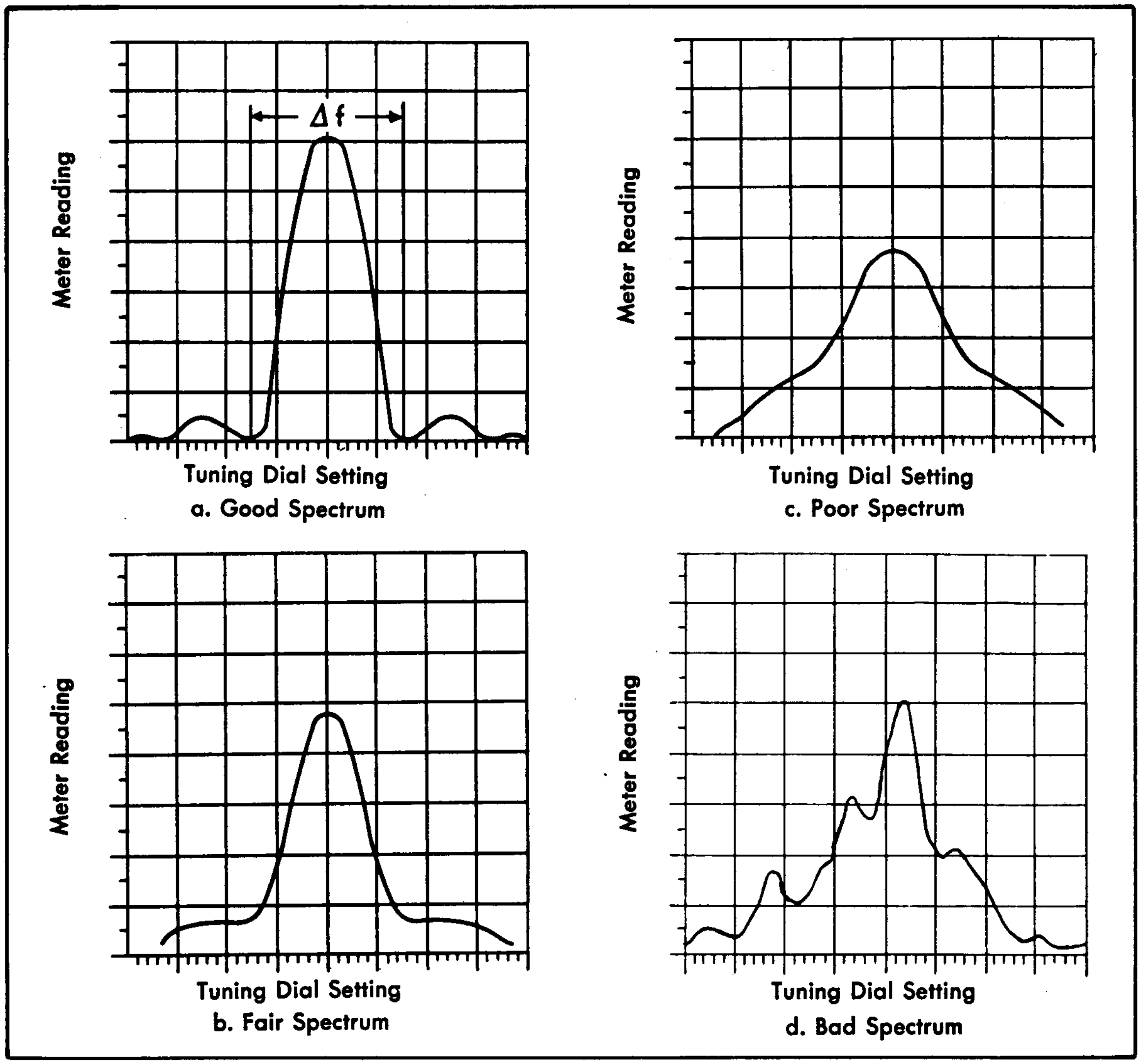


FIG. II A-9 TYPICAL RADAR SPECTRA

of the spectrum of a radar having a 1/4-microsecond rectangular pulse (Cf. Fig. IIA-9a) measured to the minimum points on either side of the center frequency, is 8 mcs. Radars with longer pulses will have narrower spectra; however, in general, an echo box is capable of responding only to a narrow sample or slice of the spectrum. When an echo box is tuned for a maximum reading on the resonance indicator, the cavity has been adjusted so that it is sampling that portion of the spectrum which contains the greatest energy. In the case of Figure IIA-9a, the box is tuned to the peak of the central lobe. The frequency then indicated on the frequency dial or tuning chart is described as the radar transmitter frequency. At this frequency, the greatest amount of energy is being generated, but it can be seen that this measurement alone does not give complete information. Additional information can be gained by graphing the entire side-band distribution.

To obtain a plot of the transmitter spectrum, tune the echo box slowly through the spectrum and record the meter readings at convenient intervals on the tuning dial. A convenient interval will be found to be one tenth to five tenths of a mcs or, on most echo boxes, one to five of the least-count units of the dial. A graph can be constructed by plotting the meter readings against the dial settings. The graph obtained should resemble one of those shown in Figure IIA-9. With a little practice, a bad spectrum can be recognized without recording or plotting the readings. The possibility of a second large peak, considerably removed from the first one, must not be overlooked.

In general, a good radar spectrum will look like Figure IIA-9a. The pattern is symmetrical; there are deep minimum points on either side of the tall main lobe; and succeeding side lobes are progressively smaller. An unsymmetrical spectrum or one without deep minimum points indicates that the transmitter is changing frequency during the pulse; that is, it is frequency modulated. In general, some degree of frequency modulation is unavoidable with magnetron-type transmitters, particularly with the longer pulse lengths, and is not a sign of trouble. A high degree of frequency modulation, resulting in a very irregular spectrum such as Figure IIA-9d, requires investigation. Instability of transmitter output, indicated by fluctuation in echo box meter readings even when tuned to the peak of the spectrum, indicates trouble. Similarly, the existence of two distinct large lobes is an indication that the transmitter is not operating on the same frequency band on every modulator pulse or, perhaps, is suddenly changing frequency during the pulse.

If the transmitter spectrum resembles Figure IIA-9a, the length of the transmitter RF pulse can easily be calculated from the graph by determining the number of mcs between the first two minimum points on either side of the main lobe. The pulse length is given by

$$T = \frac{2}{\Delta f}$$

where T is the RF pulse length in microseconds (measured at half its amplitude) and Δf is the number of mcs between the minimum points of the transmitter spectrum. This relation is strictly true only for a rectangular pulse and no frequency modulation; however, its accuracy has been investigated for a variety of shapes of pulses and has been found to be quite good (Ref. 1, p. 48 ff).

IIA. 6. 3 Measurement of Receiver Passband

To measure the receiver passband, the local oscillator must be calibrated in frequency. To measure the local oscillator frequency, the echo box is connected to the radar by a directional coupler, just as in the measurement of ringing time. An arbitrary scale is placed on the reflector voltage control of the local oscillator or on any other vernier oscillator frequency control which is provided. With the echo box tuned to an arbitrary frequency within the transmitter spectrum, the local oscillator is carefully tuned for maximum ringing time. For accuracy, reduce the gain to reduce noise and place a mark on the A-scope as described in Section IIA. 6. 1. The frequency of the echo box is then changed and again the local oscillator is tuned for maximum ringing time. By taking about ten different readings, a plot can be made of the local oscillator dial setting against frequency. Each reading obtained differs from the true local oscillator frequency by the receiver IF; the true frequency is found in each case either by adding or by subtracting the IF frequency from the reading, depending on whether the local oscillator is tuned below or above the radar transmitter.

To measure the receiver passband, the box is tuned to the peak of the radar spectrum, the gain is reduced to eliminate noise, and the local oscillator is tuned manually for maximum ringing time. The local oscillator is then detuned first to one side, then to the other, until the ringing time is reduced in each case by an amount equivalent to three decibels. The two local oscillator dial readings corresponding to the 3 db points are recorded and are converted into frequencies. The difference between these frequencies is the receiver passband.

Since a change in ringing time corresponding to 3 db is small, the ringing time must be read very carefully. The gain should be reduced and marks placed on the A-scope to help the operator make this measurement. Figure IIA-8c shows a way of marking the scope so a small change in ringing time can be measured accurately.

The change in ringing time corresponding to three decibels should be found by reference to the echo box instruction manual. Some typical values are given below (Ref. 1).

Echo Box Type	Yards per Three db
TS-270/UP	270
OBU-1, OBU-2	210
OBU-3	240
TS-275/UP	150
TS-218A/UP	180

The shape of the receiver passband can also be determined if desired.

IIA.6.4 Determination of Transmitter Pulling

With the radar antenna rotating and the echo box connected to the radar system, the ringing time is observed. If the ringing time changes as the antenna rotates, pulling is indicated. Azimuths at which the ringing time changes may be noted, and frequency measurement may be made on the transmitter with the antenna stopped at these azimuths to verify that frequency pulling is present. A change in echo box meter reading at the azimuths in question is also indicative of pulling. The change of frequency at various antenna azimuths may be caused by a defective rotating joint or by a reflecting surface near the antenna.

IIA. 6. 5 Discovering and Localizing Erratic Operation

Erratic operation is of particular interest because it can be a clue to troubles which are developing but which have not yet caused a complete failure. Erratic operation is of special interest with MTI radars, because MTI operation is quite dependent on the identical functioning of the radar on successive pulse cycles. Erratic operation is well shown on MTI radars by the failure of the decay portion of the ringing time to "cancel".

This test is best performed with the antenna stopped, and with the aid of an A-scope. The echo box tuning control is adjusted for maximum meter reading and the gain is reduced to eliminate noise. The ringing time indicated on the A-scope should be reasonably steady. Marked fluctuation, particularly the appearance of two or more ringing times apparently simultaneously, or the appearance of extra traces or noise in the ringing pattern is an indication of erratic operation in either the transmitter or the receiver, or both. If the echo box is tuned correctly to the center of the transmitter spectrum, the echo box meter should show little, if any, fluctuation. Considerable movement of the meter needle almost certainly indicates an erratic transmitter. However, the radar can be erratic and, due to the damping of the echo box meter no fluctuation may be seen. If no such movement exists, the echo box should be detuned slightly until the meter reading just begins to decrease; slight fluctuation may then be evident even in a properly operating transmitter. If the fluctuation is violent, transmitter, waveguide, rotating joint, or antenna trouble is indicated. A graph of the spectrum may be made as outlined in Section IIA. 6. 2 if two distinct modes of transmitter operation are suspected. A very useful method is to connect an oscilloscope across the echo box crystal, after having disconnected the meter and the condenser. The ringing time can then be observed on the oscilloscope, and any fluctuation is certainly caused by improper transmitter operation, since the radar receiver is not in this circuit.

IIA. 6. 6 Measurement of Transmitter Output Power

The echo box output meter reading is very roughly proportional to the output power. By observing the meter reading and knowing the meter readings of previous tests, the relative power output of the radar can be estimated. A low meter reading accompanied by a low ringing time indicates low power output. Low ringing time without low meter reading indicates trouble in the receiver. This measurement is not accurate, since meter readings for constant input power usually vary with frequency by about a factor of two over the tuning range of the echo box, and can be relied upon only to the extent of a day-to-day comparison at the same transmitter frequency. A different echo box or a different crystal in the same echo box will also, in most cases, produce a different reading. A case of spectrum trouble is also likely to cause a considerable difference in meter reading, perhaps out of proportion to the seriousness of the defect (~~Sec. IIC~~).

IIA. 6. 7 Examination of the Automatic Frequency Control

If the transmitter is changing frequency with antenna rotation, the echo box can be used to determine whether the local oscillator is following the transmitter. The antenna is first placed on an azimuth where the ringing time is reduced due to transmitter pulling and the echo box is retuned. The antenna is then rotated, and if the ringing time on the azimuth where the echo box was retuned is longer than at other azimuths, the automatic frequency control is in operation.

To determine whether the automatic frequency control is locked on the proper frequency, the antenna is stopped and the echo box is tuned for maximum meter reading. The automatic frequency control switch is then turned off and the local oscillator frequency is adjusted for maximum ringing time. If the ringing time decreases at all when the automatic frequency control switch is turned on again, the automatic frequency control is not working properly.

IIA. 6. 8 Measurement of TR Recovery Time

The TR recovery time can be measured by use of an echo box. This measurement is performed by turning down the gain of the radar receiver until the slope of the ringing time curve on an A-scope changes (Fig. IIA-10). The range at which the change occurs is the end of the TR recovery time.

IIA. 6. 9 Measurement of Receiver Recovery Time

This measurement is performed first adjusting the echo box for maximum output meter reading and then detuning the echo box and increasing

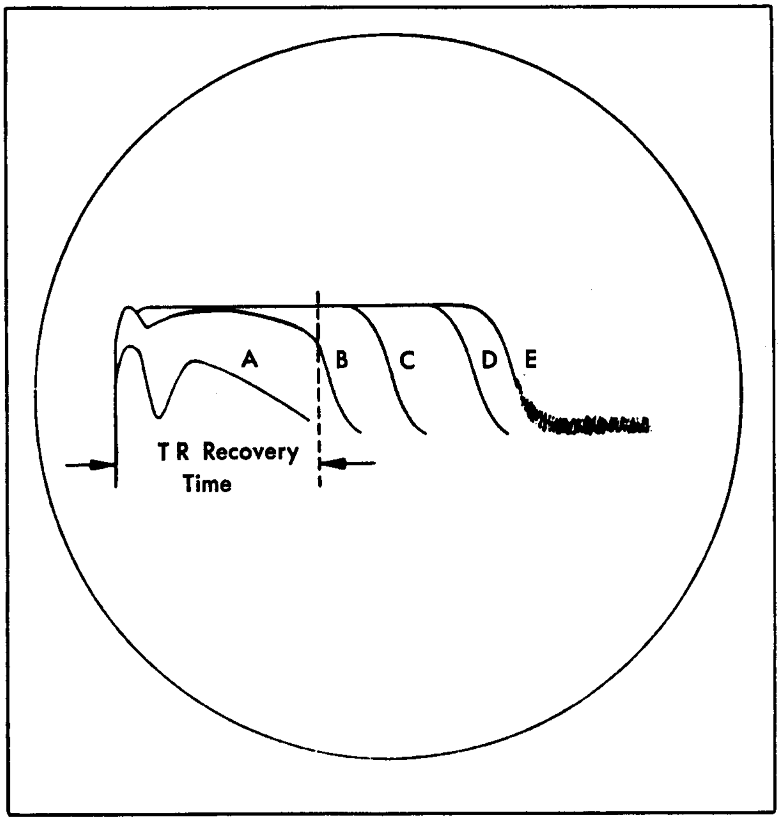


FIG. II A-10 CHECKING T R RECOVERY TIME ON AN A-SCOPE

the receiver gain until a pattern similar to that of Figure IIA-11a is obtained. On retuning the echo box, a pattern similar to that of Figure IIA-11b is obtained. If the noise reappears immediately after the pulse, and is not diminished in amplitude, then the receiver recovery time is normal. If the noise amplitude increases slowly rather than remaining constant after the end of the ringing time, receiver recovery time is slow. This slowness is usually due to a defect in the video amplifier and makes the radar more susceptible to enemy jamming.

IIA. 6. 10 Measurement of the Standing Wave Ratio

If a slotted section is provided in the radar waveguide, the echo box

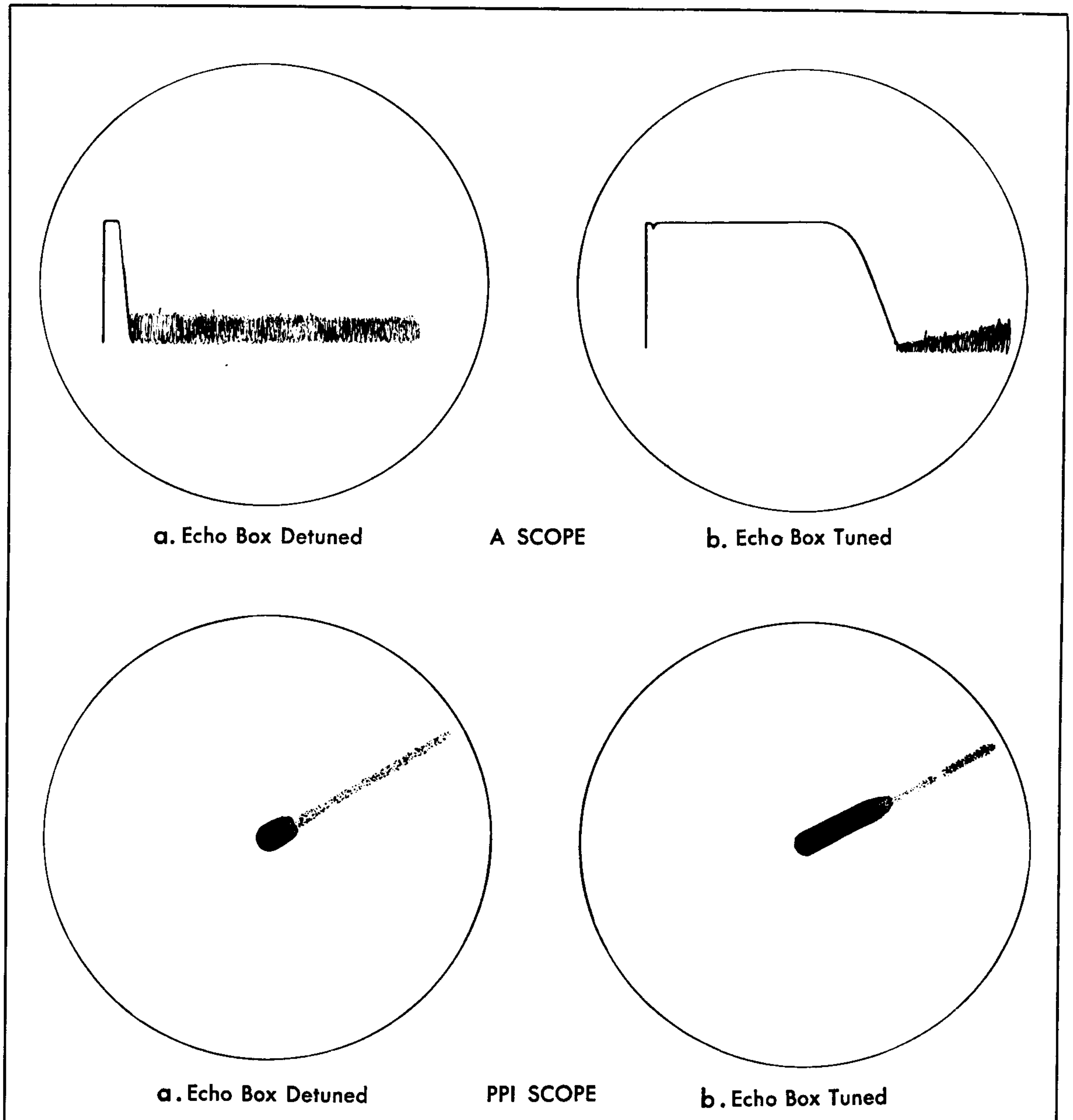


FIG. II A-11 MEASUREMENT OF RECEIVER RECOVERY TIME can be used as a satisfactory standing wave instrument. An adjustable RF probe is required as an accessory. Such a probe is provided in at least one echo box kit (AN/UPM-7). The echo box meter is read at the peak and at the trough of the standing wave pattern. The square root of this ratio is the approximate voltage standing wave ratio. An echo box is more satisfactory for this purpose than a simple crystal and meter since the high Q cavity protects the crystal from burn-out.

IIB FACTORS AFFECTING CHOICE OF ECHO BOX

IIB.1 Effect Of Ringing Time On Choice Of Echo Box

Among the factors affecting the selection of a particular design of echo box, the ringing time is the most important single consideration. The ringing time is determined by the type of radar and the use to which the radar is put. Two factors determine the minimum permissible ringing time: the TR recovery time and the clutter. The ringing time must be longer than the TR recovery time and must be sufficiently long for the end of the ringing time to be clearly seen beyond the range of the ground clutter, although it may be possible to take advantage of "holes" in the clutter in order to measure ringing time.

IIB.1.1 TR Recovery Time

The loss in sensitivity caused by TR recovery usually extends to one mile or less if the TR tube is good and if the keep-alive current is not excessive. In radars employing TR tubes or pre-TR tubes (not ATR tubes) of the "bug" type, in which the discharge occupies the entire volume of the tube rather than taking place between electrodes, the recovery is prolonged and may reach three miles.

It is possible to eliminate clutter completely for the purpose of making ringing time measurements or other radar tests by disconnecting the radar antenna and substituting a dummy antenna, or "sand load". This procedure may result in an appreciable shift in transmitter frequency, due to the "pulling" effect of the changed load impedance on the radar magnetron (Sec. IIA.6.1). This difficulty can be overcome, if the radar is equipped with a tunable magnetron, by leaving the echo box connected and its frequency setting unchanged. Upon reconnecting the radar antenna, the magnetron frequency is changed until maximum ringing time is achieved, at which time the magnetron will be at its former frequency, and the radar will again be in tune.

IIB.1.2 Clutter

IIB.1.2.1 Antenna Height

The height of the antenna influences the clutter observed, since antenna height determines the distance to the horizon. The relation between the antenna height and horizon distance is approximately

$$d = \sqrt{2h},$$

where d is in statute miles and h is in feet. The formula assumes a 4/3 radius earth; that is, the effect of atmospheric refraction is taken into consideration by assuming the radius of the earth to be multiplied by the factor 4/3. Increasing the height of the antenna not only increases the range of clutter, but also increases its intensity at all ranges (particularly true for sea clutter). Large surrounding objects tend to reduce the clutter by interfering with the outgoing radiation and the radiation returned by ground reflections. In such cases, the required ringing may be less. On the other hand, the presence of nearby objects may cause weak false echoes because of multiple reflections. The false echoes usually do not cause sufficient clutter to interfere with ringing time measurements. It is usually helpful to point the antenna toward an interfering object if clutter is objectionable, provided the interfering object is farther away than the distance corresponding to the radar pulse length.

IIB. 1.2.2 Nature of Surrounding Objects

Whether the antenna is located over land or over the sea is important. Clutter is less objectionable at sea, but varies with the condition of the water. Smooth water reflects the radar beam almost entirely in the forward direction, with negligible backscatter. In rough water the backscattering return will create noticeable clutter. Sea clutter is distinctly less in the down-wind direction than in any other.

IIB. 1.2.3 Antenna Azimuth

For a permanently installed radar, or for a specified location, the clutter depends upon the azimuth of the radar antenna, since the characteristics of the terrain may differ in different directions. When testing the radar with an echo box, it is convenient to choose an antenna azimuth for which the clutter is minimum. Hence, it is the extent of clutter in the direction of minimum clutter which determines the required ringing time.

IIB. 1. 2. 4 Antenna Elevation Angle

The extent and intensity of clutter is also affected by the antenna elevation. Elevation of the antenna directs the beam away from the earth's surface and the clutter is greatly reduced. Where the antenna cannot be elevated, it may prove useful, in some cases, to elevate the antenna beam by using a reflector made of wire mesh or meter foil on cardboard. The reflector should intercept and deflect the whole of the beam. This scheme is practical only for the small and accessible antenna whose beam is small in the region of the antenna. Such a practice, however, may tend to alter the frequency of the transmitter output. In cases where the antenna cannot be elevated sufficiently, it may be possible to reduce the maximum range at which clutter is seen by depressing the antenna so that the beam illuminates the nearby earth strongly, leaving clutter-producing objects at greater ranges illuminated weakly or not at all. This expedient is useful, of course, only for radars with a beam which is narrow in the vertical plane, such as a "pencil beam" or a "beavertail" beam.

IIB. 1. 2. 5 Antenna Beam Width and Gain

Clutter is also dependent on antenna gain, in that increased antenna gain in the direction of a given interfering object produces increased echo strength from the object. This increase in clutter is offset to some extent by the increased angular resolution which accompanies gain.

IIB. 1. 2. 6 Pulse Length

Radars with a wide beam and long transmitted pulse exhibit a more "solid" clutter than those with a narrower beam in azimuth and shorter pulse length; this is because the former radars lack the resolution in both range and azimuth which the latter possess.

IIB. 1. 2. 7 Atmospheric Conditions

Atmospheric conditions can affect the extent of clutter immensely. The phenomenon of refraction and "ducting", wherein occasional atmospheric conditions cause the radar beam to remain closer to the surface than usual, sometimes greatly increases the range at which surface objects are seen.

IIB. 1. 2. 8 Purpose of Radar

Radars used for various purposes possess various characteristics, and the type of clutter varies. Airborne radars usually have low antenna gain and high frequency. The ground clutter persists to about one-to-two miles when the plane is on the ground. Ground tests are usually made in clear areas of flat country. The antenna may be elevated because of the position of the plane on the ground. The requirements for echo boxes in such cases call for a minimum ringing time corresponding to about 2 miles.

Shipborne radar employs larger antennas, the size varying from small to medium. The frequency used varies, surface search being of higher frequency than air search. The height of the antenna varies according to the size of the ship, being over 100 feet in some cases. Sea clutter is much less pronounced than land clutter, especially in smooth seas. For surface search, an echo box will require about three miles ringing if measurements are to be made in fairly rough sea conditions. During calm days, sea clutter may extend to only about 1/4 mile. The ringing time needed for air search is somewhat longer than that for surface search.

Clutter in land based radar usually varies between 5 and 30 miles. Flat country presents less clutter than rough terrain. However, rough terrain produces the possibility that, at some azimuths, a nearby obstacle will block distant echoes. The echo box requirements for land based radar call for long ringing times to cover the long-persisting clutter.

IIB. 1. 2. 9 Clutter Measurements

Clutter observations were made at the Willow Run Research Center on the AN/CPS-5 and AN/FPS-3 radars. The center of the CPS-5 antenna was 45 feet above the ground, that of the FPS-3, 55 feet. The horizon distance of these radars are 9. 5 and 10 statute miles, respectively. (In both cases these radars had been modified by the addition of an improvised ten-foot tower extension). The observed range of ground clutter for these two radars is tabulated below. In each case two clutter readings were made, the first at the azimuth in which clutter was at a maximum, the second at the azimuth where clutter was least.

Radar	Range of Maximum Clutter	Range of Minimum Clutter	Antenna Elevation
AN/FPS-3	nautical miles?		
Lower beam	30 n. m.	15 n. m.	1 1/4 degrees
Upper beam	16 n. m.	8 n. m.	8 1/2 degrees
AN/CPS-5	10 n. m.	6 n. m.	-1 1/4 degrees

These radars were located adjacent to one another in a moderately wooded region. The surrounding area was quite flat except for a range of low hills tangent to a circle of 6 miles radius about the radars.

Clutter is worst when the ground rises gradually on all sides of the radar, and the horizon is far away. For example, it has been reported that in San Francisco Bay the OBU type of echo box is not usable with those shipborne radars whose antennas cannot be elevated. The ringing time of this echo box is typically between 6000 and 7000 yards. Inside Pearl Harbor this echo box is useable with these radars, only with difficulty. At Boston, Norfolk, Brooklyn, Portsmouth, and New London, these echo boxes have adequate ringing time.

IIB. 1. 3 Other Ringing Time Considerations

Another method for estimating the ringing time is useful under conditions in which the end of the ringing time appears in echoes of moderate strength. The azimuth of least clutter is selected. The echo box is tuned to the peak of the spectrum, then tuned slowly back and forth across this peak. The slow tuning causes the phase of the echo box signal to shift relative to that of the interfering echo, on successive pulse cycles. Since the echo box signal adds vectorially to the target echoes, the target echoes "flutter"; that is, they look like a moving target on an MTI radar before cancellation. Thus, the presence of ringing time can be detected in heavy clutter. This method is a more sensitive test for the presence of ringing than is the usual process of measuring to the range at which ringing disappears into noise, and an allowance for this increased sensitivity should be made. (This test has had only limited trial).

Because the usefulness of an echo box generally increases with an extension of ringing time, it may be thought that it is possible to design an echo box which has a sufficiently long ringing time for use on any radar within its designated tuning range. There is absolutely no recourse but to make the cavity physically larger, if longer ringing time is to be obtained in a conventional echo box. However, the larger the box is made, the more unwieldy and heavy it becomes, and if it is not made a permanent part of its associated radar, there is an increasing likelihood that it will not be removed from its place of storage and put to use. A large echo box, required for a large radar with heavy ground clutter, may become a burden with a small radar which does not require as much ringing time.

In general then, the echo box should be designed so that it provides the anticipated minimum of ringing time required to provide successful readings on the radar or radars with which it is to be used. There is, therefore, practical need for more than one echo box in a given frequency band.

IIB. 2 Effect of Frequency on Choice of Echo Box

Another important factor in determining the type of echo box required is the frequency band in which the box is to operate. At very low radar frequencies (50 - 500 mcs), where the cavity type of echo box becomes so large as to be practically out of the question, coaxial-line cavities or other unusual types of construction must be used. At the other end of the radar spectrum, it is difficult to obtain sufficient ringing time without interference from undesired modes and, in the region from 16,000 mcs up, the problem of designing a satisfactorily tuned echo box has yet to be completely solved.

IIB. 3 Other Factors Affecting Choice of Echo Box

Many other considerations confront the designer; some of the more important ones are: method of tuning indication, method of tuning (manual or remote motor-tuned), the means by which the echo box is coupled to the radar (which may determine whether the box can be located below in the radar room and tuned manually, or must be located near the antenna with tuning and tuning indication accomplished remotely), weather conditions to which the box must be subjected, the allowable variation in ringing time over the tuning band, the tuning band itself, the accuracy with which frequency must be measured by use of the box, and mechanical requirements as to shock and vibration.

Some echo boxes have given poor performance in the field because of unsatisfactory mechanical design or inadequate original specification. If the intended use of the box is detailed in the specifications, it will assist the designer greatly in producing a satisfactory design. It is important from the standpoint of economy not to specify more ringing time than is actually needed, because the cost of an echo box rises rapidly with increased ringing time.

IIC ECHO BOX TECHNIQUES COMPARED WITH OTHER RADAR TESTING METHODS

The tests described in Section IIA can also be performed with the aid of other types of test equipment frequently supplied with radars. RF signal generators, power meters, spectrum analyzers, and standing-wave ratio indicators are becoming more common in the field as the manufacturers and users of radar equipment realize the necessity for adequate maintenance. The maintenance man must sometimes make a choice between an echo box and a more specialized test set.

The choice of a method for making a particular test must be based ultimately on the circumstances immediately at hand. A set of rules cannot be devised which will cover all the possible situations to be found in the field. It is possible, however, to make comparisons of a general nature.

IIC. 1 Radar Performance Measurements

Signal generators and power meters, or a single instrument combining the two, are frequently used to measure over-all radar performance. It has been found that many technicians believe that these instruments give a more accurate result than does the echo box. Whether this is true or not depends entirely on the particular instruments involved, and how expertly they are employed. There is no justification for attributing a higher inherent accuracy to the signal generator type of instrument when used to measure over-all radar performance, despite its greater complexity and more imposing appearance.

Among the disadvantages of the signal generator-power meter, compared to the echo box, for measuring radar performance are:

1. It is,in general, a much more complex, heavy, and delicate instrument, and requires an auxiliary source of power. It is therefore harder to use, especially in exposed or inconvenient locations, and is likely to need considerable maintenance.

2. Its accuracy depends on a calibration which is difficult or impossible to perform in the field. Need for recalibration may not be apparent to the user, resulting in measurements that may be considerably in error.

3. Most field-type signal generators cannot produce an RF pulse whose power is known accurately, even when the instrument is in normal operating condition. This inaccuracy is due to inherent limitations in present-day techniques for monitoring signal generator output power.

4. It cannot be used to examine the transmitter spectrum.

5. The power meter is a broad-band device, and therefore cannot be used to detect transmitter difficulties such as double-frequency operation, which may radically affect radar performance without appreciably changing the total generated power.

On the other hand, the signal generator-power meter type of instrument has certain advantages over the echo box, such as:

1. It measures radar transmitter and receiver performance separately, and thus can more quickly isolate difficulties in one or the other. Loss of radar performance is most likely to occur in the receiver. The technician using a signal generator can measure receiver sensitivity without having to turn on the transmitter, which enables him to service this component in the absence of a transmitter (e.g., on the maintenance bench), or during radar silence.

2. It can measure transmitter power accurately, whereas the echo box cannot.

3. The results of the measurements are read directly from dials or meters on the instrument, and there is less dependence on the more difficult techniques involved in measuring and interpreting scope patterns.

4. A signal generator can be used on all radars within its frequency range, whereas the echo box is limited to radars on which ringing time sufficient to extend past permanent clutter can be obtained.

IIC.2 Transmitter Spectrum Measurements

There is very little justification for including a spectrum analyzer among items of field test equipment, if it is to be used only for observing the shape of the transmitter spectrum. It is a very complex piece of equipment which is difficult to operate, and the picture it presents requires considerable skillful interpretation on the part of the observer. The spectrum analyzer has great value as a laboratory instrument; but, for purposes of measuring transmitter spectra in the field, the echo box can be recommended as a device which is not only vastly less complex, but also much easier to use.

CHAPTER III

DESIGN

IIIA RESONANT CAVITIES

IIIA.1 General Properties of Resonant Cavities

A resonant cavity is any volume filled with dielectric and bounded by an electrically conducting surface. The shape of the boundary surface is the chief factor which determines the properties of the cavity. The dielectric may be solid, liquid, gaseous, or vacuum. In the cases to be considered, the dielectric is always air, which, for practical purposes, can be treated as a vacuum. Henceforth, the cavity is treated as though it were empty unless otherwise specified.

If a cavity is excited with a pulse of energy at a frequency at which the cavity is resonant, the energy introduced into the cavity produces oscillations which decay exponentially after the end of the pulse as the energy leaves the cavity through openings in the surface and is dissipated in the cavity walls. In this respect, the resonant cavity behaves like a parallel resonant inductance-capacitance (LC) circuit with resistive losses; in fact, for purposes of analysis, it is often convenient to think of the cavity as a resonant inductance-resistance-capacitance (LRC) circuit. Equivalent circuits for cavity resonators are discussed in more detail in Appendix II.

A cavity can resonate at an infinite number of frequencies, and each resonance is associated with a particular standing wave pattern ("mode") of the electromagnetic fields within the cavity. If two or more different modes have the same frequency of oscillation, they are termed "degenerate" modes. Cavity modes are divisible, in certain cases, into two categories, transverse electric (TE) and transverse magnetic (TM). For TE modes, the electric field is transverse to the cavity axis throughout the cavity while for the TM modes, the magnetic field is transverse to the cavity axis. Modes existing in the rectangular prism cavity, the cylindrical cavity, and the coaxial cavity can be divided into TE and TM modes. For the latter two cavities, the axis is the cylinder axis, while in the case of the rectangular cavity, any direction normal to one of the surfaces can serve as the axial direction; usually the longest dimension is selected.

When a cavity is excited, the mode or modes in which it oscillates are determined in part by the manner of excitation. The frequency of each mode is determined by the boundary conditions, and may be altered by a change in position of the boundary. If more than one mode is excited, the resonant cavity, from the equivalent circuit standpoint, can be regarded as a group of LRC circuits coupled together.

To be of the greatest use, a resonant cavity must be analyzed mathematically and the frequency and field configurations of its modes must be determined. This analysis cannot be carried out except for certain simple shapes, such as the sphere, rectangular prism, right circular cylinder, and coaxial cylinder. Expressions for the fields inside such resonant cavities are derived in such works as References ~~25~~,7,27, ~~and 28~~.

At some location on the surface, there must be an opening through which energy is coupled into and removed from the cavity. Although most cavities for echo box use have another opening for coupling energy to a resonance indicator, it is the input opening which is of greater importance in determining the electrical behavior of the cavity. In terms of electrical properties, the cavity behavior is completely specified by three quantities: the Q or quality factor, the resonant frequency, and the shunt resistance. In general, any cavity will have an infinite number of modes of oscillation, each with its own resonant frequency, Q factor, and shunt resistance.

The Q of a cavity is a quantity analogous to the Q used to describe low frequency LRC circuits. In fact, it is one of the few quantities used in low frequency work which can be carried over to microwave technique without serious modifications or limitations. The Q for a resonant cavity is defined as the ratio of the energy stored in the cavity to the energy dissipated per radian, or

$$Q = 2\pi f_r \frac{W}{P_r}$$

where

f_r is the resonant frequency

W is the energy stored in the cavity

P_r is the power dissipated (or otherwise lost) from the cavity.

Alternatively, Q may be defined as

$$Q = \frac{f_r}{f_1 - f_2} = \frac{f_r}{\Delta f}$$

where f_1 and f_2 are the half power frequencies of the cavity passband. As in the low frequency case, these two definitions are equivalent. The Q's for resonant cavities are quite high (in contrast with the low frequency case), typical values of Q for echo box cavities being between 20,000 and 200,000. The shunt resistance is an indication of the electric or magnetic field which must be maintained at some point or points to maintain the energy in the cavity at a certain level. Frequency and Q are important in the design of echo boxes. Shunt resistance, however, is not used.

IIIA.2 Conductivity Effects

Cavities are constructed of a metal such as aluminum or brass which provides the necessary structural strength, while still being economical. To give cavities the required electrical characteristics, their interior surfaces are coated with a material of high conductivity, usually silver. This coating increases the cavity Q and hence the ringing time. The conductivity of the inner surface determines the depth of penetration of the wall currents; this, in turn, affects the cavity Q, since Q is inversely proportional to the skin depth. Skin depth and resistivity are related by the equation

$$\delta = \frac{1}{2\pi}\sqrt{\frac{10^3 \rho}{f}}$$

where

δ = the skin depth in cm

ρ = resistivity in ohm - cm

f = frequency in mcs

Therefore, Q is inversely proportional to the square root of the resistivity. Larger values of resistivity mean greater depth of penetration of the wall currents and lower Q.

A few common metals and their relative resistivities are listed in Table IIIA-1. The relative Q that a cavity would have if constructed of, or plated with, the indicated metal is given in the third column of this table.

TABLE IIIA-1

Relative Resistivity and Q of Various Metals

Metal	Relative resistivity	Relative Q
Silver	.94	1.03
Copper	1.00	1.00
Gold	1.42	.84
Aluminum	1.64	.78
Brass	4.34	.48

Cavities plated with silver possess the highest value of Q. Ideally, a cavity constructed of brass has its Q doubled by silver plating. Whether the Q is increased to the extent indicated in the table depends on the quality of the plating (Chapter IV).

IIIA.3 Tuning of Cavities

The resonant frequency of a cavity operating in a specified mode is determined by the cavity size and shape. The frequency can be changed by altering one or both of these factors. This fact is used advantageously in the tuning of resonant cavities. The way in which the resonant frequency changes can be understood qualitatively from the following rule: if a cavity wall is pressed inward where the magnetic field predominates, the resonant frequency is increased; if the electric field predominates in this region, the resonant frequency decreases. If the wall is moved outward, the situation is reversed. Resonant cavities, therefore, are tuned by movement of one of the walls, or by movement of a rod projecting into the cavity. Convenient ways of tuning a cavity depend upon the shape of the cavity and upon the particular mode excited.

In some cases, a cavity used as an echo box is not tunable, but is constructed so that it will support many modes within the frequency range of interest. While the tuned cavity is designed insofar as possible to oscillate in only one mode, the untuned cavity is so designed that as many modes as possible are excited. Hence, as the exciting frequency changes, different modes are excited, and the cavity remains resonant. The untuned cavity has found some application, but cannot provide as much information on radar performance as can the tuned cavity (Ch. VI).

IIIA.4 Principle of Similitude

The principle of similitude (or scaling), which is important in cavity design, can be stated as follows: If the dimensions of a cavity are multiplied by the factor k, the resonant frequency changes by the factor 1/k, provided the resistivity of the walls is also changed by 1/k. If the Q of a cavity is extremely high, as is the case with echo boxes, the statement is approximately true even if the condition on the resistivity is omitted, which results in a more practical form of the principle. By this principle, new cavities of different dimensions can be built similar in shape to existing cavities of known characteristics, and the resulting characteristics of the new cavity can be predicted accurately. The Q of the cavity will not be invariant under this scaling process, however. The manner in which the Q will vary, for the case of the right circular cylindrical cavity, can be found as follows: The "mode shape factor" (MS) is defined as $\frac{Q\delta}{\lambda}$ (Sec. IIIB.3). For this cavity,

$$Q\,\frac{\delta}{\lambda} = F\left(\frac{D}{L}\right) = \text{a function of the ratio } \frac{D}{L} \quad \text{(App. III.2)}$$

where

D = cavity diameter
L = cavity length
λ = free space resonant wavelength
δ = skin depth.

The quantities D and L appear only in the form of the ratio $\frac{D}{L}$. If the cavity dimensions are altered by a factor K,

$$\frac{Q\delta}{\lambda} = F\left(\frac{KD}{KL}\right) = F\left(\frac{D}{L}\right)$$

This shows that the mode shape factor is not changed by scaling. However, $\delta \propto \frac{1}{\sqrt{f}} \propto \sqrt{\lambda}$, hence

$$\frac{Q\,\delta}{\lambda} \propto \frac{Q}{\sqrt{\lambda}}$$

If $\frac{Q\delta}{\lambda}$ is constant, it follows that

$$Q \propto \sqrt{\lambda}$$

The free-space wavelength in a cavity is proportional to the linear dimensions of the cavity; i.e., $\lambda \propto K$. Hence, $Q \propto \sqrt{K}$. Thus, as the cavity is scaled by a factor K, the Q will vary as $\sqrt{K}$.

The way in which the ringing time varies with the scaling factor K must also be considered, since the ringing time is of chief concern. Ringing time of a cavity is proportional to the ratio $\frac{Q}{f}$. However, since

$$Q \propto \sqrt{K}$$

and

$$f \propto \frac{1}{\lambda} \propto \frac{1}{K}$$

it follows that

$$t_r \propto \frac{Q}{f} \propto K^{3/2}$$

where t_r is the ringing time. If the cavity is scaled larger, the ringing time increases; if it is scaled downward, the ringing time decreases.

IIIA.5 Cavity Shapes

A closed cavity of any shape having conducting walls can be made to resonate at an infinite number of discrete frequencies. In designing an echo box, the modes and resonant frequencies must be known. However, they can be predicted mathematically for only a few simple shapes. In this section, the most commonly used shapes and their modes are described.

IIIA.5.1 Right Rectangular Prism Cavity

For this cavity, the resonant frequency is given by

$$f_r = \frac{c}{2}\sqrt{\left(\frac{\ell}{A}\right)^2 + \left(\frac{m}{B}\right)^2 + \left(\frac{n}{C}\right)^2}$$

where A, B and C are the cavity dimensions, c is the speed of light, and ℓ, m, and n define the modes. Physically, ℓ, m, and n indicate the number of half period sinusoidal variations of the field within the cavity along the dimensions A, B, and C, respectively. The formula does not distinguish between the TE and TM modes; hence, the $TE_{\ell mn}$ and $TM_{\ell mn}$ modes have the same resonant frequency. It is apparent that not more than one of the subscripts may have the value zero for any one mode.

Not only has every TE mode a companion degenerate TM mode, but in addition if A = B = C, there is a twelvefold degeneracy. The following modes are degenerate:

$TE_{\ell mn}$	$TM_{\ell mn}$
$TE_{n\ell m}$	$TM_{n\ell m}$
$TE_{mn\ell}$	$TM_{mn\ell}$
$TE_{nm\ell}$	$TM_{nm\ell}$
$TE_{\ell nm}$	$TM_{\ell nm}$
$TE_{m\ell n}$	$TM_{m\ell n}$

If only two of the dimensions are equal, there is a fourfold rather than an elevenfold degeneracy. This cavity has limited interest in echo box design, since only untuned echo boxes have this particular shape.

IIIA. 5. 2 Spherical Cavity

The spherical cavity is of interest from an academic standpoint since it is a cavity for which a solution of the field equations may be obtained. From a practical standpoint, however, the spherical cavity is of little use, being difficult to build and to tune.

Although the Q of even simply-shaped cavities is given by rather complex mathematical functions, Q is, as a first approximation, proportional to V/A where V is the cavity volume and A is the area of the interior surface. It would appear, then, that the spherical cavity yields higher Q's than other cavities, for equal volume. This approximation also indicates that cavities with re-entrant portions exhibit a lower Q.

IIIA. 5. 3 Cylindrical Cavity

The most widely used cavity for echo box design is the cylindrical cavity. Practical echo boxes have been confined almost exclusively to this shape, mainly because these cavities are easier to manufacture than other types and because it is easy to tune these cavities by moving one of the end plates. The cylindrical cavity possesses modes with high Q, and the properties of the cavity such as the field configurations, wall currents, and Q's can be obtained analytically.

Expressions for E and H for the different modes are given in Appendix III. 1. These expressions contain Bessel functions, and sine and cosine functions. The modes are designated by the subscripts ℓ, m, n, where ℓ is the order of the Bessel function, and m is the number of the zero of the Bessel function. In terms of the electromagnetic field quantities, ℓ is the number of cycles of variation of E_ρ or H_ρ in the θ direction, m is the number of times E_θ or H_θ is zero in the radial direction (excluding a zero on the cylinder axis), while n is the number of half-period variations of E_ρ or H_ρ in the axial direction. In the above notation, the subscript ρ refers to the direction radially outward from the cavity axis, and, when attached to E or H, refers only to that component of the E or H field which is directed in the radial direction. The subscript θ is an angle measured about the cylinder axis from an arbitrary radius (in the case of the circular cylinder), and when attached to E or H refers only to those components of E or H which are directed circularly about the cylinder axis. The subscript z is the distance measured from a reference plane (usually the end of the cavity) along the axial direction. H_z and E_z are, of course, the z-directed components of the H and E fields, respectively. Figure IIIA-1 illustrates this notation. As an example

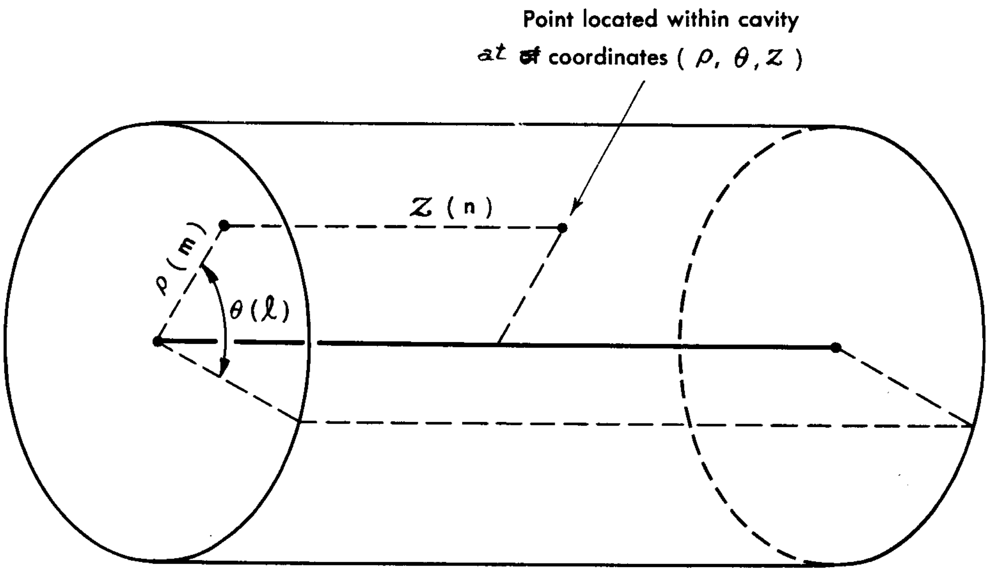


FIG. III A-1 GEOMETRY OF THE CYLINDRICAL CAVITY

of cylindrical cavity modes, consider the TE_{21} mode shown in Figure IIIC-3g. The figure represents the density and direction of current in the end plate of a circular cylindrical cavity operating in a TE_{21} mode (the third subscript would be meaningless here since it refers only to variations in the axial direction). The first subscript, 2, refers to the number of cycles of variation of E_ρ in the θ direction. Starting at an arbitrary radius and examining the magnitude and direction of the radial component of current as θ is varied, it can be seen that this current component varies through two complete cycles in 360°. Similarly, examination of the θ component of current along a radius including one of the outer nodes (light areas) shows that two points of zero current are traversed, one at the cylinder axis and one at the periphery. Since a zero at the cylinder axis is not counted, the second subscript will thus be 1. It should be noted here that the current streamlines in the end plates depict the E lines in the case of the TE modes. In the case of the TM modes the current streamlines depict the projection of the E lines on the cavity end plate.

The resonant frequency of a particular mode is given by:

$$f_r = \frac{c}{2}\sqrt{\left(\frac{2r_{\ell m}}{\pi D}\right)^2 + \left(\frac{n}{L}\right)^2}$$

where

D = diameter of cavity

L = length of cavity

$r_{\ell m}$ = m*th* root of the Bessel function of order ℓ in the case of TM modes, i.e., the m*th* root of $J_\ell(x) = 0$

$r_{\ell m}$ = m*th* root of the derivative of the Bessel function of order ℓ for TE modes, i.e., the m*th* root of $J'_\ell(x) = 0$

c = speed of light

A special case for TM modes occurs when n = 0. In this case the electric field has no transverse component, the electric lines being entirely in the axial direction. The resonant frequency does not depend upon the cavity length and the end plates may be moved without altering the resonant frequency, which is given by:

$$f_{\ell m0} = \frac{c r_{\ell m}}{2\pi D}$$

That the resonant frequency should not change for this mode can also be anticipated from the rule relating the frequency change to the relative values of electric and magnetic field where the cavity wall is altered (Sec. IIIA.3). The electric field, being purely axial, is necessarily the same for all cross-sections normal to the axis. Since the electric field is not a function of position along the axis, neither can the magnetic field be, because of the way these two quantities are related. Hence, the over-all or average magnetic field must have the same strength on any cross-section; likewise with the electric field. Therefore, on no cross-section can either predominate over the other. Moving one of the end plates normal to the cylinder axis, therefore, cannot alter the resonant frequency. For TE modes, the value n = 0 is not permissible, because of the boundary conditions imposed on the electric vector.

IIIA.5.4 Coaxial Cavity

The coaxial resonator, consisting of two coaxial cylinders, has found use in echo boxes for low frequency radar, of the order of 500 mcs, since at these low frequencies the size of cylindrical cavities is prohibitively large, while the Q for such cavities would be far in excess of what is needed. For low frequency echo boxes, the coaxial cavity is of convenient size and possesses sufficient Q to give adequate ringing time. Coaxial cavities have the additional advantage that the plunger movement needed to cover a given frequency band is less than that for the cylindrical cavity.

The reduced size at a given frequency for the coaxial cavity is possible because of the existence of a type of mode which does not exist in cylindrical cavities. These modes, designated TEM modes, have the property that neither the E nor H fields have longitudinal components. The modes may be designated by the expression TEM_{00n} where n, as before, is the number of half-period variations along the axial direction. On occasion, these modes have been designated TM_{00n}. These modes have resonant frequencies which are independent of the radii of the inner and outer conductors and depend only on the the cavity length.

In addition to the fundamental or TEM modes the coaxial cavity possesses TE and TM modes analogous to the modes in the cylinder. The TEM_{001} mode has, however, a lower resonant frequency than any other mode, and it is this factor which permits the coaxial cavity to be smaller than a cylindrical cavity for a given frequency.

The resonant frequency of the coaxial cavity for TE and TM modes is given by

$$f_r = \frac{c}{2}\sqrt{\left(\frac{2r_{\ell m}}{\pi D}\right)^2 + \left(\frac{n}{L}\right)^2}$$

which is the same expression as the one for the cylindrical case, except here $r_{\ell m}$ is determined by the roots of the equation:

$$\frac{J_\ell\,(r_{\ell m})}{Y_\ell\,(r_{\ell m})} - \frac{J_\ell\,(Nr_{\ell m})}{Y_\ell\,(Nr_{\ell m})} = 0 \quad \text{for TM waves}$$

$$\frac{J'_\ell\,(r_{\ell m})}{Y'_\ell\,(r_{\ell m})} - \frac{J'_\ell\,(Nr_{\ell m})}{Y'_\ell\,(Nr_{\ell m})} = 0 \quad \text{for TE waves}$$

where J and Y are Bessel functions of the first and second kind, respectively, and N is the ratio of the diameter of the outer cylinder to that of the inner. For the TEM modes, the resonant frequency is

$$f = \frac{cn}{2L} \qquad n = 1, 2, 3, \ldots\ldots$$

IIIA.5.5 Hybrid Cavity

The partial coaxial or hybrid cavity, which is intermediate between the coaxial cavity and the cylindrical cavity, has a central conductor which extends only partially into the cavity, as illustrated in Figure IIIA-2. When operated in the fundamental or TEM mode, the hybrid cavity can be regarded as a coaxial line short-circuited at one end and open at the other. For resonance the central conductor must thus be approximately a quarter wavelength long. However, since the cavity is actually closed at both ends, there will be a capacitive effect at the open circuit end, the

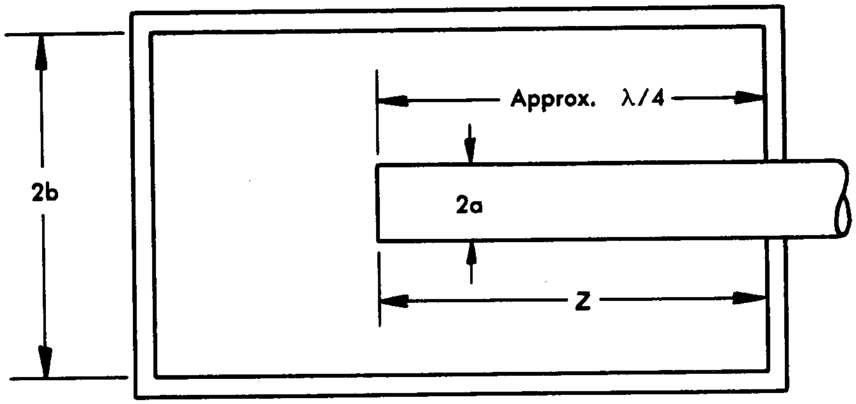


FIG. III A-2 THE QUARTER-WAVE COAXIAL CAVITY

capacitance being between the central conductor and the side walls. The cavity thus behaves as a capacitively-loaded coaxial line, and the length of the central conductor will not be exactly a quarter wave.

The hybrid cavity has not been completely solved analytically, but limited analysis can be made by regarding the cavity as an LRC circuit and finding its equivalent inductance and capacitance. Also, the cavity may be treated (though with difficulty) by dividing the cavity into regions which have either the shape of the right circular cylinder, or of the full coaxial cavity, for which the solutions are known. The infinite series solutions obtained are matched at the boundaries (Ref. 4, 5).

The design of full and partial coaxial cavities is described more extensively in Section III. F.

IIIB MODE CHARTS FOR THE CYLINDRICAL CAVITY

IIIB.1 Construction of Mode Charts

IIIB.1.1 Equation for the Mode Lines

The expression for the resonant frequency of a cylindrical cavity given in the previous section is somewhat unwieldy. Its utility can be greatly increased if it is rewritten in the form

$$(f_r D)^2 = \left(\frac{c r_{\ell m}}{\pi}\right)^2 + \left(\frac{c}{2}\right)^2 n^2 \left(\frac{D}{L}\right)^2$$

This equation, in turn, can be written as

$$(f_r D)^2 = A + Bn^2 \left(\frac{D}{L}\right)^2$$

where

$$A = \left(\frac{c r_{\ell m}}{\pi}\right)^2$$

$$B = \left(\frac{c}{2}\right)^2$$

If particular values of $r_{\ell m}$ and n are selected, a plot of $(f_r D)^2$ versus $\left(\frac{D}{L}\right)^2$ yields a straight line whose intercept on the $(f_r D)^2$ axis is $\left(\frac{c r_{\ell m}}{\pi}\right)^2$ and whose slope is $\left(\frac{cn}{2}\right)^2$. Different values of $r_{\ell m}$ and n give rise to different lines. A plot consisting of lines generated in this way is called a "mode chart". Examples of mode charts are shown in Figure IIIB-1 and in the large charts in the pocket on the back cover of this report.

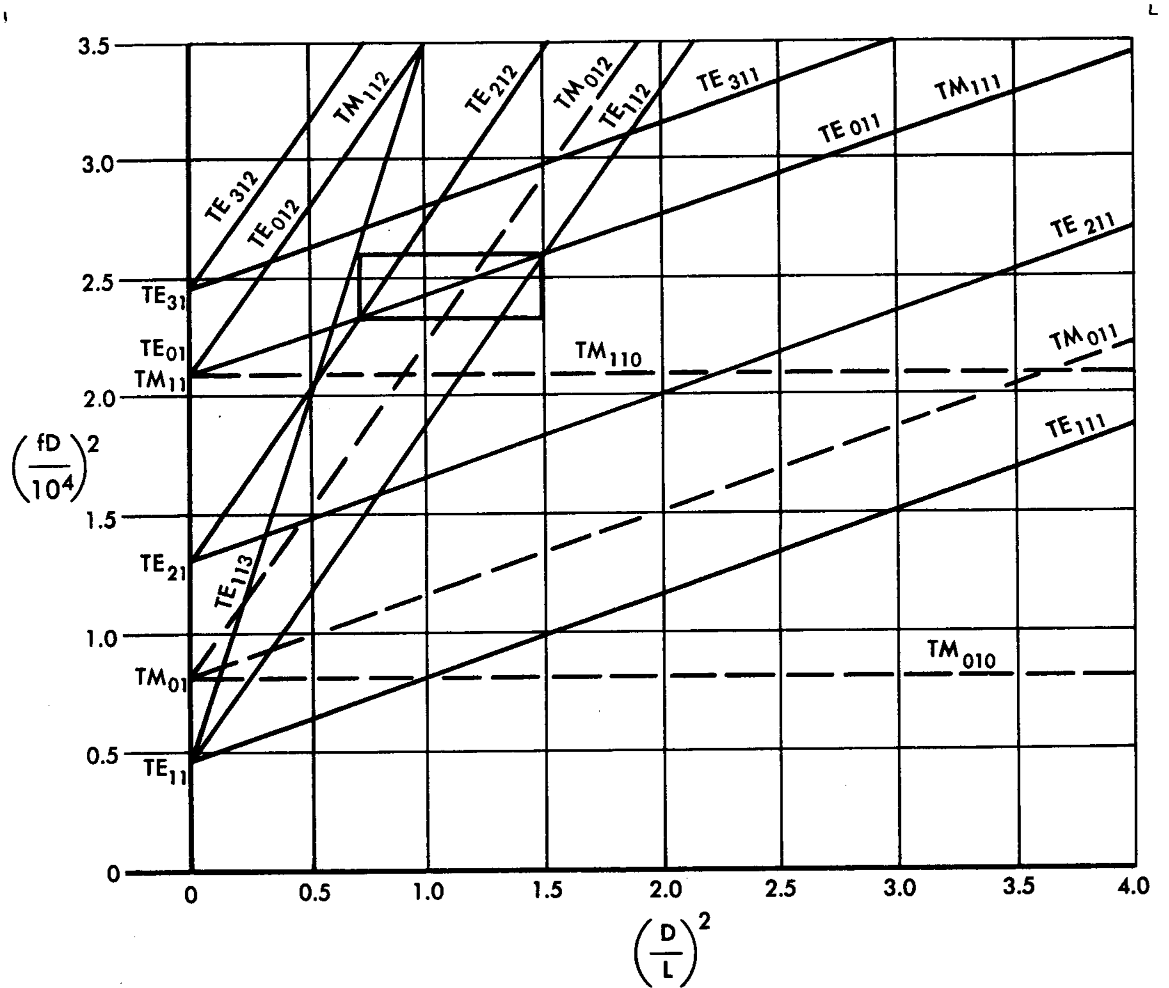


FIG. III B-1 SMALL PORTION OF A MODE CHART FOR A CIRCULAR CYLINDRICAL CAVITY

A mode chart reveals a great deal of information about the characteristics of a cylindrical cavity. Since the "y" intercept of the mode lines is determined by the value of $r_{\ell m}$, all TE modes which have the same ℓ and m value intercept the y axis at the same point. (A similar statement can be made about the TM modes). All modes with the same value for n have identical slopes.

Mode lines which have common y intercepts are termed "families". These families are designated $TE_{\ell m}$ or $TM_{\ell m}$. For example, the family of lines which are of the TE type with $\ell = 1$ and $m = 2$ is called the TE_{12} family. It should be noted that the TE_{0m} and TM_{1m} families are coincident; i.e., for a given n, the TE_{0mn} mode and the TM_{1mn} mode are both represented by the same line on the mode chart. This degeneracy results from the fact that $J_0'(X) = -J_1(X)$. Hence if a cylindrical cavity is resonant to one of the two modes it will also be resonant to the other. This fact is significant because cylindrical echo boxes are invariably designed to operate in the TE_{01n} family. The presence of degenerate modes in echo boxes is undesirable and means must be found to suppress the TM_{11n} family.

In constructing the mode charts appearing in this report it has been found convenient to use $\left(\frac{fD}{10^4}\right)^2$ as the ordinate because this quantity provides a more suitable scale. The equation actually graphed, therefore, is

$$\left(\frac{f_r D}{10^4}\right)^2 = \frac{A}{10^{20}} + \frac{B}{10^{20}} n^2 \left(\frac{D}{L}\right)^2 = A' + B' n^2 \left(\frac{D}{L}\right)^2 \qquad (i)$$

where

f_r is in mcs

D and L are in inches

$B = 0.34799 \times 10^{20}$

$A = 0.141034 \times 10^{20} \times (r_{\ell m})^2$ for air at 25°C. and 60 per cent relative humidity

In addition to the mode lines it is sometimes useful to include lines of $Q\sqrt{f}$ = a constant on the mode charts (Ref. 6). The construction and use of such lines is explained in Section IIIB. 3.

IIIB. 1. 2 Construction of Expanded Sections of Mode Charts

Since there is an infinite number of modes, it is not possible to construct a complete mode chart, and in any chart covering a large region the accuracy of reading is necessarily low. Therefore, it is generally necessary for the designer to construct his own mode chart covering in detail the region in which he is interested. The two points needed to determine the exact location of a particular mode line may be found by solving Equation (1).

- - -

Example:

Suppose an echo box is being considered to operate in the TE_{011} mode between the points of intersection of this mode with the TE_{212} and the TE_{112} modes. This region is shown as a small rectangle in Figure IIIB-1. It is of no importance to the example that this region is not a wise choice.

The coordinates of the intersection points of the modes in question are known only approximately from the chart; in order to find them exactly it is necessary to solve the equations for the mode lines simultaneously. The values for the quantities A and B for some of the more common modes are given in Tables IIIB-1 and IIIB-2. If additional values are desired, they may be computed from the values of Bessel roots given in Table

TABLE IIIB-1

Intercepts of the Mode Families on the $\left(\frac{f\ D}{10^4}\right)^2$ Axis, in Order of Increasing Values

TE Modes			TM Modes		
Mode	$r_{\ell m}$	A x 10^{-20}	Mode	$r_{\ell m}$	A x 10^{-20}
TE_{11}	1.84118	0.4781	TM_{01}	2.40483	0.81563
TE_{21}	3.05424	1.3156	TM_{11}	3.83171	2.0707
TE_{01}	3.83171	2.0707	TM_{21}	5.1356	3.7197
TE_{31}	4.20119	2.4893	TM_{02}	5.52008	4.2975
TE_{41}	5.31755	3.9879	TM_{31}	6.38016	5.7410
TE_{12}	5.33144	4.0088	TM_{12}	7.01559	6.9415
TE_{51}	6.41562	5.8050	TM_{41}	7.58834	8.1212
TE_{22}	6.70613	6.3426	TM_{22}	8.41724	9.9923
TE_{02}	7.01559	6.9415	TM_{03}	8.65373	10.5617
TE_{61}	7.50127	7.9359	TM_{51}	8.77148	10,8511
TE_{32}	8.01524	9.0606	TM_{32}	9.76102	13.4374
TE_{13}	8.53632	10.2770	TM_{61}	9.93611	13.9238
TE_{71}	8.57784	10.3772	TM_{13}	10.17347	14.5971
TE_{42}	9.28240	12.1520	TM_{42}	11.0647	17.267
TE_{81}	9.64742	13.1265	TM_{71}	11.0864	17.334
TE_{23}	9.96947	14.0175	TM_{23}	11.6198	19.043
TE_{03}	10.17347	14.5970	TM_{04}	11.7915	19.609
TE_{52}	10.5199	15.608			
TE_{91}	10.7114	16.181			
TE_{33}	11.3459	18.155			
TE_{14}	11.7060	19.326			
TE_{62}	11.7349	19.422			
TE_{10-1}	11.7709	19.541			
TE_{43}	12.6819	22.683			

TABLE IIIB-2

Slopes of the Mode Lines

n	slope ($B n^2$)
1	0.34799
2	1.3920
3	3.1319
4	5.5678
5	8.6998
6	12.528
7	17.052
8	22.271
9	28.187
10	34.799
11	42.107
12	50.111
13	58.810
14	68.206
15	78.298
16	89.085
17	100.57
18	112.75
19	125.62
20	139.20
21	153.46
22	168.43
23	184.09
24	200.44
25	217.49

[redacted]

TABLE IIIB-3

Values of the Bessel Function Zero ($r_{\ell m}$) for the First 180 Modes in a Right Circular Cylinder Resonator[1]

	$r_{\ell m}$	Mode[2]
1	1.8412	TE 11
2	2.4048	TM 01
3	3.0542	TE 21
4	3.8317	TM 11
5	3.8317	TE 01
6	4.2012	TE 31
7	5.1356	TM 21
8	5.3176	TE 41
9	5.3314	TE 12
10	5.5201	TM 02
11	6.3802	TM 31
12	6.4156	TE 51
13	6.7061	TE 22
14	7.0156	TM 12
15	7.0156	TE 02
16	7.5013	TE 61
17	7.5883	TM 41
18	8.0152	TE 32
19	8.4172	TM 22
20	8.5363	TE 13
21	8.5778	TE 71
22	8.6537	TM 03
23	8.7715	TM 51
24	9.2824	TE 42
25	9.6474	TE 81
26	9.7610	TM 32
27	9.9361	TM 61
28	9.9695	TE 23
29	10.1735	TM 13
30	10.1735	TE 03
31	10.5199	TE 52
32	10.7114	TE 91
33	11.0647	TM 42
34	11.0864	TM 71
35	11.3459	TE 33
36	11.6198	TM 23
37	11.7060	TE 14
38	11.7349	TE 62
39	11.7709	TE 10-1
40	11.791⑤	TM 04
41	12.2251	TM 81
42	12.3386	TM 52
43	12.6819	TE 43
44	12.8265	TE 11-1
45	12.9324	TE 72
46	13.0152	TM 33
47	13.1704	TE 24
48	13.3237	TM 14
49	13.3237	TE 04
50	13.3543	TM 91
51	13.5893	TM 62
52	13.8788	TE 12-1
53	13.9872	TE 53
54	14.115⑤	TE 82
55	14.372⑤	TM 43
56	14.475⑤	TM 10-1
57	14.5858	TE 34
58	14.7960	TM 24
59	14.8213	TM 72
60	14.8636	TE 15
61	14.9284	TE 13-1
62	14.9309	TM 05
63	15.2682	TE 63
64	15.2867	TE 92
65	15.5898	TM 11-1
66	15.7002	TM 53
67	15.9641	TE 44
68	15.9754	TE 14-1
69	16.0378	TM 82
70	16.2235	TM 34
71	16.347⑤	TE 25
72	16.4479	TE 10-2
73	16.4706	TM 15
74	16.4706	TE 05
75	16.5294	TE 73
76	16.6982	TM 12-1
77	17.0038	TM 63
78	17.0203	TE 15-1
79	17.2412	TM 92
80	17.3128	TE 54
81	17.6003	TE 11-2
82	17.6160	TM 44
83	17.7740	TE 83
84	17.7887	TE 35
85	17.8014	TM 13-1
86	17.9598	TM 25
87	18.0155	TE 16
88	18.0633	TE 16-1
89	18.0711	TM 06
90	18.2876	TM 73
91	18.4335	TM 10-2
92	18.6374	TE 64
93	18.7451	TE 12-2
94	18.9000	TM 14-1
95	18.9801	TM 54
96	19.0046	TE 93
97	19.1045	TE 17-1
98	19.1960	TE 45
99	19.4094	TM 35
100	19.5129	TE 26
101	19.554⑤	TM 83
102	19.6159	TM 16
103	19.6159	TE 06
104	19.6160	TM 11-2
105	19.8832	TE 13-2
106	19.9419	TE 74
107	19.9944	TM 15-1
108	20.1441	TE 18-1
109	20.2230	TE 10-3
110	20.3208	TM 64
111	20.575⑤	TE 55
112	20.7899	TM 12-2
113	20.8070	TM 93
114	20.8269	TM 45
115	20.9725	TE 36
116	21.0154	TE 14-2
117	21.0851	TM 16-1
118	21.1170	TM 26
119	21.1644	TE 17
120	21.1823	TE 19-1
121	21.2116	TM 07
122	21.2291	TE 84
123	21.4309	TE 11-3
124	21.641⑤	TM 74
125	21.9317	TE 65
126	21.9562	TM 13-2
127	22.0470	TM 10-3
128	22.1422	TE 15-2
129	22.1725	TM 17-1
130	22.2178	TM 55
131	22.2191	TE 20-1
132	22.4010	TE 46
133	22.5014	TE 94
134	22.5827	TM 36
135	22.6293	TE 12-3
136	22.6716	TE 27
137	22.7601	TM 17
138	22.7601	TE 07
139	22.9452	TM 84
140	23.1158	TM 14-2
141	23.2548	TE 21-1
142	23.2568	TM 18-1
143	23.2643	TE 16-2
144	23.2681	TE 75
145	23.2759	TM 11-3
146	23.5861	TM 65
147	23.7607	TE 10-4
148	23.8036	TE 56
149	23.8194	TE 13-3
150	24.0190	TM 46
151	24.1449	TE 37
152	24.2339	TM 94
153	24.2692	TM 15-2
154	24.2701	TM 27
155	24.2894	TE 22-1
156	24.3113	TE 18
157	24.3382	TM 19-1
158	24.3525	TM 08
159	24.3819	TE 17-2
160	24.4949	TM 12-3
161	24.5872	TE 85
162	24.9349	TM 75
163	25.0020	TE 14-3
164	25.008⑤	TE 11-4
165	25.1839	TE 66
166	25.3229	TE 23-1
167	25.4170	TM 16-2
168	25.4171	TM 20-1
169	25.4303	TM 56
170	25.4956	TE 18-2
171	25.5094	TM 10-4
172	25.5898	TE 47
173	25.7051	TM 13-3
174	25.7482	TM 37
175	25.8260	TE 28
176	25.8912	TE 95
177	25.9037	TM 18
178	25.9037	TE 08
179	26.1778	TE 15-3
180	26.2460	TE 12-4

[1] Wilson, Schramm, Kinzer (Ref. 6) used by permission.

[2] Values less than 16.0 are abridged from six-place values and are believed to be correct; values more than 16.0 are abridged from five-place values and may be in error by one unit in fourth decimal place. ⑤ in fourth place indicates that higher value is to be used in rounding off to fewer decimals.

[redacted]

IIIB-3. The equations for the modes concerned in the example are given below; for simplicity $\left(\frac{fD}{10^4}\right)^2$ has been replaced by y and $\left(\frac{D}{L}\right)^2$ by x.

$$TE_{011}: \quad y = 2.0707 + 0.34799x$$

$$TE_{212}: \quad y = 1.3156 + 1.3920x$$

$$TE_{112}: \quad y = 0.47810 + 1.3920x$$

It is of interest to know the coordinates of other modes which pass through this region because in an actual echo box design these modes may interfere with proper operation. It can be seen from Figure IIIB-1 that the TM_{012} mode is present; in addition, it is possible that the TE_{113} mode may also be present. The equations for these modes are:

$$TM_{012}: \quad y = 0.81563 + 1.3920x$$

$$TE_{113}: \quad y = 0.47810 + 3.13191x$$

It is evident that no other modes can be near the region of interest.

Solving the equation for the TE_{011} mode simultaneously with that for the TE_{212} mode, the coordinates of intersection are found to be:

$$x = 0.7233, \quad y = 2.3224$$

Similarly, the intersection of the TE_{011} line with the TE_{112} is:

$$x = 1.5255, \quad y = 2.6016$$

Interference from the TE_{212} mode will persist until the line representing it passes beyond the boundary of the rectangle. The y-coordinate of this

[redacted]

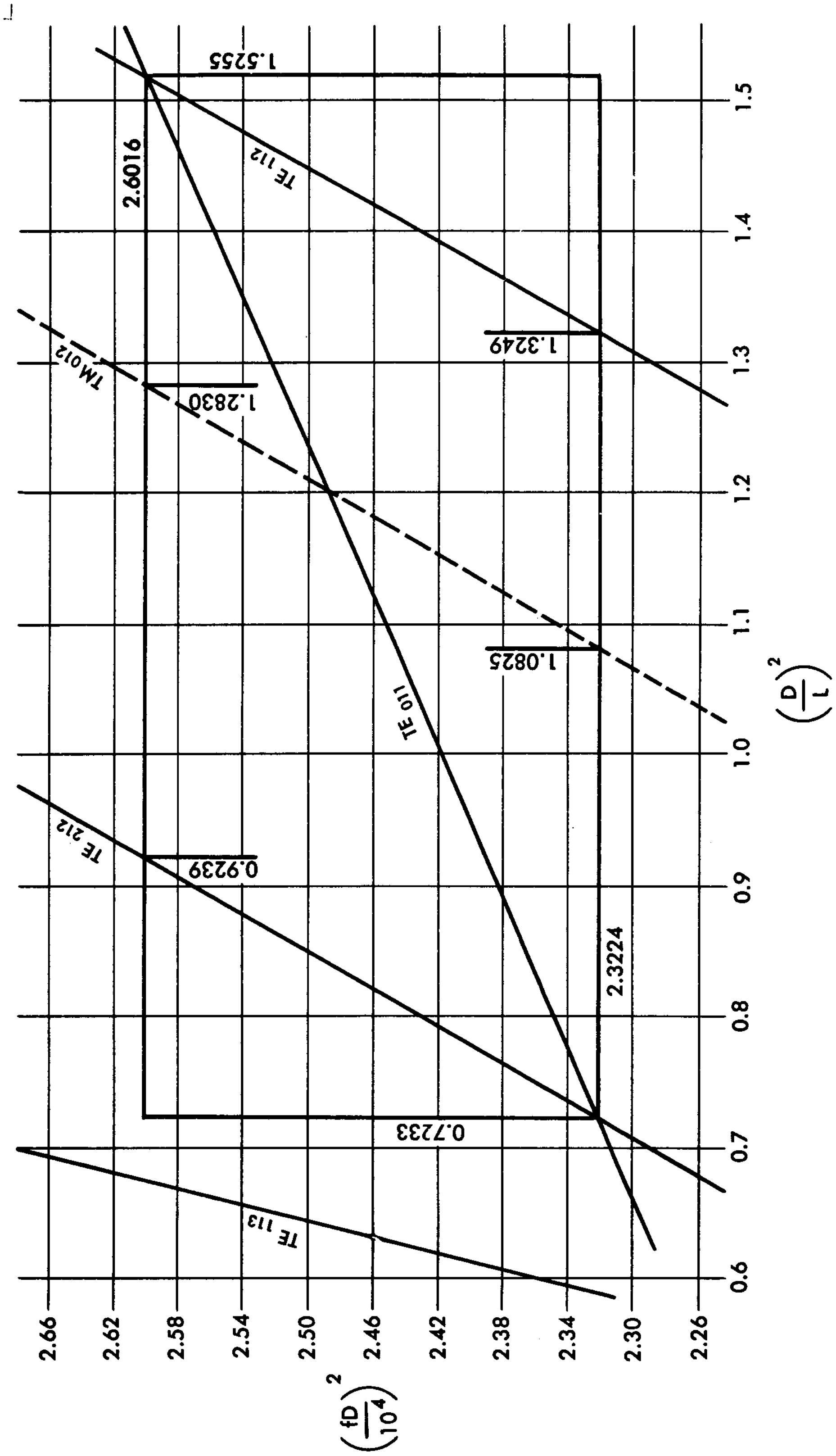


FIG. III B-2 DETAILED PORTION OF MODE CHART OF FIG. III B-1

[redacted]

point has already been found: it is 2.6016; the x-coordinate is found by substituting this value into the equation for the TE_{212} mode. The result is x = 0.9239. Similarly, the coordinates of the intersection of the boundary with the TE_{112} may be found. They are x = 1.3249 and y = 2.3224. The TM_{012} mode also passes through the area. The coordinates of the two points, found in the same way, are:

Lower: x = 1.0825, y = 2.3224

Upper: x = 1.2830, y = 2.6016

The TE_{113} mode intersects the line y = 2.6016 at the point x = 0.6780; it therefore does not pass through the rectangle but just misses the corner. The completed detailed mode chart is shown in Figure IIIB-2.

IIIB. 2 Cylindrical Cavity Modes

The number of modes of oscillation possible in any given cavity up to a particular frequency f_o is given (Ref. 6) approximately by

$$N = \frac{8\pi}{3c^3} V f_o^3$$

where

N = number of modes

V = volume of cavity in cubic meters

c = velocity of light in meters per second

f_o = frequency in cycles per second

which suggests that it would be desirable to keep the cavity volume as small as is consistent with other requirements if the requirement of operation in a single mode is to be met. From the mode chart (Fig. IIIB-1) it is also apparent that the mode lines become much more numerous in that region near the $(fD)^2$ axis and at large values of $(fD)^2$; it should be realized that all mode charts are incomplete in this region. Thus a cavity designed to operate in one of the "higher" echo box modes (TE_{01n} modes with large values of n) is in considerable danger of being able to support a great many modes besides the desired one within the frequency range of interest.

Of the numerous families of modes present in cylindrical cavities, the only one which has found application in echo box design is the TE_{01}. This family is the most satisfactory in spite of its degeneracy with the TM_{11} family. The TE_{0m} series of families was chosen since, for this series, there are no axial currents in the cavity side walls and no radial currents in the end plates. This property is shown in Section IIIC by the graphs of these currents for various modes (Fig. IIIC-2). Therefore, the cavity end plates need not make electrical contact with the side walls and in common practice are usually made slightly smaller than the cavity internal diameter, leaving a small gap. This gap eliminates the need for a sliding electrical contact for the movable end plate by which cavity tuning is accomplished. Good sliding contacts for microwave frequencies are very difficult to design and manufacture. In addition, the gap serves to suppress, to a great extent, other modes which do require a flow of current between end plate and cavity walls. This is one of the simplest and most important ways of suppressing undesired modes.

The preceding points out some exceedingly important advantages of the TE_{0m} families. Of this series, however, the TE_{01} family has added advantages. This mode has, almost without exception, a higher Q for a given volume than any other mode, and is free from interference by other modes. In addition, higher TE_{0m} modes require larger cavities for a given frequency.

IIIB.3 Use of the Mode Chart[1]

The mode chart is the prime tool for the designer of resonant cavities. Although it is sufficient to use it in the form discussed in Section IIIB.1, its utility can be increased by adding several more lines.

[1]The material in this section is based on Reference 6.

In designing a cavity, a TE_{01n} mode must first be selected in which the cavity will operate. With the design restricted to the TE_{01n} modes, it is possible to place additional information on the mode chart which may aid in selecting a suitable mode. One such addition is the contour lines defined by the equation

$$Q\sqrt{f} = \text{a constant}$$

The Q for the TE_{01n} modes in a cylindrical cavity is given by the expression

$$Q = 0.610 \frac{\lambda \left(1 + 0.168\left(\frac{D}{L}\right)^2 n^2\right)^{3/2}}{\delta \left(1 + 0.168\left(\frac{D}{L}\right)^3 n^2\right)} \qquad (2)$$

If the mode shape factor, MS, is defined by the relation

$$MS = \frac{Q\delta}{\lambda} = \frac{0.610\left[1 + 0.168\left(\frac{D}{L}\right)^2 n^2\right]^{3/2}}{1 + 0.168\left(\frac{D}{L}\right)^3 n^2} \qquad (3)$$

it will depend only on the mode of operation and the relative dimensions of the cavity.

Since the skin depth is defined by the relation (Sec. IIIA.2)

$$\delta = \frac{1}{2\pi}\sqrt{\frac{10^3 \rho}{f}} ,$$

since echo box cavities are nearly always silver plated ($\rho = 1.620 \times 10^{-6}$ ohm-cm), and since $\lambda = \frac{c}{f}$, the mode shape equation becomes

$$\frac{Q\sqrt{f}}{10^6} = 2.85 \frac{\left[1 + 0.168\left(\frac{D}{L}\right)^2 n^2\right]^{3/2}}{1 + 0.168\left(\frac{D}{L}\right)^3 n^2} \qquad (4)$$

If $\frac{Q\sqrt{f}}{10^6}$ is assigned a numerical value, and a value of n is selected, the expression can be solved for $\frac{D}{L}$. By using different values of n, a series of discrete points is obtained, each point falling on a TE_{01n} mode line, and a curve may then be drawn through the points. Other contour lines may be produced in the same manner. The form of Equation (4) is not the most amenable one for use in constructing these lines. A more suitable form may be obtained by expressing it in terms of the mode chart coordinates, $(f\ D)^2$ and $\left(\frac{D}{L}\right)^2$. This can be done by combining Equation (4) with the TE_{01n} mode line equation and eliminating n to obtain

$$\frac{D}{L} = \left(\frac{0.953}{\left(\frac{Q\sqrt{f}}{10^6}\right)} (f\ D)^3 - 1\right)\left(\frac{1}{0.483(f\ D)^2 - 1}\right) \qquad (5)$$

The $\frac{Q\sqrt{f}}{10^6}$ lines appearing on the large mode charts are plots of this equation. Each line represents a specific value for $\frac{Q\sqrt{f}}{10^6}$, and thus may be interpreted as a contour of constant $Q\sqrt{f}$. This interpretation is open to criticism, however, since the mode shape equation is physically meaningful only for integral values of n; i.e., only on the TE_{01n} mode lines. However, they may be plotted on the mode chart and used to advantage if their limitations are understood. In making use of these curves, it must therefore be kept in mind that:

1. The curves have significance only at the points where they

cross the TE_{01n} mode lines. The curves are of no significance between these mode lines, nor can they be used with any other mode family.

2. The curves are approximately correct for silver plated cavities and are not valid for any other cavity surface material.

A final curve to be put on the mode chart is the maximum $\frac{Q}{V}$ line. A cavity operating on a mode at the intersection point of this curve with the mode line will have the maximum ratio of Q to volume that is possible for that mode. This line is defined by the equation (Ref. 8)

$$(f\,D)^2 \left(\frac{D}{L}\right) = 3.11 \times 10^8$$

where, again, f is in mcs, D and L are in inches.

The maximum $\frac{Q}{V}$ curve is also plotted on the large mode charts in the back of this report. These charts show the TE modes commonly used in echo box design, and cover the most commonly used values of $\left(\frac{D}{L}\right)^2$ and $(f\,D)^2$. TM modes are not shown, because their inclusion would have increased the complexity of the charts to a point where their readability, would be greatly reduced. The cavity designer should, however, include all TM modes in his detailed mode chart covering the region in which he is interested.

IIIB.4 Designing the Cavity

In designing an echo box cavity, there will be a minimum permissible Q, which will either be stated in the specifications or obtainable from the ringing time called for in the specifications. When the frequency range of the echo box is specified, the $Q\sqrt{f}$ contours become lines of constant Q. A region of the mode chart for which the Q will be adequate can then be obtained and selection of a design restricted to this region. In general, it will be desirable to remain in the vicinity of the maximum $\frac{Q}{V}$ line since, other things being equal, a small cavity is preferable to a larger one.

In an echo box cavity, the diameter will be fixed and tuning will be done by movement of one of the end plates; that is, by altering the length of the cavity. The cavity, at any given setting of the tuning plate, will have dimensions and resonant frequency related by the mode equation $(f\,D)^2 = A + B\,n^2 \left(\frac{D}{L}\right)^2$, for the mode in which it operates. Since the diameter is fixed, the mode equation becomes an equation with f^2 and $\left(\frac{1}{L}\right)^2$ as variables. If the coordinates of the point representing the minimum frequency position of the echo box are $(f_1 D)^2$ and $\left(\frac{D}{L_1}\right)^2$ and if the maximum frequency point is $(f_2 D)^2$ and $\left(\frac{D}{L_2}\right)^2$, a rectangle can be inscribed on the mode chart with the mode line as diagonal, with the sides parallel to the coordinate lines, and with these points at diagonally opposite corners (see Fig. IIIB-1). This rectangle is termed the "operating rectangle" for the echo box. As the cavity is tuned through its frequency range, the cavity dimensions and resonant frequency will satisfy all points on the mode line segment inside the rectangle in succession.

Usually there are mode lines other than the operating mode line within the rectangle, representing extraneous modes. They are quite important, since these modes interfere with the operation of the echo box unless suppressed. There are two types of extraneous mode lines, those that intersect the operating mode line within the rectangle, and those that do not. The former are called crossovers, while the latter are called interfering modes. The lines that intersect the operating mode are of particular significance, for such a point of intersection means that both modes resonate at that frequency. Since different modes have different Q's the Q (and hence the ringing time) behaves erratically at this point. Mode crossings should be avoided if possible. The non-crossing modes should be kept out of the operating rectangle because they lead to ambiguity. Their presence means that at a given dial setting there may be two or more frequencies within the chosen frequency band at which the cavity will be resonant, and conversely, for a given frequency, there may be two or more dial settings at which the cavity will be resonant. If the presence of such interfering modes cannot be avoided, means will have to be taken to prevent their excitation. The techniques for doing so are discussed in Section IIIC.

It is apparent that designing a tunable echo box first involves finding a suitable operating rectangle on the mode chart. In finding this rectangle the first step is to find a region which is relatively free from extraneous modes and determine whether the other modes which are present can be suppressed effectively. Assuming that such a region has been found, the diameter of the cavity cylinder is then determined. A point is selected on the mode chart to be the point for which the minimum frequency occurs. The ordinate of this point, $(f_1 D)^2$, is read from the chart. Knowing the specified value of f_1, the required diameter is then known. Having found the diameter, the corresponding cavity length is found from the abscissa of the point, which is $\left(\frac{D}{L_1}\right)^2$. The coordinates of the point representing the maximum frequency are found in the same way. The size of the operating rectangle depends upon the frequency range which the echo box is required to cover, upon the mode selected, and upon the portion of the mode line selected for use. The greater the required tuning range, the greater the size of the operating rectangle, and the greater the number of extraneous modes. Hence a wide tuning range increases the difficulties of design. On a particular mode and in a particular region, the maximum tuning range permissible is set either by the nearest extraneous modes which must be excluded from the rectangle or by the nearest mode crossings which must be avoided.

In using the mode chart, certain of its properties should be noted.

1. The quantity D appears both in the ordinate and in the abscissa.

2. In general, the mode density increases to the left and in an upward direction. Larger values of n mean more interfering modes.

3. Since the size of the operating rectangle on the mode chart is a function of the mode selected and of position along the mode

line, it is not possible to select a suitable area simply by choosing an appropriate rectangle and sliding it about on the mode chart until its diagonal fits on a convenient mode line between two crossing modes, as has occasionally been suggested.

IIIB.5 Use of the Mode Chart in Scaling

An interesting application of the mode chart is its use in illustrating the principle of similitude. Suppose that a new cavity is to be designed on the same operating rectangle as an existing echo box, except that the resonant frequency is to be altered by a factor k. If the low frequency point on the rectangle has the coordinates $(f_1 D)^2$ and $\left(\frac{D}{L_1}\right)^2$, then, for $(f_1 D)^2$ to remain unchanged as f_1 is changed to kf_1, D must be altered by the factor $\frac{1}{k}$. Likewise, for $\left(\frac{D}{L_1}\right)$ to remain unchanged, L_1 must become $\frac{L_1}{k}$. Hence, to alter the frequency by a factor k, multiply all dimensions by $\frac{1}{k}$. This is just the principle of similitude discussed in Section IIIA.4. The above procedure shows that if a cavity is scaled in accordance with the principle of similitude, its operating position on the mode chart will be unchanged. Furthermore, the $Q\sqrt{f}$ lines appearing on the mode chart show that $Q\sqrt{f}$ has a value at any point on the mode chart which does not change as a cavity is scaled. Hence, as $f \rightarrow k\,f$, $Q \rightarrow \frac{1}{\sqrt{k}}\,Q$. (Sec. IIIA.4).

IIIC CAVITY COUPLING AND MODE SUPPRESSION TECHNIQUES

IIIC. 1 Coupling Devices

To make a resonant cavity into a practical echo box, a coupling device must be provided with which to introduce energy into the echo box during the transmitter pulse and to remove energy during the ringing. A second coupling device must also be provided to remove a small amount of energy to actuate the resonance indicator. Figure IIIC-1 shows typical devices for coupling an echo box to a coaxial line and to rectangular wave-guides. Figure IIIC-1a depicts coupling by means of a capacitive probe between a half wave TEM mode coaxial resonator and a coaxial line. This probe is the equivalent of a very short antenna, which provides electric or capacitive coupling to the field in the echo box. Probe coupling is useful only in providing coupling to modes in which the electric field terminates on the surface of the cavity in the vicinity of the coupling device; in practice it has been employed only with coaxial resonators. Figure IIIC-1b depicts a TE_{0mn} mode cavity coupled to a coaxial line by means of a loop. Note that the loop is placed in a plane normal to the axis of the echo box. This is the simplest form of input coupling for a cylindrical echo box, because a coaxial line is usually employed to connect test equipment to a radar, and because the loop-type coupling permits transition from the coaxial line to the echo box with a minimum of difficulty. The use of such inductive loops is limited by the fact that the loop does not provide perfect magnetic coupling; thus, it contributes a certain amount of electric coupling. This electric coupling causes excitation of TM and extraneous TE modes to some extent, and since TM modes are inevitably present in TE_{0mn} echo boxes, loop coupling is generally permissible only when it is certain that these modes are thoroughly suppressed by other methods. In practice, inductive loop coupling is used most successfully in coaxial resonators and in TE_{011} type resonators, although it has occasionally been used with cavities employing higher TE_{01n} modes. In general TE_{011} type resonators have no crossing TM modes, and the TM mode degenerate with the TE_{011} mode is perturbed sufficiently by the gap around the end plate to be well de-tuned from the TE_{011} mode resonant frequency.

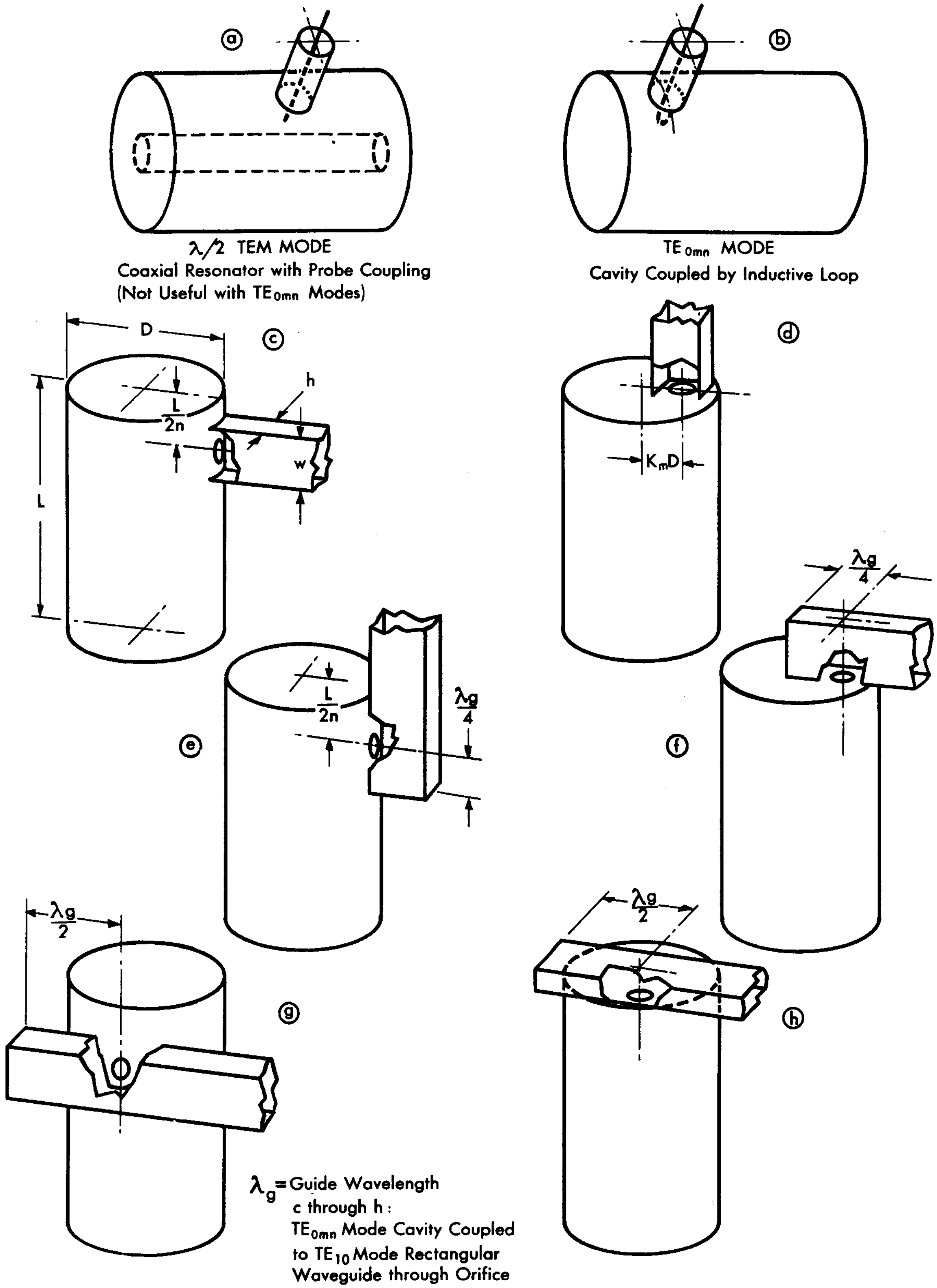


FIG. III C-1 TYPICAL DEVICES FOR COUPLING AN ECHO BOX TO A COAXIAL LINE AND TO A RECTANGULAR WAVEGUIDE

Courtesy BELL TELEPHONE LABORATORIES

The remaining six illustrations in Figure IIIC-1 show methods of coupling between TE_{10} mode in rectangular waveguide and TE_{01n} mode cavities. Drawings (c) and (d) show the methods usually employed, while (e), (f), (g), and (h) show methods which require separate short circuiting plates across the end of the waveguide. Because of this additional complication, these coupling methods are generally less desirable, but their use is occasionally necessary to fit an echo box into the space available. Methods (e) and (f) are much more desirable than (g) and (h) because in (g) and (h) there is a greater probability of introducing electric coupling which leads to excitation of the TM modes.

While the echo box is ringing, the input coupling feeds power back to the radar under test and therefore introduces a certain amount of loading into the oscillating circuit. If the coupling to the input line is made too tight, the stored energy will leave the cavity quite rapidly with the result that the echo box will have a low effective Q and a short ringing time. On the other hand, if the coupling is made too loose, the echo box will have a high Q but insufficient energy will be stored in the resonant cavity to produce a long ringing time. In this case, the bulk of the energy stored is dissipated in the internal resistance of the cavity. Expressions for the optimum value of coupling into an echo box depend upon the following factors: (Ref. 9, 10, 11, 12)

1. The "unloaded" Q_0 of the cavity (the value which Q would have in the absence of any coupling device).

2. The "dynamic range" to which the echo box is subjected during operation. This quantity is the ratio of the power level during the transmitted pulse to the power level at the end of ringing, measured at the input to the echo box. It depends upon both the radar performance and the coupling of the directional coupler or other device used to extract energy from the radar system. Greater dynamic ranges call for somewhat looser coupling into the cavity.

3. The radar pulse length. Longer pulse lengths require looser coupling.

Of these factors, the second has the most effect on the optimum value of the coupling coefficient. Since the optimum coupling must be determined experimentally (see below), it is important for the echo box designer to have a radar and directional coupler available for test purposes in which the dynamic range at the output of the directional coupler approximates that of the system with which the echo box will eventually be used, so that the correct value of cavity coupling may be achieved. This means that the ringing time on the test radar should approximate that obtained in the field. The optimum value of cavity coupling does not vary greatly under normal conditions. Generally its value is such that the ratio of the cavity "loaded Q" to "unloaded Q" (Q_L/Q_0) is between 0.85 and 0.95. "Under coupling", or coupling the cavity too loosely, is a much more serious fault than coupling the cavity too tightly. These effects are discussed in more detail in Section IIID.

Formulas have been derived for calculating the coupling hole between a waveguide and the resonant cavity, for round or elliptical holes (Ref. 6, 15). In the case of the round hole, these formulas lead to a hole size somewhat smaller than optimum. These calculations have seldom been employed in practice, since the actual hole size must, in any case, be obtained experimentally. Formulas for the size of a round coupling hole between rectangular waveguide and a TE_{01n} cavity are given in Table IIIC-1. These formulas are included for use as a starting point in design.

Electric coupling through the hole may be reduced by making the hole longer, i.e., by increasing the wall thickness at the coupling hole. However, in order to keep the coupling unchanged, the diameter must then be increased. Since the hole amounts to a perturbation of the cavity which may cause coupling between TE and TM modes, it should be kept as small as possible. Therefore, the expedient of lengthening the hole to avoid electric coupling is not a desirable one. That the presence of a hole in the cavity is likely to cause cross-coupling between TE and TM modes can easily be seen from the following considerations: in the case of the TE_{01} family, current flows in circular paths in both the end plates and the cavity walls, and there is no longitudinal current in the cavity walls and no radial current in the ends of the cavity. In the case of TM modes, current flows longitudinally in the side walls and has a radial component in the end plates.

TABLE IIIC-1

Orifice Coupling from the TE_{10} Mode in Rectangular Waveguide to a Cylindrical Cavity

CONSTANTS	CIRCULAR ORIFICE	REFER TO FIGURE
K_C, K_W: TE_{01n} 0.316, 1.322 TE_{02n} 1.058, 4.43 TE_{03n} 2.225, 9.32	$\frac{\Delta f}{f} = -K_C \frac{\lambda^2 d^3}{D^4 L}$ $W_a = K_W \frac{\lambda^2 d^6}{\lambda_g W h D^4 L}$	IIIC-1c
K_C, K_W, K_m: TE_{01n} 0.1107, 0.464, 0.2403 TE_{02n} 0.1995, 0.836, 0.1312 TE_{03n} 0.288, 1.207, 0.0905	$\frac{\Delta f}{f} = -K_C \frac{n^2 \lambda^2 d^3}{D^2 L^3}$ $W_a = K_W \frac{n^2 \lambda^2 d^6}{\lambda_g W h D^2 L^3}$	IIIC-1d
K_W: TE_{01n} 0.331 TE_{02n} 1.108 TE_{03n} 2.330	$\frac{\Delta f}{f}$ Same as first case $W_a = K_W \frac{\lambda_g \lambda^2 d^6}{W^3 h D^4 L}$	IIIC-1e
K_W: TE_{01n} 0.1159 TE_{02n} 0.2089 TE_{03n} 0.302	$\frac{\Delta f}{f}$ Same as second case $W_a = K_W \frac{n^2 \lambda_g \lambda^2 d^6}{W^3 h D^2 L^3}$	IIIC-1f
	$\frac{\Delta f}{f}$ Same as first case W_a Same as first case	IIIC-1g
	$\frac{\Delta f}{f}$ Same as second case W_a Same as second case	IIIC-1h

NOTATION:

- λ = FREE SPACE WAVE-LENGTH OF CAVITY RESONANCE
- λ_g = GUIDE WAVELENGTH
- D = DIAMETER OF CAVITY
- L = LENGTH OF CAVITY
- W = WIDTH OF WAVEGUIDE
- h = HEIGHT OF WAVEGUIDE
- f = FREQUENCY
- d = DIAMETER OF ORIFICE
- $W_a = \frac{1}{Q_a}$ = CAVITY LOADING
- K_C, K_W = CONSTANTS OF PROPORTIONALITY
- K_m is defined in Figure IIIC-1d

The presence of a hole causes the current to diverge to some extent to pass around it, with the result that in the region of the hole the direction of flow is no longer that required for a pure TE_{01} mode, and therefore, the TM mode is excited to some degree. Wave theory shows that for a small hole (a hole below cutoff for the wavelength used) this effect is very small; but it increases as the hole size is increased.

IIIC. 2 Mode Suppression Techniques

IIIC. 2. 1 General Techniques

Since most cavity designs have extraneous mode lines existing within the operating rectangle of the mode chart, steps must be taken to prevent resonance in these modes from interfering with the operation of the cavity as an echo box. Some modes have to be avoided completely since nothing can be done to suppress them. Such is the case for interfering modes of the TE_{0mn} family. Undesired responses in other modes can often be suppressed by careful placement and orientation of the coupling structures so that these modes are not excited. In the case of those modes which do not cross the main echo box mode line on the mode chart, suppression can be accomplished by lowering the Q of the undesired mode. Usually steps are taken to do both. In the case of TM modes which cross the operating mode, it is mandatory not to excite these modes. This excitation can for example be caused by the input or output coupling devices or by perturbations. TE modes which are present and cross the operating mode are best avoided entirely, although, with special effort, it may be possible to avoid excitation of such modes. If crossing modes are strongly excited, there will be a transfer of energy between the very-high-Q echo box mode and the lower-Q crossing mode at the frequency at which both are resonant (namely, the frequency at which the mode lines cross), even though stringent measures may have been taken to lower the Q of the second mode. The result is a "hole" (a reduction in ringing time at the crossing frequency), a highly undesirable effect. Lowering the Q of the crossing mode will not eliminate the "hole", but will make it broader and shallower. To overcome the effect of crossing modes the designer must therefore see to it that they are not energized.

In the case of TM modes which are degenerate with the TE_{0mn} modes, effective suppression is obtained in the case of TE_{011} echo boxes (and some others) from the gap between plunger and cylinder. To enhance this effect, sometimes both end plates are separated from the cavity wall and concentric annular grooves are cut in the end plates of the cavities.

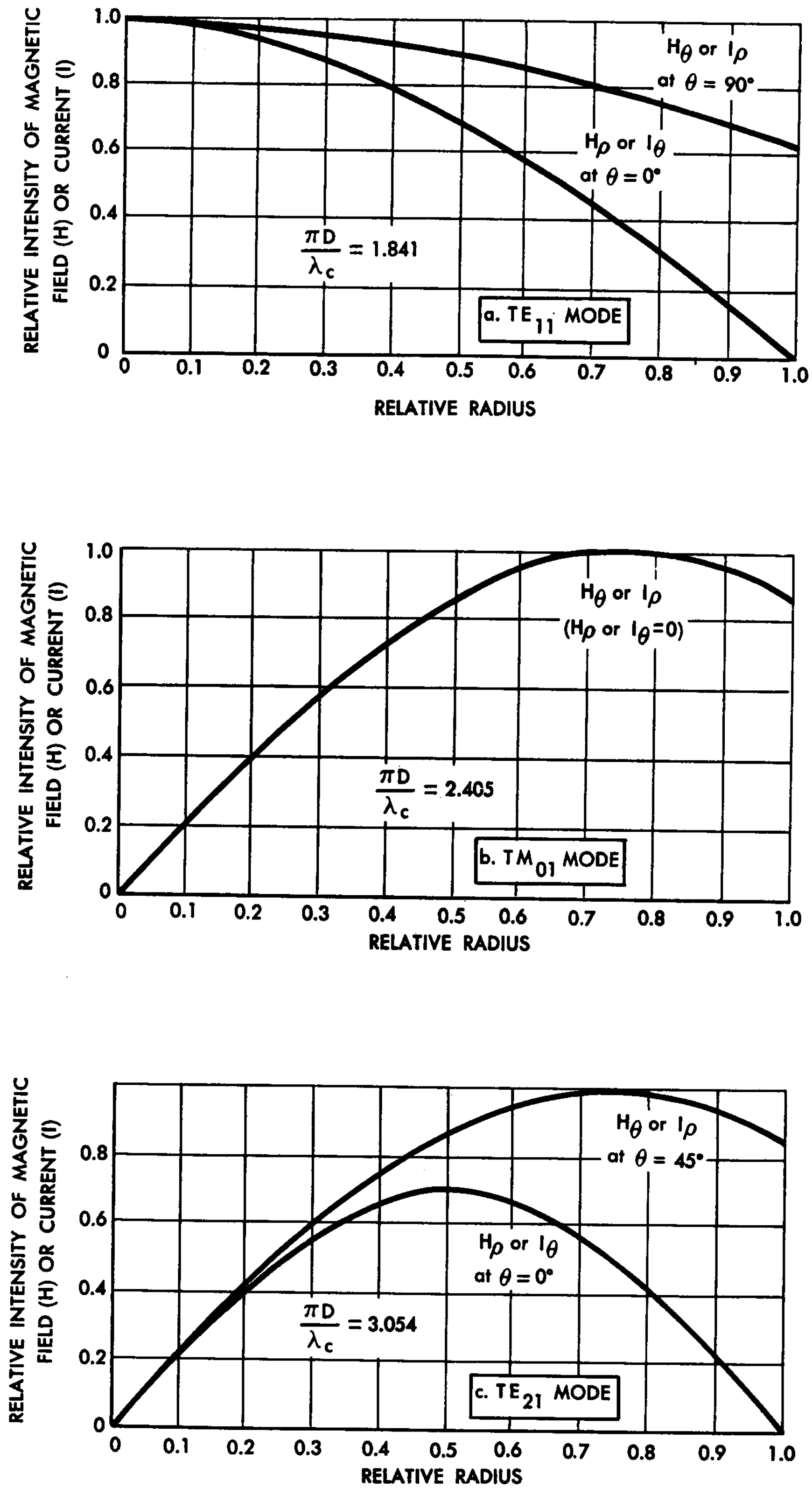
A practical echo box has other modes of resonance than those which are shown on the mode chart. For example, the cavity existing behind the tuning plunger also has strong modes. It is essential to minimize the excitation and to reduce the Q of such resonances. Minimum excitation of back cavity modes can be obtained by minimizing the gap between the tuning plunger and the cylinder wall; however, this gap performs an essential function in perturbation of the degenerate TM_{11n} mode and, in fact, in the suppression of TM modes in general. In order to meet these conflicting requirements the following steps have been found satisfactory: making the gap .03" to .05"; making the edge of the plunger as thin as is mechanically convenient to reduce the capacity between the end plate and the cylinder wall; and providing a layer of RF absorbing material of considerable thickness on the back of the tuning plunger. (This absorber is usually made of paper-filled Bakelite of deliberately poor dielectric quality.) Another category of resonance possible in the practical echo box, but not existing in the ideal right circular cylinder, is a family of resonances in the isolated end plate or end plates of the echo box. These are also usually satisfactorily suppressed by the Bakelite on the edge of the plunger. They exist when the circumference of the plunger is approximately equal to an integral number of wavelengths. Plunger resonances, and resonances in TE and TM modes which require radial currents in the end plates, are reduced in Q by filling the annular grooves in the end plate with "lossy" dielectric.

IIIC.2.2 Suppression by Selective Coupling

The location and orientation of the coupling loop or the location and shape of the orifice are strong factors in coupling to a desired mode. An additional factor in the case of orifice coupling is the location of the orifice relative to the waveguide which feeds energy to the orifice from the radar.

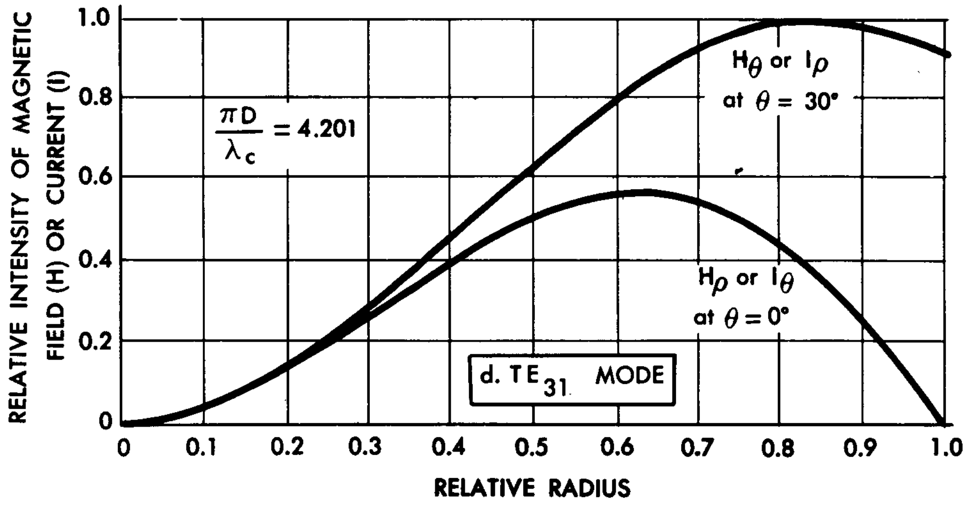
IIIC.2.2.1 Loop Coupling

The coupling loop may be placed either on the cylinder wall or on the stationary end plate. Both of these locations have been used. If no extraneous modes are present, the coupling loop may be introduced where the magnetic field is a maximum for the desired mode. If, however, it is necessary to avoid exciting certain modes, it is desirable to introduce the coupling where the undesired modes have zero magnetic field, or at least where that component of the magnetic field which couples to the loop is zero at the coupling point. This condition may necessitate coupling to the desired mode at a compromise position where the H field is not maximum for that mode. To suppress modes in this manner requires a thorough knowledge of the distribution of the currents in the cavity walls. To aid in mode suppression, charts have been prepared by Kinzer and Wilson (Ref. 6) for the cylindrical cavity which show the current contours and streamlines for the cavity end plates. These charts, taken from Reference 6, show the relative intensity and direction of the currents in the end plates as well as the magnetic field at the end plates for various modes. Figure IIIC.2 contains plots of H_θ (relative intensity of magnetic field) or I_ρ (current) and H_ρ or I_θ in the end plates as a function of the relative radius ρ. As usual the subscripts indicate that only that component of the current or field which is in the direction indicated by the subscripts is plotted; however, the angles θ are chosen in each case so that there is no other component of current or field, and therefore the plots actually show the total current or field at the end plate. In the case of the TE modes, when $\theta = 0$, $H_\theta = 0$, and the current is entirely in the θ direction; in the case of TM modes, when $\theta = 0$, $H_\rho = 0$ and the current is entirely in the ρ direction. When $\theta = \pi/2\ell$, the inverse condition exists, and the second curve in each figure is plotted for this value of θ. (It is to be noted that at the end plates $H_\rho = I_\theta$ and $H_\theta = I_\rho$, in the MKS rationalized system of units). Sidewall currents and fields are more difficult to portray and are not shown. The characteristics of the sidewall currents and fields which the cavity designer must know are readily obtained without the use of charts.



III C-2 END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES



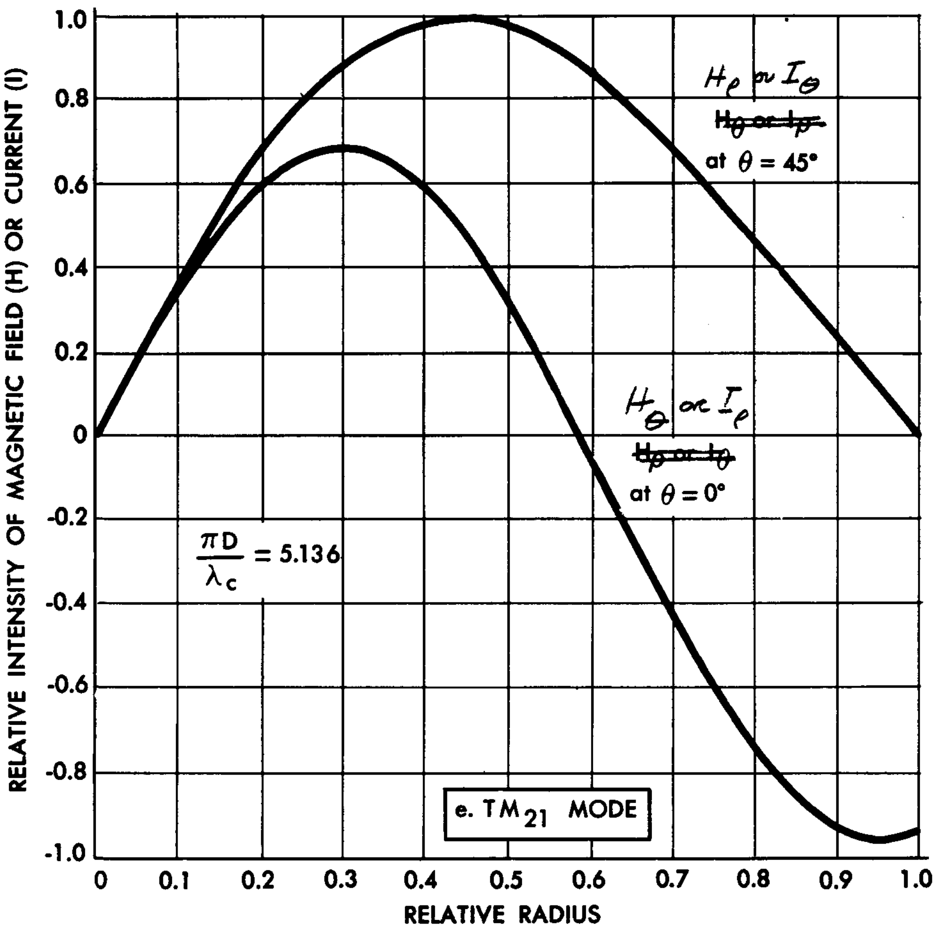


FIG. III C-2 (Continu d) END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES

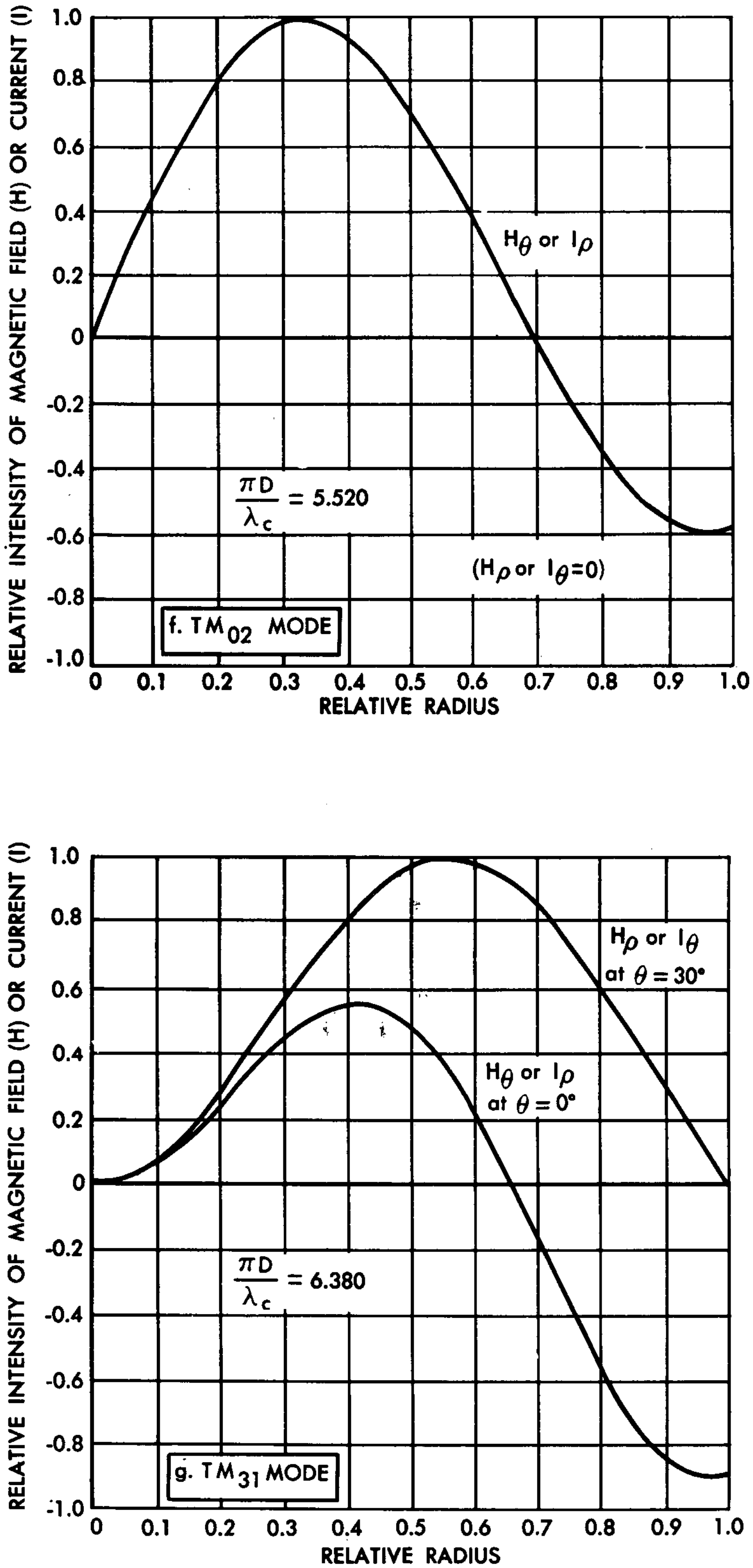
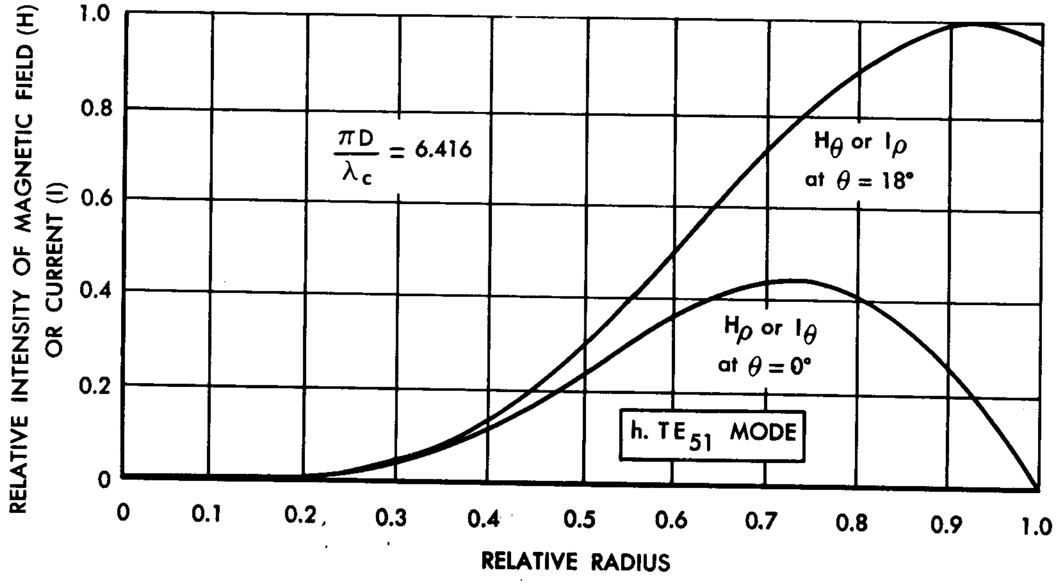


FIG. III C-2 (C ntinued) END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES



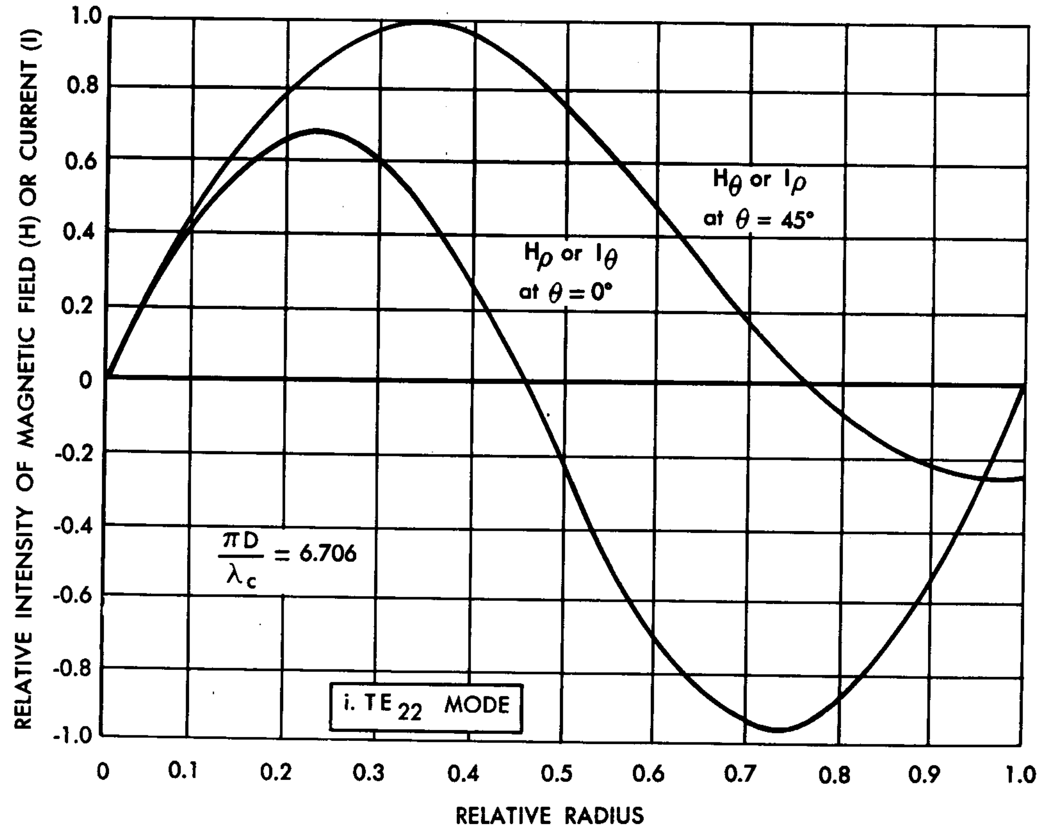


FIG. III C-2 (Continu d) END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES

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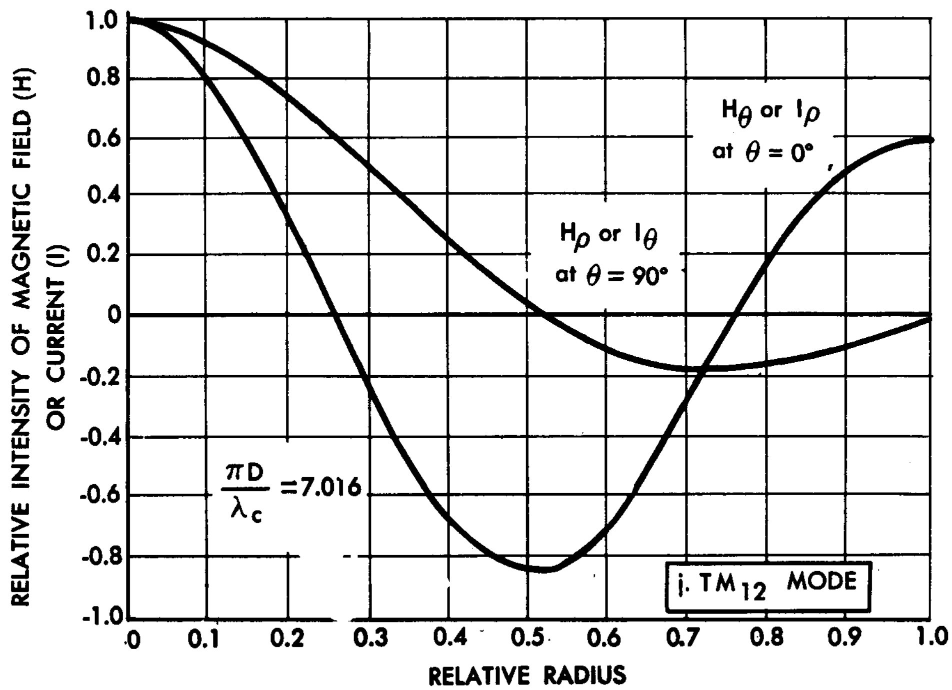

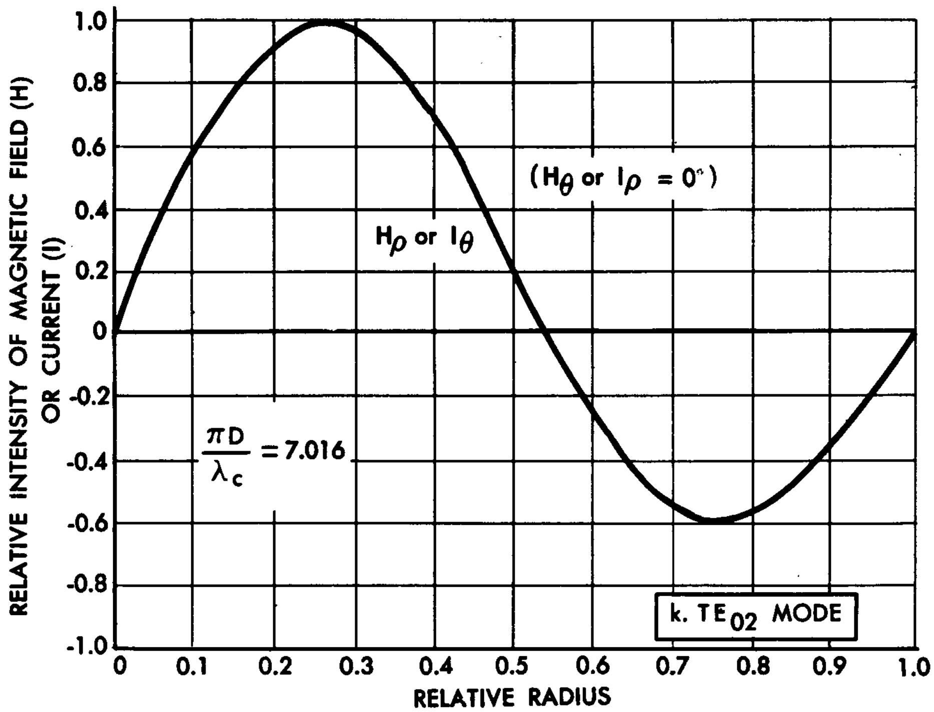

FIG. III C-2 (Continued) END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES

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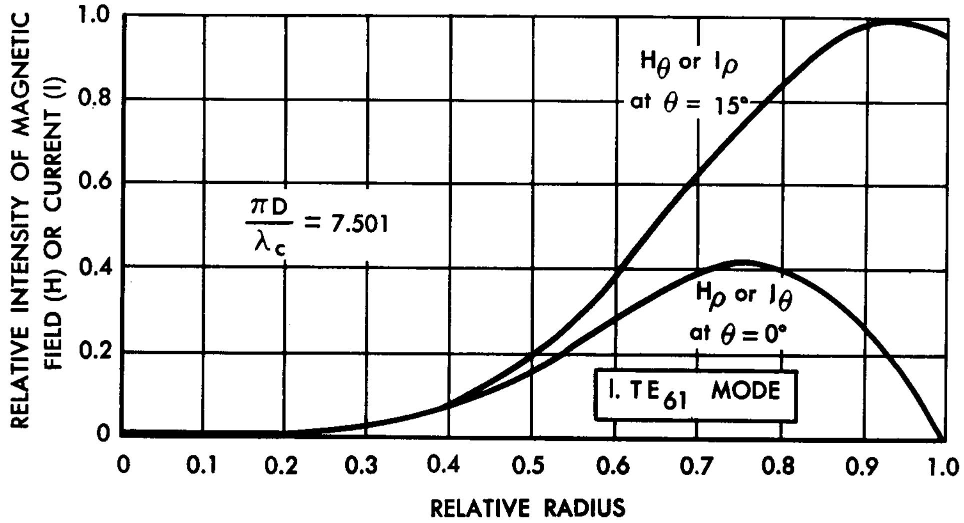

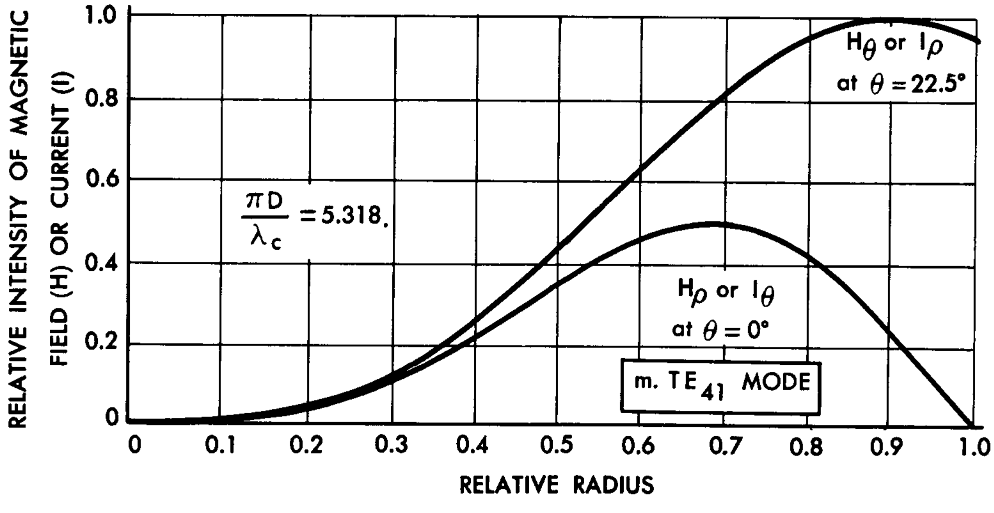

FIG. III C-2 (Continued) END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES

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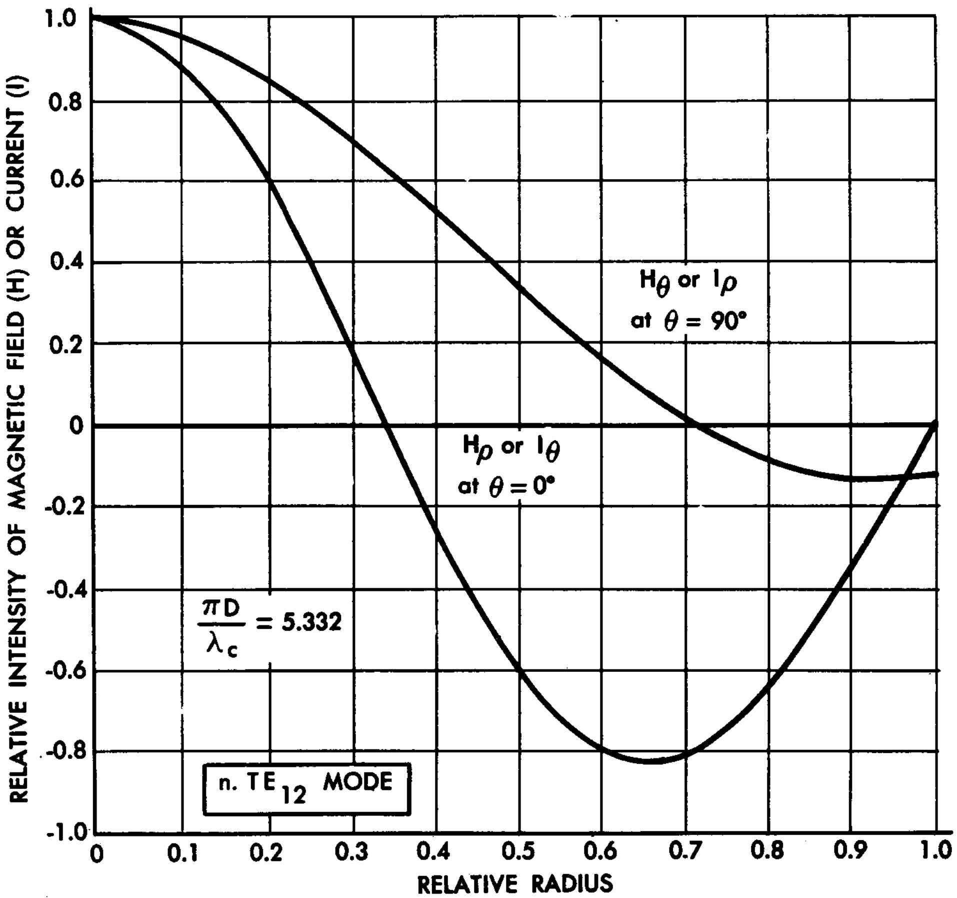
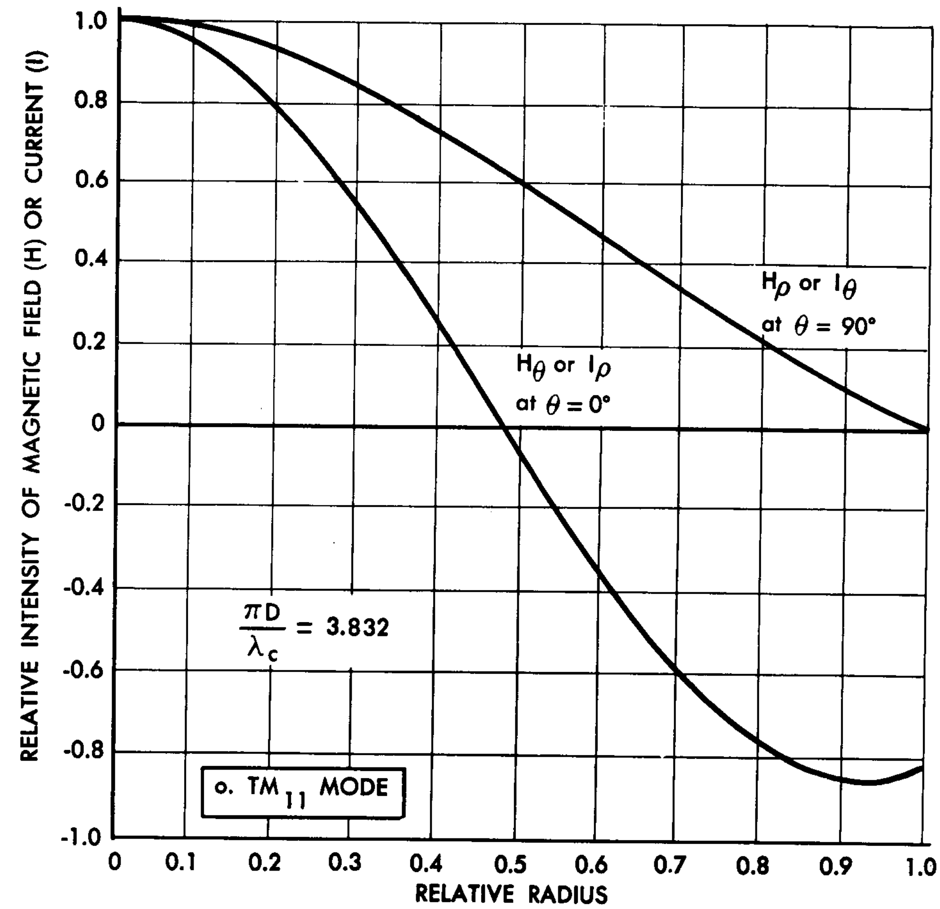


FIG. III C-2 (Continued) END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES



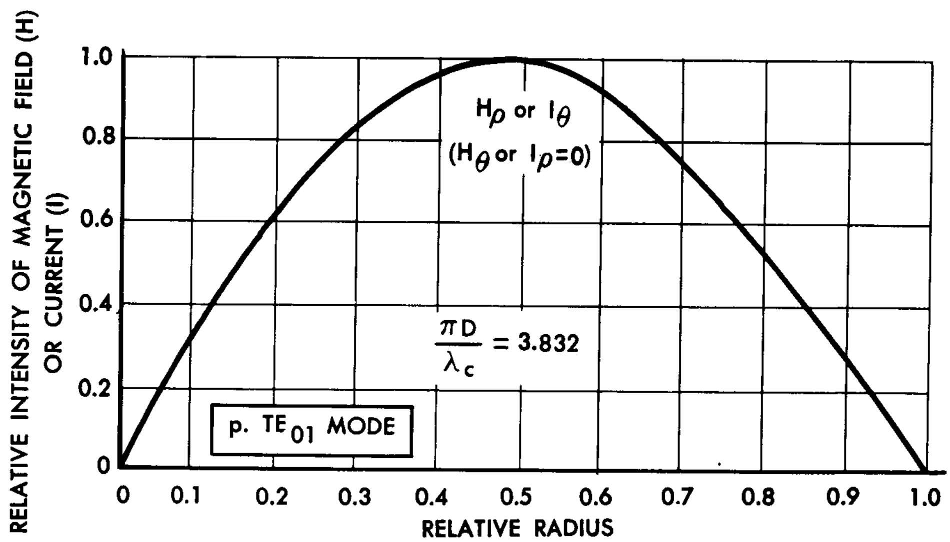


FIG. III C-2 (Continued) END PLATE CURRENTS AND FIELDS

Courtesy BELL TELEPHONE LABORATORIES

[redacted]

The magnetic field at the end plates is given by:[1]

TE modes:

$$H_\rho = \frac{k_3}{k} J'_\ell (k_1\rho) \cos \ell \theta \tag{1}$$

$$H_\theta = -\ell \frac{k_3}{k} \frac{J_\ell (k_1\rho)}{k_1\rho} \sin \ell \theta \tag{2}$$

TM modes:

$$H_\rho = -\ell \frac{J_\ell (k_1\rho)}{k_1\rho} \sin \ell \theta \tag{3}$$

$$H_\theta = -J'_\ell (k_1\rho) \cos \ell \theta \tag{4}$$

where

$k_1 = \frac{2r_{\ell m}}{D}$, $k_3 = \frac{n\pi}{L}$, D and L are the diameter and length of the cavity, $k = \frac{2\pi}{\lambda} = \sqrt{k_1^2 + k_3^2}$, and J_ℓ is a Bessel function of order ℓ.

The magnitude of the magnetic field is given by:

$$|H| = \sqrt{H_\rho^2 + H_\theta^2}$$

For TE modes, when $\theta = 0$, the magnetic field is entirely radial and is proportional to $J'_\ell (k_1\rho)$. When $\theta = \frac{\pi}{2\ell}$, $H_\rho = 0$ and H_θ is proportional

---

[1]In these formulas, as in all other expressions for cavity fields given in the handbook, the time varying factor has been omitted. The expressions, therefore, describe spatial variations and relative magnitudes only.

[redacted]

to $\frac{J_\ell (k_1\rho)}{k_1\rho}$. For TM modes this situation is reversed. The following functions have been plotted on the end plate current charts (Fig. IIIC-2).

TE modes

H_ρ vs ρ for $\theta = 0$

H_θ vs ρ for $\theta = \frac{\pi}{2\ell}$

TM modes

H_θ vs ρ for $\theta = 0$

H_ρ vs ρ for $\theta = \frac{\pi}{2\ell}$

These curves are essentially graphs of $\frac{J_\ell(x)}{x}$ and $J'_\ell(x)$ in normalized form. From these charts the relative intensity and direction of the magnetic field (or current) can be found for any point on the end plates.

\- - - - - -

Example (IIIC.1):

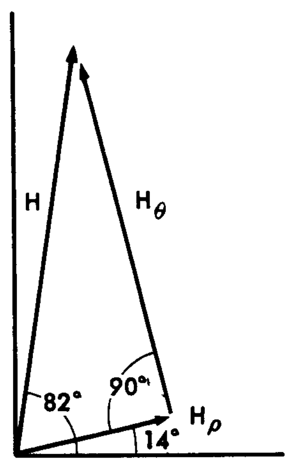
Find the relative intensity and direction of the magnetic field and current for the TM_{111} mode at a position on the end plate .32 of the distance out from the center and at an angle $\theta = 14^\circ$ from the radius where H_ρ is a maximum.

Solution: From the chart for the TM_{11} modes it is found that at a relative radius of .32 and at $\theta = 90^\circ$, H_ρ or I_θ = .82, and H_θ or I_ρ = .52 at $\theta = 0^\circ$. At $\theta = 14^\circ$, from Equations (3) and (4),

$$H_\rho \text{ or } I_\theta = .82 \sin 14^\circ = .20$$

$$H_\theta \text{ or } I_\rho = .52 \cos 14^\circ = .50$$

Hence the magnitude and direction of I and H at this point are given by adding the above vector components, as shown below:



Thus

$$H = .54 \text{ and is directed at an angle of } 82.5^\circ$$

$$I = .54 \text{ and is directed at an angle of } (90 + 82.5)^\circ = (172.5)^\circ$$

- - -

Example (IIIC.2):

Find H_ρ and H_θ for the TE_{31} mode at $\rho = .60$, $\theta = 20^\circ$

Solution: From the charts:

$$H_\rho = .58 \text{ at } \rho = .60,\ \theta = 0^\circ$$

$$H_\theta = .80 \text{ at } \rho = .60,\ \theta = 30^\circ$$

From Equations (1) and (2):

$$H_\rho = .58 \cos 20^\circ = .54 \text{ at } \rho = .60,\ \theta = 20^\circ$$

$$H_\theta = .80 \sin (3 \times 20)^\circ = .69 \text{ at } \rho = .60,\ \theta = 20^\circ$$

[redacted]

The total field may now be found in the same way as in the previous example.

These charts (Fig. IIIC-2) also list $r_{\ell m} = \frac{\pi D}{\lambda_c}$, where λ_c is the cutoff wavelength in a circular guide of diameter D. This ratio of circumference to wavelength gives the diameter of the smallest cylinder in which the given mode can exist at a given wavelength λ_c.

The relative current density and direction of current flow for the entire end plate for various modes is shown in Figure IIIC-3. These charts, while largely qualitative, give the user an over-all picture of the end plate current distribution. Dark areas are areas of high current density. The pictorial charts are sufficiently accurate to be used in the determination of mode suppression techniques. The curves are more suitable for locating a position for cavity coupling.

In considering the cylindrical walls no difficulty is encountered because the fields at the walls and the currents in the walls vary sinusoidally in both the θ and z directions. The equations for the magnetic field, (Appendix III. 1) become, for TM modes,

$$H_\theta = I_z = -J'_\ell \left(k_1 \frac{D}{2}\right) \cos \ell\theta \cos \frac{n\pi}{L} z = K \cos \ell\theta \cos \frac{n\pi}{L} z$$

$$H_z = I_\theta = 0$$

where $$K = -J'_\ell \left(k_1 \frac{D}{2}\right) = -J'_\ell \left(r_{\ell m}\right) .$$

These equations show that, for TM modes, the magnetic field at the walls is entirely in the θ direction and the currents are purely axial, both being maximum at the ends of the cavity.

For the TE modes there will be, in general, both z and θ components of H and I, and when the one component is maximum, the other is minimum. This relation can be seen from the equations for the TE modes at the cylinder wall.

[redacted]

[redacted]

a. TE_{01} MODE

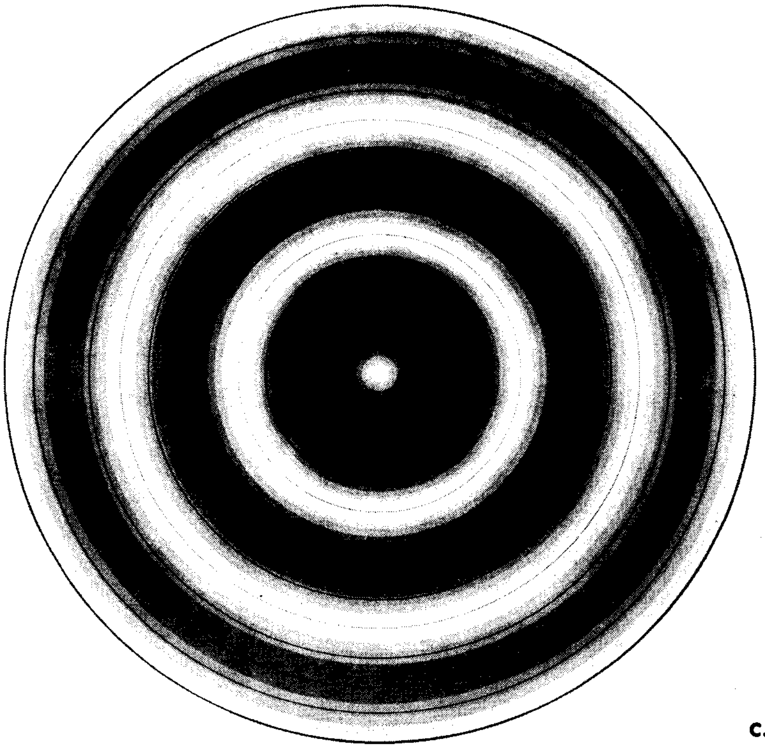
see p. 52-51 for explanations

b. TE_{02} MODE

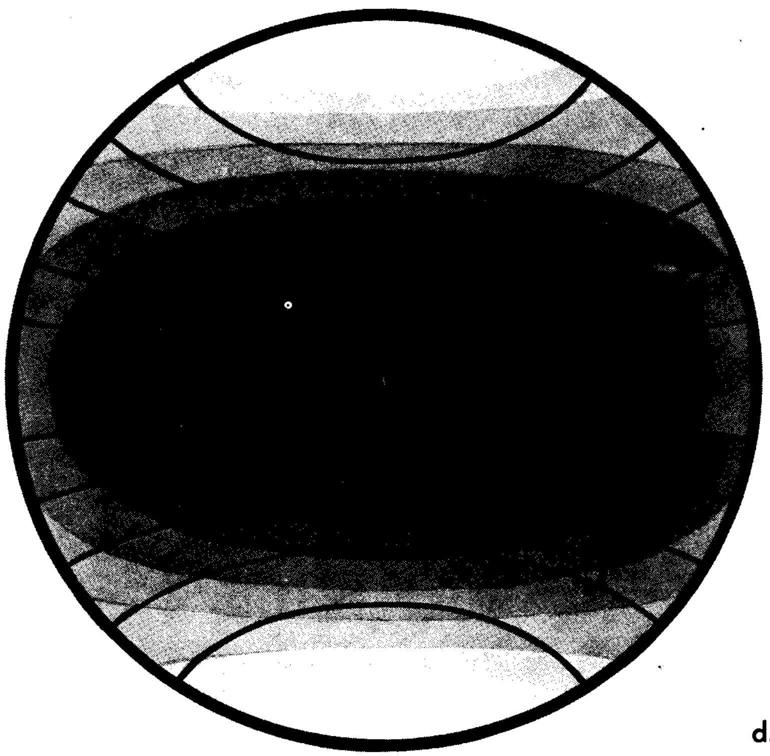
FIG. III C-3 END PLATE CURRENTS

Courtesy BELL TELEPHONE LABORATORIES

[redacted]

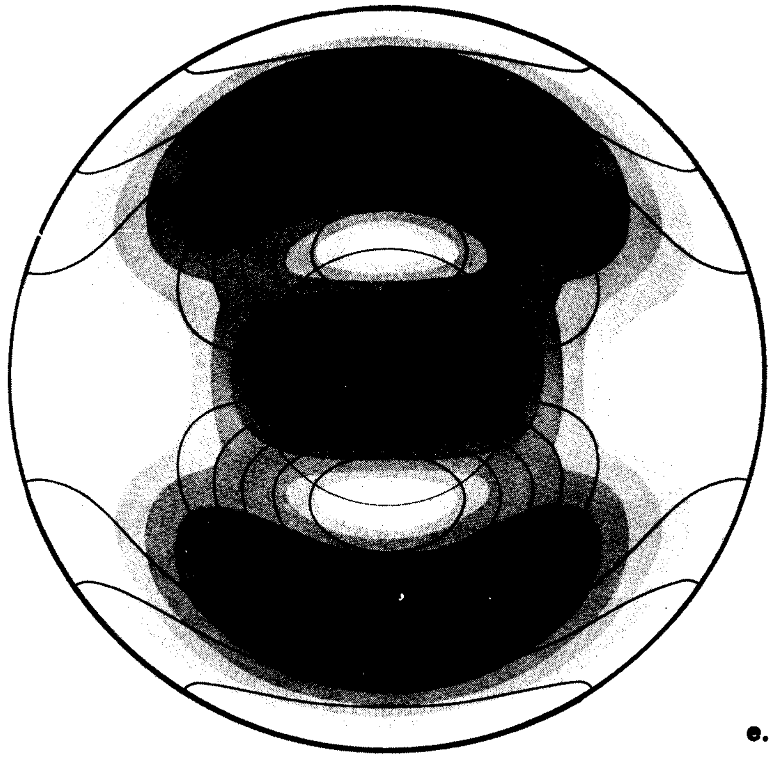


c. TE_{03} MODE

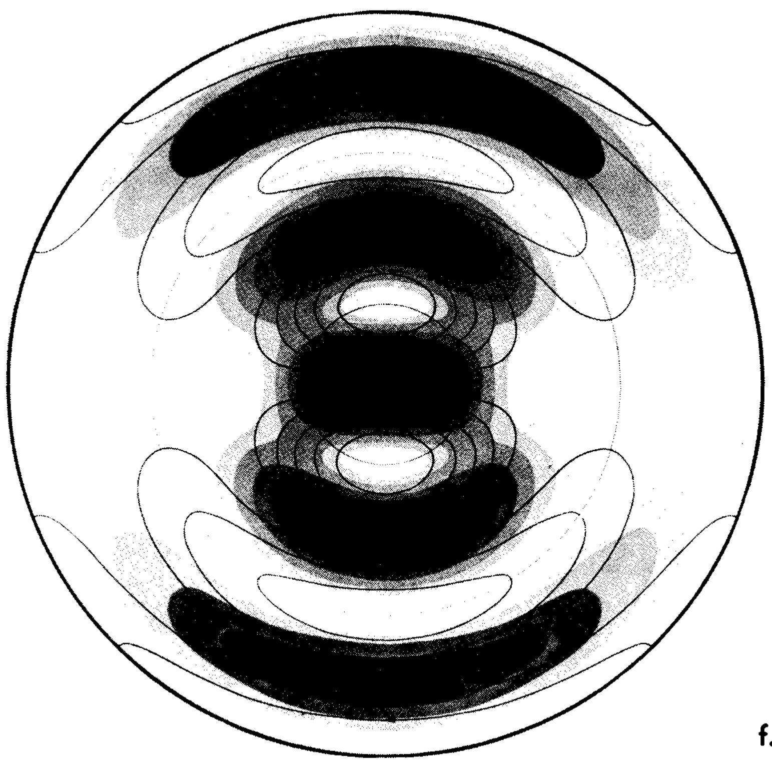


d. TE_{11} MODE

FIG. III C - 3 (Continued) END PLATE CURRENTS
Courtesy BELL TELEPHONE LABORATORIES



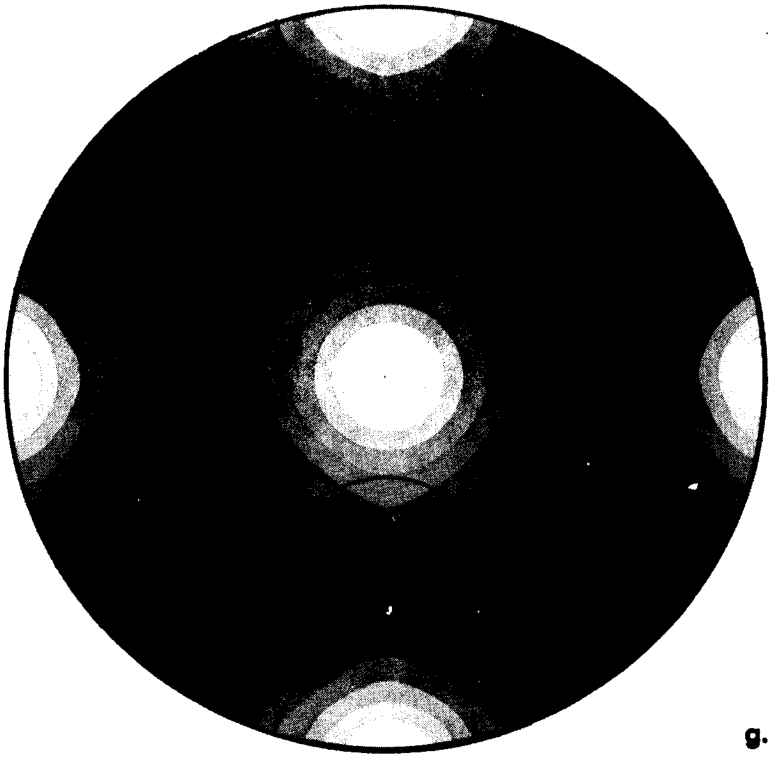
e. TE_{12} MODE



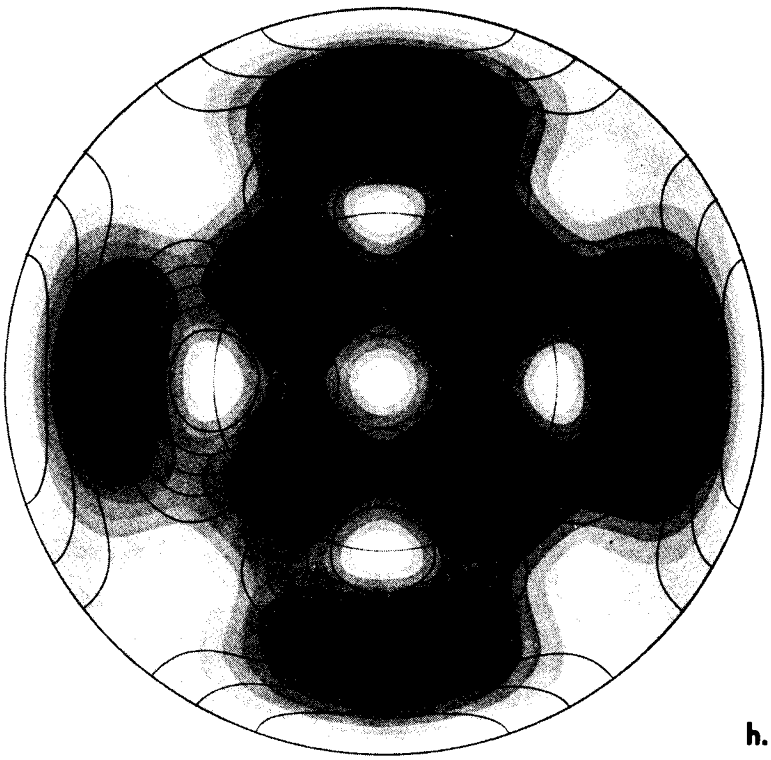
f. TE_{13} MODE

FIG. III C-3 (Continued) END PLATE CURRENTS

Courtesy BELL TELEPHONE LABORATORIES



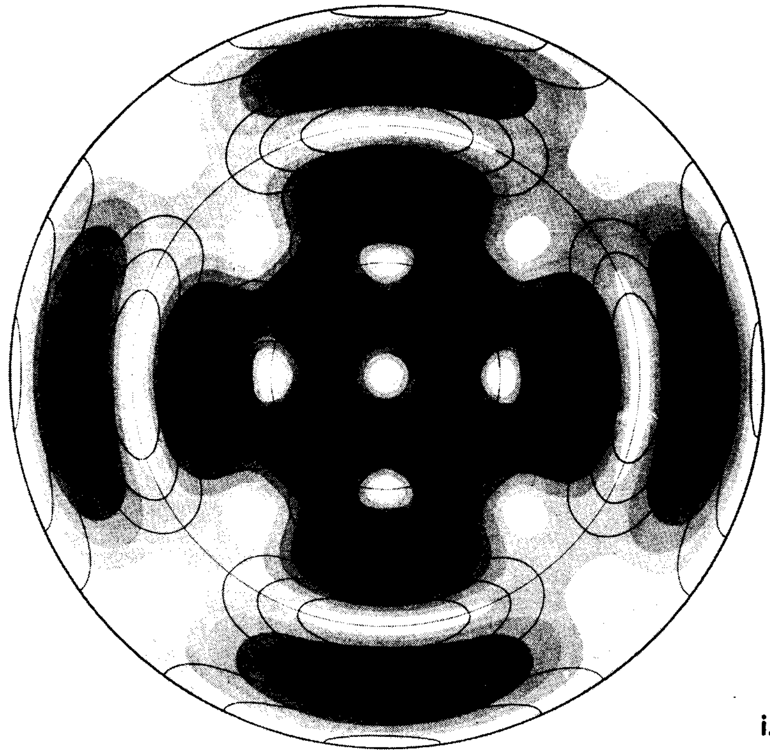
g. TE_{21} MODE



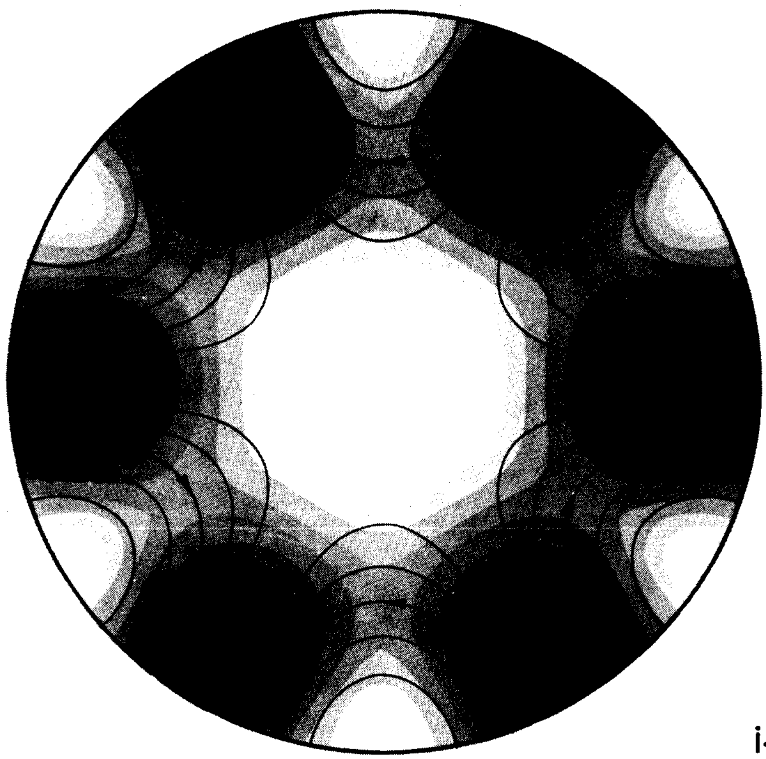
h. TE_{22} MODE

FIG. III C - 3 (Continued) END PLATE CURRENTS

Courtesy BELL TELEPHONE LABORATORIES

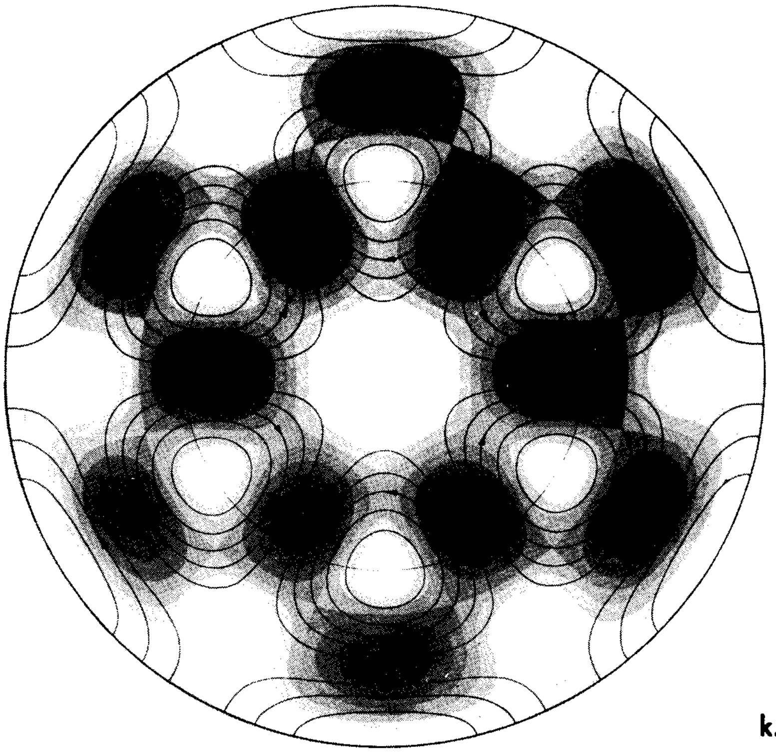


i. TE_{23} MODE

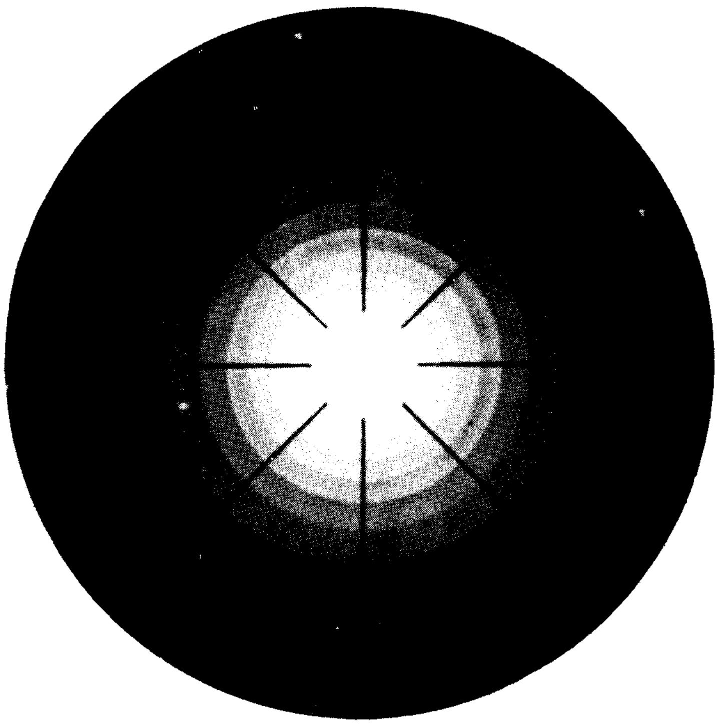


j. TE_{31} MODE

FIG. III C-3 (Continued) END PLATE CURRENTS
Courtesy BELL TELEPHONE LABORATORIES



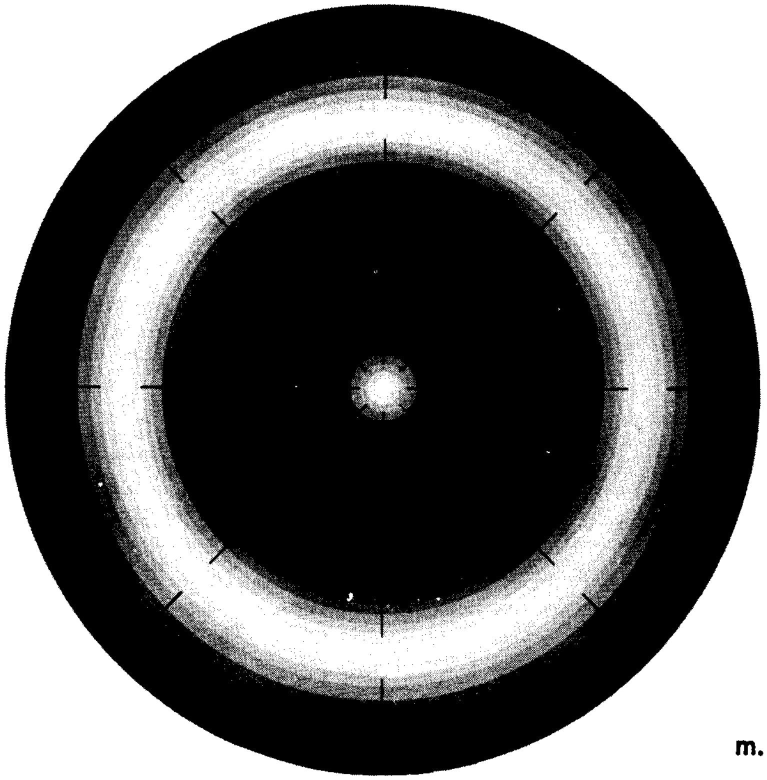
k. TE_{32} MODE



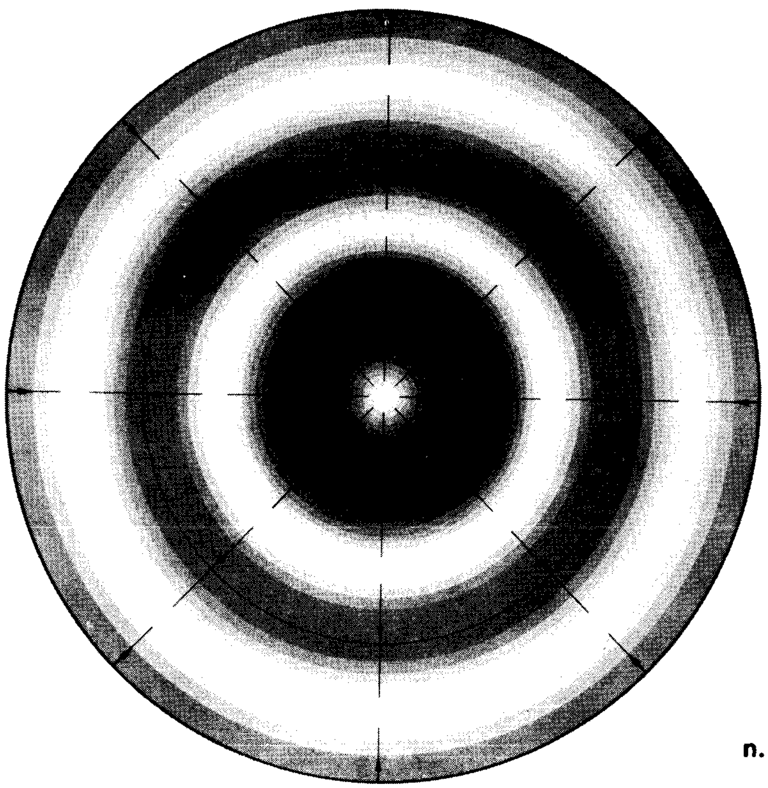
l. TM_{01} MODE

FIG. III C-3 (Continued) END PLATE CURRENTS

Courtesy BELL TELEPHONE LABORATORIES

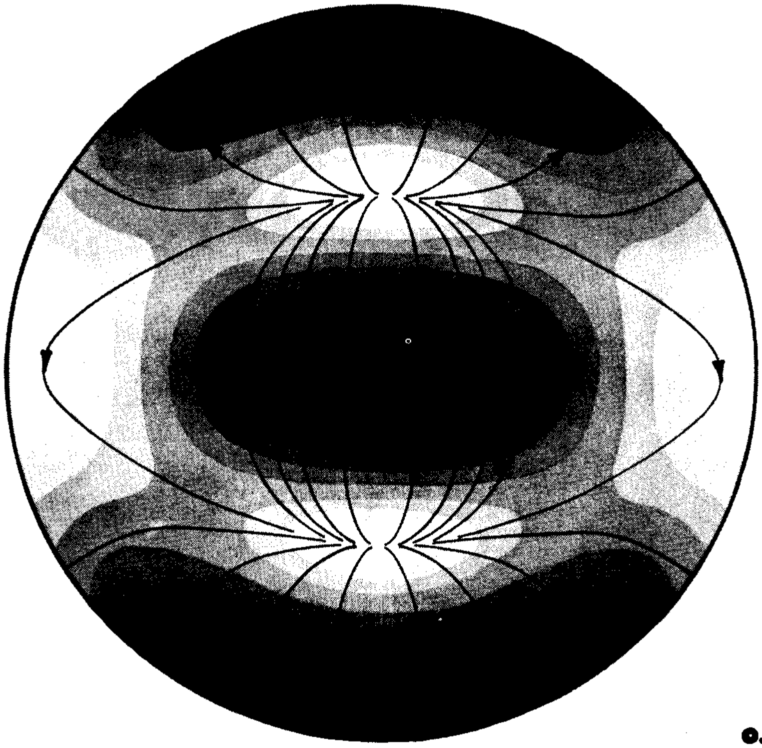


m. TM_{02} MODE

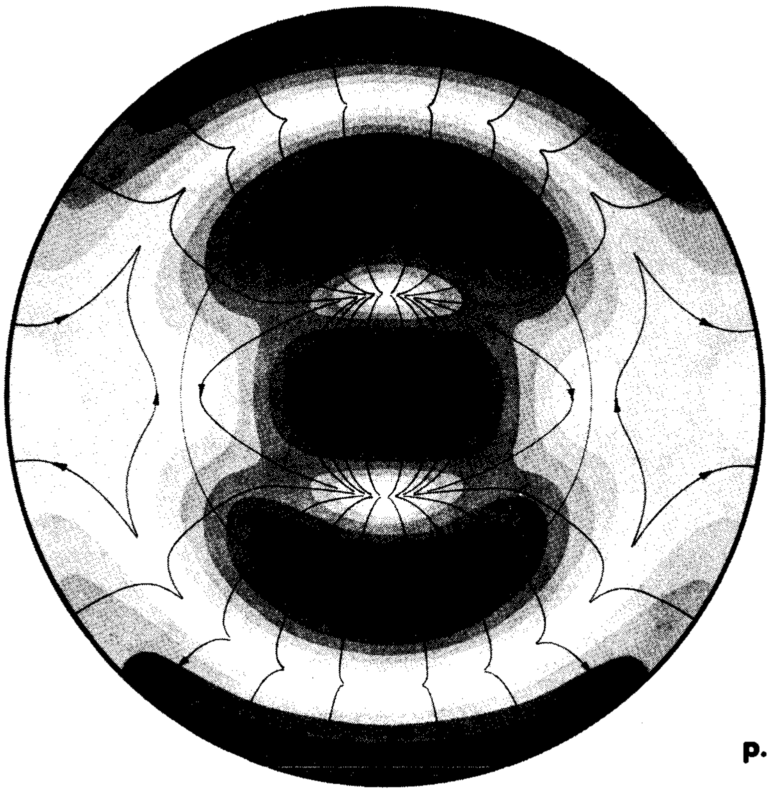


n. TM_{03} MODE

FIG. III C-3 (Continu d) END PLATE CURRENTS
Courtesy BELL TELEPHONE LABORATORIES



o. TM_{11} MODE



p. TM_{12} MODE

FIG. III C-3 (Continu d) END PLATE CURRENTS

Courtesy BELL TELEPHONE LABORATORIES

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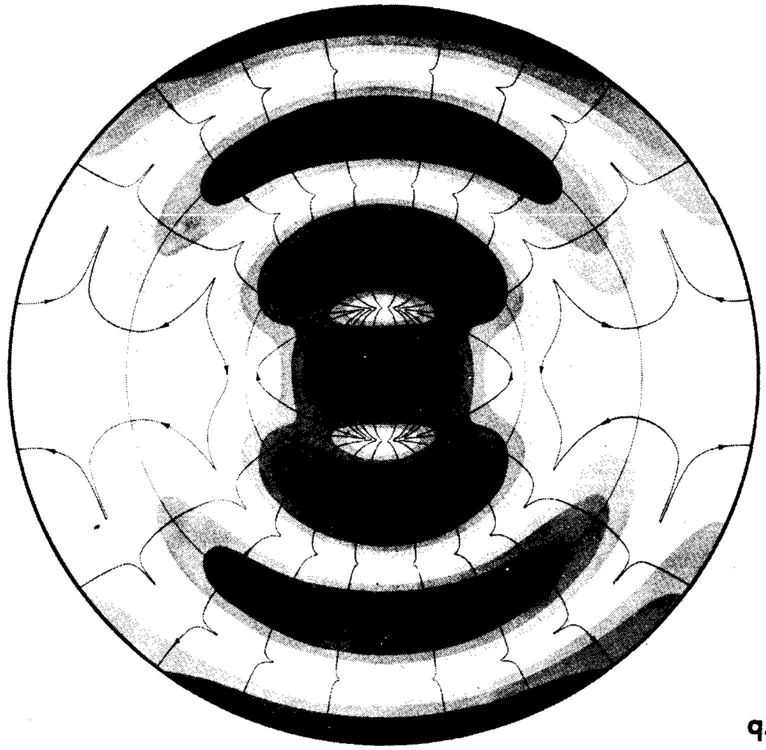
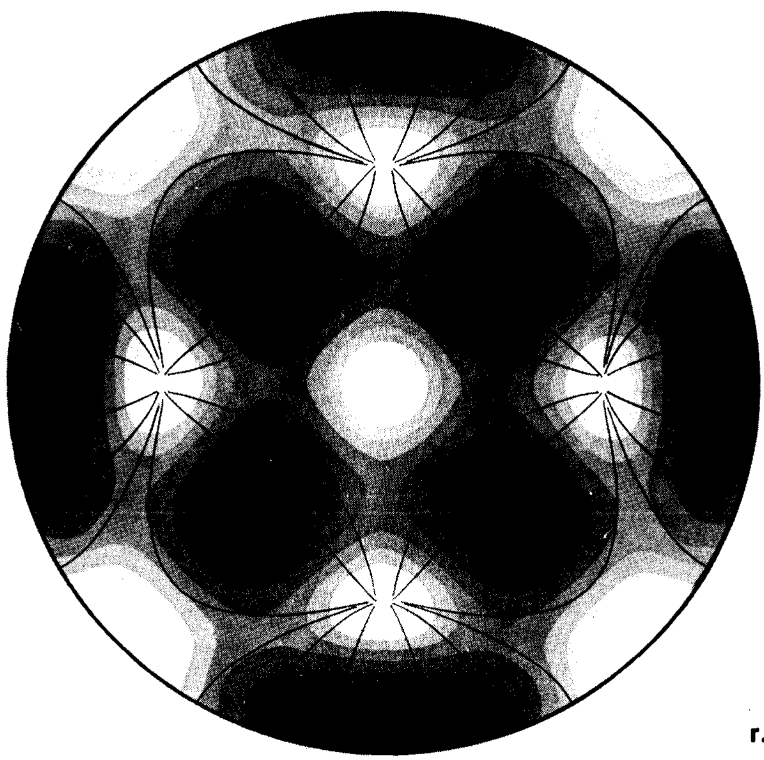


q. TM_{13} MODE



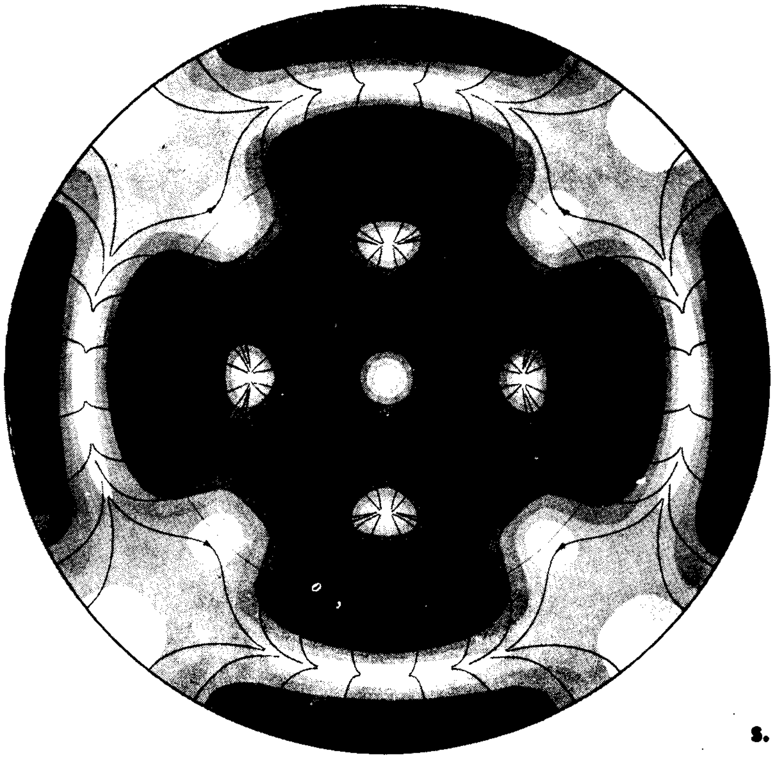
r. TM_{21} MODE

FIG. III C - 3 (Continued) END PLATE CURRENTS

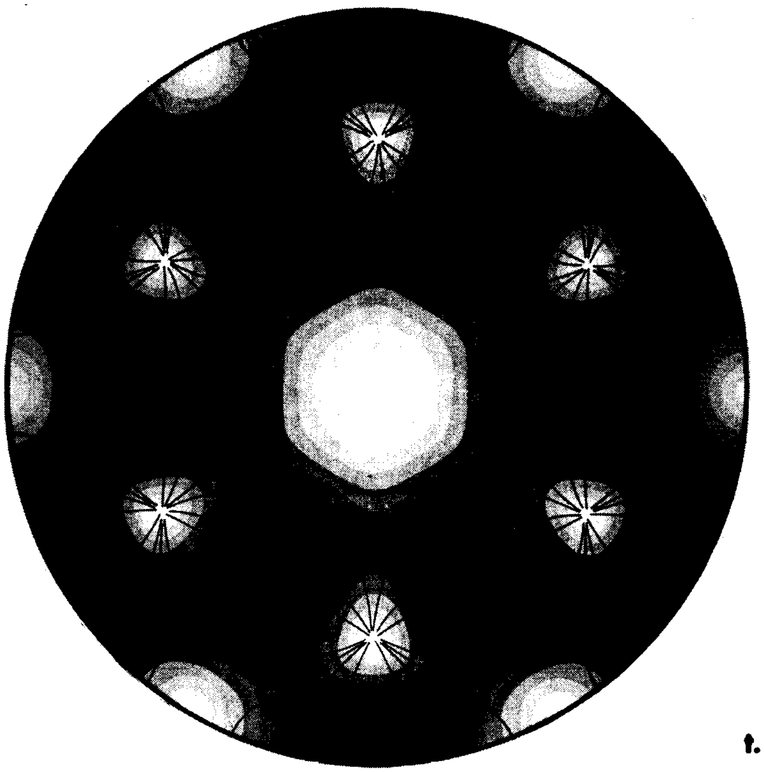
Courtesy BELL TELEPHONE LABORATORIES

[redacted]

[redacted]



s. TM_{22} MODE



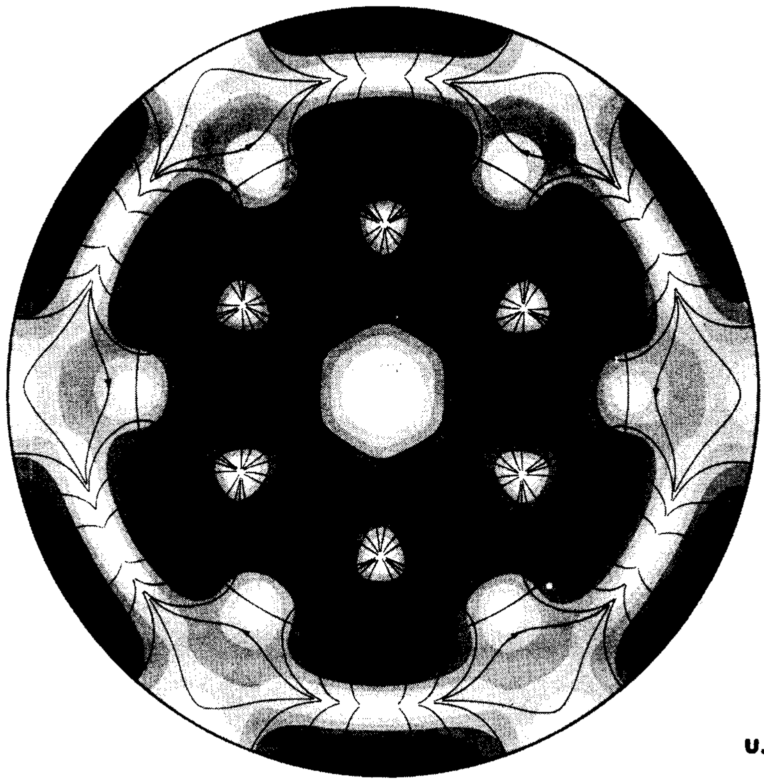
t. TM_{31} MODE

FIG. III C-3 (Continu d) END PLATE CURRENTS

Courtesy BELL TELEPHONE LABORATORIES

[redacted]

[redacted]



u. TM_{32} MODE

FIG. III C-3 (Continued) END PLATE CURRENTS
Courtesy BELL TELEPHONE LABORATORIES

[redacted]

[redacted]

$$H_\theta = I_z = -\ell \frac{n\lambda}{2L} \frac{J_\ell\,(r_{\ell m})}{r_{\ell m}} \sin \ell\theta \cos \frac{n\pi}{L} z$$

$$= K' \sin \ell\theta \cos \frac{n\pi}{L} z$$

where

$$K' = -\ell \frac{n\lambda}{2L} \frac{J_\ell\,(r_{\ell m})}{r_{\ell m}}$$

$$H_z = I_\theta = \frac{r_{\ell m}\lambda}{\pi D} J_\ell\,(r_{\ell m}) \cos \ell\theta \sin \frac{n\pi}{L} z$$

$$= K'' \cos \ell\theta \sin \frac{n\pi}{L} z$$

where

$$K'' = \frac{r_{\ell m}\lambda}{\pi D} J_\ell\,(r_{\ell m})$$

At the ends of the cavity, H_θ and I_z are maximum while H_z and I_θ are zero. If $\ell = 0$, the expressions become

$$H_z = J_0\,(r_{0m}) \sin \frac{n\pi}{L} z$$

$$H_\theta = 0$$

For this very important case, the magnetic field is entirely axial, the side-wall currents are entirely circumferential, and there are variations in these quantities only in the axial direction.

[redacted]

[redacted]

This discussion gives sufficient information for finding the optimum position at which to couple to the cavity. If it is desired to find the direction of the total current and magnetic field vectors, a procedure given by Kinzer (Ref. 6) will save the trouble of working directly with the equations for the cavity fields. However, usually only the z component of the magnetic field is of interest, since in sidewall coupling the coupling loops are always placed with their planes normal to the z direction and couple only to the z component of the field. By orienting the loop in this way, excitation of all TM modes will be minimized.

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Example (IIIC.3):

A cavity operating in the TE_{012} mode has the following dimensions:

$$D = 12.0'' \qquad L_{max} = 12.0'', \qquad L_{min} = 9.24''.$$

Solution: From an examination of the mode chart (see Fig. IIIC-4) the interfering modes are found to be:

$$TE_{113},\ TE_{212},\ TE_{312},\ TE_{411},\ TE_{121},\ TM_{211},\ TM_{013},\ TM_{210}.$$

The gap between the tuning plunger and the side walls, in combination with the effect of damping material on the back side of the tuning plunger, should reduce the response of most of these modes, including all the TM modes. In addition, placing the coupling loop normal to the cavity axis will reduce coupling to the TM modes, since these have $H_z = 0$.

Figure IIIC-5 shows the variation of H_z along the cylinder wall for the various TE modes. For n = 1, there is a single half-period sinusoidal variation; for n = 2, there are two; etc. The TE_{012} mode has maximum H_z at L/4 and 3L/4. Hence a loop placed at these points will give maximum coupling to the TE_{012} mode, although coupling to the TE_{113} mode will also be large. Placing the loop at L/3 results in the minimum excitation of the TE_{113} mode while that of the TE_{012} will be reduced only slightly. The TE_{212}

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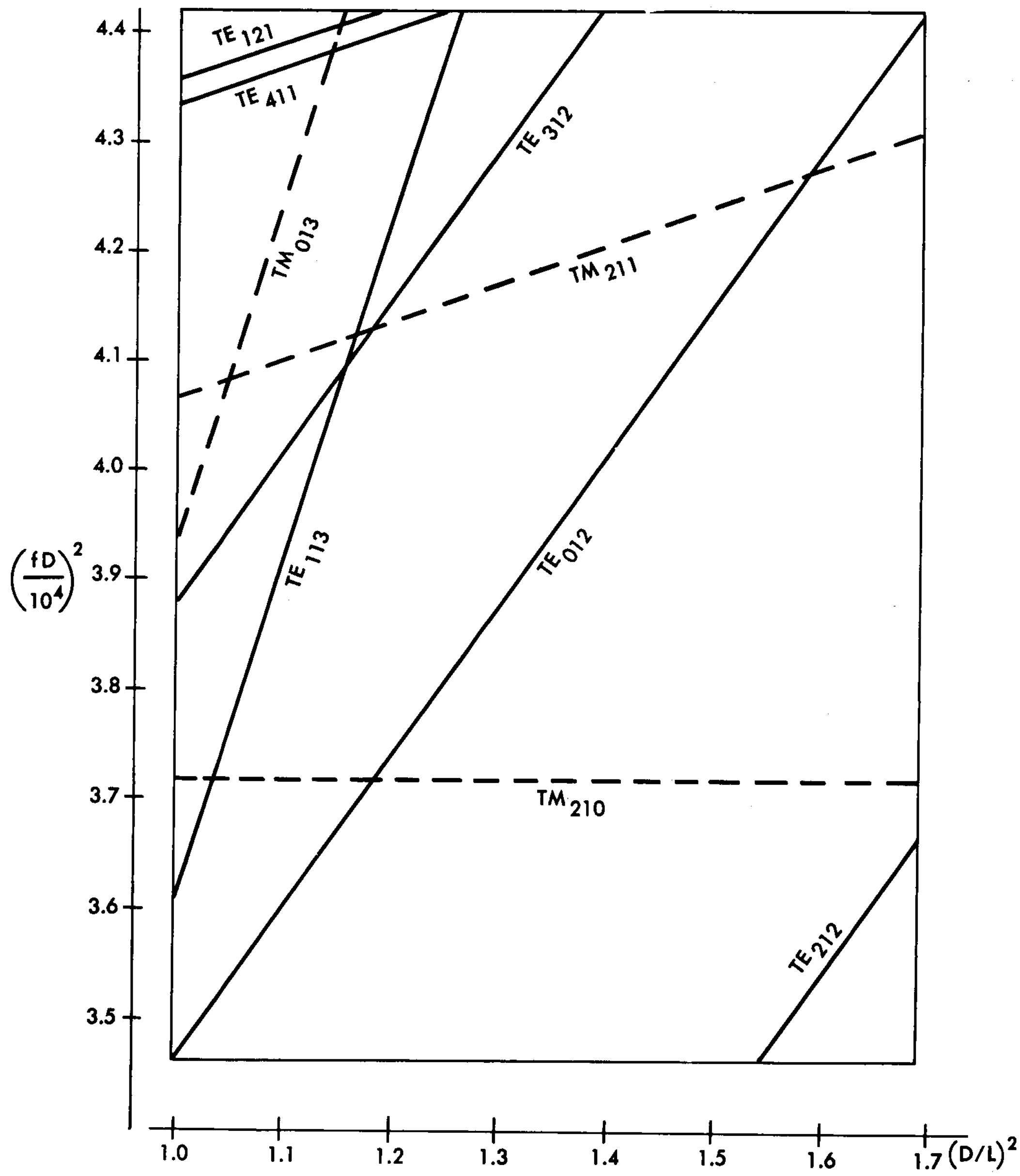

FIG. III C-4 MODE CHART FOR EXAMPLE III C-3

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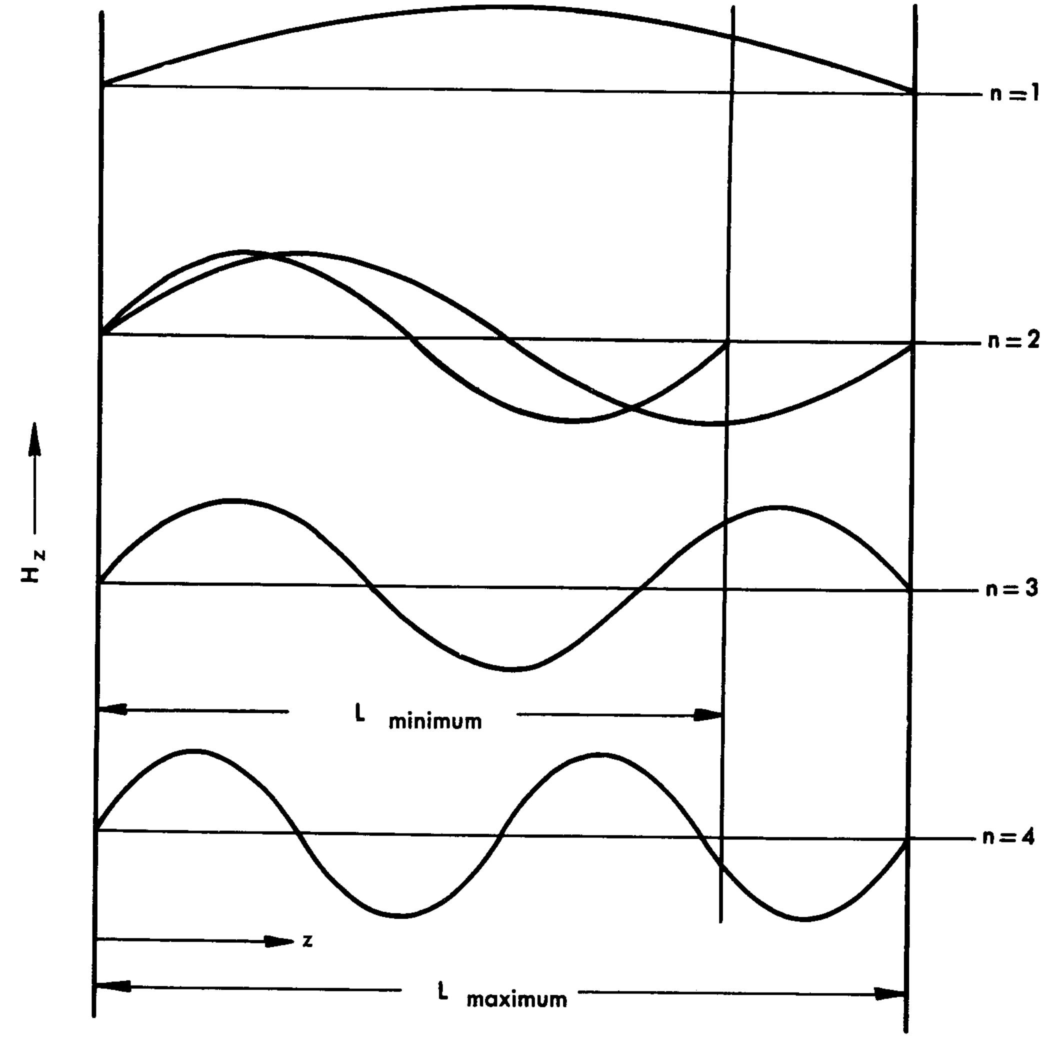

FIG. III C-5 H_z AS A FUNCTION OF Z FOR VARIOUS TE MODES and TE_{312} modes cannot be reduced relative to the TE_{012} mode by varying the axial position of the loop, since H_z has the same axial variation for all three modes. Likewise, the TE_{411} and TE_{121} modes cannot be reduced significantly by such a procedure since their H_z fields are zero only at the end plates. As the plunger is moved in the process of tuning, the field configuration will be altered, so that if the loop is located in an optimum position at maximum cavity length, it will not be located in an optimum position at minimum cavity length (cf Fig. IIIC-5) . The mode chart shows that the interfering TE modes with slope $n > 2$ (those for which selective coupling can be employed) enter the picture only near minimum $(D/L)^2$, or where the cavity has maximum length. Hence, it would be well to have the loop positioned so that it is near a null for the TE_{113} mode at the lower frequencies. However, this placement will cause the loop to be near a position of minimum H_z for the TE_{012} mode. The proper position of the loop is therefore probably somewhere between $L_{max.}/4$ and $L_{max.}/3$, depending upon how well mode suppression techniques reduce the response to extraneous modes.

It is meaningless to attempt to find an optimum θ position for the input coupling loop, since the position of this loop determines from where θ is to be measured. The variation of H_z in the θ direction is of concern only in connection with the output coupling, i.e., the coupling to the resonance indicator. Assuming an optimum or compromise position for the input loop, the output loop will ordinarily be at the same axial position, but displaced by an angle θ determined by the θ variation of the cavity fields. In the case of the main mode, the TE_{012}, the magnetic field does not vary with θ, so that the loop position is not important in this respect. It is desirable, however, to reduce or eliminate false meter indications and to reduce the mode cross-coupling which is due to the presence of the loop. If possible, the output loop should be located where no extraneous modes have components of magnetic field perpendicular to the loop.

There are values of θ for which the H_z component of the field is zero for the extraneous TE modes present in the cavity. These values of θ depend upon the first number of the mode designation. For the TE_{121} and TE_{113} modes, there is one complete sinusoidal variation of H_z as θ varies from 0 to 360° or 2π radians; for the TE_{212} there are two such cycles, and so on. It is convenient to construct a diagram showing these variations (Fig. IIIC-6). In this figure the abscissa represents angles measured from the position of the input coupling loop, and the angles at which H_z becomes maximum and zero for the various interfering TE modes in this cavity are indicated by X's and O's, respectively. Hence X's represent undesirable locations for the output loop relative to the input loop. The position finally chosen for the output loop depends on which modes affect the meter reading most; this, in turn, depends on how successfully interfering modes have been suppressed. Since the location of the loop is most critical in the case of the modes with greatest value of ℓ, the loop should be located at or near a zero for this mode if it is feared that this mode will give a strong response. From the figure, the zeros for the TE_{411} mode are at odd multiples of $22\frac{1}{2}°$. On the other hand, the TE_{411}, the TE_{312} and the TE_{212} modes can be more effectively suppressed than the TE_{121} by grooves in the end plate and by the gap between the end plate and the cylinder walls, as can be seen by reference to the charts of end plate currents. It is therefore likely that the TE_{121} mode will be present to a greater extent than the other undesired modes and is likely to produce a spurious resonance indication. The zeros for this mode are at 90° and 270°, which are in a poor location with respect to the TE_{212} and TE_{411} modes. If the designer is reasonably sure that these modes are strongly suppressed, 90° may be a satisfactory loop location; if not, a location somewhere near 150° is recommended. Locating the output loop close to the input loop (near 0°) is not desirable; direct coupling from input to output loops is likely. For this reason the region near 0° and 360° has been ruled out of consideration as a loop location.

It can be seen that compromises must be made in regard to loop location. For this reason it is possible that more than one prototype box may have to be constructed before a satisfactory solution to this problem is found.

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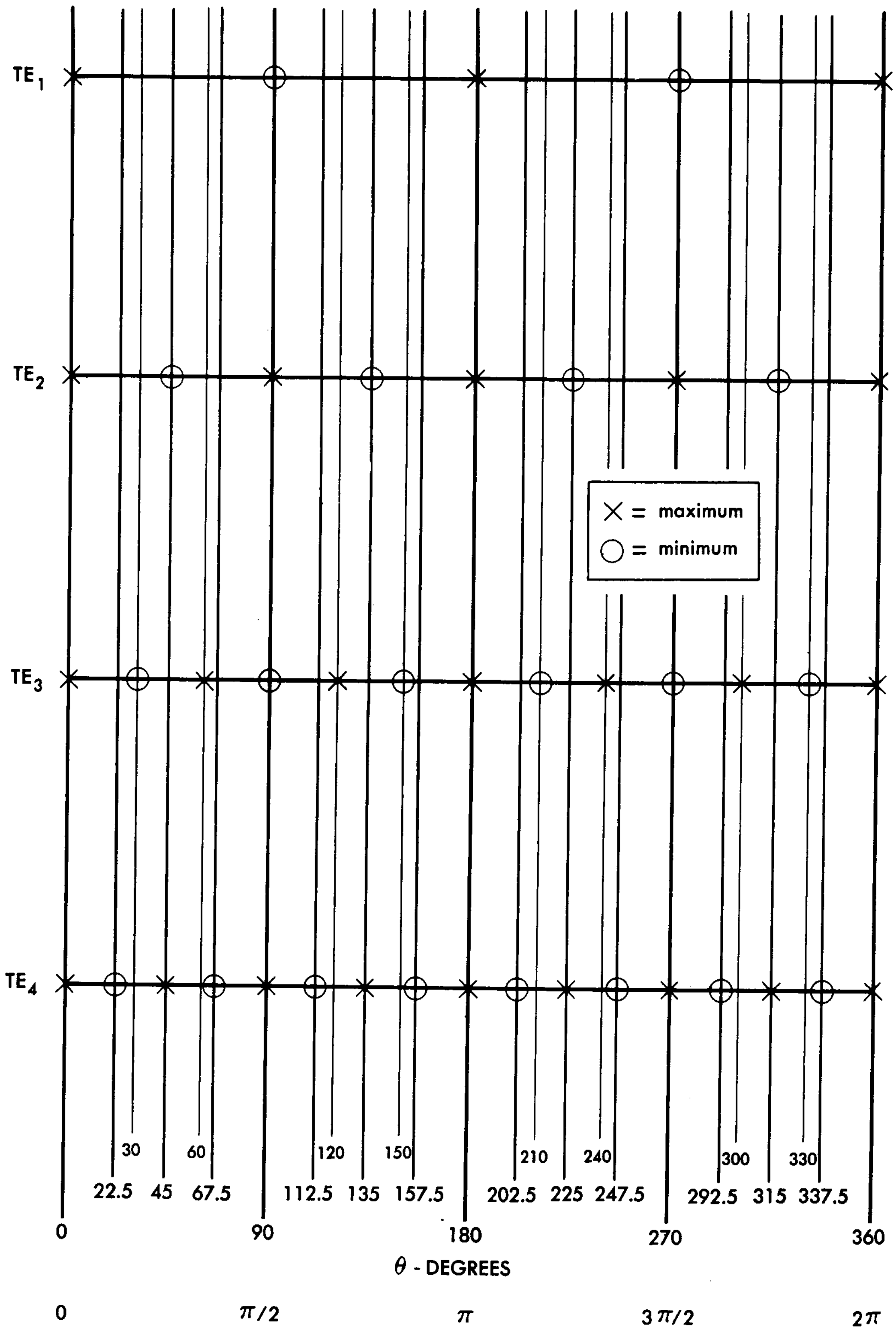

FIG. III C-6 ZEROS AND MAXIMA OF H_z FOR VARIOUS TE MODES AS A FUNCTION OF θ

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Example (IIIC.4):

A cylindrical cavity of the following dimensions is to operate in the TE_{011} mode: $L_{max.} = 4.544"$; $L_{min.} = 3.052"$; and $D = 5.725"$. The mid-band frequency is 3000 mcs; TE_{311}, TE_{112}, and TM_{012} are the interfering modes (see Fig. IIIC-7).

Solutions: As in the preceding example, orienting the coupling loop normal to the cylinder axis will inhibit excitation of the TM mode. Placing the coupling loop at $z = L/2$ will reduce excitation of the TE_{112} mode, but there is no location which will reduce coupling to the TE_{311} mode without affecting the TE_{011} mode, since both modes have the same axial variation of H_z. In an actual cavity of these characteristics, the OBU-3, the loop has been located about 1.67" from the fixed end of the cavity, so that it is at L/2 when $(D/L)^2$ is about 2.95, near the high-frequency end of the tuning range. The loop was located in this position in an attempt to decrease the variation of ringing time with frequency. This location increases the coupling to the TE_{011} mode near the high-frequency end of the band. The Q of this cavity is much greater at the low end of the band than it is at the high end; hence, it is deliberately undercoupled at the low frequency end. This attempt was only partially successful because optimum coupling depends upon the energy level difference at the echo box. Therefore, even should this device prove successful when the box is used with one particular radar, it will not necessarily prove successful with another.

The output loop has been placed at $\theta = 90^{\circ}$ relative to the input loop, which is a position of minimum H_z for both the TE_{312} and the TE_{112} modes.

A coupling loop can be inserted through the cavity end plate as well as the side wall. In this case, the curves of Figures IIIC-2 are useful in determining its proper location. Since the magnetic field for the TE_{0mn} modes is entirely radial at the end plates, the plane of the coupling loop will be normal to this direction. However, the TM modes are not automatically discriminated against by the orientation of the coupling loop, as was done with the loop in the side wall. Here only the TM_{0mn}

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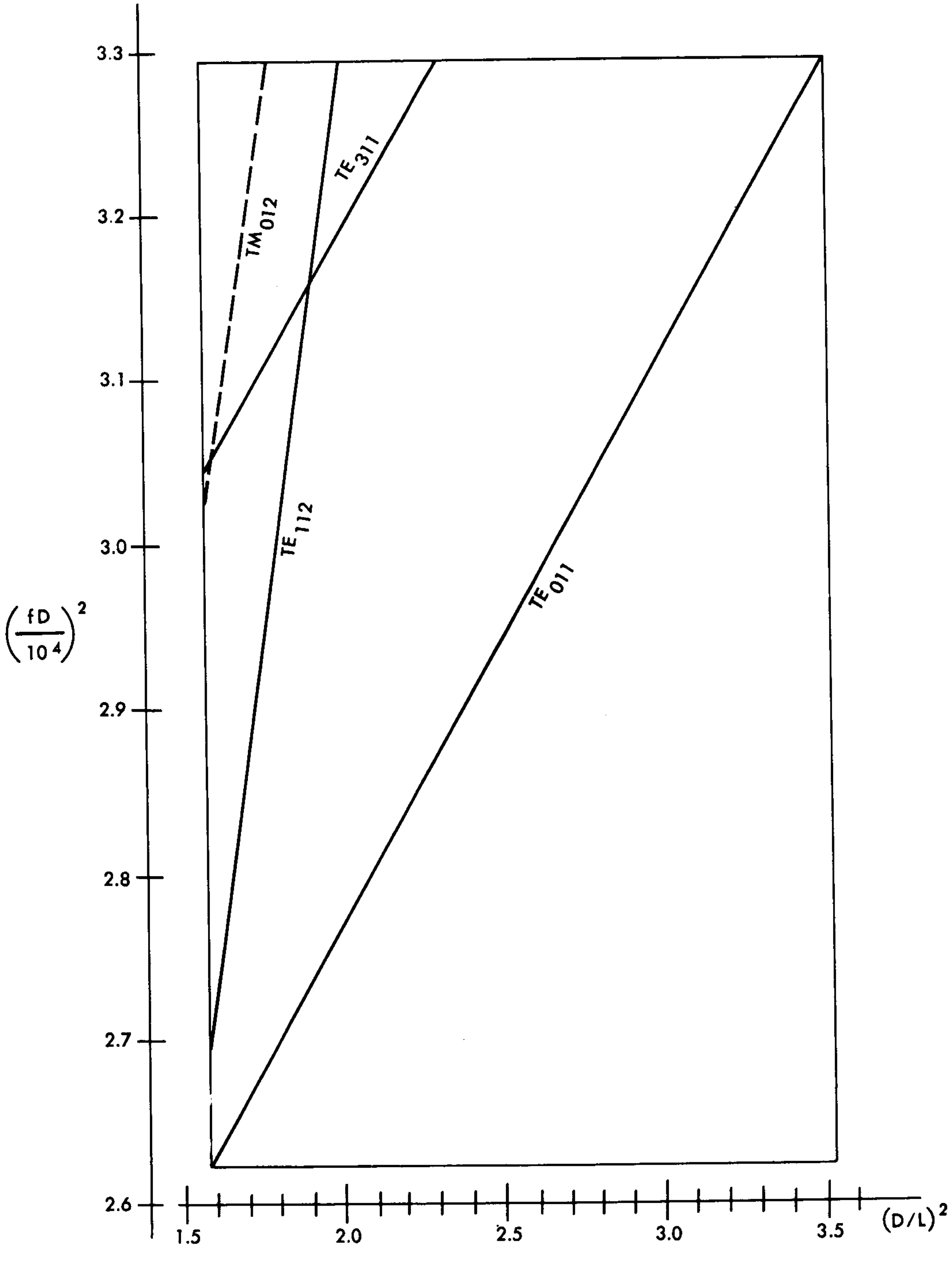

FIG. III C-7 MODE CHART FOR EXAMPLE III C-4

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modes have no component of magnetic field in the radial direction and will thus not be excited by a loop perpendicular to this direction; the other TM modes must be discriminated against individually by proper radial location of the loop. For this reason, locating the loop in the end plate is not desirable except under special conditions. If space requirements make coupling through the side wall difficult, and if the TM modes which are present can easily be dealt with, end-plate coupling is worth considering.

In end-plate coupling it is possible to discriminate between various TE_{0mn} modes, since different TE_{0mn} modes have different field patterns at the end plates. In the case of the TE_{01n} modes, the location for maximum coupling is nearly half way (48 per cent) out from the center to the edge. Coupling to a TE_{02n} mode is least when the loop is 54 per cent from the center, and this location does not appreciably reduce coupling to the TE_{01n} mode. In general, to discriminate against a mode, the loop should be placed where H_ρ is zero for that mode.

A method of suppressing undesired modes which has found some use in resonant cavity design is the use of two or more coupling loops. These loops are so placed that, for the desired modes, the fields excited by the two loops enhance each other, while for the undesired mode the fields excited by the loops tend to cancel each other.

- - -

<u>Example (IIIC.5):</u>

It is desired to excite the TE_{011} mode, but the TE_{311} mode is interfering and is not easily suppressed by convenient means.

Solution: Two coupling loops can be used to suppress the TE_{311} mode while enhancing the TE_{011}. A coupling loop placed at $z = L/2$ will give maximum coupling to both modes. A second loop, energized in phase with the first and placed at $z = L/2$ but on the opposite side of the cavity, 180° from the first loop, will tend to excite a TE_{311} configuration which, when superimposed on the TE_{311} from the first loop, will result in nearly complete cancellation, while both couplings will excite the TE_{011} mode in such manner that the interference will be constructive. The same effect could be had by separating the loops by an angle $\theta = 60^\circ$.

This method of coupling is open to the objection that if the currents in the two loops are in phase at one frequency, they will not be so for others. This technique is of limited use for tunable echo boxes, because of their relatively large tuning range.

IIIC.2.2.2 Orifice Coupling

When orifice coupling is used, the orifice position can also be selected so as to reduce coupling to unwanted modes. What has been said previously about positioning coupling loops applies also to orifice coupling. Although there is no loop to be oriented to avoid exciting TM modes, there is an analogous technique: the input waveguide or transducer is oriented so that the fields at the orifice will not couple to TM modes. The six ways of coupling from waveguide to cavity illustrated in Figure IIIC-1, can be understood by reference to Figure IIIC-8, which shows the standing-wave field configurations in a rectangular waveguide, with a short-circuiting plate over the end, excited in the TE_{10} waveguide mode.

In the case of coupling through a hole in the shorting plate, as shown in Figures IIIC-1c and d, the magnetic field is parallel to the longer dimension of the waveguide. For side-wall coupling the guide is oriented so that the longer dimension of the guide is parallel to the cavity axis. The magnetic field at the hole is then parallel to the cavity axis, correct for TE modes. Coupling through the end plate is accomplished by orienting the guide so that the magnetic field at the orifice is radial (Fig. IIIC-1d). Figures IIIC-1e and f show coupling through an orifice in the narrow wall of the guide, located $\lambda_g/4$ from the shorting plate. Figure IIIC-8 shows that this is again magnetic coupling, the field being parallel to the axis of the guide.

The final method, (Fig. IIIC-1g and h) is coupling through an orifice in the wide face of the guide, located $\lambda_g/2$ from the shorting plate. Here

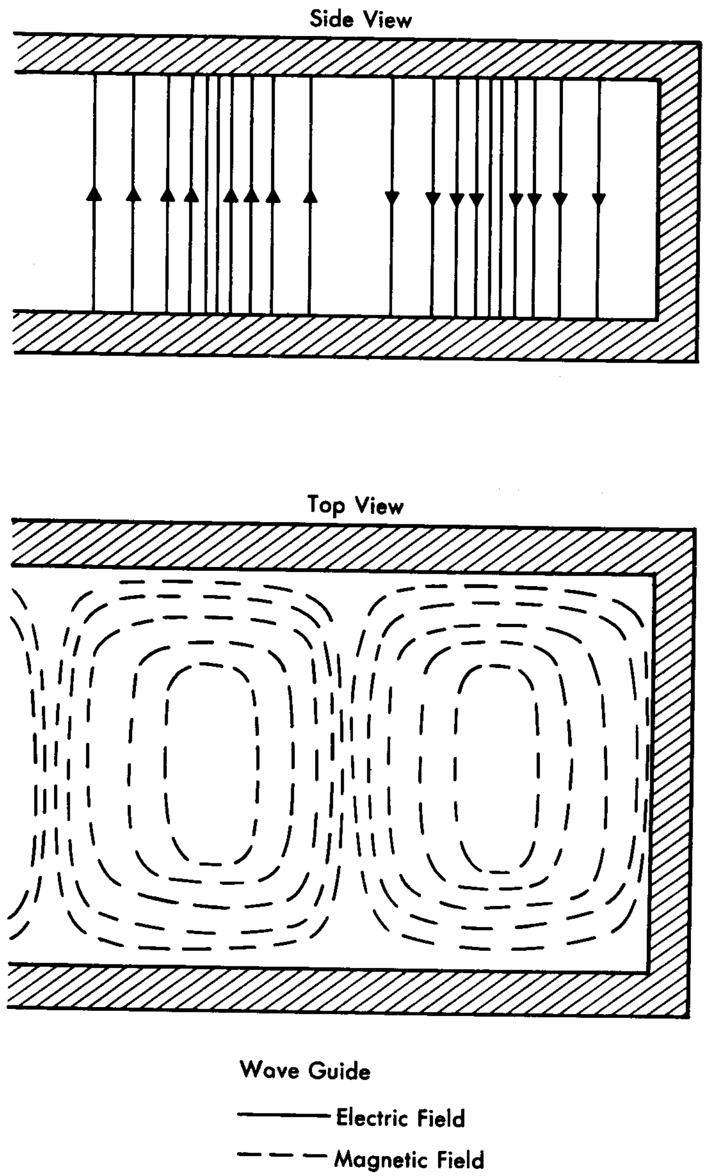

FIG. III C-8 STANDING-WAVE FIELD CONFIGURATIONS IN A SHORT-CIRCUITED RECTANGULAR WAVEGUIDE (TE_{10} WAVEGUIDE MODE) the coupling is also magnetic, the field direction being across the wide face of the guide transverse to the axis of the guide. This method has the disadvantage that there is a strong possibility of electric coupling to extraneous modes.

Orifices should be located relative to the cavity by using the same procedure outlined above for loops. The orifice locations shown in Figure IIIC-1 refer only to the optimum location of the hole relative to the desired TE_{01n} mode and must frequently be modified in the interest of mode suppression. Orifices have two noteworthy advantages over loops for coupling devices; the fields within the cavity are perturbed or distorted less by the presence of an orifice than they are by the presence of both a loop and an orifice (as is the case in loop coupling) and the dimensions of an orifice can be controlled more easily in production.

IIIC.2.3 Suppression by Current-Interrupting Devices

It is not possible to make a clear distinction between current-interrupting devices and perturbations, since any modification of the cavity is a perturbation. The term current-interrupting device is used here to refer to any device whose primary object is to prevent the flow of surface currents which are required by an undesired mode, whereas the term perturbation is used to refer to distortions of the ideal cavity shape which are designed to shift the resonant frequency of the undesired mode so that it no longer interferes with the proper operation of the cavity. It is possible that many current-interrupting devices also act as perturbations.

The most common current-interrupting device is the gap between the tuning plunger and the cavity wall (Sec. IIIC.2.1). Since the presence of the end plate gap obstructs current flow between end plate and side wall, undesired modes will be, to varying degrees, inhibited. In addition, the presence of the gap introduces reactance, which shifts the frequency of these modes. Hence, the companion degenerate TM_{11n} mode will be shifted so that it no longer coincides with the TE_{01n} mode. In some existing echo boxes, for example the TS-62/AP, there are gaps at both plates. Gaps are ordinarily 0.030" to 0.050" long, although occasionally they are much longer. The 14ABA-1 echo box, for example, has a gap of 0.125" around the tuning plunger, but no gap at the fixed end of the cavity, and the dielectric damping material on the back of the tuning plunger is approximately 1/4" thick over the metal.

Cavity symmetry must be carefully preserved if good performance in the desired mode is to be obtained, and if undesired modes are to be avoided. This means, so far as the end plate gaps are concerned, that gap length must be identical when measured along any radius, within very close tolerances, for any position of the tuning plunger. Also both end plates must at all times be accurately perpendicular to the cavity axis. These two conditions together impose rigid requirements on the mechanical construction of the cavity.

A second type of current-interrupting device which is frequently used consists of annular slots cut in the end plates concentric with the cylinder axis. These slots are located so they are in a region of dense radial current for some interfering mode. If several such modes are present, the locations of the cuts may be a compromise. In order to be of maximum efficiency, the slots should be made so they are a quarter wavelength deep for the unwanted modes, since then they will act as a quarter-wavelength short-circuited transmission line in the path of the offending mode and will effectively be an open circuit. In order to be effective over an appreciable band of frequencies the slots are filled, or "loaded", with lossy dielectric material, which broadens the resonance curve of the slot.

In some boxes of Bell Telephone Laboratories design, such as the TS-62/AP, the TS-218/AP, and the TS-172/UP, one end plate is made of Bakelite or phenolic fiber with silver-plated copper foil or a thin silvered aluminum disk cemented to it. If this type of construction is followed, the annular slots may be made merely by cutting and removing a portion of the conducting material. Various types of slot design are illustrated in Figure IIIC-9.

Slots are very effective in suppressing certain modes and much less effective for others, depending on the pattern of the currents in the end plates. By examining the charts of current distribution in the end plates, it may be seen, for example, that TE modes with $m = 1$ should be strongly hindered by the presence of a ring, whereas TE modes with $m > 1$ will be much more difficult to deal with by this method.

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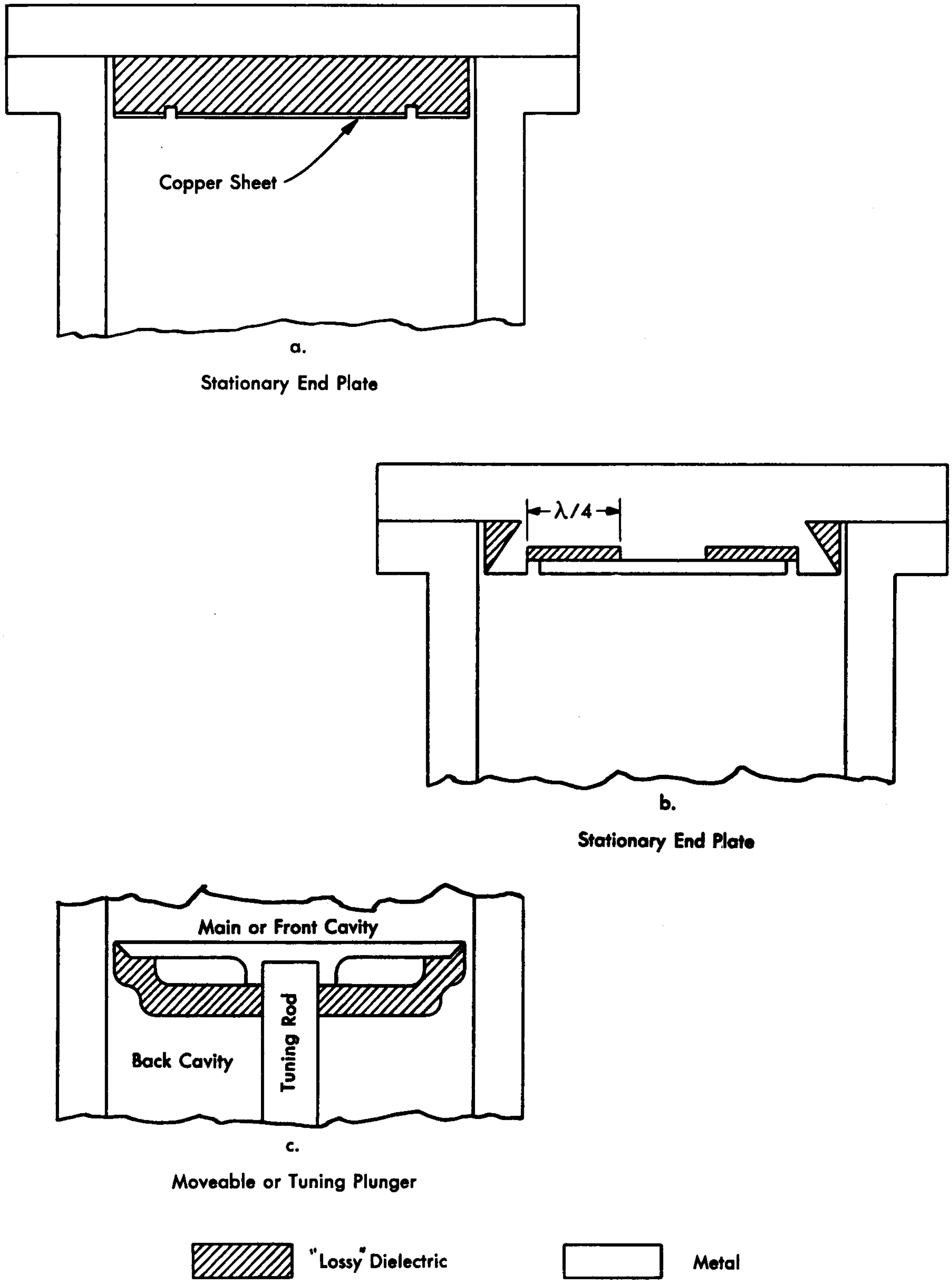

FIG. III C-9 VARIOUS TYPES OF END PLATE SLOTS

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The width of the gaps is not critical. Usually it is of the order of 1/16" to 1/8".

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Example (IIIC.6):

The cavity of Example IIIC.3 operates in the TE_{012} mode and the extraneous modes, repeated here for convenience, are:

TE_{113}, TE_{212}, TE_{312}, TE_{411}, TE_{121}, TM_{211}, TM_{013}, and TM_{210}.

The TM modes should be adequately suppressed by the coupling loop orientation and by the end plate gap. In addition, the companion degenerate mode, the TM_{112}, should be sufficiently perturbed by the end plate gap so that its resonant frequency is different from that of the TE_{012}.

By inspection of the charts and graphs of end plate currents (Fig. IIIC-3), it appears that a ring placed at almost any radius will be effective in suppressing the TE_{11} modes. The most favorable position to suppress the TE_{21} modes will be at a relative radius greater than 0.5. For the TE_{31} and TE_{41} modes, a value of 0.75 is good. For the TE_{12}, the ring should be much closer to the center, between 0.25 and 0.35, although this mode will not be too effectively suppressed by a ring.

If the ring is placed in the movable end plate, or if there is an end plate gap in the stationary plate as well as in the movable, then a relative radius exceeding .75 would bring the ring close to the end plate gap, which itself is a very effective suppression means for the TE_{11}, TE_{21}, TE_{31} and TE_{41} modes. Therefore, unless these modes prove troublesome, an additional ring does not appear to be necessary. If one is used, a relative radius of about 0.70 to 0.75 should be chosen. The TE_{12} mode will probably cause trouble and a ring at about 0.3 may help to suppress it.

IIIC.2.4 Suppression by Perturbation

Deliberately changing the shape of the cylinder from its ideal right-circular configuration is a way in which the degenerate TE_{11n} mode may be separated from the TE_{01n}. If this can be done, then it is possible that the very rigid requirements placed on the alignment of the end plates can be relaxed. This technique has been investigated by Baños (Ref. 13) and others, and a theoretical discussion of cavity perturbation is included as Appendix I of this manual. The effect of cavity perturbation is to displace all the modes from their normal positions on the mode chart, and the designer attempts to find a perturbation which will displace the TM_{11n} mode relative to the TE_{01n}, so that they are no longer coincident. Very little practical work has been done toward investigating the effects of deliberate cavity perturbations, and this field is a promising one for further work. To prevent the cavity from being unsymmetrical, and thus invite the appearance of undesirable nonsymmetrical modes, the only types of perturbations open for consideration are those which preserve cavity symmetry, such as a curved or conical end plate, or the gap presently used between the end plate and the cylinder wall.

IIID THE RINGING TIME PROPERTIES OF THE CYLINDRICAL CAVITY

IIID. 1 Relation of Ringing Time to Cavity Parameters

IIID. 1. 1 The Ringing Time Equation

In Section IIA, the various factors which determine the ringing time of an echo box were listed and discussed. Briefly, they are:

1. Radar performance (measured at the echo box), D
2. Coupling loss, W_1
3. Line loss, W_2
4. Coupling loss, W_3
5. Charging loss, W_4
6. Echo box Q

A graphical relationship between these factors was shown in Figure IIA-4. They can also be related by an equation, known as the ringing time equation, which can be obtained by reference to Figure IIA-4. Let P_t denote the power level during the transmitter pulse at the input to the coupling device, expressed in dbm or dbw. At the input to the echo box the energy level is therefore

$$P_t - W_1 - W_2$$

where W_1 and W_2 are expressed in decibels. The power at the echo box is attenuated further by the coupling loss, W_3.

The energy level within the box cannot reach a steady value because of the high value of Q and the shortness of the transmitter pulse. Therefore, the energy leaving the box at the end of the transmitter pulse does not equal that entering it during the pulse, and the discrepancy is denoted by an additional loss, W_4.

The energy returning from the echo box to the radar will again encounter the loss due to mismatch W_3, and the losses W_2 and W_1. At the end of ringing, the power level at the echo box will have decreased by a number of decibels D, the equivalent of the radar performance figure measured at the echo box. At the end of ringing, therefore, the power at the radar transmission line has decayed to the level

$$P_t - 2W_1 - 2W_2 - 2W_3 - W_4 - D \quad \text{dbm or dbw}$$

This expression assumes that at the end of ringing, the power at the radar receiver corresponds to the receiver noise level, or in other words, is a measure of the receiver noise figure. This assumption is probably not justified, since it appears fairly certain that ringing time is generally measurable down into the noise, particularly in the case of A-scopes. To correct the ringing time so as to reflect the actual radar performance, it is necessary to add a correction factor W_5. This figure is probably in the neighborhood of 2 to 5 db. Therefore, if P_n is the noise power of the receiver, in dbm,

$$P_n = P_t - 2W_1 - 2W_2 - 2W_3 - W_4 + W_5 - D$$

If t_2 is the time required for the power to decrease D db during ringing, and if t_1 is the duration of the transmitted pulse, the ringing time, t_r, is

$$t_r = t_1 + t_2$$

The decrement of the cavity is defined as the number of db by which the power decreases per microsecond of ringing time and is related to the Q of the cavity by (App. III)

$$d_L = \frac{27.3f}{Q_L}$$

where d_L is the decrement of the cavity when coupled to an external circuit ("loaded" decrement), Q_L is the Q of the cavity under the same conditions, and f is the resonant frequency of the cavity in megacycles per second. Expressing t_2 in terms of the decrement, $t_2 = D/d_L$.

Therefore,

$$t_r = t_1 + \frac{1}{d_L}\left[P_t - 2(W_1 + W_2 + W_3) - W_4 + W_5 - P_n\right] \qquad (1)$$

or

$$t_r = t_1 + \frac{Q_L}{27.3f}\left[P_t - 2(W_1 + W_2 + W_3) - W_4 + W_5 - P_n\right] \qquad (1a)$$

Using these equations, the necessary Q_L or decrement for a specified ringing time can be calculated, or the expected ringing time can be calculated from a known Q_L or decrement.

Unfortunately, these equations have d_L and Q_L implicit in them; that is, some of the terms within the bracket contain these quantities. This implicitness can be seen by examining the terms individually.

The term W_1 can be obtained from the characteristics of the directional coupler. W_2, the line loss, should generally be about 3 db for best results. The coupling loss W_3 is due to reflection or mismatch at the echo box. For optimum coupling into the box the impedance match is very poor, and the standing wave ratio very high. An analysis made on the basis of an equivalent circuit has shown this term to be (Ref. 9)

$$-W_3 = 10 \log_{10}\left(1 - \frac{Q_L}{Q_0}\right) \text{db}$$

or,

$$W_3 = 10 \log_{10} \frac{1}{1 - \frac{Q_L}{Q_0}} \quad \text{db}$$

where Q_L/Q_0 is the ratio of "loaded" to "unloaded" Q. This ratio ordinarily is between 0.90 and 0.95, and W_3 is therefore between 10 and 13 db.

A similar analysis shows that the charging loss W_4 can be expressed by

$$-W_4 = 20 \log_{10} \left[1 - \exp.\left(-\frac{\pi f t_1}{Q_L} \right) \right] = 20 \log_{10} \left[1 - \exp.\left(-\frac{\pi d_L t_1}{27.3} \right) \right]$$

or,

$$W_4 = 20 \log_{10} \frac{1}{1 - \exp.\left(-\frac{\pi f t_1}{Q_L} \right)} = 20 \log_{10} \frac{1}{1 - \exp.\left(-\frac{\pi d_L t_1}{27.3} \right)}$$

W_4 is plotted as a function of $t_1 d_L$ in Figure IIID-1. The decrement d_L of a box can easily be found (if its sensitivity in yards/db is known) by dividing number of yards (round trip) electromagnetic energy travels per microsecond (164 yards) by the sensitivity of the box.

$$d_L \text{ (db/microsecond)} = \frac{164 \text{ (yards/microsecond)}}{\text{Sensitivity (yards/db)}}$$

The ringing time equation can now be written:

$$t_r = t_1 + \frac{Q_L}{27.3f} \left\{ P_t - P_n - 2 \left[W_1 + W_2 \right] + 20 \log_{10} \left[1 - \frac{Q_L}{Q_0} \right] + 20 \log_{10} \left[1 - \exp.\left(-\frac{\pi f t_1}{Q_L} \right) \right] + W_5 \right\} \quad (2)$$

or,

$$t_r = t_1 + \frac{1}{d_L} \left\{ P_t - P_n - 2 \left[W_1 + W_2 \right] + 20 \log_{10} \left[1 - \frac{Q_L}{Q_0} \right] + 20 \log_{10} \left[1 - \exp.\left(-0.115\, t_1 d_L \right) \right] + W_5 \right\} \quad (2a)$$

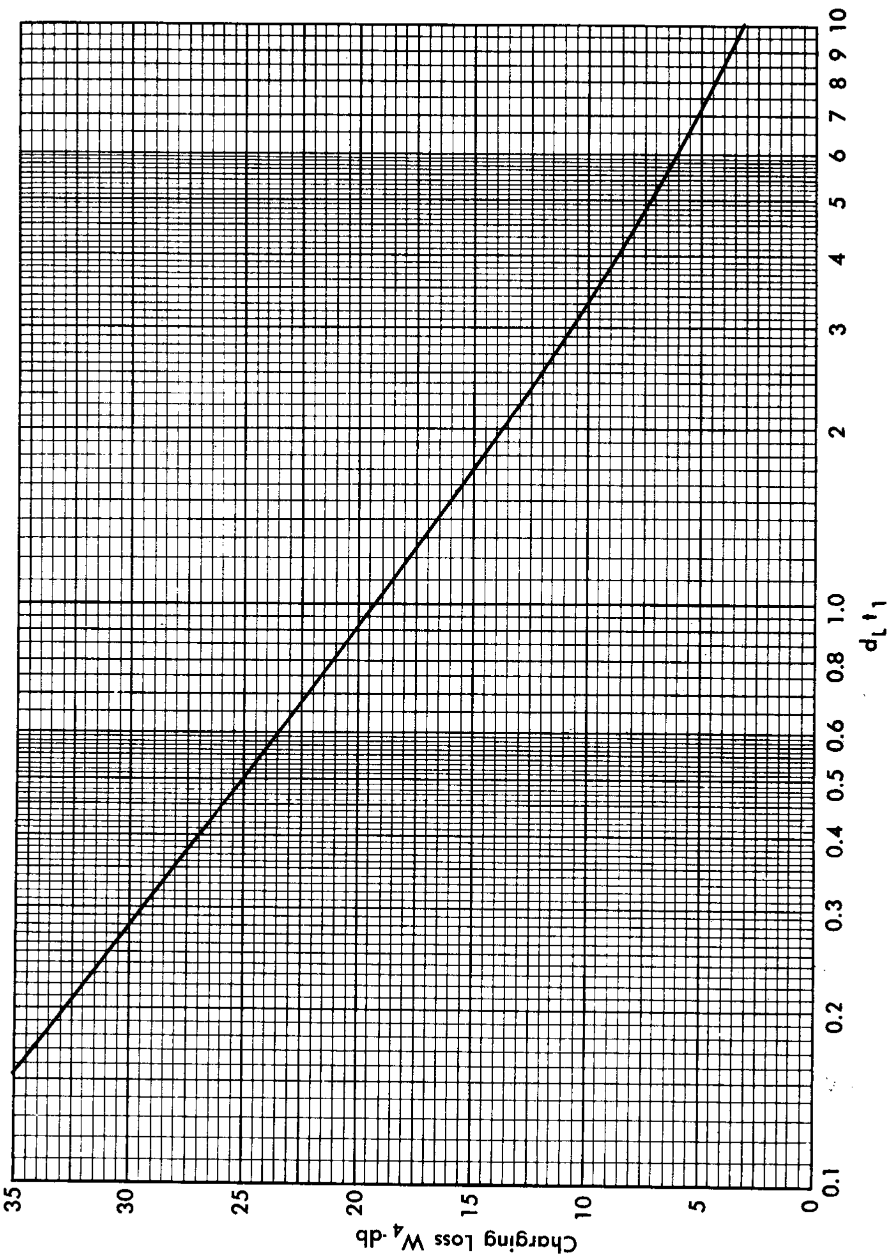

FIG. III D-1 CHARGING LOSS AS A FUNCTION OF $d_L t_1$

If a representative value of 12 db is assumed for W_3 (this figure is accurate enough for most purposes), the equation becomes:

$$t_r = t_1 + \frac{Q_L}{27.3f}\left\{P_t - P_n - 2\left[W_1 + W_2 + 12\right] + 20\log_{10}\left[1 - \exp.\left(-\frac{\pi f t_1}{Q_L}\right)\right] + W_5\right\} \quad (3)$$

or,

$$t_r = t_1 + \frac{1}{d_L}\left\{P_t - P_n - 2\left[W_1 + W_2 + 12\right] + 20\log_{10}\left[1 - \exp.\left(-0.115 t_1 d_L\right)\right] + W_5\right\} \quad (3a)$$

Equation (2) may be used to determine the ratio Q_L/Q_0 which results in the maximum ringing time. The equation is too complex to differentiate with respect to Q_L or Q_L/Q_0 to find conditions for maximum ringing time. However, in Figures IIID-2, IIID-3, and IIID-4, the ringing time is plotted as a function of the ratio Q_L/Q_0 with different values assigned to the parameter's pulse length, frequency, and level difference. (These curves are reproduced from Reference 9).

Figure IIID-2 shows the ringing time as a function of Q_L/Q_0, with the pulse length as a parameter. The fact that these curves possess a distinct maximum indicates that there is an optimum value for the coupling and this value depends upon the pulse length. The maximum moves to the left as the pulse becomes shorter, showing that a system with shorter pulses can tolerate tighter coupling of the echo box. Figure IIID-3 shows the variation in ringing time with coupling with ω/Q_0 as parameter. In Figure IIID-4, F, the ratio of the voltage input to the echo box at the end of the transmitter pulse to the voltage at the same point at the end of ringing, is varied. This parameter is related to quantities in the ringing time equation by

$$20\log_{10} F = P_t - P_n - 2(W_1 + W_2)$$

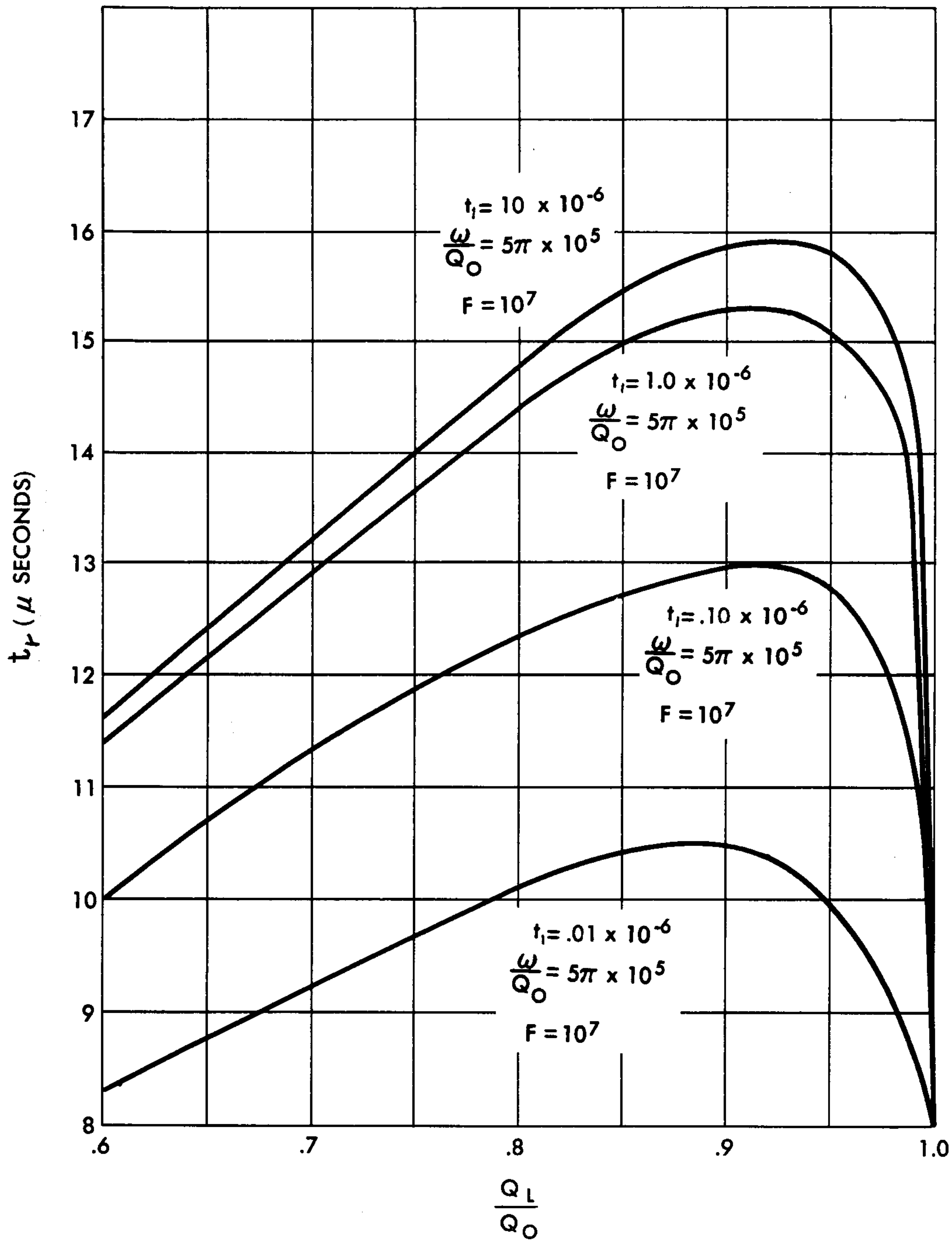

FIG. III D-2 RINGING TIME AS A FUNCTION OF Q_L/Q_O, PULSE LENGTH AS PARAMETER

Courtesy RAYTHEON MANUFACTURING COMPANY

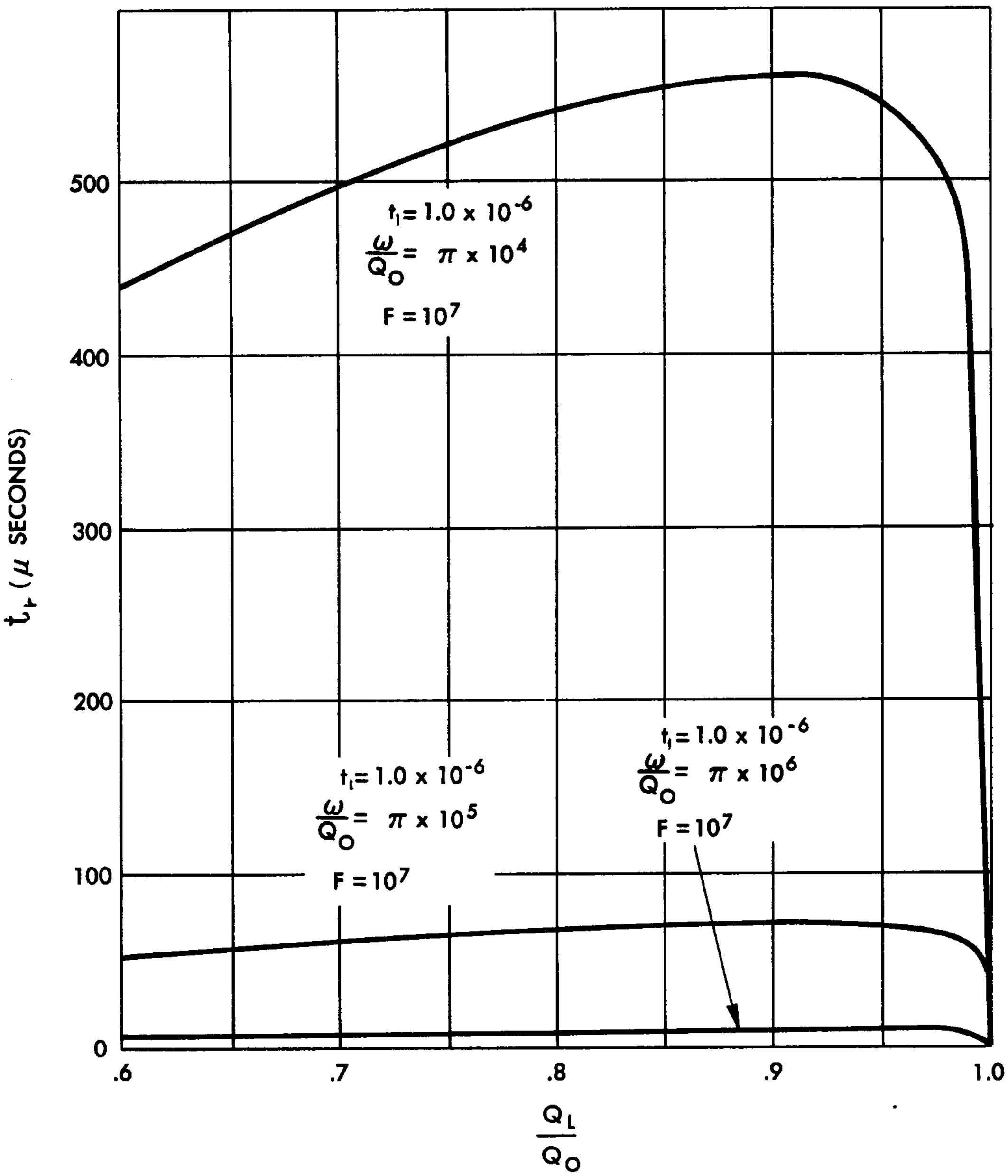

FIG. III D-3 RINGING TIME AS A FUNCTION OF Q_L/Q_O, ω/Q_O AS PARAMETER

Courtesy RAYTHEON MANUFACTURING COMPANY

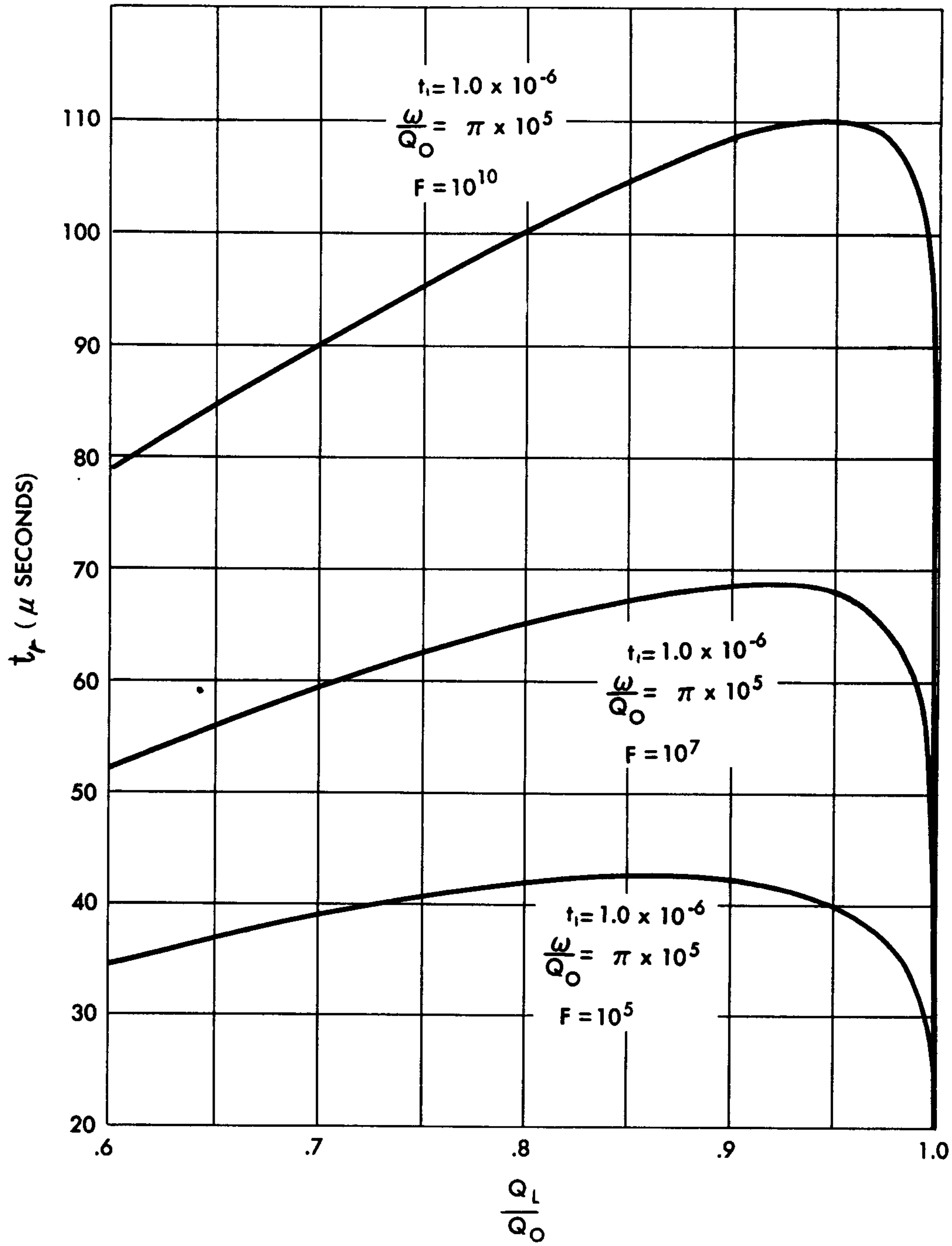

FIG. III D-4 RINGING TIME AS A FUNCTION OF Q_L/Q_O, F AS PARAMETER

Courtesy RAYTHEON MANUFACTURING COMPANY

These curves show that the coupling to the echo box should be closer for systems with small dynamic range. All three sets of curves indicate that undercoupling (Q_L/Q_0 very close to unity) results in a much more drastic loss in performance than overcoupling (coupling too closely). Since the proper value of coupling in a new echo box design is obtained experimentally, these curves are not of great value to the designer and serve mainly to show qualitatively what effect may be expected from a proposed change.

IIID. 1. 2 Theoretical Q

The theoretical Q of the cavity, Q_T, is the value of Q which is computed on the basis of cavity dimensions and the conductivity of silver, assuming perfect cavity construction and no loading effects. Q_T can be calculated from the equation given in Section IIIB or by using the curves of $Q\sqrt{f}/10^6$ on the mode charts, once the cavity dimensions and frequency band are known. In practice the actual unloaded Q of the cavity, Q_0, is not as great as Q_T because of imperfections in plating and in achieving the ideal cavity shape, as well as deliberate perturbations introduced into the cavity. Since the ratio of Q_0 to Q_T is generally about 0.85 to 0.90 and since the loaded Q of the cavity, Q_L, is generally about 0.90 Q_0 to 0.95 Q_0, it can be stated axiomatically that Q_L = 0.75 to 0.85 Q_T, approximately. This relationship can be used to simplify the cavity design problem.

IIID. 1. 3 Procedure for Determining the Required Theoretical Q

A required value of Q_T can be obtained from the equation for ringing time, provided a required value of ringing time and the other parameters in the equation are known or can be assumed. If the following assumptions are made:

$$20 \log_{10} \left(1 - \frac{Q_L}{Q_0}\right) = -23 \text{ db}$$

$$W_5 = 2 \text{ db}$$

and $$Q_L = 0.80\, Q_T$$

Equation (2) of Section IIID. 1. 1 becomes

$$t_r = t_l + 0.0293 \frac{Q_T}{f} \left\{ P_t - P_n - 2 (W_1 + W_2) - 21 + 20 \log_{10} \left[1 - \exp\left(\frac{-3.93 \, ft_l}{Q_T} \right) \right] \right\}$$

where f is in mcs, and t_r and t_l are in microseconds. To find Q_T from this equation it is necessary to use a successive approximation method. This method consists of assuming an initial value for the charging loss, calculating a trial value for Q_T, and, by use of this value, calculating a new value for the charging loss. This procedure is repeated until the value of charging loss does not change in the last significant digit desired.

Example: An echo box is to be designed according to the following specifications:

- f = 9000 to 9500 mcs
- t_r minimum = 24.5 microseconds
- Transmitter power = 50 kw peak
- t_l = 0.25 microsecond
- Coupling of directional coupler = -20 db
- Cable loss = 3 db
- Receiver band pass = 8 mcs
- Receiver noise figure = 13 db

The theoretical receiver noise power can be calculated from the relationship:

$$P'_n = KT\Delta f$$

where
- P'_n = theoretical receiver noise power, watts
- K = Boltzmann's constant = 1.38×10^{-23} joules per degree Kelvin
- T = absolute temperature (usually taken as 291° K.)
- Δf = receiver passband, in cycles per second

It is convenient to remember that a receiver with a 1-mcs passband has a theoretical noise power output of -114 dbm. An 8-mcs receiver has a theoretical noise power 8 times as much, or -105 dbm. The actual receiver of this example has 13 db more noise than theoretical, making P_n = -92 dbm. The transmitted pulse power = 50 kw or +77 dbm. Therefore,

$$P_t - P_n = 77 - (-92) = 169 \text{ db}$$

Assume a charging loss of -20 db. The ringing time will be least at the high frequency end of the band. A trial value for Q_T can be found by substituting these values into the ringing time equation.

$$24.5 = 0.0293 \frac{Q_T}{9500} \left[169 - 2\,(20 + 3) \quad -21 \quad -20\right]$$

$$= 3.08 \times 10^{-6}\, Q_T\,(82) = 253 \times 10^{-6}\, Q_T$$

$$Q_T = 96{,}800$$

From this figure the charging loss is:

$$W_4 = 20 \log \left[1 \quad -\exp\left(- \frac{3.93 \times 9500 \times 0.25}{96{,}800}\right)\right] \qquad = 20.7 \text{ db}$$

which is in good agreement with the assumed figure. Therefore, calculation of a second trial value for Q_T is not required. The required ringing time in this example is rather short (2 nautical miles), hence, the rather low figure for Q_T.

IIID. 2 Variation of Ringing Time with Frequency

The dependence of ringing time on frequency is an important factor in the design of an echo box. The ringing time equation (Eq. (2), Sec. IIID. 1. 1) shows how ringing time can be expected to vary with frequency, assuming constant radar performance. In practice, the pulse length is short compared to the ringing time, so the term t_1 in this equation can be neglected. The ringing time, therefore, is proportional to Q/f, and to the expression within the brackets. In the bracketed expression, the radar

performance term, $P_t - P_n$, is much larger than the other terms. Furthermore, these remaining terms do not change greatly over the tuning range of a typical echo box. To a first order approximation, therefore, the bracketed expression can be considered constant. With these approximations, the ringing time equation becomes:

$$t_r = K \frac{Q}{f} \tag{4}$$

To investigate the frequency dependence of ringing time, the most obvious approach is to find how Q varies with frequency. An equally valid and more convenient approach is to determine how Q/f behaves as a function of D/L. To do this, the expression for $Q\sqrt{f}$ (Eq. 4, Sec. IIIB. 3) and the mode line equation for TE_{01n} modes will be used. These equations are:

$$\frac{Q\sqrt{f}}{10^6} = 2.85 \frac{\left[1 + 0.168\left(\frac{D}{L}\right)^2 n^2\right]^{3/2\,[1]}}{1 + 0.168\left(\frac{D}{L}\right)^3 n^2} \tag{5}$$

$$(fD)^2 = 2.0707 + .34799\, n^2\left(\frac{D}{L}\right)^2 \tag{6}$$

Raising (6) to the 3/4 power,

$$(fD)^{3/2} = \left[2.0707 + .34799\, n^2\left(\frac{D}{L}\right)^2\right]^{3/4} \tag{7}$$

The ratio of equations (5) and (7) is

$$\frac{Q}{f} \times \left(\frac{D}{10^6}^{-3/2}\right) = 1.65 \frac{\left[1 + 0.168\left(\frac{D}{L}\right)^2 n^2\right]^{3/4\,[1]}}{1 + 0.168\left(\frac{D}{L}\right)^3 n^2} \tag{8}$$

f in mcs, D in inches.

[1]This equation assumes a silver plated cavity.

$\frac{Q}{f} \times \left(\frac{D^{-3/2}}{10^6} \right)$ has been plotted as a function of D/L for representative values of n in Figure IIID-5. The ordinate of this curve involves the factor D because it is not possible to express Q/f as a function of D/L (and n) alone, as is possible with the quantity $Q\sqrt{f}$. However, for a given cavity, D is a constant, so that numerical values of Q/f can be calculated. Futhermore, it is the shape of the curves which is their most useful property, and the shape will not depend on D, since a change in D only expands or contracts the curves vertically.

The curves have maxima at values of D/L between 0.2 and 0.5, the smaller values of D/L corresponding to larger values of n. This figure also shows the curve of maximum Q/f. This curve is a plot of the equation

$$n^2 = 5.95 \frac{1 - 2\frac{D}{L}}{\left(\frac{D}{L}\right)^3} \tag{9}$$

obtained by maximizing Q/f with respect to D/L.

Frequency increases with an increase of D/L. Hence, a cavity designed with values of D/L to the right of the maximum of the Q/f curve will have ringing time which decreases with frequency. Conversely, a cavity operating on the left side of the maximum point will have ringing time which increases with frequency. To obtain a cavity with the least amount of variation of ringing time across the tuning band, the cavity, ideally, should be designed to operate in the region of the maximum point of the curve.

Echo boxes are generally not designed to operate near the maximum of these curves, however, because other conditions are not optimum here. For example, the maximum tuning ranges, as limited by the presence of the $TE_{01(n+1)}$ mode (where n is the operating mode), are relatively small within this region; the cavities are far removed from the region of maximum Q/V; and finally, such cavities are rather elongated, which means that for many purposes they are undesirable for physical reasons. For

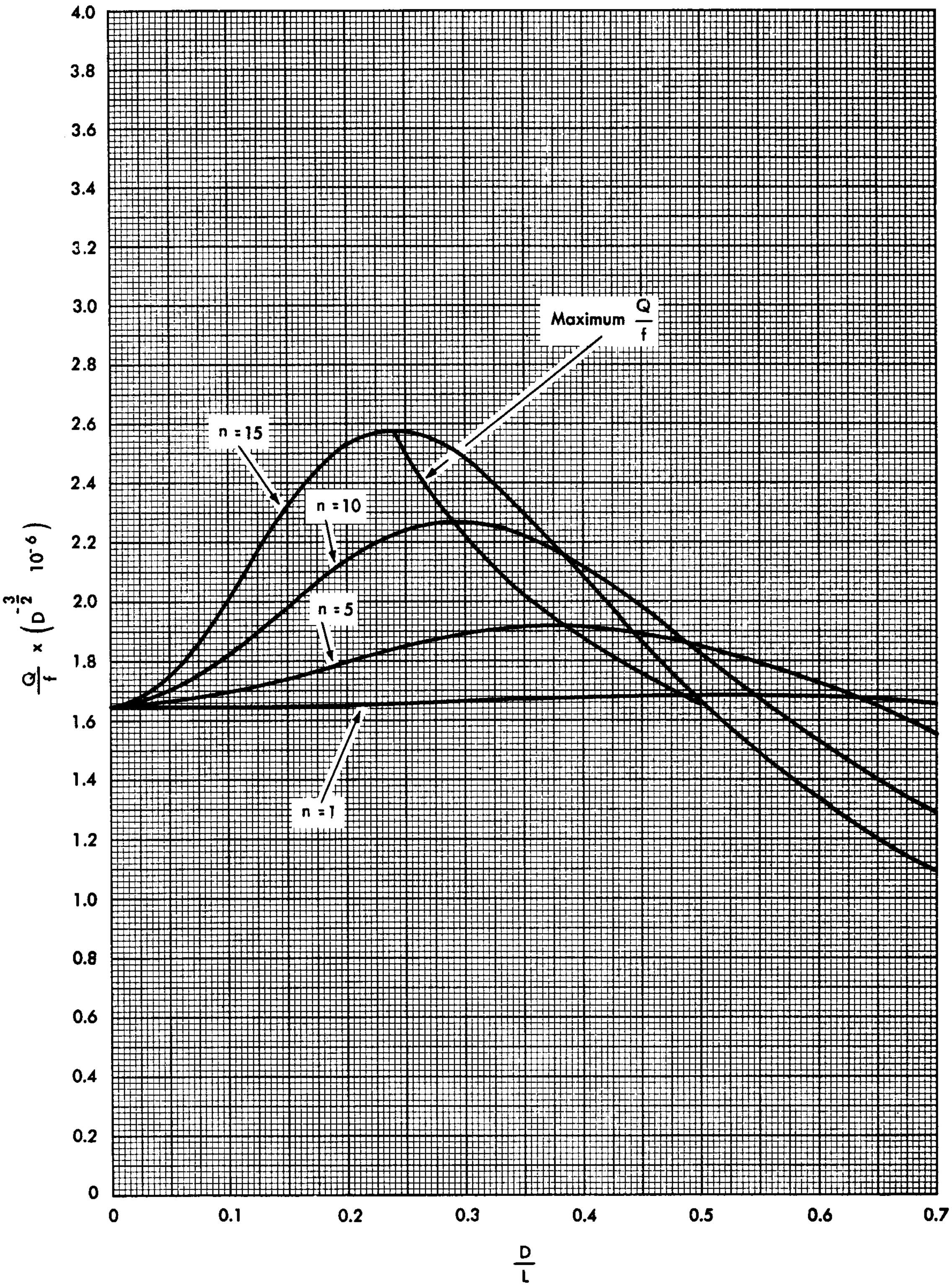

FIG. III D-5 Q/f vs. D/L FOR SILVER PLATED CYLINDRICAL CAVITIES OPERATING IN THE TE_{01n} MODE, FOR VARIOUS VALUES OF n example, at n = 10, a cavity designed to operate in the region where ringing time is nearly independent of frequency, will have a length more than three times the diameter. In view of these considerations, the region to the right of the maximum points has always been utilized in echo box design. Therefore, ringing time will always be greatest at the low frequency end of the echo box tuning band. In general, the farther the operating region is from the point of maximum Q/f, the greater is the variation of ringing time with frequency. This is true even though the slopes of the curves of Figure IIID-5 decrease at values of D/L considerably removed from the points of maximum Q/f, a fact which, considered alone, indicates that ringing time variation should be smaller for cavities having these dimensions. However, the ringing time variation depends not only on the slope of the curve, but also on the value of Q/f. Small values of Q/f, such as occur far from the maximum point, overcome the effect of the decrease in slope and cause the variation of ringing time to be large.

The Q/f curves can be used to compute the expected ringing time variation over a specified tuning band, as follows:

Since $$t_r = K \frac{Q}{f},$$

$$\frac{t_{r2} - t_{r1}}{t_{r0}} = \frac{\left(\frac{Q}{f}\right)_2 - \left(\frac{Q}{f}\right)_1}{\left(\frac{Q}{f}\right)_0} \quad \text{or,} \quad \frac{\Delta t_r}{t_{r0}} = \frac{\Delta \frac{Q}{f}}{\left(\frac{Q}{f}\right)_0}$$

where t_{r2} and t_{r1} are the ringing times at the high and low frequency extremeties, respectively, of the tuning band, t_{r0} is a reference value of ringing time, usually the mid-band value; and $(Q/f)_2$, $(Q/f)_1$, and $(Q/f)_0$ are the values of Q/f corresponding to t_{r2}, t_{r1}, and t_{r0}, respectively.

The percentage variation in ringing time over the tuning band is therefore found by reading values for $(Q/f)_2$, $(Q/f)_1$, and $(Q/f)_0$ from

Figure IIID-5 and applying the above expression. It is not necessary to evaluate D, since, in taking the ratio $\frac{\Delta \frac{Q}{f}}{\left(\frac{Q}{f}\right)}$, the factor $\frac{D^{-3/2}}{10^6}$ cancels.

The Q/f curves, although helpful to the understanding of the ringing time dependence on frequency, are not the most practical means of calculating ringing time variation. An easier means for obtaining the expected ringing time variation for a given operating rectangle quickly and easily can be developed using the mode shape factor. Curves of this factor are plotted in Figures IIID-6, 7 and 8. Since ringing time is proportional to Q/f,

$$t_r = K\frac{Q}{f} = K\frac{Q}{f} \times \frac{\sqrt{f}}{\sqrt{f}} = K\frac{Q\sqrt{f}}{f^{3/2}}$$

The mode shape factor, however, has been shown (Sec. IIIC) to be proportional to $Q\sqrt{f}$:

$$MS = \frac{Q\delta}{\lambda} = K' \quad Q\sqrt{f}$$

Therefore, $t_r = K\frac{Q\sqrt{f}}{f^{3/2}} = \frac{K}{K'}\frac{MS}{f^{3/2}} = K''\frac{MS}{f^{3/2}}$

Both MS and frequency are functions of the ratio D/L.

If D/L is increased by Δ D/L, the above expression for t_r then becomes

$$t_r + \Delta t_r = K''\frac{MS + \Delta MS}{(f + \Delta f)^{3/2}}$$

The increments ΔMS and Δf result from the increment ΔD/L. An increase in D/L increases f, so that Δf is positive. In the case of ΔMS,

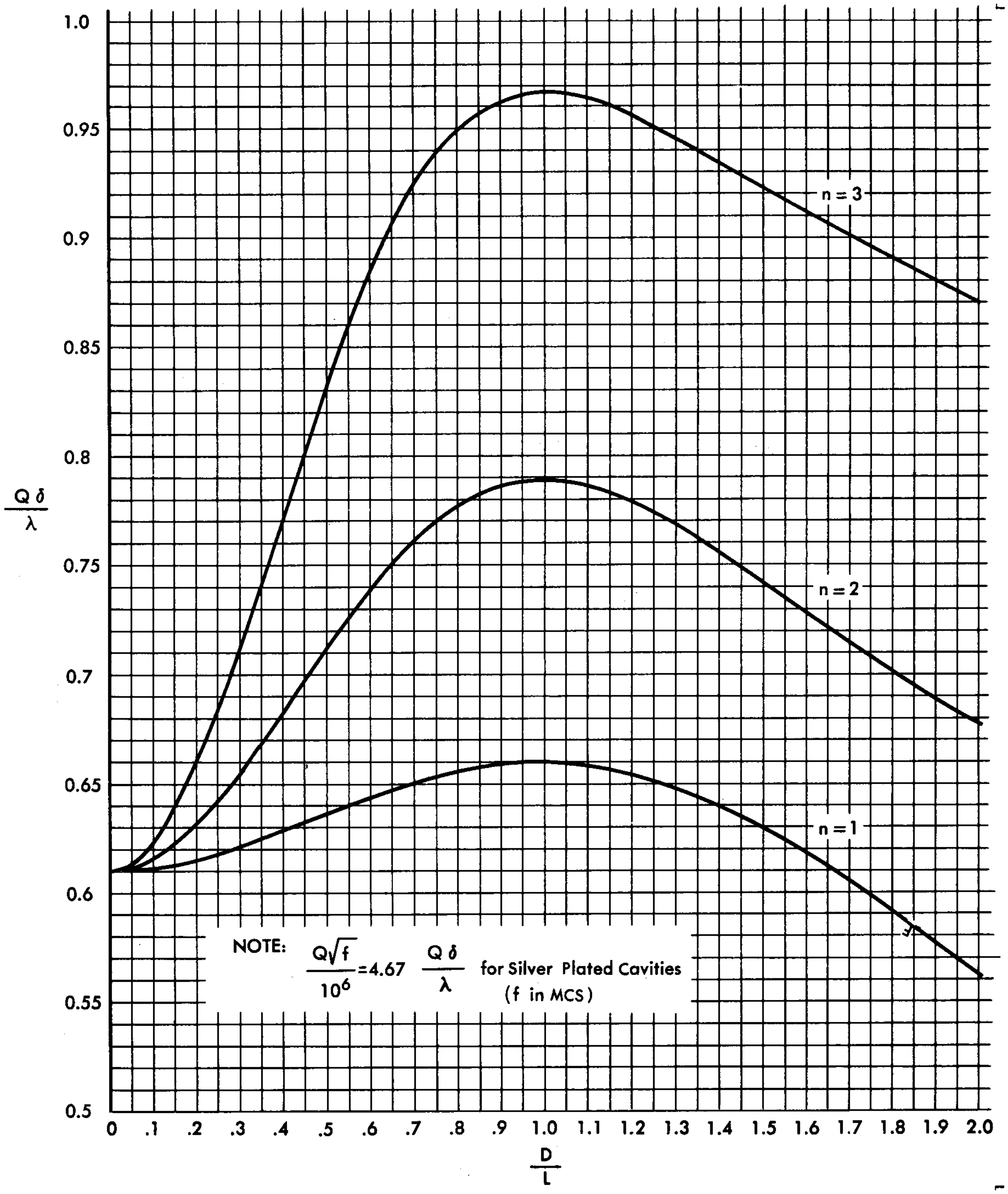

FIG. III D-6 Q δ/λ vs. D/L FOR CYLINDRICAL CAVITIES OPERATING IN THE TE_{01n} MODE, n = 1 - 3

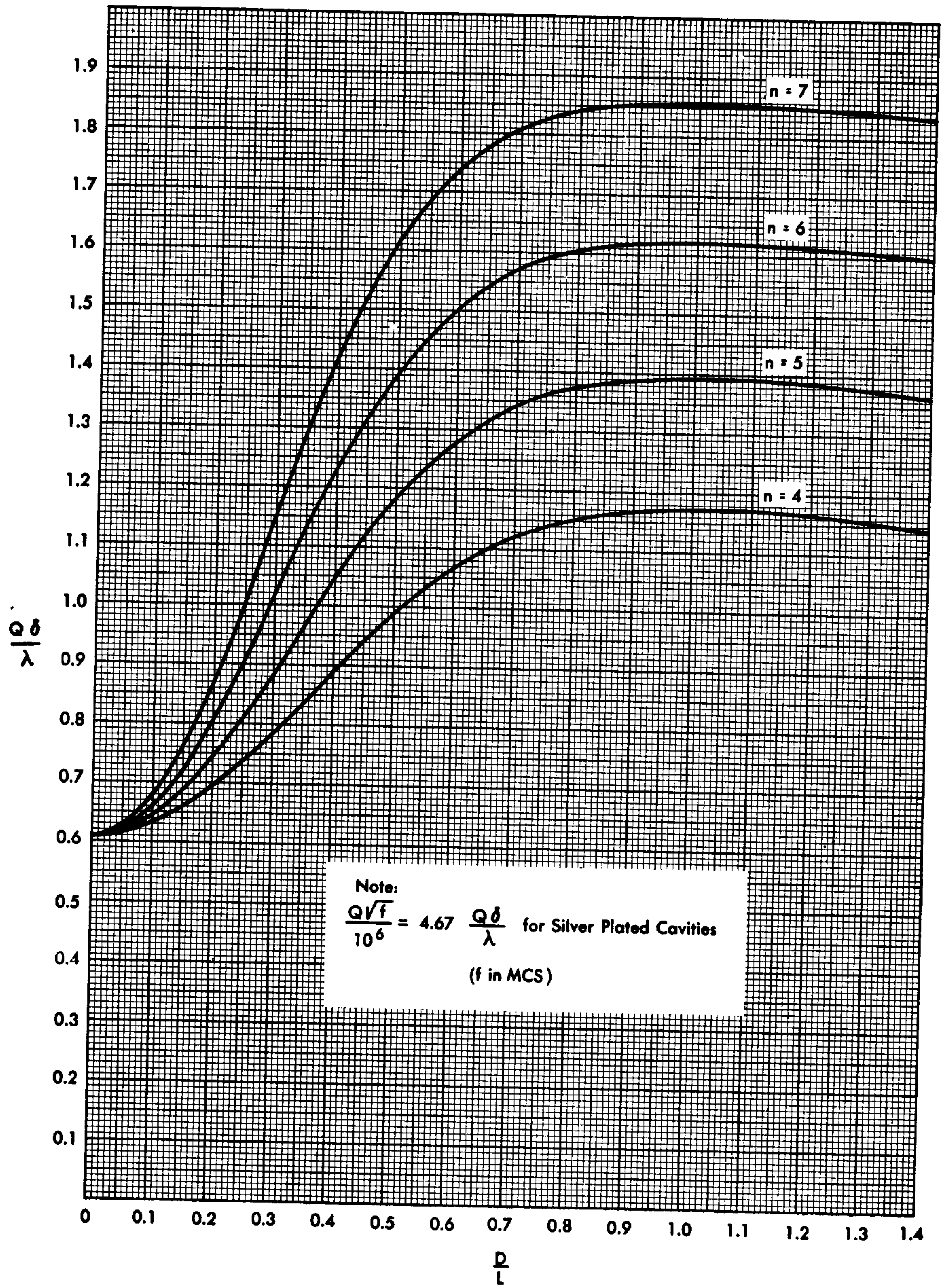

FIG. III D-7 $Q\delta/\lambda$ vs. D/L FOR CYLINDRICAL CAVITIES OPERATING IN THE TE_{01n} MODE, n = 4 - 7

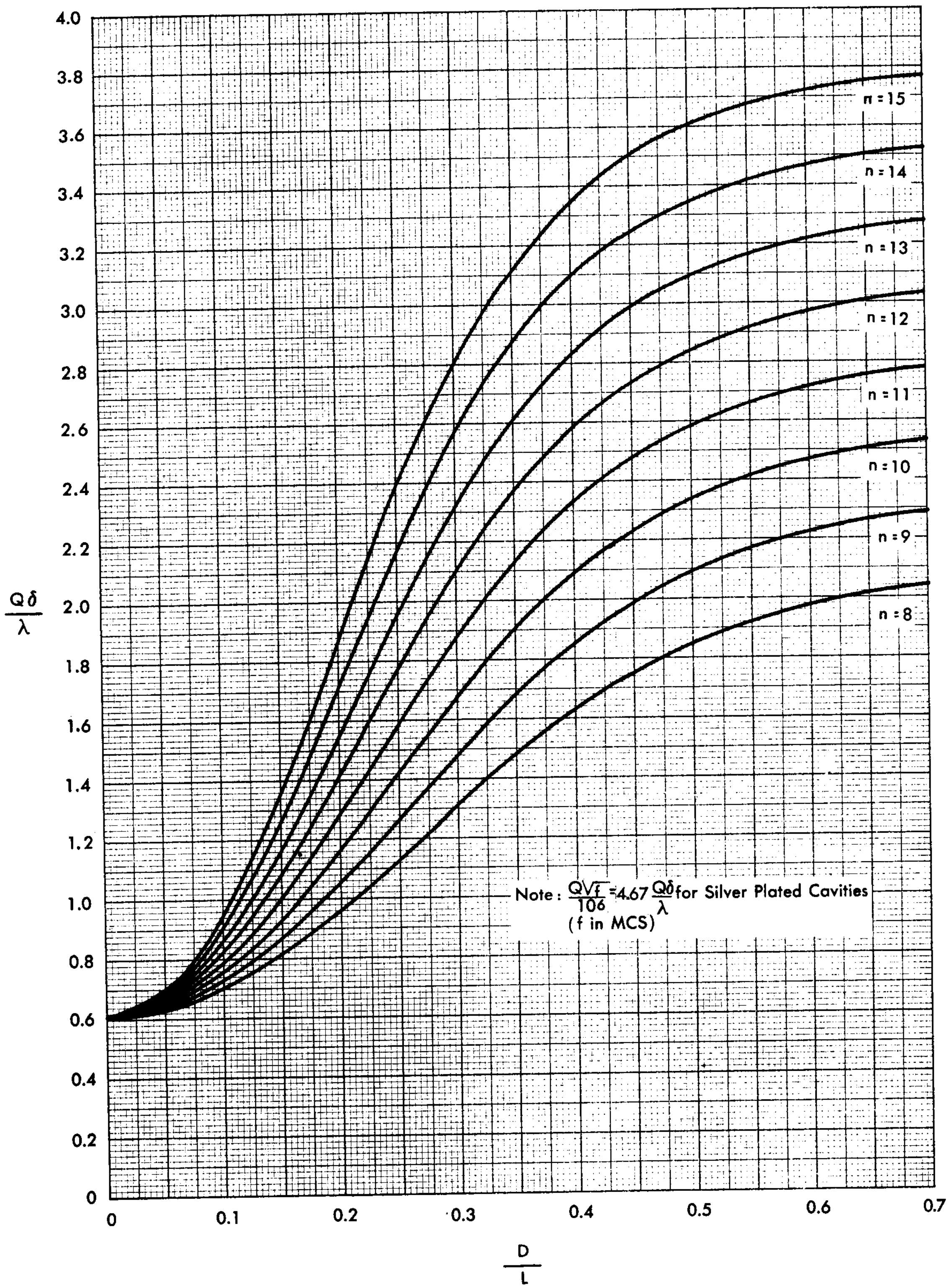

FIG. III D-8 $Q\delta/\lambda$ vs. D/L FOR CYLINDRICAL CAVITIES OPERATING IN THE TE_{01n} MODE, n= 8 - 15 however, the increment is positive if D/L<1 and negative if D/L>1, as can be seen from the MS curves. Rearranging the above equation:

$$t_r\left(1+\frac{\Delta t_r}{t_r}\right) = K'' \frac{MS}{f^{3/2}}\left[\frac{1+\frac{\Delta MS}{MS}}{\left(1+\frac{\Delta f}{f}\right)^{3/2}}\right]$$

or

$$1+\frac{\Delta t_r}{t_r} = \frac{1+\frac{\Delta MS}{MS}}{\left(1+\frac{\Delta f}{f}\right)^{3/2}} \qquad (10)$$

This equation can be used to determine the ringing time variation over a given tuning band. In the above expressions, t_r, MS, and f refer to the low frequency end of the tuning band, but they can also be any other set of corresponding values, including those at the mid-band frequency. To use this expression, the appropriate values of MS are read from the mode shape curves and substituted into the expression. In addition, the corresponding values of frequency must be known.

IIID. 3 Q-Lowering Methods for Achieving Uniform Ringing Time

If the requirements on linearity of ringing time are too stringent to be obtained merely by selecting a suitable region on the mode chart, the linearity can be improved by one of various Q-lowering devices. These devices improve the ringing time uniformity by lowering the ringing time at all frequencies, but have the effect of lowering it more at some frequencies than at others. Only devices actually used in echo boxes are discussed here.

One technique is that of using two kinds of plating (Ref. 14). Figure IIID-9 shows an echo box in which the end plates and most of the cylindrical surface are plated with silver, the cylindrical surface near the tuning plunger being coated with cadmium. Cadmium has roughly one fourth the conductivity of silver, and its presence lowers the Q of the cavity. As the tuning plunger is moved outward, the ringing time tends to increase, but as more of the cadmium coated surface is

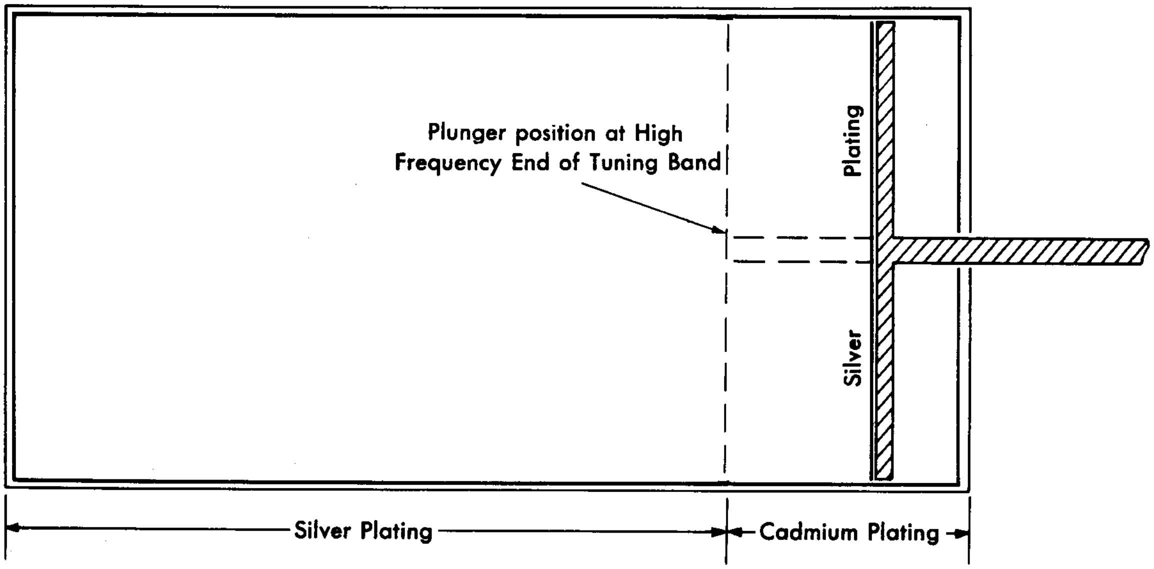

FIG. III D-9 ECHO BOX PLATED WITH SILVER AND CADMIUM TO PRODUCE RINGING TIME UNIFORMITY

exposed, the effective conductivity of the walls decreases, and this factor tends to lower the Q and hence the ringing time. If the cavity is designed correctly, the ringing time variation in some cases may be made as small as 1 per cent over the tuning band. The compensation which is obtainable by this technique is quite large, permitting cavities to be designed for which $D/L>1$, and still achieving fair uniformity of ringing time. Cavities operating at X-band have been designed for TE_{011} operation in the region of $(D/L)^2 = 2.5$. This region is desirable because there are few interfering modes here. The ringing time uniformity is very poor, however, and ringing time variation without compensation will range in the neighborhood of 20 to 40 per cent. The type of compensation described above can reduce this variation to 5 per cent or less.

The effectiveness of this dual plating depends upon two factors, the relative conductivities of the two metals and the relative strength of the wall currents in the region where the higher resistivity metal is plated. In his patent on the process (Appendix 4), Edson suggests other high resistivity metals to use in conjunction with the silver. If the cavity is constructed of brass, the portion of the cavity near the tuning plunger may be left unplated, since the brass itself has a lower electrical conductivity than silver. Other metals suggested are an alloy of 60 per cent copper and 40 per cent nickel, which has a resistivity 25 times that of silver, and an alloy of 98 per cent bismuth and 2 per cent tin, which has a resistivity 140 times that of silver.

The minimum current in the cylindrical wall for the TE_{01n} modes is at the ends of the cavity, so that higher resistivity metal placed in this region will not be so effective in altering ringing time as would otherwise be the case.

Since for higher modes the variation in L for a given tuning range is a smaller percentage of L than at lower modes, the variation in effective Q will be smaller. For this reason, cavities constructed to operate in higher modes will require metals whose resistivity is greater than that of cadmium to produce linearity of ringing time.

Among the existing echo boxes which utilize the two-metal method of obtaining ringing time uniformity are the TS-61/AP, the TS-110/AP, and the CXGU. These all operate near 3000 mcs and use cadmium as the metal of lower conductivity.

Linearity of ringing time also may be obtained by a loading loop or probe projecting into the cavity and coupling the cavity to a resistive element. This loading increases the power dissipated in the cavity and lowers the cavity Q. The loading is made sensitive to frequency so that Q/f remains substantially constant throughout the tuning range by locating the loading loop or probe at a point where the field, and hence the coupling, is a function of frequency. The coupling should be greater for lower frequencies and decrease as the cavity is tuned to higher frequencies. The resistor may be a conventional carbon type mounted in a tube attached to the cylinder wall. This technique may be used for both coaxial and cylindrical cavities. Such a coupling device is shown in Figure IIID-10(a).

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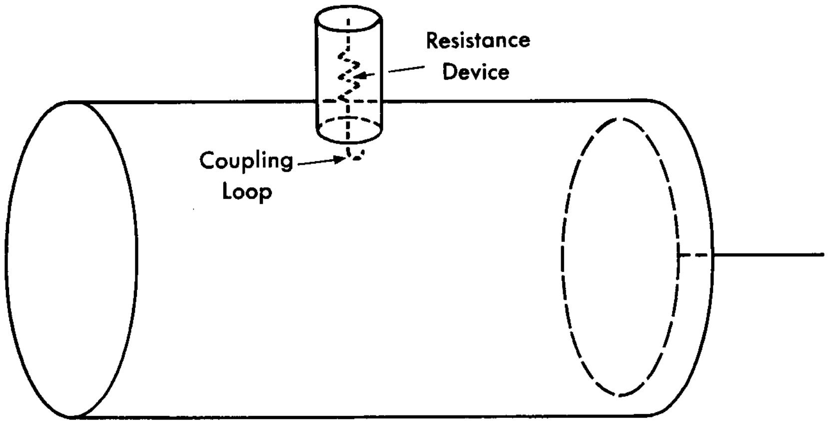
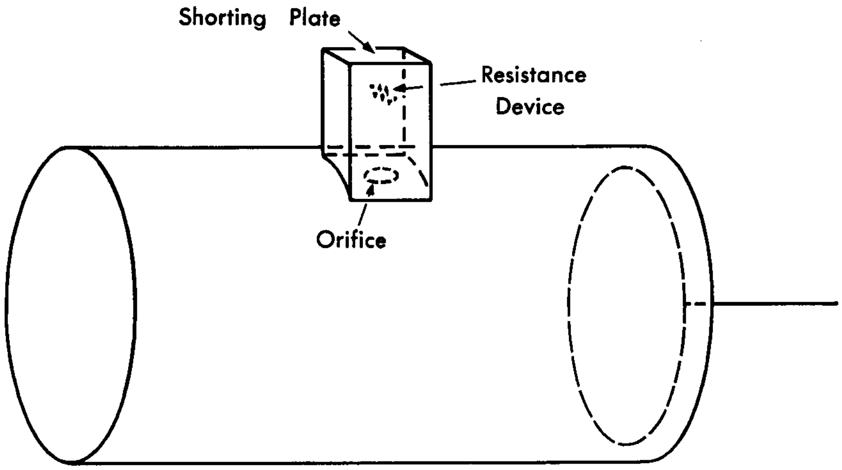


a. Loading Device Mounted on a TE_{01} Cavity



b. Another Form of Loading Device

FIG. III D-10 LOADING OF ECHO BOXES TO IMPROVE UNIFORMITY OF RINGING TIME

[redacted]

In the case of the coaxial cavity, a suitable position for the coupling loop is at the center, when the cavity is tuned to its highest frequency. As the frequency is lowered by moving the plunger outward, the loop is no longer at the center, and the magnetic field is no longer zero. The coupling and resulting coupling losses increase as the frequency is lowered and it is possible to achieve a condition where Q/f is constant over the tuning range.

In using a loop with a cylindrical cavity, the principle is the same. A position is selected at which the z-component of the magnetic field is zero for the higher frequency. Such positions are easily found from considerations of the field configuration in the cavity. In a TE_{012} cavity, the z-component of the magnetic field is zero at a position equidistant from the cavity ends. For the general case of the TE_{01n} mode, there will be (n-1) such zeros along the cavity length, excluding those at the ends.

The region of zero magnetic field is chosen because the Q should not be lowered more than necessary, which implies that there should be no lowering at the higher frequency, and because the rate of change of the magnetic field with position is maximum at the zeros.

Another form of the Q-lowering device is obtained by coupling a short-circuited section of waveguide to the cavity by means of an orifice. A resistive element is mounted across the waveguide sufficiently far from the shorting plate so that the electric field is strong enough to give the required power dissipation in the resistor. This device is shown schematically in Figure IIID-10(b).

IIID.4 Variation of Ringing Time with Temperature

A change in the temperature alters the ringing time in two ways; the resonant frequency changes since the cavity dimensions are altered, and the Q will change since it is a function of the resistivity, which changes with temperature. The variation in frequency is usually negligible, so that the change in ringing time depends only upon the change in Q due to the change in resistivity of the cavity walls.

The variation of ringing time with temperature can be found by starting with the expression for the Q of the TE_{01n} modes.

$$Q = \frac{.610\lambda}{\delta} \frac{\left[1 + 0.168\left(\frac{D}{L}\right)^2 n^2\right]^{3/2}}{1 + 0.168\left(\frac{D}{L}\right)^3 n^2} \qquad (11)$$

λ is in cm
δ is the skin depth in cm
ρ is in ohm cm
f is in mcs

The resistivity ρ varies with temperature according to the following relation:

$$\rho = (1 + \alpha \Delta T)\, \rho_o \qquad (12)$$

where ΔT is the difference between the actual temperature and that at which ρ_o is measured. For silver, α = 0.00211 ohms per ohm per degree F, with ρ_o measured at 70° F.

$$\delta = \frac{1}{2\pi}\sqrt{\frac{10^3}{f}(1 + \alpha \Delta T)\, \rho_o} \approx \frac{1}{2\pi}\sqrt{\frac{10^3 \rho_o}{f}}\left(1 + \frac{\alpha}{2}\Delta T\right) = \delta_o\left(1 + \frac{\alpha}{2}\Delta T\right)$$

and

$$Q \approx \frac{.610\lambda}{\delta_o\left(1 + \frac{\alpha}{2}\Delta T\right)} \frac{\left[1 + 0.168\left(\frac{D}{L}\right)^2\right]^{3/2}}{1 + 0.168\left(\frac{D}{L}\right)^3 n^2}$$

$$\approx \frac{.610\lambda}{\delta} \frac{\left[1 + 0.168\left(\frac{D}{L}\right)^2\right]^{3/2}}{1 + 0.168\left(\frac{D}{L}\right)^3 n^2} \left(1 - \frac{\alpha}{2}\Delta T\right) \qquad (13)$$

$$\approx Q_0\left(1 - \frac{\alpha}{2}\Delta T\right)$$

[redacted]

Therefore,

$$t_r = t_{r_o} \left(1 - \frac{\bar{\alpha}}{2} \Delta T\right)$$

or

$$t_r = t_{r_o} \left[1 - .0011 \, (T - 70^\circ \, F)\right] \qquad (14)$$

where t_{r_o} is the ringing time at 70° F.

This equation assumes that the resistivity of silver is a linear function of frequency, which is not strictly true. Figure IIID-11 shows a plot of percentage change in ringing time vs. temperature, based on International Critical Table values of the resistivity of silver. It can be seen that the function departs appreciably from a straight line. Only a limited amount of experimental work has been done on this problem, but the experiments seem to verify the accuracy of this curve.

[redacted]

[redacted]

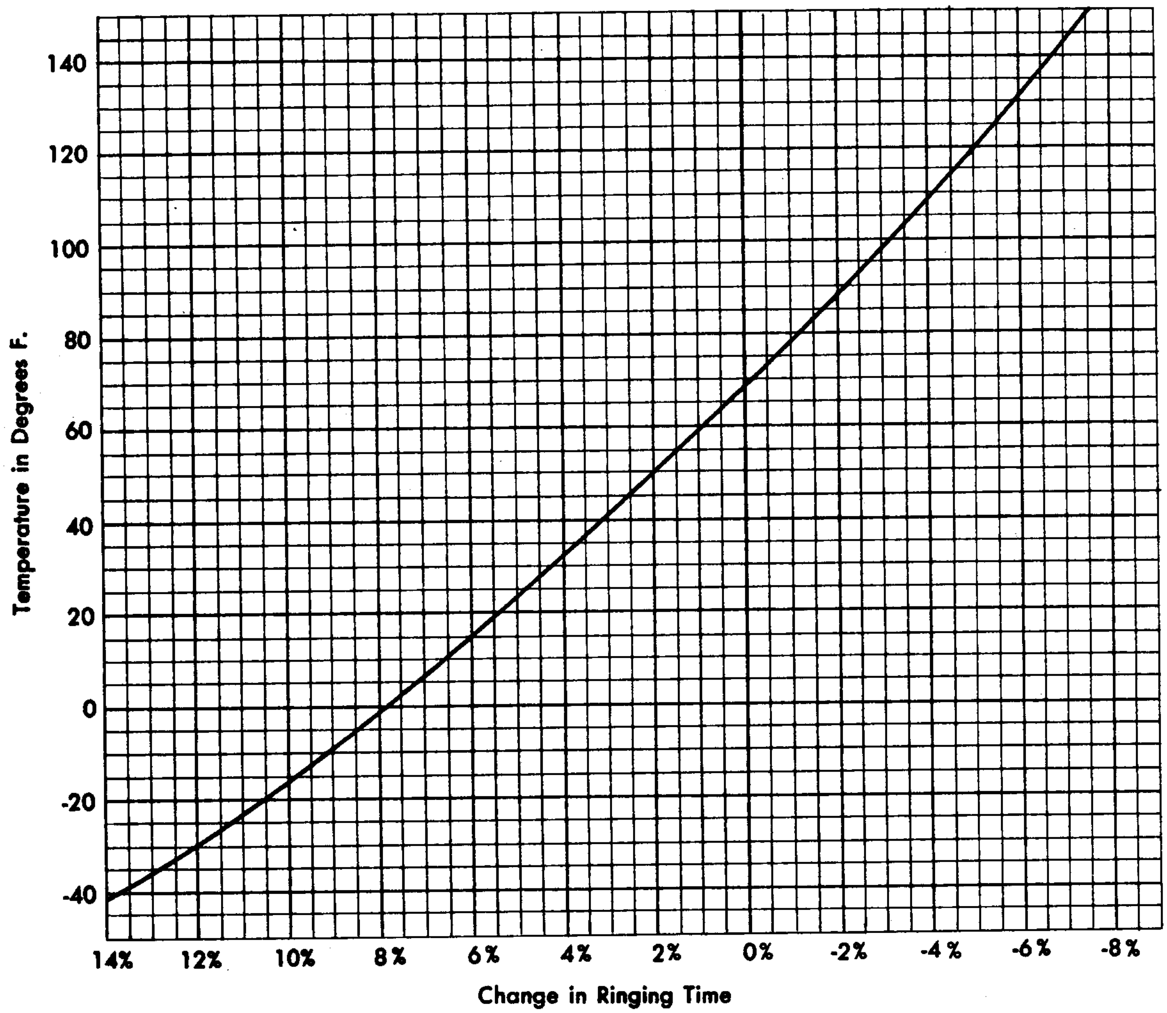


FIG. III D-11 EFFECT OF ECHO BOX TEMPERATURE ON RINGING TIME

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IIIE AN EXAMPLE OF ECHO BOX DESIGN

The design of the TS-270/UP echo box will be used as an example illustrating some of the design principles discussed previously. This box, shown in Figure IIIE-1, is of World War II design. Its salient characteristics are

Tuning range as a wavemeter:	2630 - 2970 mcs
Intended ringing range:	2700 - 2900 mcs
Inside diameter:	6.140"
Maximum length:	4.954"
Minimum length:	3.237"
Pitch of tuning screw:	32 threads per inch

The movable plunger is mounted on the end of a hollow shaft having a nut on the other end. The tuning knob turns a threaded shaft in this nut so as to move the plunger back and forth without causing it to rotate. The inner or fine-tuning dial is an extension of the tuning knob. Concentric with the inner dial is an outer or coarse-tuning dial, rotated by planetary gearing from the inner dial so that it advances one dial division per revolution of the inner dial. The threads on the tuning plunger shaft are precision-ground to eliminate any variation of pitch throughout its length, and the entire tuning assembly is very carefully made to eliminate any backlash or extraneous motion of the plunger. The extra 70 mcs on either end of the ringing range is for possible use as a wavemeter in adjusting radar local oscillators.

The cavity is designed to operate in the TE_{011} mode with a diameter-to-length ratio well over one, assuring good freedom from extraneous responses over the band, but providing only average ringing time and considerable variation of Q with frequency. It employs a fixed input coupling loop and an adjustable output loop.

A mode chart for the box is shown in Figure IIIE-2. It can be seen that, over the frequency range in which ringing will take place, the cavity is completely free of interfering modes with the exception of the TM_{111} mode which is degenerate with the TE_{011} . In the region in which the cavity

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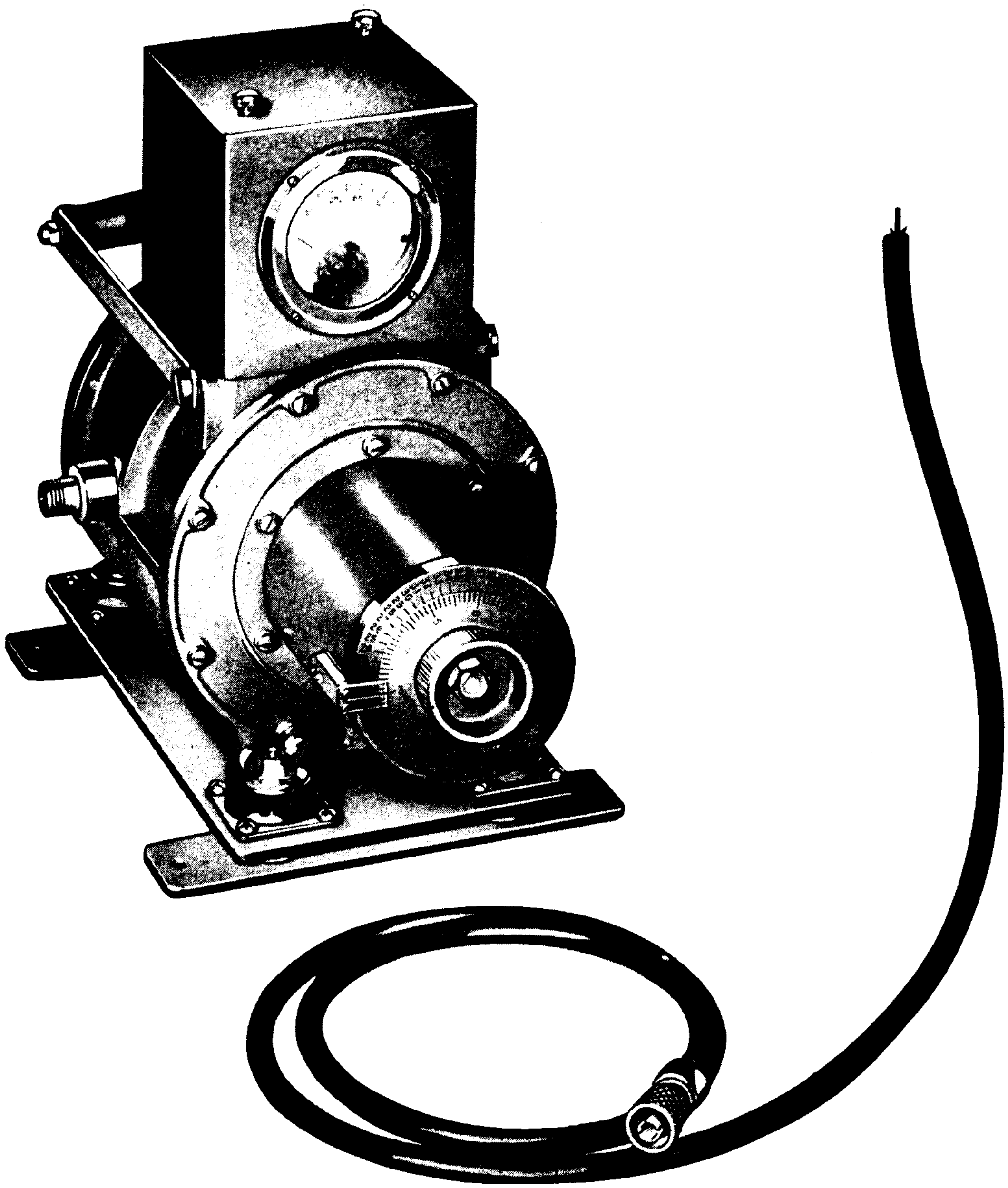

FIG. III E-1 TS-270/UP ECHO BOX

Courtesy JOHNSON SERVICE COMPANY

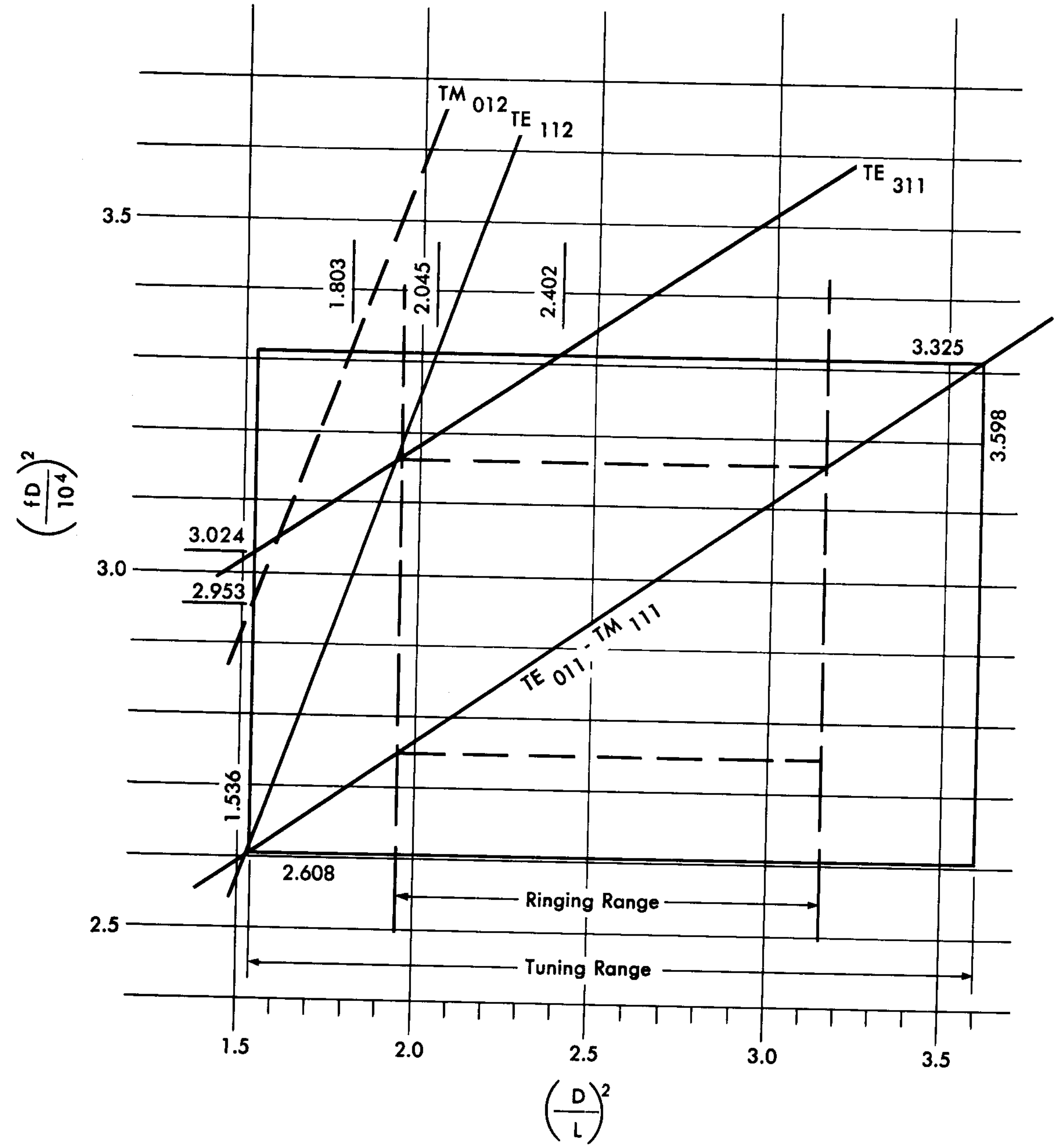

FIG. III E-2 MODE CHART FOR TS-270/UP ECHO BOX

[redacted]

will be used only for a wavemeter there are some interfering modes, but these should cause little trouble. Freedom from interfering modes is a characteristic of the lower TE_{01n} modes, and in particular, of the TE_{011} at a diameter-to-length ratio somewhat greater than one. The price that must be paid for this feature is that the ringing time is less than can be obtained by the use of higher modes.

The large mode chart in the back of this book covering this region (Chart No. 1) shows that the box is close to the line of maximum Q/V, and that the line $Q\sqrt{f} = 3 \times 10^6$ passes through the operating rectangle.

The designer should compute a table of values of the different constants pertaining to the box after he has settled upon a trial design, so as to determine the manner in which his proposed box will perform. Quantities of interest are: 1) frequency; 2) $(fD/10^4)^2$; 3) $(D/L)^2$; 4) $Q\delta/\lambda$ 5) $Q\lambda$ (or Q/f); 6) $\frac{\Delta Q\lambda}{Q\lambda}$ (variation of ringing time with frequency); 7) frequency versus dial setting; 8) rate of tuning. The value of c (the velocity of light) used here is $c = 2.9967 \times 10^{10}$ cm per second, from which the value of A in the equation for the mode lines is computed.

$$A = 0.141034 \times 10^{20} \, (r_{\ell m})^2$$

(for air at 25° C and 60 per cent relative humidity).

$(D/L)^2$ is found by substitution into the equation for the mode used; in this case the equation is:

$$\left(\frac{fD}{10^4}\right)^2 = 2.0707 + 0.34799 \left(\frac{D}{L}\right)^2$$

D/L and L are found from $(D/L)^2$. $Q\delta/\lambda$ can be found either from the curves of $Q\delta/\lambda$ included in this chapter, or by direct computation from the formulas. The formula for $Q\delta/\lambda$ is:

[redacted]

$$\frac{Q\delta}{\lambda} = \frac{r_{\ell m}}{2\pi}\left[1 + p^2R^2\right]^{3/2} \frac{1 - \left(\frac{\ell}{r_{\ell m}}\right)^2}{1 + p^2R^3 + p^2(1 - R)R^2 \left(\frac{\ell}{r_{\ell m}}\right)^2}$$

where $p = \frac{n\pi}{2r_{\ell m}}$. This equation becomes, for the TE_{011} mode

$$\frac{Q\delta}{\lambda} = 0.610\left[1 + 0.168\ R^2\right]^{3/2} \times \frac{1}{1 + 0.168\ R^3}$$

where $R = \frac{D}{L}$. $Q\lambda$ is found from $Q\delta/\lambda$ as follows:

$$\frac{Q\delta}{\lambda} \cdot \frac{\lambda^2}{\delta} = Q\lambda$$

$$\delta = \frac{1}{2\pi}\sqrt{\frac{10^3\rho}{f}} = \frac{1}{2\pi\sqrt{f}}\sqrt{1629 \times 10^{-6}}$$

$$\delta = \frac{6.42 \times 10^3}{\sqrt{f}}$$ cm, where f is in mcs

$$\frac{\lambda^2}{\delta} = \frac{\frac{c^2}{f^2}}{\delta} = \frac{(2.997 \times 10^{10})^2 \quad f}{6.42 \times 10^{-3} \times f^2 \times 10^{12}} \quad \text{(f in mcs)}$$

$$= \frac{8.982 \times 10^{20} \sqrt{f}}{6.42 \times 10^9 \quad f^2} = \frac{1.40 \times 10^{11}}{f\sqrt{f}}$$

Table IIIE-1 gives the values of the various characteristics at 20-mcs intervals throughout the tuning range of the cavity.

[redacted]

TABLE IIIE-1

Characteristics of the TS-270/UP

f(mcs)	λ(cm)	$\left(\frac{fD}{10^4}\right)^2$	$\left(\frac{D}{L}\right)^2$	$\left(\frac{D}{L}\right)$	L	$\frac{Q\phi}{\lambda}$	$f\sqrt{f}$	$\frac{\lambda^2}{\phi}$	Relative Ring $Q\lambda$	Variation in Ring[1] $\frac{\Delta Q\lambda}{Q\lambda_{2802}}$
2630	11.40	2.608	1.543	1.242	4.943	0.652	1.349 x 10^5	1.039 x 10^6	0.677 x 10^6	----
2650	11.31	2.647	1.655	1.286	4.774	0.649	1.364	1.028	0.667	----
2670	11.22	2.688	1.773	1.331	4.613	0.646	1.380	1.016	0.656	----
2690	11.14	2.728	1.888	1.374	4.469	0.642	1.395	1.005	0.645	+10.3%
2710	11.06	2.769	2.006	1.416	4.336	0.638	1.411	0.994	0.634	+ 8.4%
2730	10.98	2.810	2.124	1.457	4.214	0.634	1.426	0.983	0.623	+ 6.5%
2750	10.90	2.851	2.241	1.497	4.102	0.630	1.442	0.972	0.612	+ 4.6%
2770	10.82	2.893	2.362	1.537	3.995	0.625	1.458	0.962	0.601	+ 2.7%
2790	10.74	2.935	2.483	1.576	3.896	0.621	1.474	0.951	0.591	+ 1.0%
2810	10.67	2.977	2.603	1.613	3.806	0.617	1.490	0.941	0.581	- 0.9%
2830	10.59	3.019	2.724	1.651	3.718	0.612	1.506	0.931	0.570	--2.6%
2850	10.52	3.062	2.848	1.688	3.637	0.606	1.522	0.921	0.558	- 4.6%
2870	10.44	3.105	2.971	1.724	3.561	0.602	1.538	0.912	0.549	- 6.2%
2890	10.37	3.149	3.097	1.760	3.488	0.597	1.554	0.902	0.538	- 8.0%
2910	10.30	3.192	3.221	1.795	3.421	0.591	1.570	0.893	0.528	- 9.7%
2930	10.23	3.236	3.347	1.830	3.355	0.587	1.586	0.884	0.519	----
2950	10.16	3.281	3.477	1.865	3.292	0.582	1.602	0.875	0.509	----
2970	10.09	3.325	3.603	1.898	3.234	0.576	1.619	0.866	0.500	----

[1] This is inscribed on the outer dial of the echo box as a "Ring Prediction" scale, used in predicting the expected ringing time.

[redacted]

The theoretical Q, Q_T, of this cavity varies from

$$\frac{0.677 \times 10^6}{11.40} = 59{,}500$$

to

$$\frac{0.500 \times 10^6}{10.09} = 49{,}500$$

over the entire tuning range. However, it is the variation in the quantity $Q\lambda$ over the ringing band which determines the variation in ringing time with frequency. This variation is tabulated in the last column of Table IIIE-2. From these values a curve can be plotted for use in the field. Such a curve is shown in Figure IIIE-3.

One undesirable feature of cylindrical cavities is that the resonant frequency is not a linear function of the length of the cavity. Therefore, if a simple screw is used for tuning, as is done in the case of TS-270/UP and many other echo boxes, the frequency scale engraved on the dial will have to be non-linear. However, this slight inconvenience usually is more than offset by the greater simplicity of a linear tuning mechanism, and few echo boxes have been designed using a more complex device. The stringent restrictions on backlash and the requirement for high tuning accuracy usually found in the specifications, in addition to the necessity for avoiding any eccentricity, tipping or wobbling of the movable plate, all point toward the desirability of employing the simplest and most rugged tuning device obtainable. Such a device is the simple screw. The screw must be made very precisely in order to eliminate any unevenness of pitch, called "drunkenness".

The TS-270/UP outer dial is engraved with a frequency scale. In addition, for more precise measurements, two curves are provided in the instruction manual. One is a curve of dial reading versus frequency, while the second is a curve of mcs per revolution of the inner dial versus the outer dial reading, and is therefore a rate of tuning curve.

Comparison of the maximum and minimum cavity lengths given at the beginning of this section with those in Table IIIE-1 reveals that the actual

TABLE IIIE-2

Tuning Calibration for the TS-270/UP

L	$(D/L)^2$	$(fD/10^4)^2$	f	Δf	Dial	mc/rev.	Plot At Dial Reading
4.94300	1.543	2.608	2630		0		
				18		3.6	2.5
4.78675	1.645	2.643	2648		5		
				19		3.8	7.5
4.63050	1.758	2.683	2667		10		
				22		4.4	12.5
4.47425	1.883	2.726	2689		15		
				24		4.8	17.5
4.31800	2.022	2.774	2713		20		
				26		5.2	22.5
4.16175	2.177	2.828	2739		25		
				29		5.8	27.5
4.00550	2.349	2.888	2768		30		
				32		6.4	32.5
3.84925	2.544	2.956	2800		35		
				36		7.2	37.5
3.69300	2.764	3.033	2836		40		
				41		8.2	42.5
3.53675	3.014	3.120	2877		45		
				45		9.0	47.5
3.38050	3.299	3.219	2922		50		
				48		10.2	52.5
3.23362	3.605	3.325	2970		54.7		

cavity will tune slightly beyond either end of the specified tuning range. The total motion of the plunger is such as to permit 55 turns of the knob, whereas the tuning range is traversed with 54.7 revolutions. The outer dial has 55 marks on it, each mark representing 1 turn of the inner dial. The inner dial is graduated into 100 equal divisions. Computing the tuning calibration will consist of computing the cavity length for each complete revolution of the inner dial, and from these values obtaining the corresponding frequencies by use of the mode equation. The dial is assumed to read zero when the cavity is at a length corresponding to 2630 mcs, namely 3.234". Each rotation of the inner dial adds 1/32" or 0.03125" to the cavity length, and 1 to the outer dial reading. The results of the frequency calibration are recorded in Table IIIE-2, which also includes the data with which to plot the rate-of-tuning curve. The two curves themselves are shown in Figures IIIE-4 and IIIE-5.

If an echo box for this band were being designed today certain modifications might be made. Consideration would be given to employing a higher mode, to gain additional ringing time and less dependence of ringing time on frequency. A desirable TE_{013} region exists for this bandwidth. Against these advantages of a higher mode, increased size, weight, manufacturing difficulty, and cost would have to be considered.

The new design, assuming that it was found undesirable to go to a different mode, would differ from the present design in minor respects.

1. The tuning range would be restricted to the band of interest, plus and minus a very few mcs, because the wavemeter region of echo boxes has been found of limited use. In present day radar, it is usually not possible to connect to the local oscillator, and other means of adjusting the local oscillator are provided.

2. The dial would be provided with a screw having a coarser thread. The 32-thread screw used in the TS-270 was adopted for manufacturing convenience during the war, since this same screw was employed in another echo box. A thread would be selected which would make the tuning rate over the ringing region approximately ten mcs per revolution, as this has been found an entirely adequate rate. A screw of 21 threads per inch would accomplish this.

[redacted]

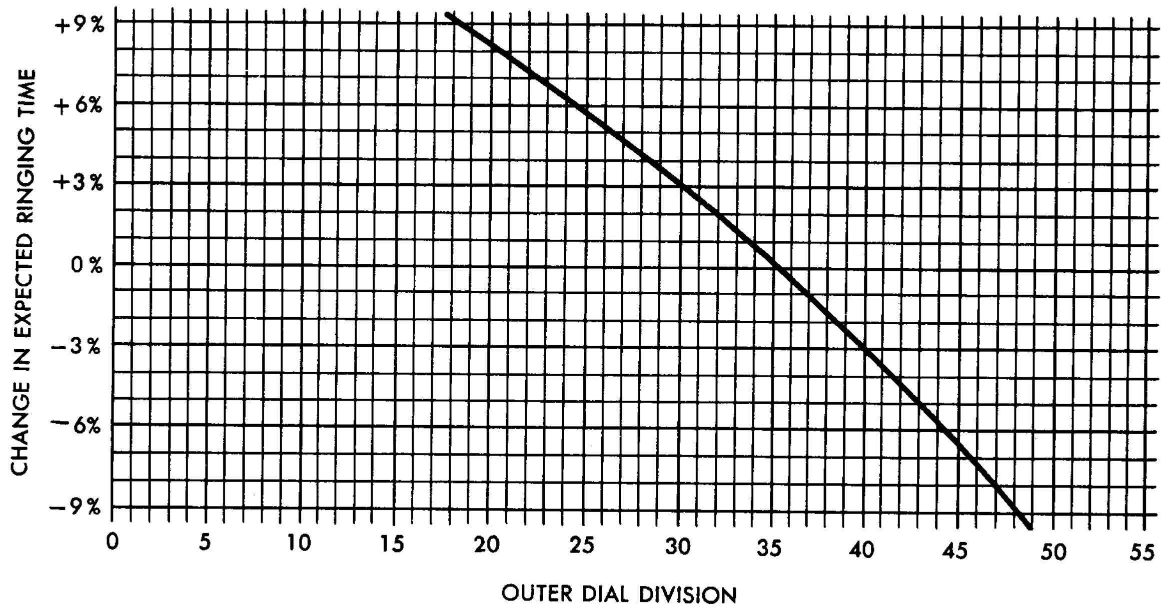

FIG. III E-3 VARIATION OF RINGING TIME WITH FREQUENCY FOR THE TS-270/UP

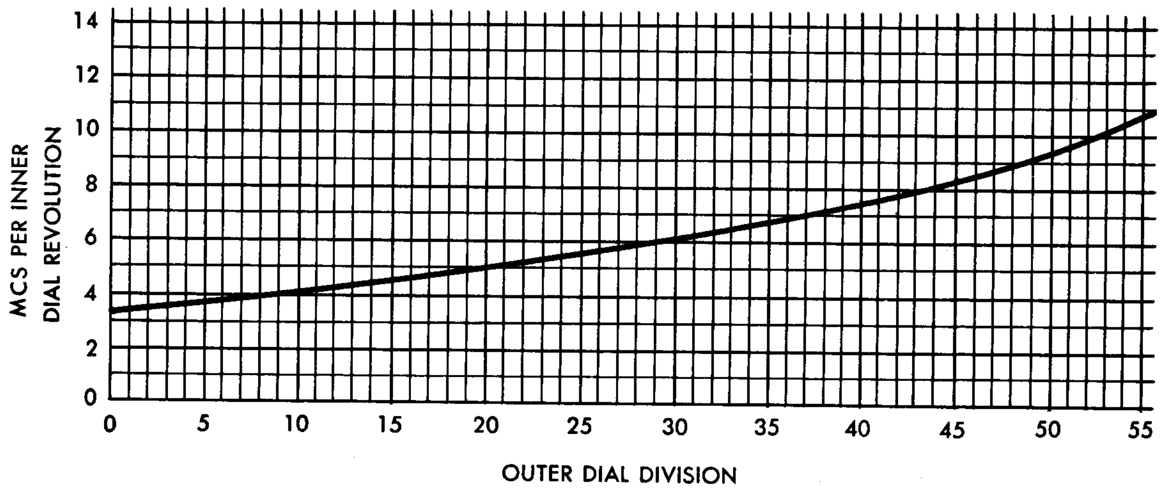

FIG. III E-4 RATE OF TUNING CURVE FOR THE TS-270/UP

[redacted]

[redacted]

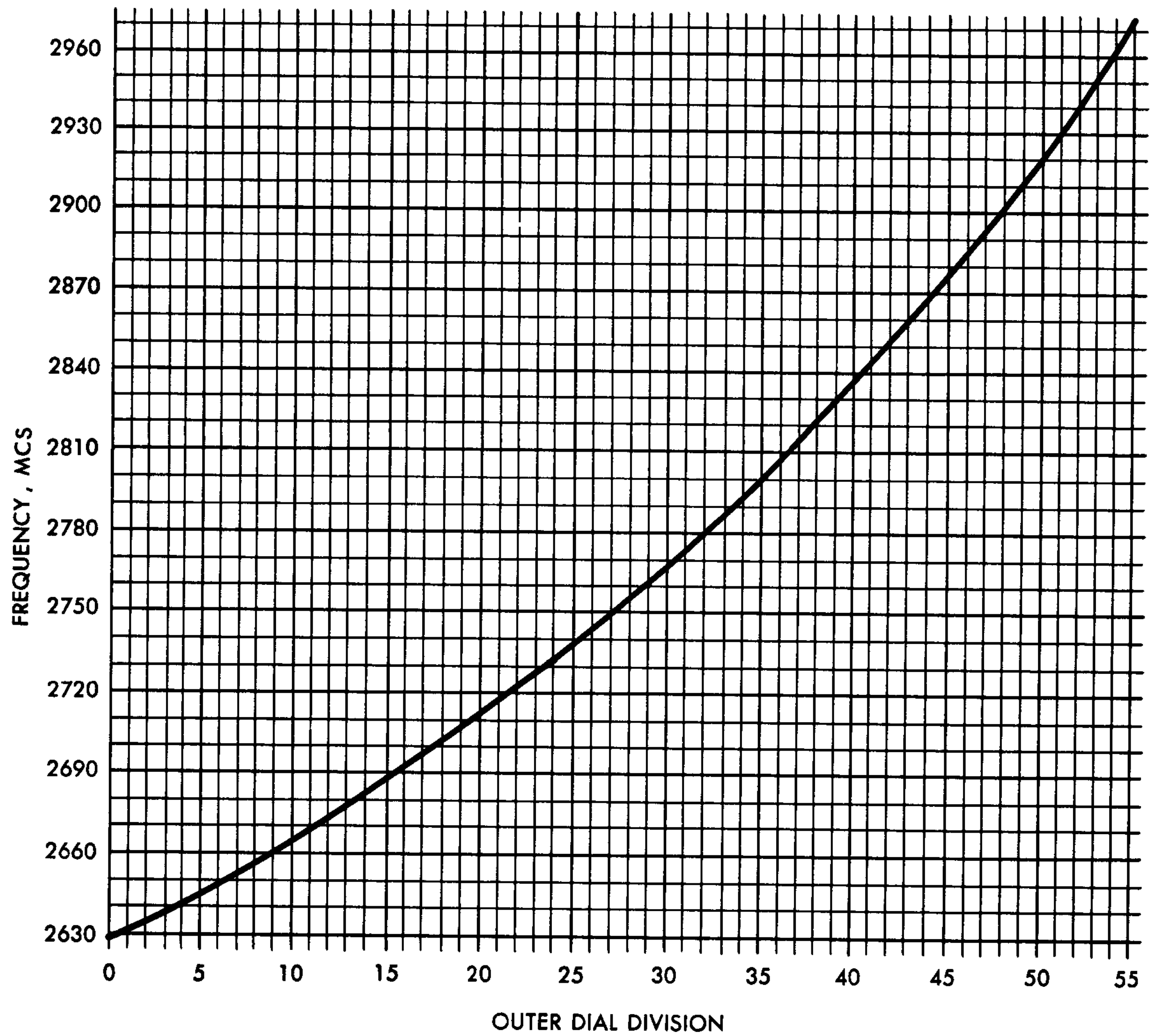

FIG. III E-5 FREQUENCY CALIBRATION CURVE FOR THE TS-270/UP

[redacted]

3. With this new screw it would be possible to mark the outer dial directly in approximate frequency, so that the outer dial reads "280" at 2800 mcs, and when read in conjunction with the inner dial would read "2800", the exact frequency. The rough frequency scale could then be omitted from the outer dial.

4. The frequency calibration curve could be dispensed with by providing a frequency correction scale, on the outer dial. The reading on this scale, when added to the main dial reading, would give the exact frequency.

Table IIIE-3 shows the echo box dial readings and the correction to be added, based on the values in Table IIIE-2.

TABLE IIIE-3

Dial Reading of Modified TS-270

(Box with 21 threads per inch, adjusted to read correct frequency at 2800 mcs)

Old Dial Reading	Frequency	New Dial Reading	Correction to be Added
15	2689	2668.8	+20.2
20	2713	2701.6	+11.4
25	2739	2734.4	+ 4.6
30	2768	2767.2	+ 0.8
35	2800	2800.0	+ 0.0
40	2836	2832.8	+ 3.2
45	2877	2865.6	+11.4
50	2922	2898.4	+23.6

Figure IIIE-6 shows this correction as a function of frequency on the left-hand scale. It is evident that the absolute amount of the correction could be minimized by using both positive and negative corrections. This makes the dial reading without correction more nearly accurate in the event that a user chooses not to make the correction. The scale to the right of the graph is computed so as to minimize the absolute correction, and shows that the effect is to make the echo box read directly in frequency without correction with a maximum error of +8 and -9 mcs.

5. The output loop mechanism could be changed to make the output loop adjustable to two positions from the "front panel". The loop could ordinarily be completely retracted from the cavity but, by operation of the control, could be inserted to a definite depth, adjustable by a set screw. The reason for this change is that the energy coupled into the output circuit causes a reduction in ringing time, and changing the crystal in an echo box changes the ringing time.[1] The insertion of the output loop should be variable since different power, pulse length, pulse repetition frequency, directional coupler coupling, and crystals influence the echo box meter reading. The output coupling may be constructed so that there is a two-position adjustment with spring return to the retracted position, so that the output circuit will be entirely eliminated when reading ringing time. The removal of the loosely coupled output circuit would have no effect on the resonant frequency of the echo box.

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[1] Echo box crystals can apparently have indefinite life when carefully used. The Johnson Service Company has had several such crystals in almost daily use for nine years without apparent change.

[redacted]

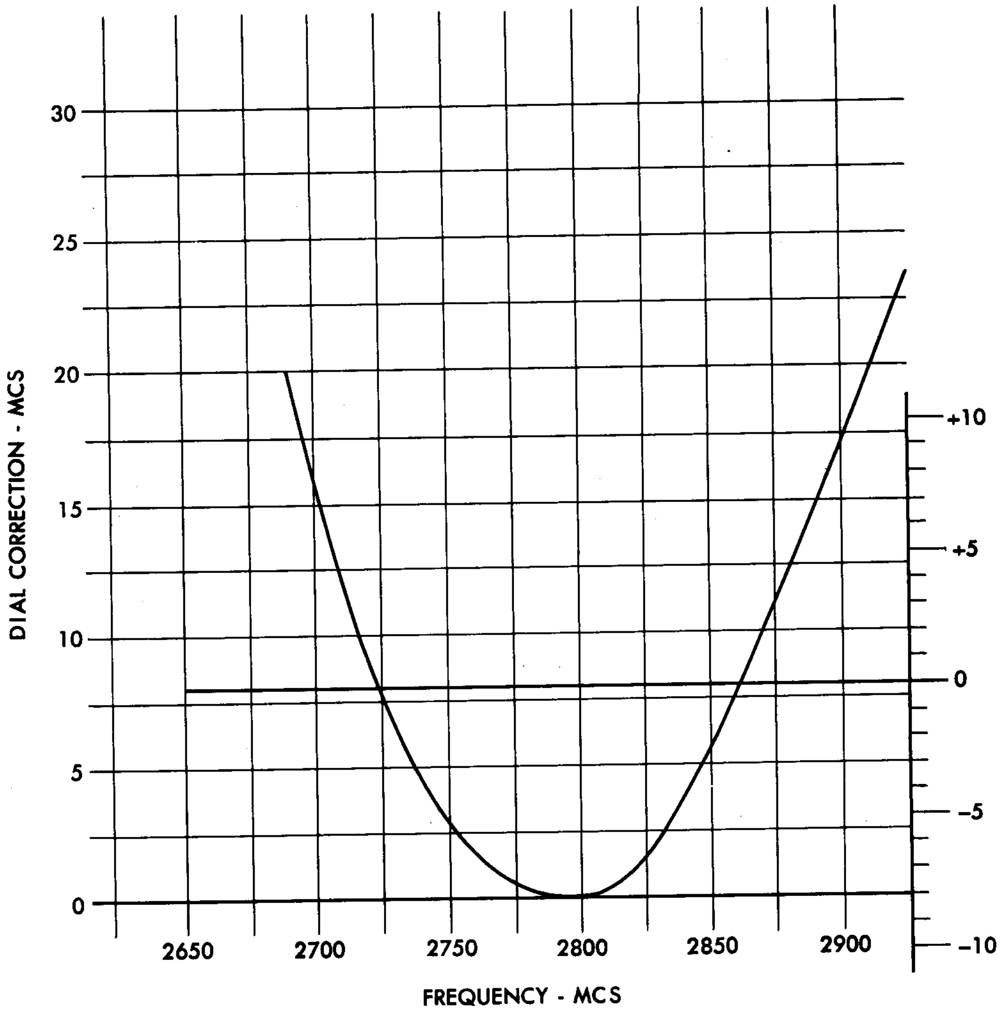

FIG. III E-6 FREQUENCY CORRECTION CURVE FOR TS-270/UP WITH NEW DIAL

[redacted]

IIIF THE DESIGN OF COAXIAL AND PARTIAL COAXIAL CAVITIES

At radar frequencies below 1000 mcs, cylindrical cavities for echo boxes become too large for convenience. The smallest cavities for a given frequency will be found on the TE_{011} mode. The region near $(D/L)^2 = 2$, which is a suitable region for echo box design at L-band frequencies, will require a box approximately 12 inches long and 17 inches in diameter at 1000 mcs. The Q for such a cavity would be in the neighborhood of 100,000. At 500 mcs, these dimensions would be doubled and the Q would be greatly in excess of what is needed. Hence, for low frequency radars the cylindrical cavity does not provide a satisfactory design. Echo boxes for these frequencies are usually of the coaxial or partial coaxial type.

The full coaxial cavity differs from the cylindrical cavity in that there is a central conductor concentric with the outer cylinder and extending the full length of the cavity. This central conductor makes electrical contact with both the movable and stationary end plates of the cavity. The partial coaxial or hybrid cavity has a central conductor which extends only a part of the full cavity length and is connected to only one of the cavity end plates. The full coaxial cavity is known as a half-wave cavity, since the cavity is a half wavelength long. The partial coaxial or hybrid cavity is often referred to as a quarter-wave cavity, since the inner conductor is approximately a quarter wavelength long and the cavity can be treated as approximately a quarter wavelength coaxial line.

IIIF. 1 The Full Coaxial Cavity

IIIF. 1. 1 The Mode Chart for the Full Coaxial Cavity

The full coaxial cavity has the same types of modes as the cylindrical cavity, and the mode equations are of the same form. Because of the presence of the central conductor, coaxial cavities are also capable of supporting the TEM or transmission line modes.

For the TE and TM modes, the resonant frequency is given by

$$f_r = \frac{c}{2}\sqrt{\left(\frac{2\, r_{\ell m}}{\pi D}\right)^2 + \left(\frac{n}{L}\right)^2} \qquad (1)$$

[redacted]

which is identical with the corresponding formula for the cylindrical cavity except that in this case $r_{\ell m}$ is given by the roots of

$$J_\ell (r_{\ell m}) Y_\ell (N r_{\ell m}) = J_\ell (N r_{\ell m}) Y_\ell (r_{\ell m}) \qquad \text{for TM modes}$$

and

$$J'_\ell (r_{\ell m}) Y'_\ell (N r_{\ell m}) = J'_\ell (N r_{\ell m}) Y'_\ell (r_{\ell m}) \qquad \text{for TE modes}$$

where J_ℓ and Y_ℓ are Bessel functions of the first and second kind, respectively,

N = ratio of the diameter of the inner conductor to that of the outer cylinder.

The mode chart equation can be obtained by rearranging (1), analogous to the cylindrical case. The resulting equation is:

$$(f_r D)^2 = \left(\frac{c\, r_{\ell m}}{\pi}\right)^2 + \left(\frac{c}{2}\right)^2 n^2 \left(\frac{D}{L}\right)^2 \qquad (2)$$

$$= A + B\, n^2 \left(\frac{D}{L}\right)^2$$

From this equation a mode chart can be constructed, exactly as in the case of the cylindrical cavity. However, since the value of $r_{\ell m}$ depends upon N, the intercepts of the mode lines will vary for different values of N. Usually it is convenient to use a value of .278 for N, since this ratio will result in the maximum value of Q (see below). Mode charts for N = .278 are shown in Figure IIIF-1. In these charts, as in the cylindrical cavity mode charts, the equation plotted is

$$\left(\frac{f_r D}{10^4}\right)^2 = \left(\frac{c\, r_{\ell m}}{10^{10}\pi}\right)^2 + \left(\frac{c}{2 \times 10^{10}}\right)^2 n^2 \left(\frac{D}{L}\right)^2 \qquad (2a)$$

[redacted]

[redacted]

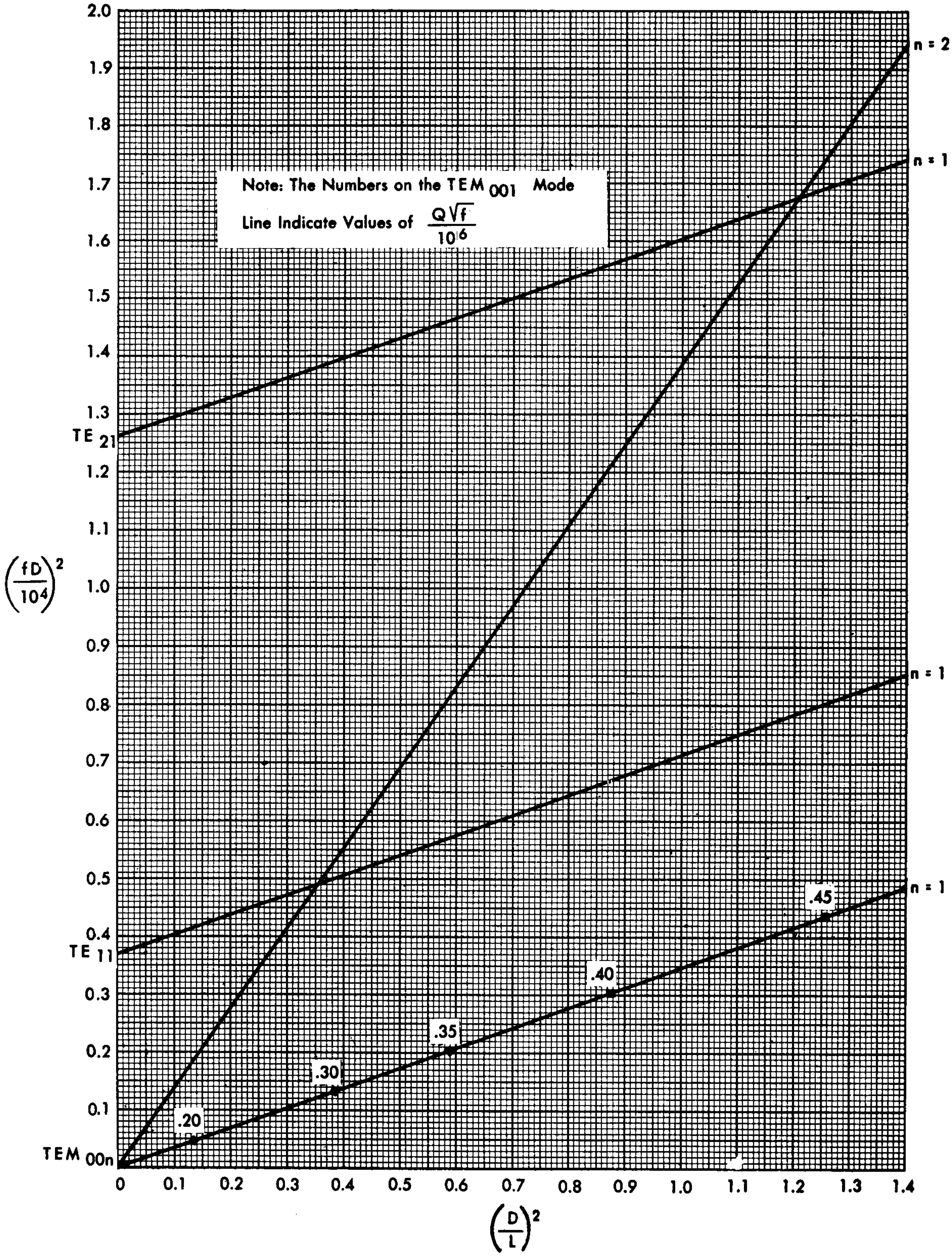

FIG. III F-1a MODE CHART FOR THE FULL COAXIAL CAVITY, N = .278

[redacted]

[redacted]

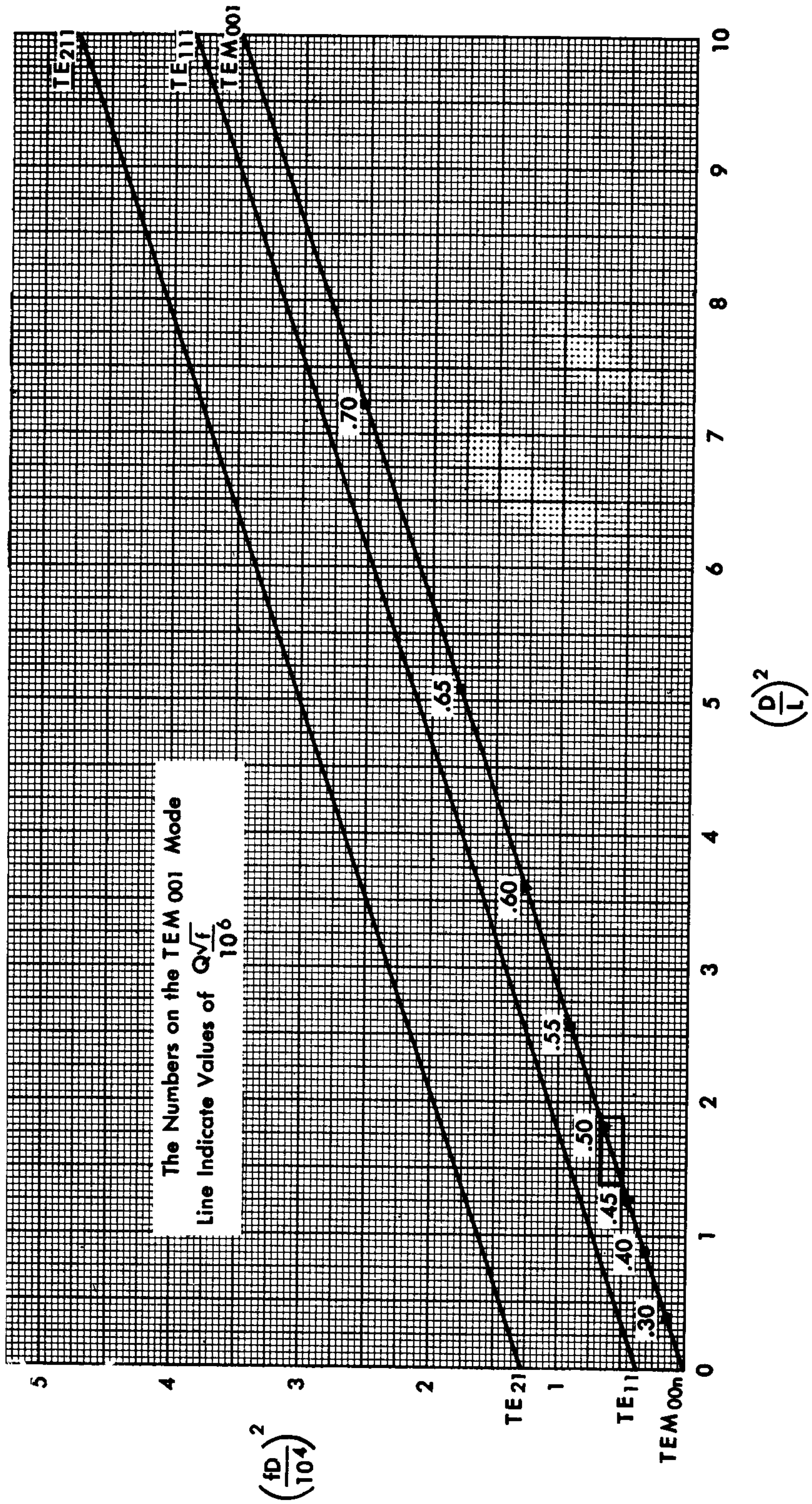

FIG. III F-1b MODE CHART FOR THE FULL COAXIAL CAVITY, N=.278

[redacted]

which is identical with (1) except that f_r is in mcs rather than in cycles per second. As before, the mode chart coordinate axes are $(D/L)^2$ and $(fD/10^4)^2$. If a value of N different from .278 is used, the designer can construct a mode chart, using the data of Figure IIIF-2 which show $r_{\ell m}$ as a function of N. With these curves, the intercepts of the mode lines can be found for any value of N.

In addition to the TE and TM modes, there are the TEM, or coaxial line, modes. For these modes the resonant frequency is given by the conventional standing wave formula for a coaxial line,

$$L = \frac{n\lambda_r}{2}$$

where L = length of line or cavity

$\lambda_r = c/f_r$ = resonant wavelength.

This formula may be rearranged so that it is in the form of the mode line equation; that is,

$$L = \frac{n}{2} \; \frac{c}{f_r}$$

Solving for f_r,

$$f_r = \frac{c}{2} \; \frac{n}{L}$$

Multiplying both sides by D and squaring, the equation becomes

$$(f_r D)^2 = \left(\frac{c}{2}\right)^2 n^2 \left(\frac{D}{L}\right)^2 = B\, n^2 \left(\frac{D}{L}\right)^2$$

This equation is the mode line equation, with A = 0. By modifying this equation as was done with Equation (2) above, a form more suitable for plotting on the mode chart is obtained:

$$\left(\frac{f_r D}{10^4}\right)^2 = \left(\frac{c}{2 \times 10^{10}}\right)^2 n^2 \left(\frac{D}{L}\right)^2$$

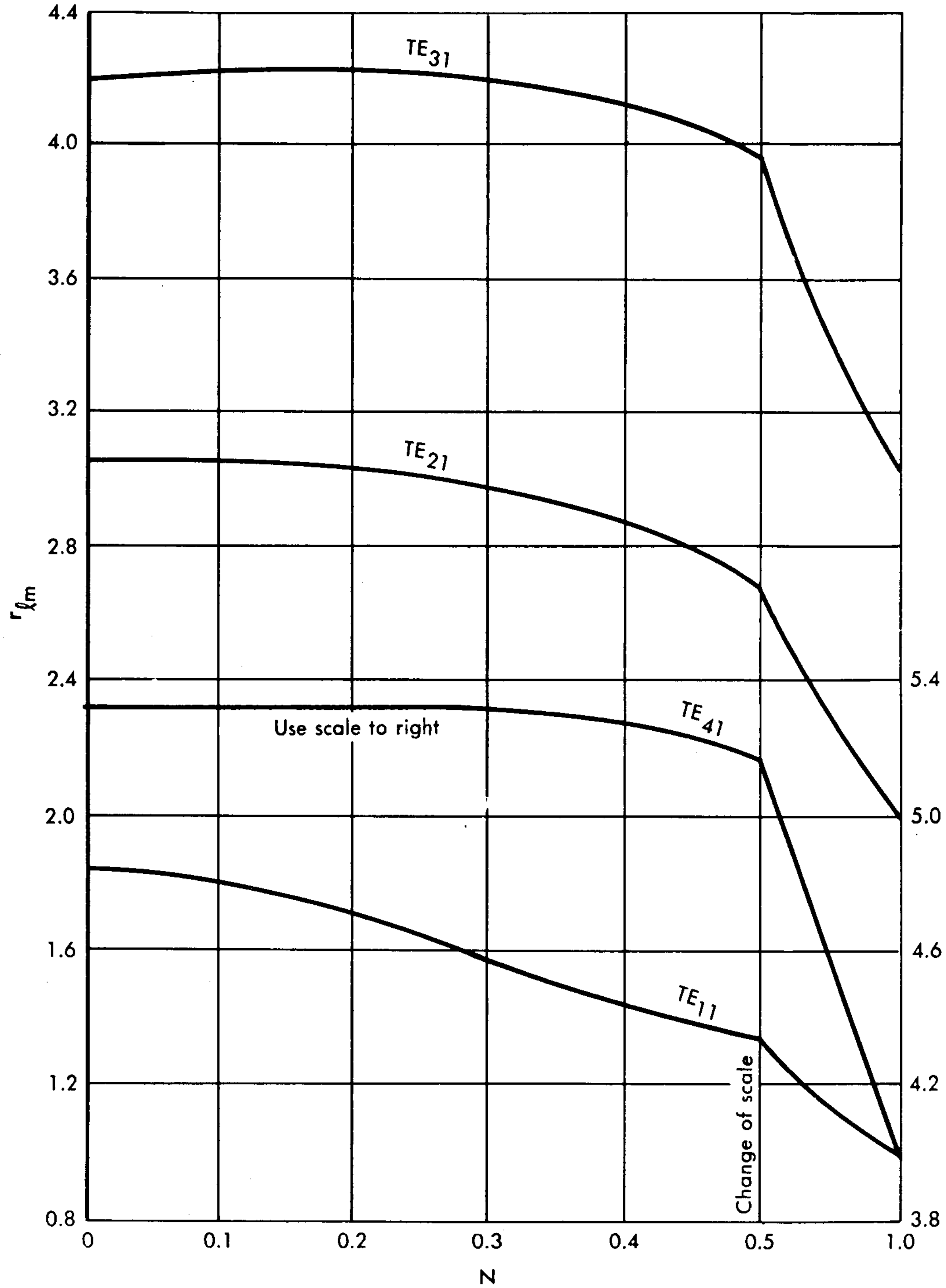

FIG. III F-2a $r_{\ell m}$ AS A FUNCTION OF N FOR COAXIAL CAVITIES (TE MODES)

Courtesy BELL TELEPHONE LABORATORIES

[redacted]

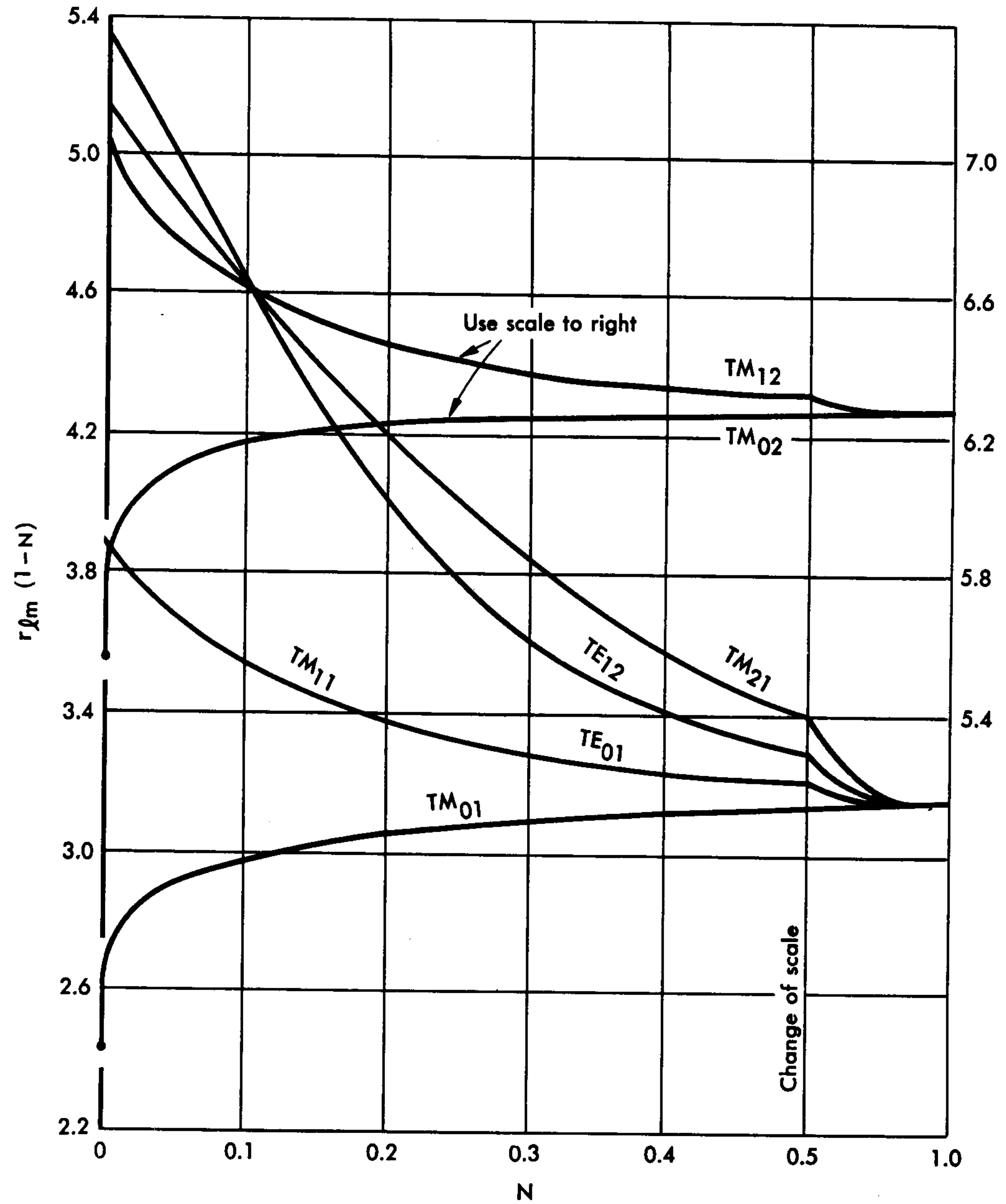

FIG. III F-2b $r_{\ell m}$ AS A FUNCTION OF N FOR COAXIAL CAVITIES (TM MODES)
Courtesy BELL TELEPHONE LABORATORIES

[redacted]

[redacted]

Using this equation, TEM mode lines have been placed on the mode chart in Figure IIIF-1.

The TEM modes have slopes determined by n. A TEM mode has the same slope as the TE or TM modes with the corresponding value of n. The intercept of all TEM lines, however, is at the origin, so that there is no cutoff frequency for these modes.

From the mode charts of Figure IIIF-1 it is seen that the TEM_{001} is the lowest mode; that is, for a given value of $(D/L)^2$, $\left(\frac{f_r D}{10^4}\right)^2$ is smaller for the TEM_{001} than for any other mode. This means that, for a cavity of given dimensions, the lowest possible resonant frequency will be that of the TEM_{001} mode. The frequency will also be lower than that possible for any mode in a cylindrical cavity of the same dimensions. The coaxial cavity will, therefore, be smaller than a cylindrical cavity for a given frequency, and it is this fact which makes the coaxial cavity of importance in low frequency echo boxes. Using the TEM_{001} mode of coaxial cavities, the frequency range 100 to 1000 mcs may be covered using coaxial cavities of moderate size. The Q for such cavities will not be large, but will be adequate if an extremely long ringing time is not required.

The use of higher order TEM_{00n} modes in coaxial cavities is, in general, not practical for echo box design. If a higher Q is needed, cylindrical cavities would be used, since they have a much higher ratio of Q to volume than coaxial cavities.

The Q for the TEM modes is given by:

$$Q = \frac{\lambda_r}{\delta} \quad \frac{n}{4 + \frac{2}{\left(\frac{D}{L}\right)}\left(\frac{1 + \frac{D}{a}}{\log_e \frac{D}{a}}\right)} \qquad (3)$$

[redacted]

[redacted]

where δ = skin depth

D = diameter of outer conductor

a = diameter of inner conductor

By the methods of elementary calculus it can be shown that, for constant D, L and frequency, Q is maximum for N = 0.278. For this reason, the coaxial cavity echo box is usually built with N approximately 0.278. In Figure IIIF-3 the mode shape factor is plotted as a function of D/a (= 1/N). The curve is observed to have a maximum at D/a = 3.6, or N = a/D = 0.278. The flatness of the top portion of the curve shows that this value of N is not critical and that a 30 per cent variation either way will not affect the mode shape factor greatly.

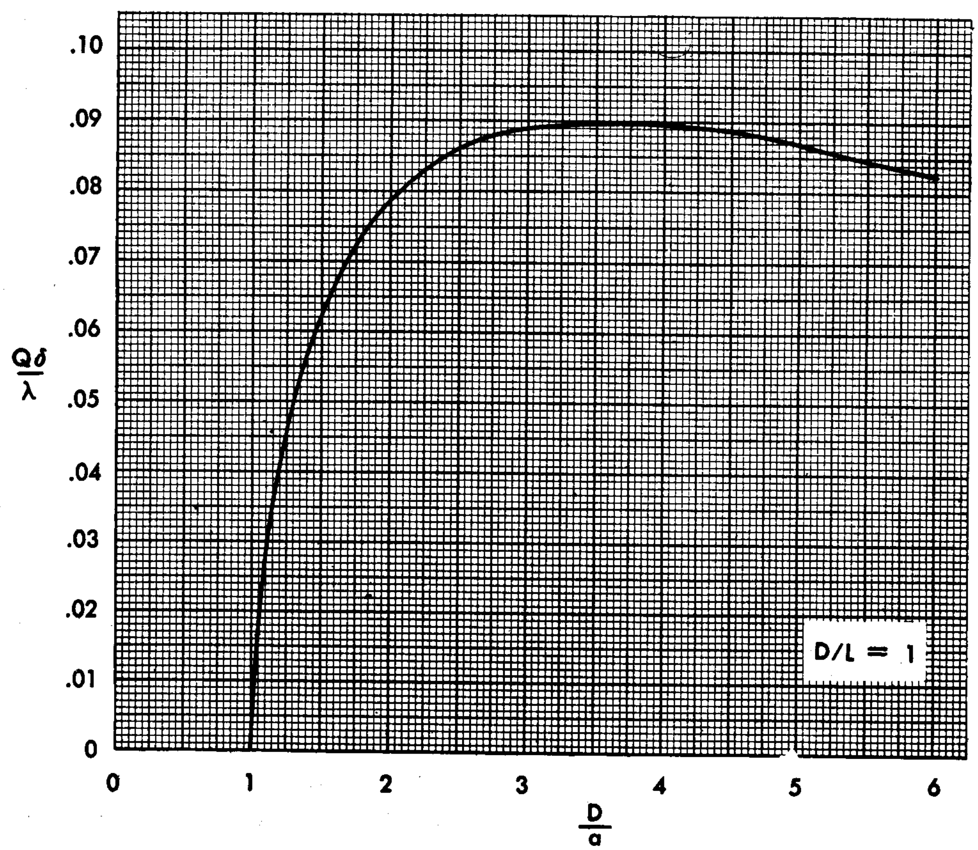

FIG. III F-3 MODE SHAPE FACTOR vs. D/a FOR TEM_{001} MODE COAXIAL CAVITY

[redacted]

[redacted]

Assuming a value of N = 0.278, the expression for Q becomes

$$\frac{Q\delta}{\lambda} = \frac{n}{4 + \frac{7.182}{\frac{D}{L}}} \tag{3a}$$

or, for silver plated cavities,

$$\frac{Q\sqrt{f}}{10^6} = 4.67 \quad \frac{n}{4 + \frac{7.182}{\frac{D}{L}}} \tag{3b}$$

where f is in mcs.

On the mode chart of Figure IIIF-1, points have been marked on the TEM_{001} mode line denoting various values of $Q\sqrt{f}/10^6$. This procedure is essentially the same as the plotting of the $Q\sqrt{f}$ lines on the cylindrical mode chart, except that, since the only TEM mode of interest is the TEM_{001}, only points are necessary.

The mode shape factor as a function of D/L is plotted in Figure IIIF-4. Using this chart, the variation in ringing time over the tuning band may be found by using the formula

$$1 + \frac{\Delta t_r}{t_r} = \frac{1 + \frac{\Delta MS}{MS}}{\left(1 + \frac{\Delta f}{f}\right)^{3/2}} .$$

This expression was derived in Chapter IIID and since, in the derivation, no assumptions were made regarding the shape of the cavity, the formula applies equally well to coaxial cavities.

A mode chart is not required to design the full coaxial cavity; formula (3a) and the relation $L = n\lambda/2$ may be used quite easily to determine the

[redacted]

[redacted]

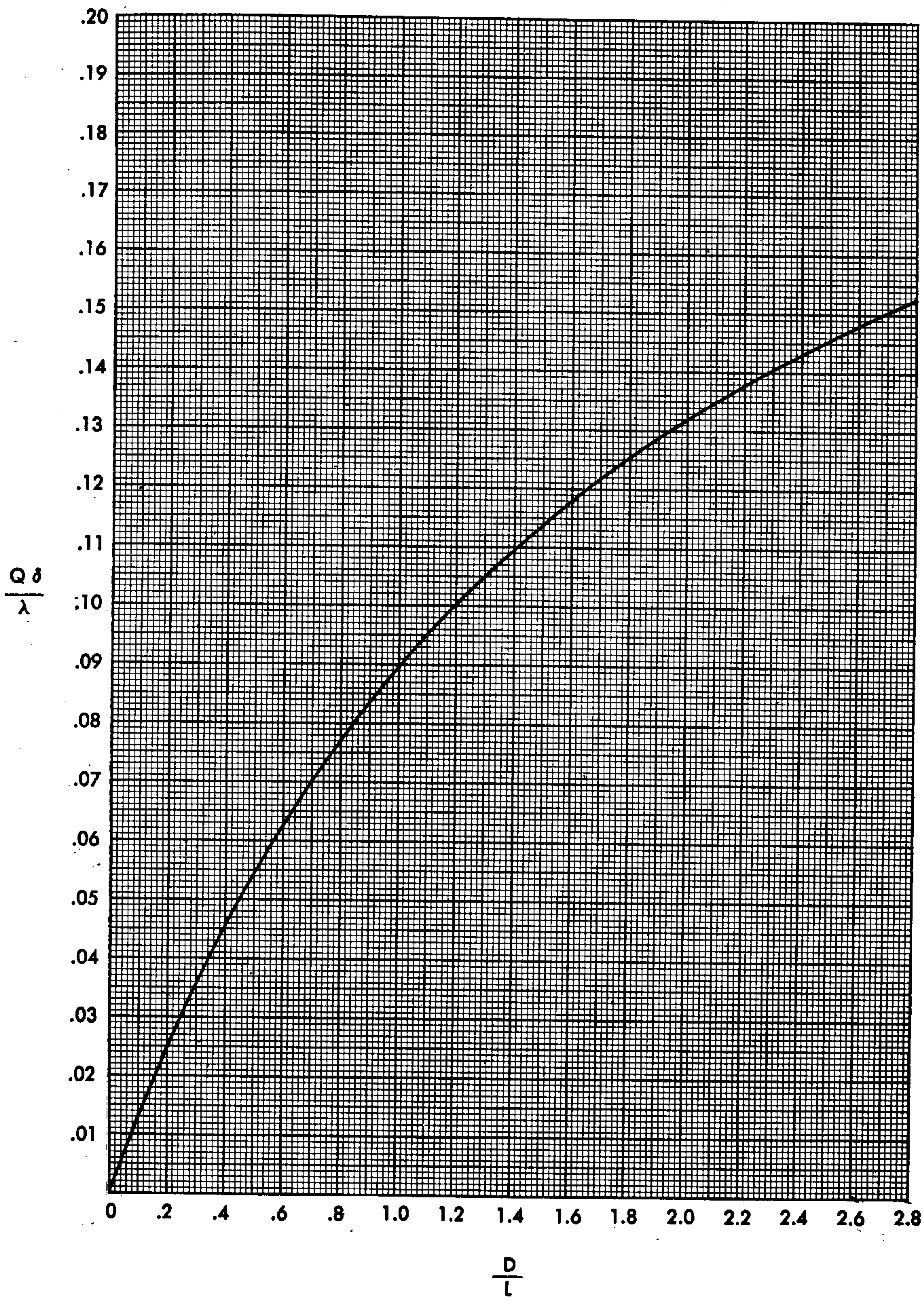

FIG. III F-4 MODE SHAPE FACTOR FOR COAXIAL RESONATORS IN THE TEM_{001} MODE

[redacted]

cavity dimensions. The length of the cavity is determined by the frequency; and, with the length specified, the diameter will be determined by the required Q. Finding the cavity dimensions is then a straightforward procedure which gives the designer no alternative sets of dimensions from which to choose. While not necessary, the mode chart does provide a method for coaxial cavity design which is analogous to that used for the more common cylindrical cavity echo box. Furthermore, in constructing the operating rectangle, a better physical "picture" of the design is obtained, and it is immediately seen where extraneous responses may occur, since the extraneous mode lines are present on the mode chart.

IIIF. 1. 2 Excitation of the TEM_{001} Mode

In the TEM modes the fields do not vary with θ. The electric field is directed radially outward from the inner conductor to the outer, and its intensity is proportional to $1/\rho$. The magnetic field forms closed loops concentric with the cavity axis. The wall currents are radial in the end plates and axial in the cylinder wall. The electric field is maximum at L/2, while at the same location the magnetic field is zero. The equations for the field quantities are:

$$E_\rho \propto \frac{1}{\rho} \text{Sin} \frac{\pi z}{L} \qquad H_\theta \propto \frac{1}{\rho} \text{Cos} \frac{\pi z}{L}$$

$$E_z = E_\theta = 0 \qquad H_\rho = H_z = 0.$$

The cavity may, therefore, be excited by three methods:

1. By a probe in the cylinder wall at L/2,
2. By a loop placed through the cylinder wall near the end of the cavity,
3. A loop extending through the end plate.

A loop placed at the cylinder wall must have its plane parallel to the cavity axis to give maximum coupling. For end plate coupling, the loop must have its plane directed radially.

[redacted]

If the operating rectangle is sufficiently large, the cavity may contain extraneous modes within the operating rectangle. The first interfering mode that will appear will be the TE_{111}. This mode and others, with the exception of higher order TEM_{00n} modes and TM_{0mn} modes, could be suppressed by radial slots of non-conducting material in the end plates. Such slots would be analogous in structure and would serve the same purpose as the annular rings in the cylindrical cavity end plates.

In general, the mode suppression techniques for the coaxial cavity are similar to those for the cylindrical cavity except that the current flow for the desired mode is radial in the end plates and axial in the cylinder wall, instead of being in the θ direction as is the case with the TE_{01n} modes of cylindrical cavities. In practice, it is quite unlikely that the designer of a coaxial cavity echo box will have to resort to mode suppression techniques, since for the tuning ranges usually encountered in echo box specifications the operating rectangle will not contain extraneous modes. For this reason, a more extensive discussion of possible mode suppression techniques will not be given.

Because of the directions of current flow, a gap at the movable end plate is not permissible. The TEM modes have currents which pass between the end plates and the cylinder wall. This fact requires that the moving parts make good electrical contact with the stationary parts. One method of obtaining good contact is shown in Figure IIIF-5. The sliding fingers are used to give good electrical contact between the moving and non-moving parts. If the contacting fingers are of the order of a quarter wavelength long, the current at the point of contact will be small, since the contact will be made near a current node. A quarter-wave-choke type non-contacting short circuit is not suitable for this purpose, both because it is a narrow-band device and because the quarter-wave open-circuit line constitutes a second cavity of low Q coupled tightly to the main cavity, which will have the effect of drastically reducing the Q of the main mode.

[redacted]

[redacted]

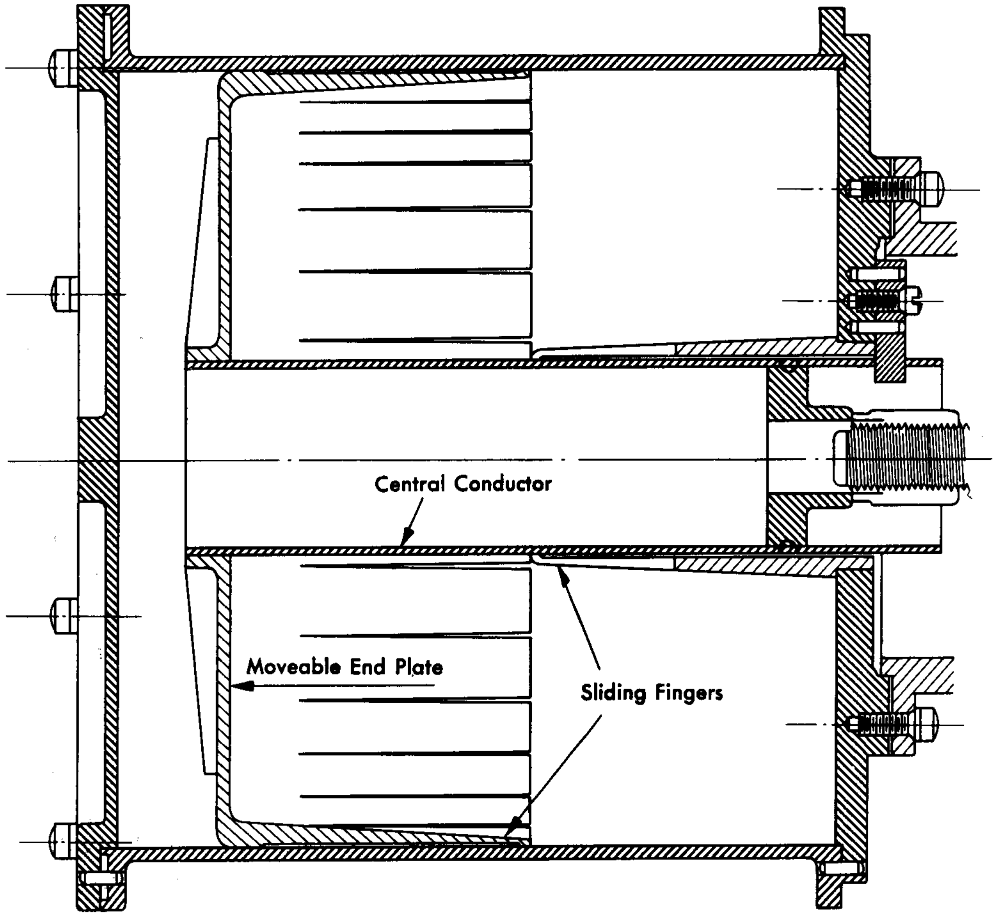

FIG. III F-5 CROSS-SECTION OF COAXIAL ECHO BOX (TS-545/UP) SHOWING SLIDING FINGERS

Courtesy JOHNSON SERVICE COMPANY

IIIF.1.3 The Tuning Range

The tuning range possible for a TEM_{001} coaxial cavity in which the TE_{111} mode has been excluded from the operating rectangle can be found using the mode line equation. For the TEM_{001} mode this equation is

$$\left(\frac{f\,D}{10^4}\right)^2 = .348\left(\frac{D}{L}\right)^2$$

[redacted]

while for the TE_{111} mode the equation is

$$\left(\frac{f\,D}{10^4}\right)^2 = .362 + .348\left(\frac{D}{L}\right)^2$$

For the TEM_{001} operating rectangle to be as large as possible without including the TE_{111} mode, the ordinate of the upper right-hand corner of the rectangle must be equal to the ordinate of the TE_{111} mode at the point where this mode line touches the operating rectangle. This statement can be justified by reference to the mode chart of Figure IIIF-1. For the lower corner of the operating rectangle, the TEM_{001} mode equation is

$$\left(\frac{f_1 D}{10^4}\right)^2 = .348\left(\frac{D}{L_1}\right)^2$$

while for the upper corner it is

$$\left(\frac{f_2 D}{10^4}\right)^2 = .348\left(\frac{D}{L_2}\right)^2$$

The TE_{111} mode equation must satisfy the condition

$$\left(\frac{f_2 D}{10^4}\right)^2 = .348\left(\frac{D}{L_1}\right)^2 + .362$$

Hence,

$$F^2 = \left(\frac{f_2}{f_1}\right)^2 = \frac{(f_2 D)^2}{(f_1 D)^2} = \frac{.362 + .348\left(\frac{D}{L_1}\right)^2}{.348\left(\frac{D}{L_1}\right)^2}$$

where F is the ratio of the maximum to the minimum frequency. A more convenient form is:

$$F^2 = 1 + \frac{1.04}{\left(\frac{D}{L_1}\right)^2}$$

This equation shows that the greatest tuning range will be had for small values of $(D/L_1)^2$. In a cavity where $(D/L)^2$ is in the neighborhood of 0.4, which is a typical value for coaxial cavities, F = 1.89. This tuning range is much larger than required for echo boxes and much larger than can be obtained with cylindrical cavities, even when non-crossing extraneous modes are admitted into the operating rectangle. If $(D/L_1)^2$ is less than 0.348, it is seen from the mode charts that the first extraneous mode to enter the operating rectangle will be the TEM_{002}. If it is the TEM_{002} mode which limits the tuning range by its presence in the operating rectangle, the tuning range F will be 2.

IIIF. 1.4 <u>Design of the Cavity</u>

In some respects, designing the coaxial cavity echo box is much easier than designing a cylindrical cavity because, as discussed earlier, there is only one mode from which to choose. Specifying a frequency and the desired Q determines a point on the mode line uniquely, provided $Q\sqrt{f}$ is within the range of possible values for this mode (0 to approximately 1×10^6). The following is one suggested procedure for designing the coaxial cavity.

The required Q must be found first. This Q can be determined if the required ringing time is known. The ringing time can be obtained from the expression developed in Section IIID. 1. 1. This equation was developed without any assumptions as to the shape of the cavity, so it may be applied to coaxial cavities as well as to cylindrical ones. The procedure for determining the required Q from the specified ringing time was also discussed in connection with the ringing time equation.

The maximum and minimum cavity lengths, L_1 and L_2 respectively, can be found from the relation $L = \lambda/2 = c/2f$. From the required Q,

[redacted]

the required diameter of the cavity can be found. To find the diameter, Equation (3a) or (3b) or Figure IIIF-3 can be used. Having found the dimensions of the cavity, it will be informative to construct the cavity operating rectangle on the coaxial cavity mode chart.

Knowing the cavity dimensions at both extremes of the tuning range, the variation in ringing time over the band may be found, using the relation

$$1 + \frac{\Delta t_r}{t_r} = \frac{1 + \frac{\Delta MS}{MS}}{1 + \frac{\Delta f}{f}}$$

There remains the task of coupling in and out of the cavity. Coupling may be made by means either of a loop or a probe, and at either the side wall or the end plate. The choice is left to the designer and depends on his preference, and on what sort of coupling appears most satisfactory from a mechanical or production standpoint. Having selected a position for the input loop, a satisfactory position for the output must be determined. The only restriction on the output loop position is that it must be sufficiently removed from the input loop so that there is no direct coupling between them. If the input loop is in the side wall, the output loop is usually placed at the same axial position but separated from the input loop by an angle of at least 90^o.

Example: Design of the TS/545

This cavity covers the frequency range 1150 to 1350 mcs, with a 10-mcs overlap on each side of the tuning range. The internal dimensions of this cavity are: D = 6.000", a = 1.500", L_1 (at 1150 mcs) = 5.1166", L_2 (at 1350 mcs) = 4.3474". On calculating the dimensions L_1 and L_2 from the relation $L = \lambda/2 = c/2f$, it is found that L_1 = 5.1317" and L_2 = 4.3715". The small discrepancy between the actual and the theoretical lengths, which is of the order of a half of one per cent, can be attributed

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to the perturbing effects of the contacting f ngers in the cavity, which make the cavity somewhat irregular internally. The ratio of the inner to the outer conductor diameters is 1.5 to 6, or 0.25, which is sufficiently close to the optimum ratio of 0.278.

The mode chart coordinates are found to be:

$$\left(\frac{D}{L_1}\right)^2 = 1.3751; \quad \left(\frac{f_1 D}{10^4}\right)^2 = 0.47610$$

$$\left(\frac{D}{L_2}\right)^2 = 1.9047; \quad \left(\frac{f_2 D}{10^4}\right)^2 = 0.65610$$

The operating rectangle has been inscribed on the mode chart of Figure IIIF-1(b). It is seen that the TE_{111} mode does not enter the operating rectangle. It should be pointed out, of course, that the mode chart was constructed for N = 0.278, so that the TE_{111} mode is not quite in the correct place for the cavity, in which N = 0.250. Actually the TE_{111} mode is displaced a rather small distance upward for N = 0.250. Likewise, the calibration of $Q\sqrt{f}/10^6$ on the mode line will not be quite right, since it is a function of N. The error here is negligible, however, as can be seen from Figure IIIF-3, which shows the variation of $Q\delta/\lambda$ as a function of D/a (= 1/N). The cavity has a theoretical Q of about 13,600 at the low frequency end of the band and about 13,800 at the upper frequencies.

The expected percentage variation in ringing time over the band is

$$1 + \frac{\Delta t_r}{t_r} = \frac{1 + \frac{\Delta MS}{MS}}{1 + \frac{\Delta f}{f}}$$

$$\frac{\Delta t_r}{t_r} = 6\%$$

[redacted]

[redacted]

This 6 per cent variation is reduced by the presence of a compensating loop which provides the cavity with frequency-sensitive loading.

The input loop is positioned 0.750" from the front or stationary end plate. The output loop is the same distance from the end plate but at an angle of 90° from the input loop. The input loop has a 51-ohm resistor in series with it to reduce the standing wave ratio in the input line. The compensation loop, which couples to a 200-ohm carbon resistor, is located at an angle of 165° from the input loop and is 2.148" from the stationary end. In addition, there is a standardizing loop coupled to a 200-ohm resistor, which is used for reducing the ringing time of each box to that of a standard box. This loop is 0.596" from the front end plate and has the same angular position as the compensating loop.

IIIF.2 The Partial Coaxial Cavity

IIIF.2.1 Design Theory of the Partial Coaxial Cavity

The partial coaxial or hybrid cavity is similar to the full coaxial cavity. These two types of cavities can be used in the same frequency ranges, and the two types are of approximately the same size and have approximately the same Q. The hybrid cavity has advantages as well as disadvantages when compared to the full coaxial cavity. The hybrid cavity is tuned by axial movement of the central conductor (Fig. IIIF-6). Such a tuning arrangement has the advantage that there are fewer sliding electrical contacts. The only moving electrical contact is between the central conductor and the supporting end plate. In the case of the hybrid cavity there is also less movement of the tuning element to cover a specified band.

The partial coaxial cavity has the disadvantage that it cannot be analyzed exactly. However, there are methods of treating the cavity which lead to approximately correct results. Using such methods, a trial cavity may be designed. After a prototype has been constructed, some final adjustments are invariably necessary. These adjustments are made experimentally and consist of such operations as adjusting the insertion depth of the central conductor.

The design formulas which are presented here are based on the consideration of the cavity as a coaxial transmission line short circuited

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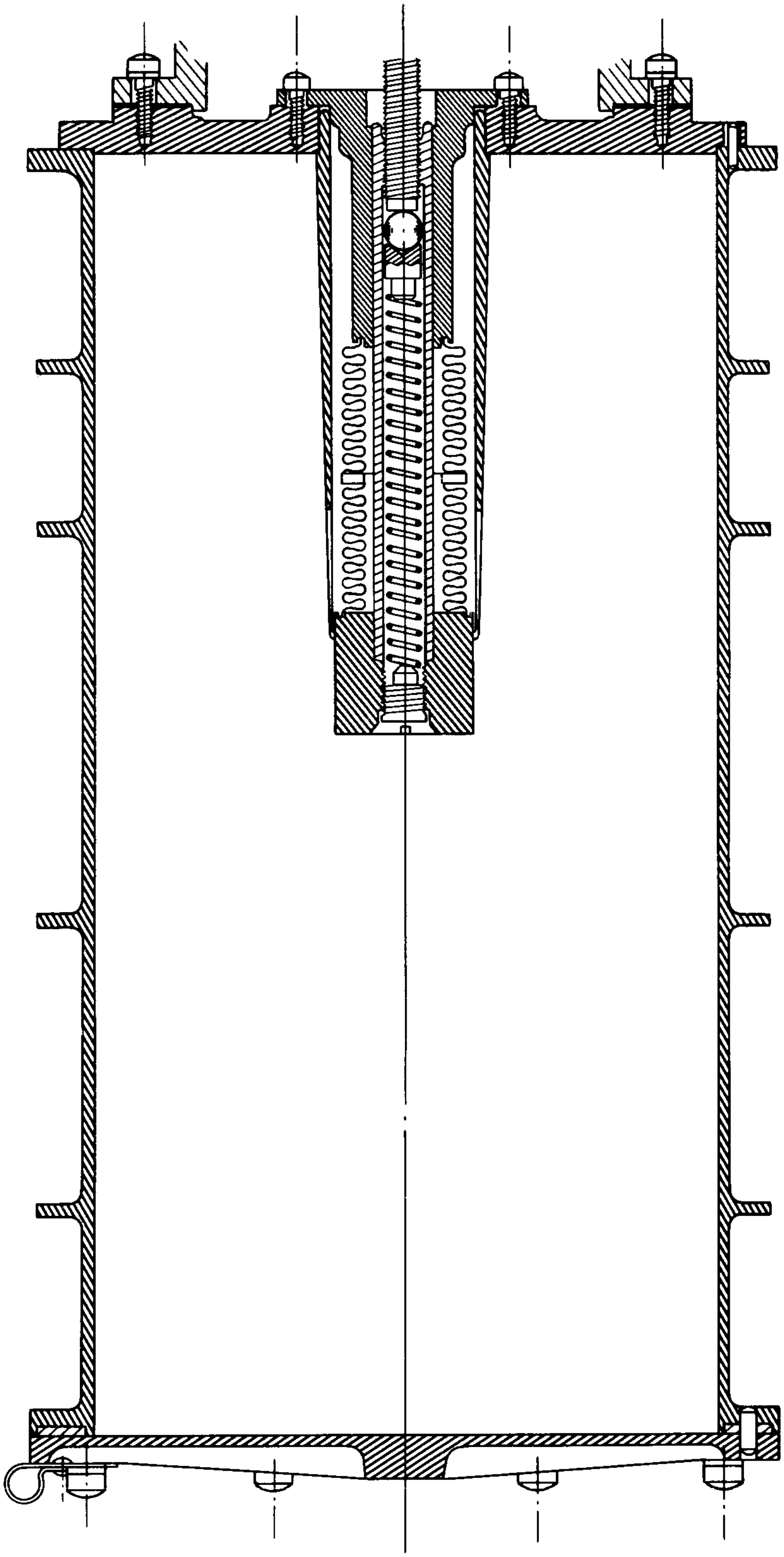

FIG. III F-6 CROSS-SECTION OF PARTIAL COAXIAL ECHO BOX (TS-544/UP)

Courtesy JOHNSON SERVICE COMPANY

at one end and capacitively loaded at the other (Ref. 15). This loading increases the electrical length of the line. Figure IIIF-7 shows a coaxial

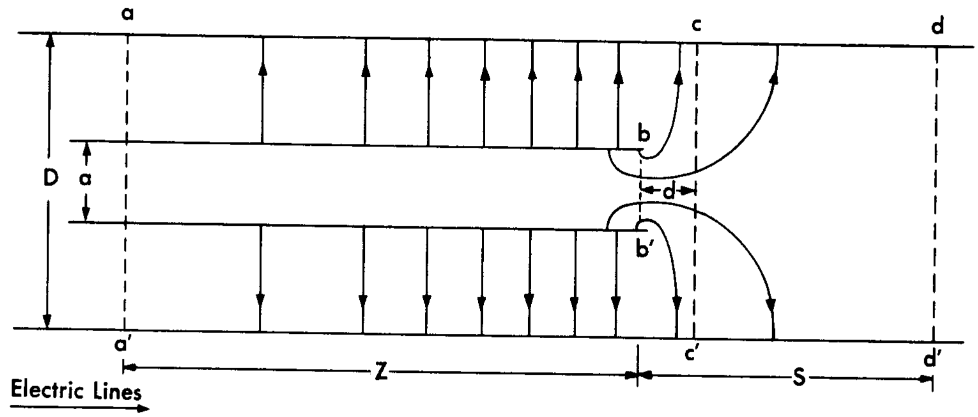

FIG. III F-7 COAXIAL LINE WITH HOLLOW CENTRAL CONDUCTOR

line with a hollow central conductor which is terminated at the plane bb'. To the right of this plane, the coaxial line becomes a circular waveguide. The coaxial line is excited in the TEM mode, but there is no conduction in the circular guide because the frequency is below cutoff. There is complete reflection from the region to the right of bb' and standing waves are set up in the coaxial part of the line. The behavior of the electric field in the vicinity of bb' should be noted. The field lines are bowed outward in the region of bb', so that they extend somewhat beyond this plane, but there is very little field as far to the right as dd'. The lines which enter the inside portion of the inner conductor are approximately normal to plane bb' when they intersect this plane. Therefore, if conducting planes are placed at bb' and at dd', the field configuration will remain essentially unaltered. If plane aa' is assumed to be the first null of the electric field (remembering that there are standing waves in the coaxial line), a conducting plane there will likewise have no effect on the field configuration. The insertion of the three conducting planes has produced a partial coaxial cavity, without greatly altering the configuration of the fields.

The reason for comparing the partial coaxial cavity to the waveguide configuration is that the waveguide configuration has been analyzed. The above discussion indicates qualitatively that this same analysis is applicable to a partial coaxial cavity.

The coaxial line of Figure IIIF-7 is effectively terminated by an open circuit located at the plane cc', at a distance d from the end of the central conductor. The capacitance at the region of termination of the central conductor has the effect of adding a length d to the central conductor. The distance d is a function of the wavelength λ and the quantities D and a, the diameters of the outer and inner conductors, respectively. That is,

$$\frac{2\pi d}{\lambda} = F\left(\frac{D}{\lambda}\right) - F\left(\frac{a}{\lambda}\right) - F\left(\frac{D-a}{\lambda}, \frac{D}{a}\right)$$

where

$$F(x) = x \log_e x + \sum_{n=1}^{\infty} \left(\sin^{-1} \frac{x}{\beta_n} - \frac{x}{n} \right)$$

$$F(x, \alpha) = x \log_e x + \sum_{n=1}^{\infty} \left(\sin^{-1} \frac{\pi x}{\beta_n' (\alpha - 1)} - \frac{x}{n} \right)$$

$$x < \beta_1$$

$$\beta_n = n\textit{th} \text{ root of } J_o(\pi\beta_n) = 0$$

$$\beta_n' = n\textit{th} \text{ root of } J_o(\beta_n) N_o(\alpha\beta_n) - J_o(\alpha\beta_n) N_o(\beta_n) = 0$$

This formula is complicated and is in infinite series form, but the equation is plotted in Figure IIIF-8, which is taken from the Waveguide Handbook (Ref. 15). This curve applies to a transition from a coaxial line to a below-cutoff cylindrical waveguide. It is also applicable to the partial coaxial cavity.

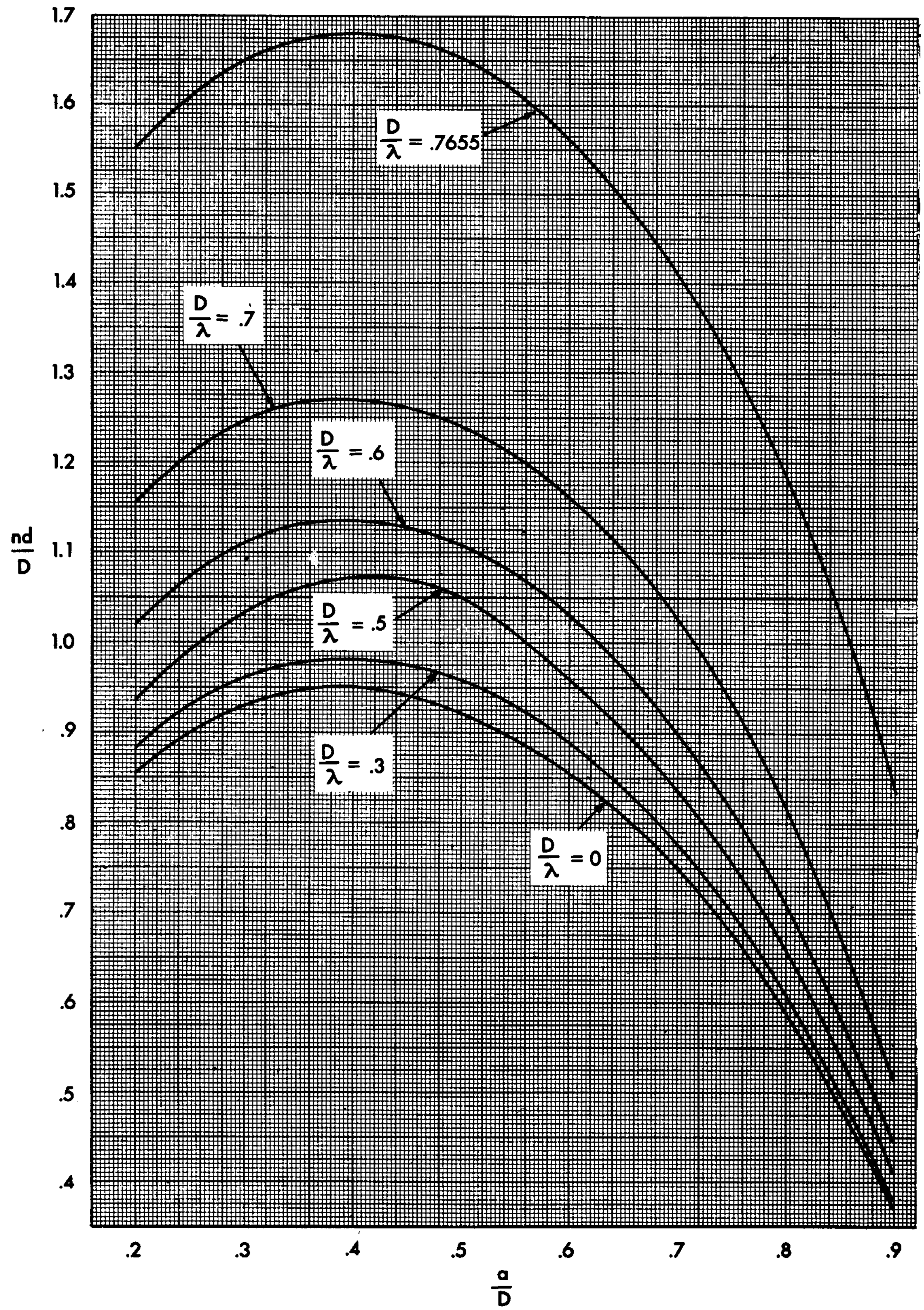

FIG. III F-8 d AS A FUNCTION OF VARIOUS PARAMETERS FOR A PARTIAL COAXIAL CAVITY

Courtesy McGRAW-HILL

[redacted]

The distance between bb' and dd' is not critical, since there is little field in this region. In order for this part of the cavity to be below cutoff the diameter of the cavity must satisfy the relation

$$D \leqq \frac{6920}{f}$$

f is in mcs
D is in inches

The quantity 6920/f is the cutoff wavelength for the TE_{11} waveguide mode, which is the lowest frequency mode other than the TEM group. If a waveguide is below cutoff for this mode, it will be below cutoff for all other modes. In order for the TE_{11} mode generated at the discontinuity to be sufficiently attenuated in traversing this section of cylindrical waveguide, a one-way attenuation of at least 30 db is required. The attenuation for this mode is

$$A = \frac{32.0}{D} \sqrt{1 - \left(\frac{1.71\, D}{\lambda}\right)^2} \tag{4}$$

where A is the attenuation in db per unit length in the same units used for D and λ. The length required for 30 db attenuation is

$$S = \frac{30}{A} \tag{5}$$

Such a design ensures that the field at the end plate is small and good electrical contact between end plate and the cylinder wall will not be needed. Furthermore, the presence of the end plate will not significantly alter the resonant frequency as calculated by means of the curves of Figure IIIF-8.

The theoretical Q of the hybrid cavity is

$$Q_T = \frac{492\sqrt{f}}{\left(\frac{1}{D} + \frac{1}{a}\right) + \dfrac{1.288}{Z + \dfrac{\lambda}{15.57}\sin\dfrac{720Z}{\lambda}}} \quad \text{(Ref. 16)} \tag{6}$$

[redacted]

Z is the length of the center conductor in inches

f is in mcs

D, a, and λ are in inches

In the derivation of this expression, the cavity was considered to be a co-axial line with additional losses because of the presence of the shorting plate at aa'. If these additional losses are neglected, (5) becomes

$$Q_T = \frac{384 \quad D\sqrt{f}\ \log_e \frac{D}{a}}{1 + \frac{D}{a}} \qquad \text{(Ref. 16)} \qquad (7)$$

(7) is more useful than (6) for obtaining an approximate value of D, because the term involving Z is absent.

IIIF. 2. 2 Design Procedure

Designing the hybrid cavity is somewhat troublesome, because some of the required constants must be found by successive approximations.

Assuming that the tuning range and Q_T are known, and that a value for a/D has been selected, an approximate value of D can be found by using Equation (7). After this approximate value of D is obtained, the curves of Figure IIIF-8 can be used to obtain an approximate value for d. This value can next be used to calculate Z, the length of the center conductor, using the relation

$$Z = \frac{\lambda}{4} - d \qquad (8)$$

Having found Z, it is then possible to use Equation (6) to obtain a second, and more accurate, value of D, with which the curves of Figure IIIF-8 can again be used to obtain a second value for d. In turn, new values for Z and D can be calculated using Equations (6) and (8). It is possible, by repeated use of Equations (6) and (8), and the curves of Figure IIIF-8, to obtain values for D, d, and Z which satisfy both the equations and the curves to the desired accuracy.

S, the length of the waveguide-below-cutoff portion of the cavity, can be found by use of Equations (4) and (5). The over-all length of the cavity is L = Z + S.

Example: Design of a Partial Coaxial Cavity Echo Box: the TS-544/UP

The TS-544/UP echo box is designed to operate in the frequency range 580 to 620. The inside diameter of the cavity is 5.000 inches. The ratio N of the central conductor diameter to the cavity diameter is nominally 0.225, although the central conductor is not of uniform diameter, being tapered toward the end. In fact, the ratio varies between 0.225 and 0.277, the maximum value being at the shorting plate which supports the conductor.

The TS-544 is illustrated in cross-section in Figure IIIF-6. The construction of the central conductor should be noted. It consists of a portion supported from the shorting end plate. At the end of this portion are contacting fingers which press against a short retractable section. By retracting this movable section into the remainder of the central conductor, the over-all length of the central inductor can be varied, thereby varying the resonant frequency.

Using a value of 0.225 for N, the following data were obtained from the curves of Figure IIIF-8.

$\frac{D}{\lambda}$	$\frac{2\pi d}{D}$
0.0	0.877
0.3	0.906
0.5	0.965
0.6	1.045
0.7	1.183
0.7655	1.582

By constructing a curve of D/λ vs. $2\pi d/D$ from these data, the information in Table IIIF-1 can be obtained. Columns 1 and 7 can be used to obtain a curve relating the resonant frequency with the physical length of the central conductor.

TABLE IIIF-1

(1) f(mcs)	(2) λ (inches)	(3) $\frac{D}{\lambda}$	(4) $\frac{2\pi d}{D}$	(5) d(inches)	(6) $\frac{\lambda}{4}$(inches)	(7) Z(inches)
560	21.077	.23722	.8963	.7134	5.2693	4.5559
570	22.441	.24146	.8969	.7135	5.1768	4.4634
580	22.835	.24570	.8974	.7138	5.0874	4.3736
590	23.228	.24993	.8980	.7146	5.0016	4.2870
600	23.622	.25417	.8986	.7150	4.9181	4.2031
610	24.016	.25840	.8992	.7154	4.8374	4.1220
620	24.409	.26264	.9000	.7161	4.7594	4.0433
630	24.803	.26688	.9006	.7165	4.6838	3.9673
640	25.197	.27111	.9012	.7169	4.6106	3.8937

The theoretical Q of the cavity, as calculated from Equation (6), varies from 8800 at 580 mcs to 9000 at 620 mcs. These are the frequencies at the ends of the specified tuning band.

At 580 mcs. the distance from the effective end of the central conductor to the opposite end plate is approximately 4.86". Considering this portion of the cavity to be a below-cutoff cylindrical waveguide, the attenuation for the TE_{11} mode, by Equation (5), is

$$A = \frac{32.0}{D} \sqrt{1 - \left(\frac{1.71\ D}{\lambda}\right)^2}$$

$$= 5.82 \text{ db/inch at } 580 \text{ mcs}$$

The round trip attenuation will be

$$= 2 \times 4.86'' \times 5.82 \text{ db/inch or } 57 \text{ db}$$

which is sufficient.

Loop coupling has been used. The input loop has been placed at the cylinder wall 0.71" from the shorting plate. The output loop has been placed at the same distance from the end plate, but 90° from the input loop. In addition, the TS-544 has a standardization loop, which permits ringing time to be standardized for all individual boxes; this loop is located in the cylinder wall near the shorting plate. There is also a compensating loop, designed to reduce the variation of ringing time with frequency, located at the outer conductor in the vicinity of the end of the center post. The exact location for this loop (4.043" from the shorting plate) as well as the amount of loading required were determined experimentally.

The relation between the resonant frequency and the corresponding length of the central conductor is shown in Figure IIIF-9. The calculated value is contrasted with the experimentally obtained value. The curves indicate that the required length of the center post for a specified frequency, as calculated from the design curves of Figure IIIF-8, is in error by only about 2 per cent.

The sensitivity of this echo box was measured and found to be 62.5 yds/db. From this, the loaded Q was calculated to be 6200. The ratio of loaded Q to theoretical Q is, therefore, about 0.7. This value is entirely satisfactory considering that the sensitivity test was made with the loading loops adjusted so as to lower the ringing time by about 10 per cent. The measurement also suggests that Equation (6) is satisfactory for the calculation of the theoretical unloaded Q.

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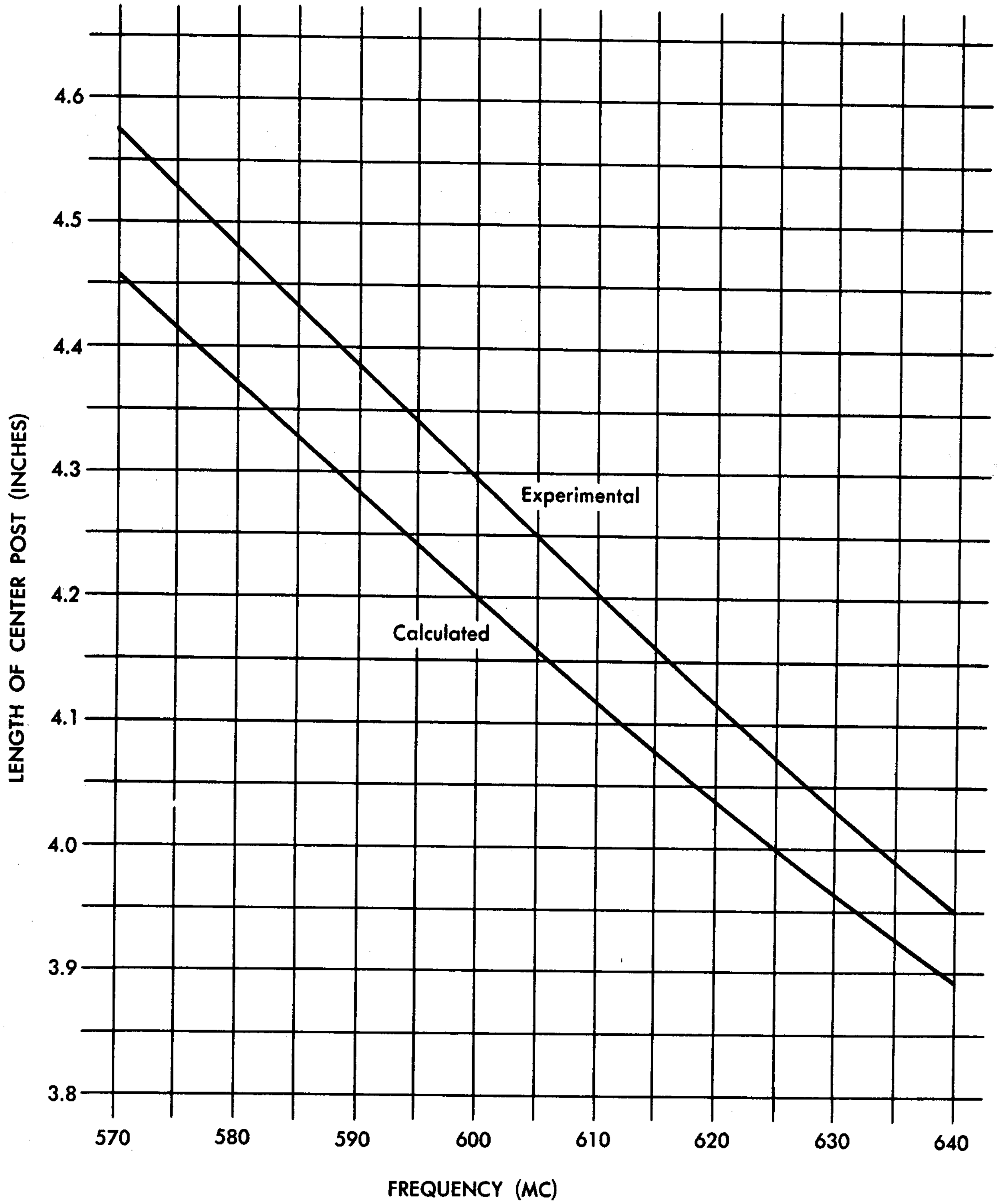

FIG. III F-9 FREQUENCY vs. LENGTH OF CENTRAL CONDUCTOR, FOR TS-544/UP ECHO BOX

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CHAPTER IV

MANUFACTURE[1]

IVA CONSTRUCTION OF THE CYLINDER

To ensure sufficient rigidity, echo box cylinders and end plates are generally machined from castings. It is also possible in certain designs to cast such auxiliary devices as meter mountings and mounts for input and output couplers integrally with the cylinder. Except where light weight is required, red brass (85 per cent copper, 5 per cent tin, 5 per cent lead, 5 per cent zinc) is a satisfactory material. It makes high quality castings, is easily machined, and is easily soldered and silver plated. If a material of lesser weight is required, an aluminum alloy is used. Aluminum is more difficult to cast and to machine, and much more difficult to solder and plate. An alloy which has been found satisfactory is Al 195 (95 per cent aluminum, 5 per cent copper).

The casting of cylinder parts is done by conventional casting techniques. Sand casting has proved successful, but blow holes or sand holes may cause trouble if they are located so that the machining of the interior of the casting exposes them. In a good many cases it may be possible to fill these holes with solder later in the operation.

The cylinder may be machined on a boring mill, a lathe, or on more specialized production tools. One such tool is shown schematically in Figure IV-1. This device machines the inside of the cavity and at the same time faces the cavity ends. The inside diameter of the casting is about .075" to .100" smaller than the finished diameter, and this amount of material is removed by the machine in three operations. About .050" of material is removed in the first operation; the remainder is removed in the next two operations. The two spindles holding the cutting tools

[1]Much of the material in this chapter was supplied through the courtesy of the Johnson Service Company and represents their experience in the manufacture of echo boxes.

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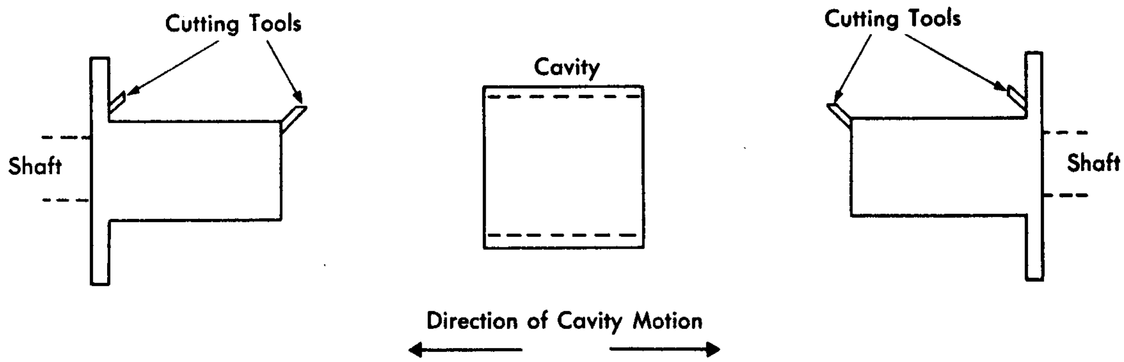

FIG. IV-1 STOKER UNIT USED IN MACHINING AN ECHO BOX CYLINDER

have no linear motion. The cylinder is mounted on a carriage between these two spindles and moves toward the first cutting tool, which makes the coarse cut. When the coarse machining has been completed, the machine automatically moves the cavity across to the other spindle, where a finer cut is made. In this operation, less material is removed and the speed of the cutting tool is lower, producing a smoother finish. Finally a finish cut of about .003" is made. While the boring is being done, a second cutting tool faces the cavity ends, and also provides a ring about .058" in depth and about 1/2" wide, into which a gasket fits.

Before the third or final cutting is made, the interior surface of the cavity is examined for imperfections such as blow holes and sand holes; these may be ground out and filled with a high temperature soft solder. The final machining will remove excess solder and should leave a machined surface free from imperfections. Silver plating will then form a surface over the brass and the solder, and the echo box quality will be unimpaired.

Caution should be observed in the choice of the cooling liquid used. If the casting is aluminum, oil should not be used. It is difficult to

[redacted]

remove all the oil from the pores of the casting, which is essential if the cylinder is to be plated. (A solution of baking soda has been found fairly effective for cleaning oil from casting).

In turning the cylinder on a lathe, the rough casting is first clamped to a face plate, and the flange on the opposite end is machined. The cavity is then turned end for end, and clamped to a special face plate having a machined ridge which fits into the gasket ring in the cavity flange. The remainder of the casting, including the inside, can then be machined without removing the casting. Sufficient material is removed from the face plate for the boring tool to machine the full length of the cavity interior.

In drilling or tapping the required holes in the echo box cylinder, precautions should be taken not to distort the echo box cylinder. In the case of "blind" holes, special care must be exercised so that the drilling or tapping instrument does not indent the inside surface of the cylinder. It may be found necessary to grind off the end of a standard tap until only the complete threads are exposed. This procedure permits the threading to extend farther into the hole and reduces the possibility of the end of the tap being forced against the bottom of the hole.

All holes should be drilled sufficiently large or tapped with a thread large enough to compensate for the plating which must be done. Otherwise, the holes will be too small after the plating and will have to be retapped or redrilled, which will remove the plating.

On some echo box models, the input connector is in a region where an ordinary die will not have the necessary clearance. In this event, an acorn die is recommended. If the clearance is still too small, the nipple may be made separate from the cavity and silver soldered into the cavity.

To make the coupling hole, which is usually keyhole shaped, the hole location is first positioned from the nipple. A circular hole is then drilled and reamed to size. The remaining portion is then cut. An alternative method is to use a broach. A hole, sufficiently large to accomodate the broach, is drilled into the cavity; the broach then enlarges the hole and gives it the desired shape and size.

[redacted]

Many echo box models of a given manufacturer will commonly have coupling holes of identical shape and size. Figure IV-2 shows the dimensions of a coupling hole commonly found in echo boxes using loop-type coupling. In the case of orifice coupling, the holes are usually circular.

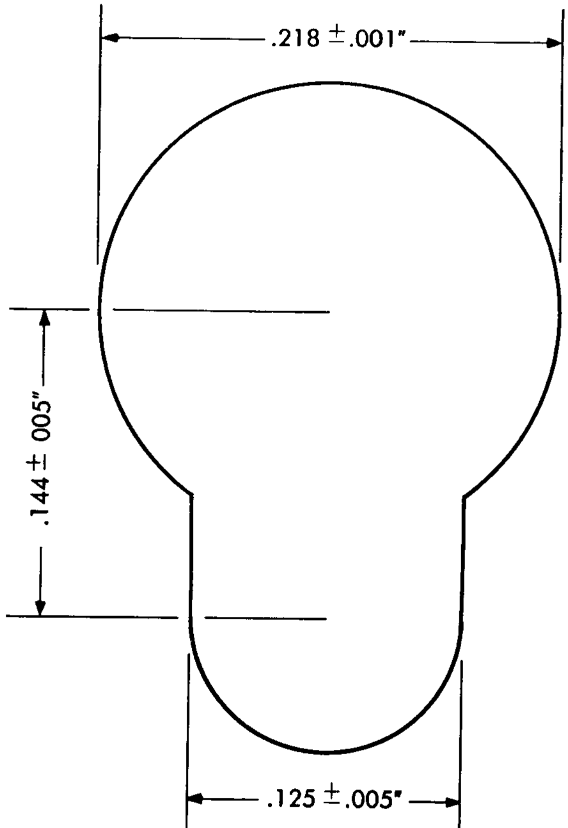

FIG. IV-2 A TYPICAL COUPLING HOLE USED IN ECHO BOXES EMPLOYING LOOP COUPLING

IVB PLATING

The plating process is of great importance in the manufacture of cavities and must be performed with care. Plating is not done for decorative purposes or for protection against corrosion, but is used to improve the electrical conductivity of the cavity interior. This means that the plating requirements are stringent. A plating procedure which meets the requirements for the first two purposes is not necessarily satisfactory from an electrical standpoint. Improper plating is the predominant source of trouble in echo box manufacture.

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Recent investigations have shown that the electrical quality of the silver plate is quite critical with regard to the current density used in plating, as well as the particular process used. It is noteworthy that the best silver plate presently obtainable has a conductivity of only 96 per cent that of annealed copper, and a poor plate may have a conductivity as low as 55 per cent that of annealed copper. Under laboratory conditions, the best plate, insofar as conductivity is concerned, has been obtained by periodically reversing the plating current, with use of the following constants:

Forward current density - - - - - - 18 - 20 amps. per square foot

Reverse current density - - - - - - - 11 - 16 amps. per square foot

Forward to reverse time ratio - - - 9/4

Cycling frequency - - - - - - - - - - 5 per minute

The best plate obtained by this method displayed about 5 per cent better conductivity than the best plate obtained with DC plating. Commercial "brightening" compounds, on the other hand, have been found to be detrimental to the conductivity (Ref. 17).

The plating should be of uniform thickness and at no point should it be thinner than the required minimum. Porosity of the plating must not be present because it reduces the electrical conductivity and resistance against corrosion. Pores may permit solutions to penetrate the plating and produce, at the junction of the metals, electrolytic action which accelerates corrosion. To produce high quality plating, the surfaces to be plated must be carefully prepared, smooth, and free from extraneous material such as oil films.

The required thickness of the plating is determined by the skin depth, which may be calculated. Practice suggests that the actual skin depth is much greater than the calculated value, supposedly due to imperfections in the plating, such as porosity. Therefore, the plating thickness should be several times the calculated skin depth. At microwave frequencies, the required plate thickness is between 0.0005" and 0.001". A plate of this thickness will conduct almost all of the wall current. In practice, the required plating thickness may be determined by plating a cavity until further plating no longer increases the ringing time. At this point the cavity behaves electrically as if it were made entirely of silver.

Plating procedures have been developed empirically. In plating brass or bronze, the following procedure has proved satisfactory.

1. To aid in uniform deposition of silver, the cavity interior is polished with rouge and a buffing wheel.

2. The cylinder is next rinsed thoroughly in hot water, and then cleaned in a 5 per cent or 10 per cent solution of sodium cyanide. This cleaning is followed by a second rinsing with water. (Alkali solutions are not used for cleaning cavities, since they cannot be used on aluminum).

3. The plating electrodes are thoroughly cleaned before each production run.

4. A silver strike is made. This initial silver plating is done with high current density and the plating solution has a low concentration of silver.

5. The cylinder is then put into the main plating bath. It is plated for about 10 minutes and then removed, rinsed first with cold, then with hot water, wire brushed and returned to the plating bath. This procedure is repeated about three times during the plating process. The purpose of the wire brushing is to remove any lumps in the plating because silver deposited subsequently would tend to increase the unevenness still further. An alternative method is to reverse the plating current periodically, which tends to remove high spots in the plate.

The silver bath has the following composition:

Silver cyanide	4 av. oz. per gallon
(weight of silver	3.6 troy oz. per gallon)
Sodium Cyanide	9.8 av. oz. per gallon
(weight of sodium	4.6 av. oz. per gallon)
Sodium Carbonate	6.0 av. oz. per gallon

If the cavity is aluminum, some additional steps are necessary before plating. After polishing, cleaning and rinsing, the cavity is anodized in a solution of 6 av. oz. of oxalic acid per gallon. Alternating current is used, with the voltage starting at 5 volts and gradually increasing to 50 volts as the current drops. It is very important that the anodizing bath contain no metal other than aluminum. The hooks holding the work must be washed in nitric acid after using; otherwise they will become non-conducting.

After rinsing, the work is dipped in a 1/4 per cent solution of hydrofluoric acid to remove silicon (silicon is an impurity found in aluminum), rinsed very thoroughly, and then nickel-plated for a time sufficient for the work to take on the appearance of nickel. After a rinse, the work is ready for silver plating. The nickel plating bath is made as follows:

Nickel ammonium sulfate	8 av. oz. per gallon
Nickel sulfate	4 av. oz. per gallon
(weight of nickel	2 oz. to 2-1/2 oz. per gallon)
Ammonium chloride	2 av. oz. per gallon
Boric acid	2 av. oz. per gallon

The pH of this solution ranges from 5.6 to 6.2.

All the baths used are at room temperature, and the temperature is not critical.

An echo box cylinder is plated by placing an anode along the axis so that the inside of the cylinder receives more silver than the outside. Navy specifications call for all portions of echo boxes to be plated, so the cylinders are completely plated with silver. This method is preferable to masking the inside of the cylinder and plating the outside separately with zinc or some other metal.

IVC THE TUNING MECHANISM

A cross-section of the type of tuning mechanism used in many Johnson Service Company echo boxes is shown in Figure IV-3. The tuning

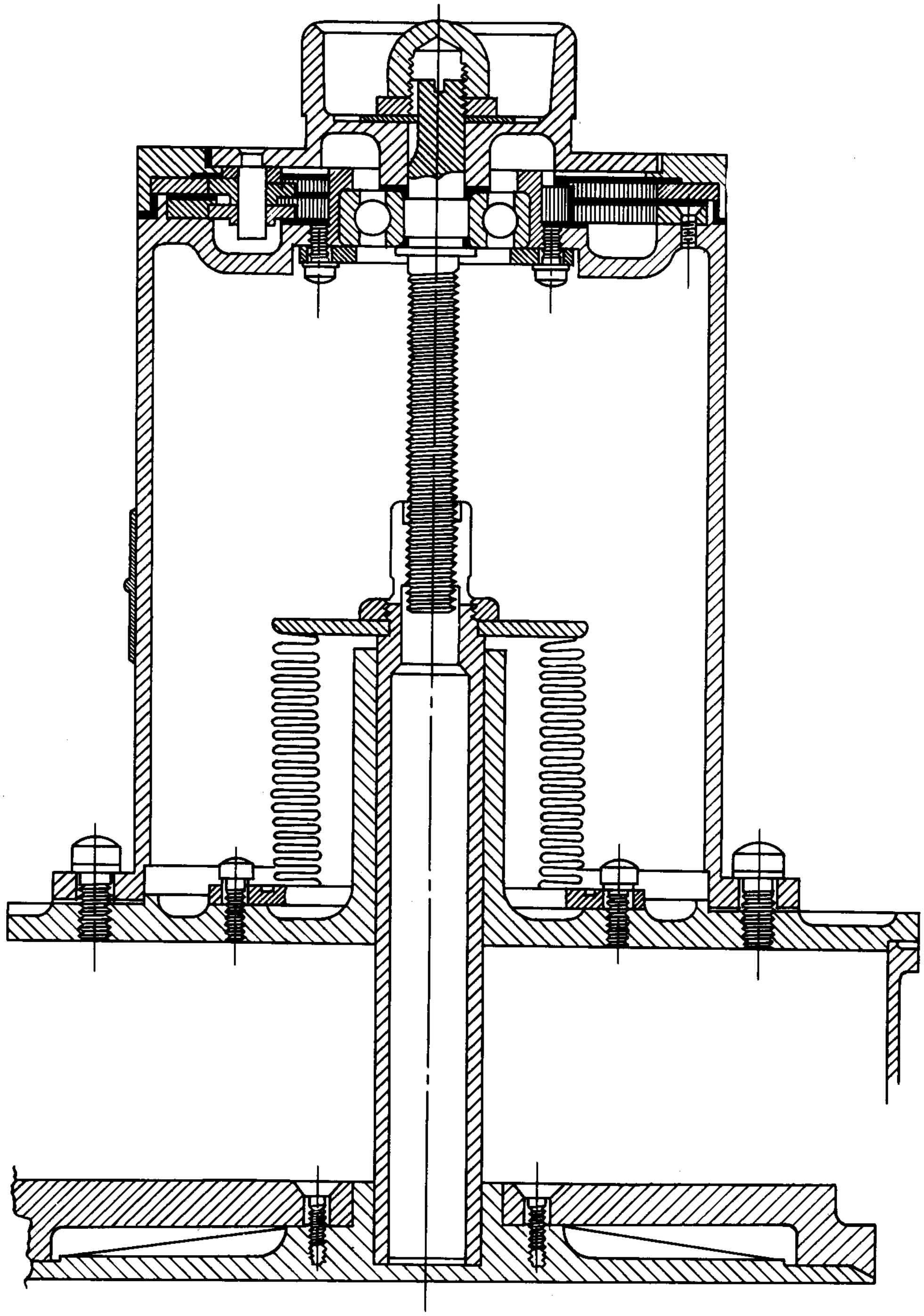

FIG. IV-3 TUNING MECHANISM USED IN JOHNSON SERVICE COMPANY ECHO BOXES

Courtesy JOHNSON SERVICE COMPANY

plunger is mounted on the end of a hollow shaft, which slides in a closely fitted bearing. The end of the shaft or spindle is provided with a nut which fits the threaded drive screw, so that rotation of the drive screw causes axial motion of the spindle and the tuning plunger. The spindle and tuning plunger are kept from rotating by the spring bellows, which is keyed to the shaft at one end and fastened to the end plate of the echo box at the other end. The bellows also makes an air-tight joint to keep moisture from entering the cavity.

The drive screw passes through a pre-loaded ball bearing at the dial end of the tuning housing and is fastened to the inner dial and knob by a lock nut under which there is a small pointer keyed to the drive screw.

In order to set the dial correctly in relation to the position of the tuning plunger, the cavity is completely assembled and the lock nut on the end of the drive screw is left loose. The cavity is connected to a radar or signal generator operating on a known frequency, and the drive screw turned with a screwdriver (a slot is provided for this purpose) until resonance in the main mode is indicated by a reading on the resonance indicator, or ringing on the radar scope. The dial is then set to read the correct frequency, without moving the drive screw, and the lock nut tightened. The position of the small pointer is then marked with a prick punch so that if the cavity is ever taken apart, it may be reassembled without losing its calibration. The punch mark and pointer make it necessary to set the plunger depth when reassembling the box to within only one-half revolution of the drive screw, which is not difficult. The final adjustment is made by realigning the pointer and punch mark, which resets the cavity reasonably close to its calibrated position. The outer dial is driven by planetary gearing from the inner dial. This dial's only function is to count the revolutions of the inner dial and, hence, backlash or play in the outer dial mechanism has no effect on the precision of tuning. It is convenient to have the outer dial make from 1/2 to about 9/10 of a revolution for the whole tuning range. The amount that the outer dial will rotate depends upon the pitch of the threads on the drive screw and upon the gear ratio between the inner and outer dials. By adjusting these two parameters, a convenient arrangement may be found which will suit most echo boxes. It is usually convenient to use a standard gear ratio and various standard pitches for the thread, and by selecting one of these values for the pitch, the range of movement of the outer dial may be made to fall within the suggested range. For S-band echo boxes, a pitch is usually selected which will give a tuning rate of the order of 10 mcs per rotation of the inner dial.

The spindle is a critical part of the assembly. It is made of Everdur bronze and it and its bearings are honed to close tolerances. Silicone grease (Dow-Corning No. 33) is used for lubrication. Everdur is difficult to solder so, if soldering is necessary, the end is first copper flashed.

The drive screw is made of case-hardened steel, and the threads are ground on a thread-grinding machine. The thread must be of very high quality to produce smooth and accurate tuning with minimum backlash.

IVD COUPLING LOOP ASSEMBLIES AND RESONANCE INDICATORS

Coupling loops vary considerably in size and shape. The selection of the most suitable one for a given purpose is determined experimentally. The dimensions of coupling loops used with various echo boxes are listed in Table IVD-1. It should be noted that the coupling loop for the TS-545, a coaxial cavity, is markedly larger than that for the other cavities.

TABLE IVD-1 Dimensions of Coupling Loops

Echo Box	Loop	Description	Dimensions length	Dimensions width
TS-270	input	has semi-circular end	.140"	.125"
14 ABA-1	output	has semi-circular end	.140"	.125"
TS-275	input	has semi-circular end	.125"	.125"
	output	has semi-circular end	.140"	.125"
FR-58	input	has semi-circular end	.156"	.125"
	output	has semi-circular end	.140"	.125"
TS-545	input	tear-shaped	.531"	.300"(approx.)
	output	rectangular	.280"	.125"
	standardization	has semi-circular end	.375"	.125"
	compensation	rectangular	.250"	.125"

The width of the loop is measured from the inside surface of the loop wire.

Silver plated copper wire has been found to be a suitable material for coupling loops. The wire is bent into the required shape with the use of hardened steel templates. By this method, the coupling loops may be manufactured rapidly and uniformly. The individual sections of the coupling loop and assembly are plated separately and then assembled. The grounded end of the coupling loop is soft soldered to the connector. The connector at this point has a small notch in which the end of the loop is placed before soldering.

The resonance indicator is usually a 0 - 100 microampere meter, although other sensitivities may be required in order to meet specifications. A typical meter circuit is shown in Figure IV-4. The meter most used in Johnson Service Company boxes has been the Weston NS-9490. The rectifier commonly used is the 1N21-B. A 1 to 2 microfarad 40-volt oil impregnated condenser has proved satisfactory.

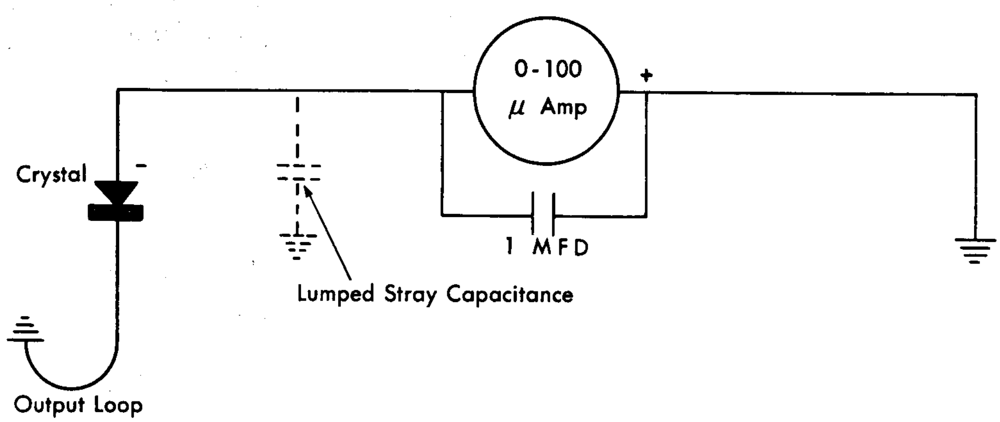

FIG. IV-4 A RESONANCE INDICATOR CIRCUIT

The meter deflection in the case of some boxes is adjustable by varying the output coupling, that is, by varying the depth of insertion of the output loop. In some boxes, the coupling loop insertion depth is adjustable only by removing the housing from the meter and adjusting the meter loop coupling assembly. In other cases, provisions have been made for adjusting the loop depth by controls mounted on the echo box. At X-band, where orifice coupling is used, a vane attenuator may be used in the output waveguide to provide attenuation between the echo box output orifice and the meter probe, as shown in Figure IV-5.

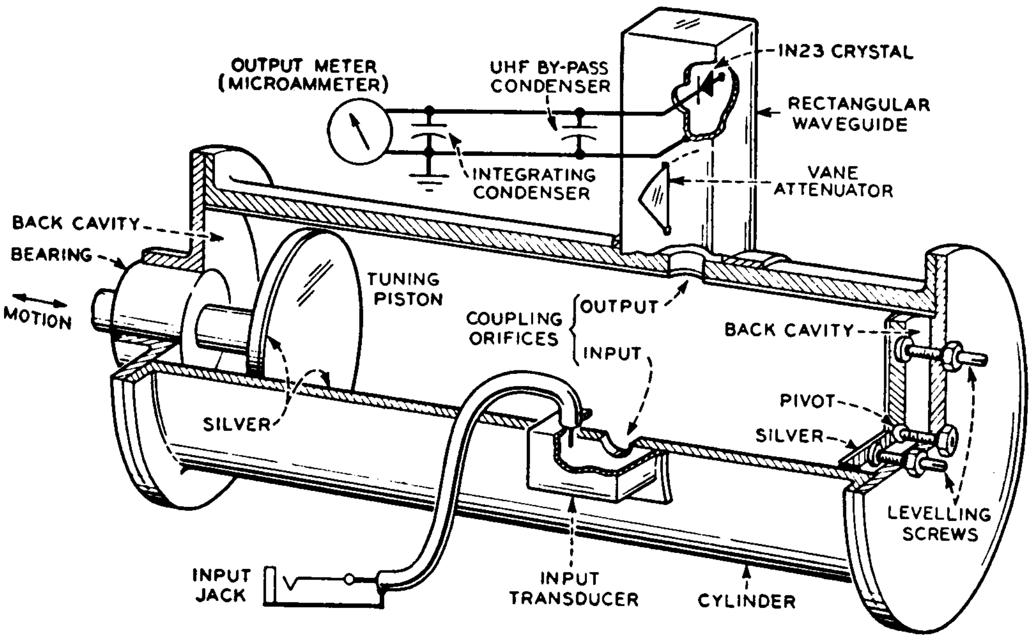

FIG. IV-5 METHOD OF VARYING OUTPUT COUPLING IN ORIFICE COUPLED BOXES

Courtesy BELL TELEPHONE LABORATORIES

IVE TOLERANCES

The most critical dimensions are to be found in the cylinder, spindle, and drive screw. The cylinders on smaller echo boxes have tolerances on the order of $\pm .002''$; on larger boxes, this tolerance is correspondingly larger. On extremely large, low frequency boxes the tolerances may be several hundredths of an inch.

The tolerance on backlash in the tuning mechanism is, for example, about 250 kc on S-band boxes and about 500 kc on X-band boxes. Tolerances on the drive screw threads are held to ±.0005". The use of the pre-loaded ball bearing also reduces end play.

The angle between the end plate and the cavity axis should ideally be 90°. In the case of a typical S-band box the end plate should not be off the perpendicular by more than about .003", measured at the cavity wall. In an experiment performed on an S-band box by one of the authors, the ringing time was measured for various tilt angles. The results are shown in Figure IV-6. It can be seen that, for slight tilt, there is little effect on the ringing time; but once the tilt goes beyond a certain point the ringing time drops rapidly.

The tolerances on ringing time are usually given in the specifications. Typically, the variation of ringing time of an individual box from its standard will be about ±4 per cent. The permissible variation from standard according to the specifications may be as high as -10 per cent to +15 per cent. In general, the upper limit of ringing time is not as important as the lower; in some cases no limit will be imposed on the maximum ringing time allowable.

In the production of echo boxes the ringing time variation among the boxes of the run is held to ±5 per cent unless some trouble is encountered which does not permit this degree of uniformity to be met. It is usual to try to keep the ringing time above standard, although the ease with which this may be accomplished varies greatly from one model to another, depending, of course, upon the ringing time standard which has been established for the model.

IVF SEALING TECHNIQUES

Echo box cavities are usually sealed to keep out moisture. While not air tight, the cavities are sufficiently sealed so that if exposed to water for a short time, the inside of the cavity will remain dry. It is expected that in a moist atmosphere some water vapor will find its way into the cavity over a period of time.

Moisture may enter the cavity either at the seal between end plates

[redacted]

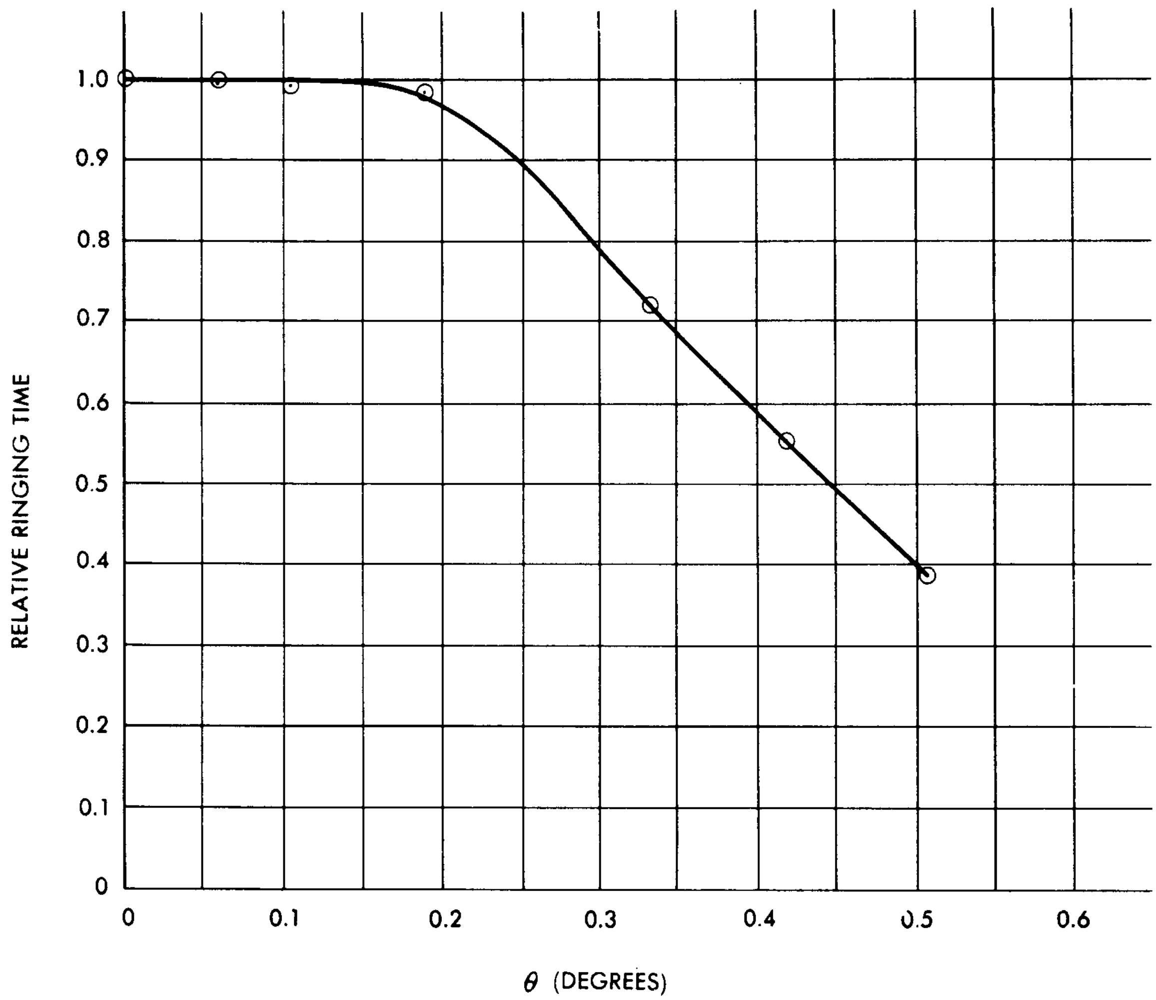

FIG. IV-6 LOSS OF RINGING TIME WITH TILTING OF END PLATE

[redacted]

and the cylinder wall, at the coupling holes, or at the region where the spindle enters the cavity. Each of these three possibilities must be considered in providing a tight seal for the cavity.

Between the cavity end plate and the cylinder there is a rubber gasket which fits in a rim on the cylinder end face and which extends beyond the rim by about .003" to .007". This gasket provides efficient sealing between the cavity cylinder and the end plate.

The use of the metal bellows to seal the cavity at the tuning end has proved to be quite satisfactory, as has the use of rubber gaskets, to seal around the coupling loops. It may be expected that more leakage of moisture into the cavity will occur through the RF couplings than elsewhere. In cases where considerable auxiliary equipment is used on the echo box, such as resonance indication meters and motors for tuning, the entire echo box assembly may be fitted with a cover which will adequately seal the equipment against moisture. Some echo boxes are also equipped with indicating dehydrating capsules sealed into the cavities.

IVG OTHER MANUFACTURING DIFFICULTIES

Serious loss of ringing time is to be expected in the case of coaxial or partial-coaxial boxes if even one of the spring fingers makes poor electrical contact with the side walls. Continuous electrical contact throughout the width of each finger is apparently not necessary, but there must be one good contact for each finger.

Another trouble peculiar to the coaxial cavity is a poorly soldered stationary end plate. Since the TEM mode requires current between the end plate and side walls, a perfect soldered joint must be produced between the end plate and side walls throughout the periphery of the end plate.

Glyptal varnish is usually employed for an interior coating to protect the plating. Occasionally a sample of this substance will exhibit undesirable characteristics, lowering the ringing time considerably. No reason for this variation in quality is known to the authors.

If plating salts are not very carefully washed off all parts after the plating operation, trouble will develop, particularly if such material remains on the coupling loops. Residue from chemical cleaning solutions used to prepare the cavity for plating will, if not thoroughly removed from the surface and from any pores or holes in the surface, eventually react to cause detachments or bubbles in the silver plate.

If the average ringing time for all types of boxes being produced begins to decrease, the plating operation should be suspected. Such a tendency can easily be seen if a record is kept of the ringing time of each box manufactured. In such cases the boxes will usually be found to ring satisfactorily after receiving additional plating. Gradual contamination of the plating solutions, or possibly a tendency on the part of platers to skimp on plating time in the interests of greater production, are possible reasons for such a deterioration in quality of plate.

CHAPTER V

TEST

VA DESIGN AND ACCEPTANCE TESTS

A new echo box design or prototype model must be thoroughly tested before the box can be put into production. The nature of the responses obtained, including both the desired or main mode response and extraneous responses must be known.

The tests which are customarily performed on a new echo box are:

1. frequency calibration of the dial for the main mode response;
2. mode search of the operating rectangle for all extraneous modes, using a CW signal generator;
3. determination of the echo box sensitivity, or the rate at which ringing time decreases as power to the echo box is decreased;
4. measurement of ringing time and output meter reading as a function of frequency;
5. search for extraneous ringing time and extraneous meter readings using a pulsed source; and
6. measurement of the effect of non-parallel or tilted end plates upon the ringing time.

VA. 1 Frequency Calibration

To calibrate the dial for the main mode response, a CW signal generator, a means of detecting the signal, and a wavemeter capable of measuring frequency very accurately are required. For the signal generator, a klystron oscillator, tunable over the echo box frequency band, is satisfactory. Because the frequency calibration of the klystron oscillator will in all probability be inadequate for this purpose, the precision wavemeter is needed. The wavemeter should be capable of measuring frequency (or wavelength) to five significant figures. For detecting the cavity response, a sensitive detecting device is required. The echo box resonance indicator is not satisfactory for this purpose, since it may not have sufficient sensitivity to detect resonance in the cavity when a low power exciting source such as a signal generator is used. In addition, the meter may not peak sharply enough to enable the dial reading to be found with the desired precision. The output loop should couple to an oscilloscope with a good amplifier. A spectrum analyzer, if available, will prove even more useful for this experiment and, in addition, will be ideal for the next test, the mode search.

Figure VA-1 shows a laboratory setup for making the frequency calibration test. This setup can, with some minor modifications, also be

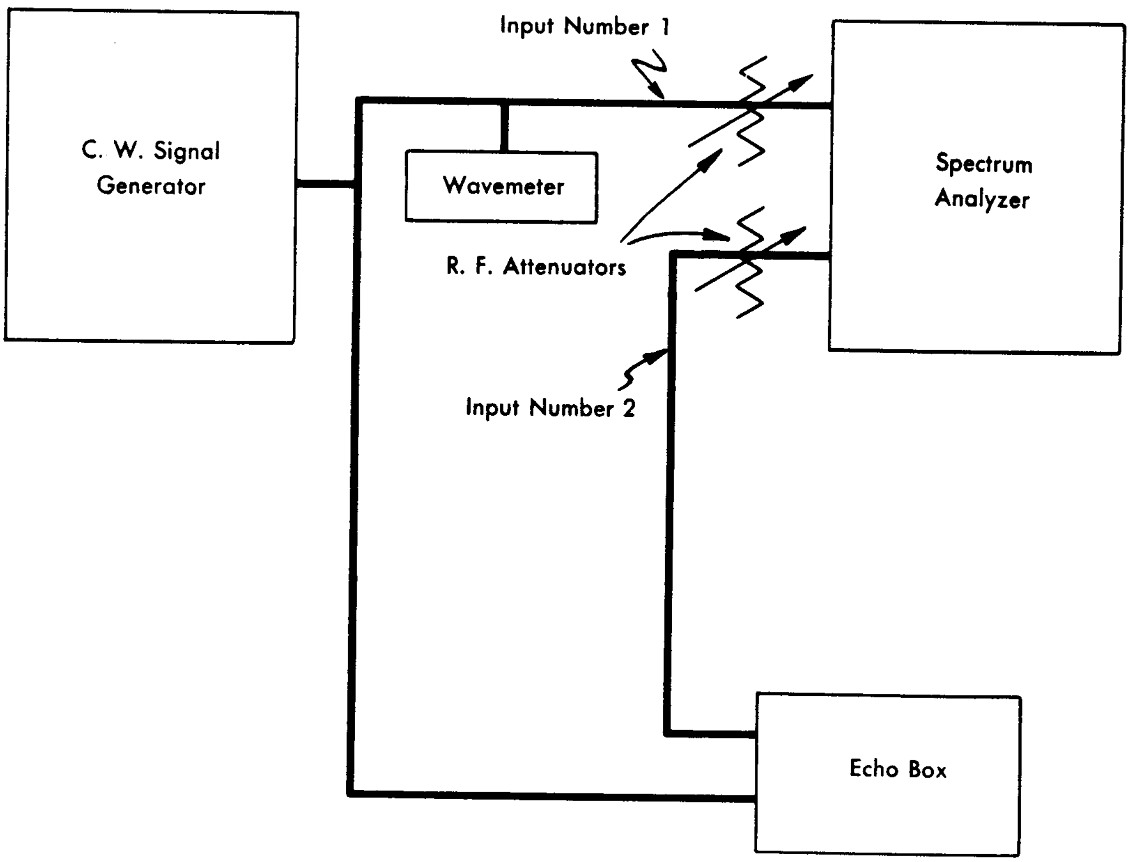

FIG. V A-1 LABORATORY SET-UP FOR PERFORMING FREQUENCY CALIBRATION AND CW MODE SEARCH used for the mode search test. The CW signal is fed into the cavity by way of the input loop and the response is obtained from the output coupling. (The crystal should be removed from the cavity and replaced by a brass or copper dummy.) Response represents transmission through the cavity. A spectrum analyzer is used to detect the cavity response. By means of a tee connector, the output of the signal generator is connected to the cavity input and also directly to the spectrum analyzer, enabling the latter to be easily tuned to the signal generator frequency.

With the signal generator adjusted to produce a CW signal at a particular frequency within the echo box tuning range, the attenuation in the No. 1 input channel of the spectrum analyzer is reduced to a minimum, and the spectrum analyzer tuned to the output of the signal generator. The No. 1 attenuator is then increased to its maximum setting, which should remove the signal from the screen, and the echo box tuned until its main-mode response (which should be vastly greater than any spurious response) appears on the spectrum analyzer screen by way of the No. 2 input. The echo box dial reading is then recorded along with the signal generator frequency as read on the wavemeter. It is advisable to have sufficient attenuation (10 db or so) in the output line from the signal generator to keep the external circuit from affecting the signal frequency. Measurements should be made every few mcs across the entire echo box tuning band. In a typical case, about 30 readings are desirable. For a tuning range of 300 mcs, then, measurements will be at 10 mcs intervals.

After plotting frequency versus dial reading, it is useful to plot a curve of calculated response versus dial setting on the same graph for comparison. The theoretical response is calculated from the equation

$$\left(\frac{f\,D}{10^4}\right)^2 = 2.0704 + .34799 n^2 \left(\frac{D}{L}\right)^2$$

where f = frequency
D = diameter
L = length
n = mode index

To plot frequency vs. dial reading from the above equation, it is necessary to correlate dial reading with cavity length. This correlation can be done by measuring the cavity length at various dial settings. Any systematic deviation between the experimental and theoretical curves, or any deviations exceeding the probable error of the measurements, should be examined in detail. It will be useful for this purpose to plot frequency error versus frequency, using the theoretical frequency curve as a standard.

Systematic deviations may be caused by cavity perturbations or periodic changes in the pitch of the tuning screw. Perturbations cause the experimental curve to be displaced to one side of the theoretical one, changes in pitch cause the experimental curve to fluctuate, sometimes with an easily-noticed period.

As another method of treating the data, a mode line can be obtained by plotting $(f\ D)^2$ versus $(D/L)^2$. Any deviation from a straight line can be detected fairly easily.

VA. 2 The Mode Search

Using the apparatus of the previous test, the entire operating rectangle must be searched for extranous responses. The sensitivity of the measuring apparatus can be increased further by connecting the echo box output directly to the mixer of the spectrum analyzer. The use of an extremely accurate wavemeter is not needed in this test, accuracy to four significant figures being adequate. If the signal generator is frequency calibrated or has a built-in wavemeter, it will serve to measure frequency. When the spectrum analyzer and the signal generator are in tune, the echo box can be tuned across the band and all extraneous responses can be recorded.

The responses obtained are plotted on a mode chart. Since the quantities measured are frequency and dial reading, while the mode chart coordinates are $\left(\frac{f\ D}{10^4}\right)^2$ and $(D/L)^2$, the mode chart coordinates would have to be calculated for each response. This procedure can be avoided by marking the operating rectangle of the mode chart with two auxiliary scales; the $\left(\frac{f\ D}{10^4}\right)^2$ axis can be marked with a frequency scale while the $(D/L)^2$ axis can be marked with a scale of dial reading. In this way, extraneous responses can be rapidly and easily plotted on the mode chart.

The echo box itself may be used as a frequency meter, provided the frequency calibration made previously disclosed satisfactory performance in this respect. The main mode response is easily identified because of its much greater amplitude and sharpness. The dial reading corresponding to the main mode response should be found before extraneous responses are noted, since this response locates the proper ordinate on the mode chart at which to plot all other responses. The other responses are then plotted at this same ordinate, opposite their respective dial readings. In this manner an experimental mode chart can be constructed point by point, since each change of frequency and the ensuing search for responses throughout the echo box tuning range corresponds to a horizontal slice through the mode chart. It is desirable to plot the data as the experiment proceeds, since doing so permits the experimenter to observe the course of events, and to take additional readings where desirable to investigate such significant areas of the chart as mode crossings.

Figure VA-2 shows a sample mode chart operating rectangle. The auxiliary scales of dial reading and frequency make the chart adaptable for mode searching. The calculated mode lines are drawn relatively lightly while the mode lines determined experimentally in the mode search are drawn more heavily.

In the figure it is seen that some of the modes are found where theory predicts they should be, while others are somewhat displaced. The displacement can be attributed to such perturbations as the end plate gap, end plate rings, coupling holes and loops, and to a lesser extent, non-parallelism of the end plates and non-uniformity of the cavity diameter. Some modes are stronger than others, and some are not detected at all. Some of the modes are detected in spots but not throughout their entire length in the operating rectangle. In the neighborhood of crossing modes the responses sometimes behave erratically, due to interaction of the two modes. In the region of a mode crossing, if one mode appears more strongly than another, the weaker one is usually lost in the response of the stronger. Figure VA-2 shows an example of this phenomenon where the TM_{215} mode crosses the operating mode. There is a 40 db response level difference between the two modes, so that the TM_{215} is completely lost when it is within 10 or 15 mcs of the peak of the main mode response. As two responses merge, the weaker one first becomes a small peak on the

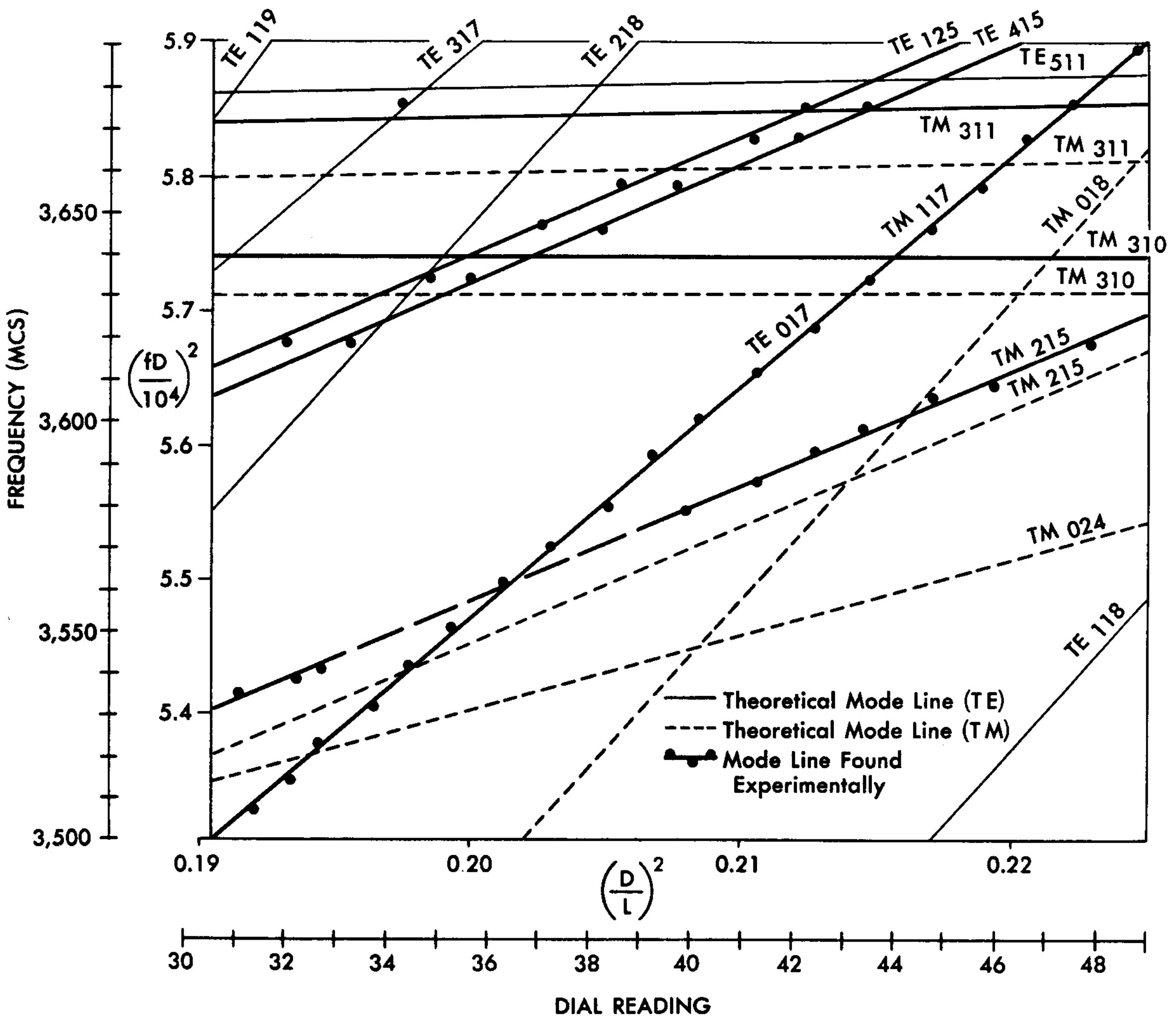

FIG. V A-2 SAMPLE MODE CHART OPERATING RECTANGLE SHOWING RESULTS OF MODE SEARCH larger response curve, then merely a ledge or flattened portion on the larger response, and finally is lost completely.

$TM_{\ell m0}$ modes, such as the TM_{310} mode shown in the figure, present a special problem. These modes are almost never detected by the above procedure since their resonant frequency is not affected by tuning the echo box. If the correct frequency is selected, the $TM_{\ell m0}$ mode will appear and produce a response which does not alter with dial setting (except possibly in the region of crossing modes). Modes with zero slope must be investigated by searching the operating rectangle in a vertical direction, i.e., by altering the frequency of the input signal instead of the dial setting. The vertical search is more difficult to make than the horizontal search, since the frequency of the signal generator has to be altered gradually, without the instrument going out of oscillation at any time. Simultaneously, the spectrum analyzer has to be kept tuned with the signal generator. During this time the experimenter must also look for extraneous echo box responses. These three operations can be done simultaneously by having the attenuation in input No. 1 of the spectrum analyzer adjusted so that the response from the signal generator is barely visible, enabling the experimenter to keep the spectrum analyzer in tune with the signal generator. When a response is obtained from the echo box, it will be superimposed on the response directly from the signal generator. By following this procedure, modes such as the TM_{310} and the TM_{311}, whose slope is nearly zero, will be detected. Because of the difficulty in searching the operating rectangle vertically, such searching is recommended only in the region where horizontal or nearly horizontal modes are expected.

If many modes are present in a region, or if a response is, for some reason, of particular interest, it will be desirable to stay on one mode line, following it along, taking small increments of frequency, say 1 to 4 mcs at a time, instead of sweeping the entire operating rectangle in steps of about 10 mcs.

In regions where two modes cross, the Q of one of the modes may be considerably lowered; i.e., its resonance curve may be broadened. This phenomenon can easily lead to mistaken identity of extraneous responses. An example will show how this mistake is possible. In Figure VA-2 the

TM_{311} mode crosses the TE_{317} mode. In this region the TM_{311} is resonant at about 3672 mcs. Suppose that a horizontal search across the operating rectangle is made at 3677 mcs. At this distance from r sonance, the TM_{311} mode is not ordinarily detected. At the crossover point, however, the interaction of the TM_{311} with the TE_{317} mode broadens the response curve of the former mode so that it gives a small though detectable response even 5 mcs from the peak of the resonance curve. In tuning past the region of crossover, a response is obtained which looks exactly like the response obtained from tuning across an extraneous mode. It will appear, then, that the TE_{317} mode has been detected whereas it is actually the TM_{311} mode which caused the response. The identity of the mode can be verified as follows: With the echo box tuned to the apparent TE_{317} response, the oscillator frequency is varied slightly. The response will be found to increase as the frequency is decreased slightly, with the peak falling on the experimentally found TM_{311} mode line.

When a response is obtained, its relative intensity and Q may be calculated. To find the intensity of an extraneous response relative to the main mode, the echo box is tuned to the main mode and the attenuation at the signal generator is increased until the response on the spectrum analyzer indicator is reduced to that of the extraneous response. If the signal generator has a calibrated attenuator in the output circuit, it can readily be determined how many decibels down the extraneous response is from the main mode response. In a good echo box design this reduction will be of the order of 40 db for the strongest extraneous responses. The Q of the response may be found by detuning the echo box until the response drops to .707 of its maximum value (the half power point). The Q is given by

$$Q = \frac{f_0}{f_2 - f_1} = \frac{f_0 D}{\frac{f_2 D}{10^4} - \frac{f_1 D}{10^4}}$$

where f_0 = frequency at peak of resonance curve

f_2, f_1 = frequency at upper and lower 0.707 amplitude points respectively

$\frac{fD}{10^4}$ = the square root of the mode chart ordinate

VA. 3 Ringing Time vs. Frequency

The ringing time test usually is the most difficult and time consuming one. In this test, the object is to determine the ringing time and meter reading as a function of frequency throughout the tuning band, find the echo box sensitivity, and in addition, discover extraneous ringing and meter readings. In brief, the test is carried out by measuring the ringing time, measuring the radar performance, and correcting the ringing time to some arbitrarily chosen standard performance. The echo box is then tuned across the band to search for extraneous ringing and meter readings.

Because of its relative difficulty and the large amount of equipment involved, various suggestions have been made for avoiding this test and substituting more easily performed tests. However, this test is the most important one from the standpoint of determining the ultimate usefulness of the echo box, and no substitute has yet been found.

The most satisfactory test setup consists of a radar tunable over the band covered by the echo box, together with adequate equipment for determining the over-all performance of the radar at each frequency to which it will be tuned. Auxiliary equipment may consist of a signal generator-power meter combination, a signal generator plus a separate power meter, and if available, a second echo box whose characteristics are known accurately throughout the band. In addition, a vacuum-tube voltmeter capable of measuring signal voltage at the radar second detector and an oscilloscope or synchroscope (such as the DuMont 256-D or E) capable of measuring ringing time accurately and furnishing a trigger to the radar will be required. If a tunable radar covering the band is not available, other expedients may have to be employed.

In the absence of a tunable radar a pulsed signal generator can be substituted for the radar transmitter. The signal generator output may be fed into the echo box input, while the radar receiver is connected to the echo box output. Thus, ringing is accomplished "through" the box, in a fashion similar to the way in which the mode search is made. This arrangement is more satisfactory than connecting the echo box input to a tee connector located in a cable leading directly from the pulsed signal generator to the receiver mixer. The second method eliminates the necessity for two connections to the echo box, but is likely to give poorer results because of its much greater sensitivity to the effects of impedance mismatches at the echo box, radar mixer, and signal generator. If sufficient power is available, attenuation may be introduced into all lines to minimize these effects. However, most available signal generators do not have sufficient power output to permit attenuation to be introduced without losing too much ringing time.

The pulsed signal generator method of checking ringing time is not a desirable alternative to using a radar. Despite its greater simplicity and ease of operation, this method is undesirable because the power level difference existing at the echo box is likely to be different from that occurring during normal operation of the echo box, which precludes the possibility of correctly adjusting the input and output couplings. At best this method will provide data to determine whether the ringing time varies erratically with tuning. Usually the ringing time will be very short unless the length of the pulse from the signal generator is much greater than the usual radar pulse length. It is not possible to connect the echo box meter when using the "ring-through" method, and when using the second, or tee method, the meter reading will, in all probability be zero. Therefore, questions regarding meter readings and spurious meter indications will remain unanswered.

The pulsed signal generator test is more sensitive to spurious ringing than the radar test. The reason for the increase in sensitivity is that no TR is included in the circuit, and ringing can be seen to the end of the signal generator pulse, since the loss of sensitivity during TR recovery is eliminated.

In order to correct the ringing time readings to be standard performance, it is necessary to know the echo box sensitivity. From the ringing time equation [Equation (2a), Sec. III-D], it is seen that the sensitivity, in decibels/microsecond, is the reciprocal of d_L, the decrement. The sensitivity is somewhat frequency dependent and therefore should be measured near the echo box mid-band frequency for a most representative value. It may be desirable to measure the sensitivity at several frequencies, particularly if the variation of decrement with frequency is large.

The method of determining the sensitivity (Sec. IIA. 5) consists of measuring the ringing time twice, one of the measurements being made with a known amount of attenuation in the cable leading to the echo box. The echo box sensitivity is the difference in the ringing times divided by twice the amount of attenuation. Certain cautions must be observed when making this test. Attenuator pads must be well matched and accurately calibrated. Even the best coaxial pads change attenuation as the frequency is changed. They are physically delicate, and the coaxial connectors tend to break or wear out with use. It is advisable, therefore, to calibrate them before use if the necessary equipment is available. A good standard for comparison in a substitution-type calibration is a waveguide-below-cutoff attenuator such as is incorporated in a spectrum analyzer of good design (Ref. 2).

In performing the sensitivity measurement, pads of various values should be used. The ringing time should be read at least 5 times for each measurement, and the readings averaged. Throughout the test, a check should be made on the constancy of radar performance, by making measurements of the ringing time without attenuation, before and after the ringing time has been measured with the attenuator in the line. If the radar performance is not constant, the difficulty should be found and corrected before continuing.

The sensitivity may also be measured using the pulsed signal generator setup mentioned previously, provided enough power output is available so that two readings of ringing time can be obtained, corresponding to two settings of the signal generator attenuator. The sensitivity will then be the difference in ringing times divided by the difference between the two signal generator attenuator settings. In this case, the energy passes but once through the attenuator, and the factor two is deleted.

[redacted]

Whatever method is used, it is advisable to make several measurements so that a plot of ringing time versus attenuation can be made. If these are all made at the same frequency, it should be possible to fit a straight line to the resulting series of points.

After obtaining the sensitivity of the echo box, it is possible to proceed to the ringing time measurements proper. The radar performance must be measured immediately before the ringing time measurement is made, and for a safeguard it should be measured immediately afterward as well.

Figure VA-3 shows one possible experimental setup for performing the test. A typical test is made as follows: First the radar is tuned to the desired frequency. Before any measurements are made, the spectrum analyzer (or echo box) is used to examine the radar spectrum. The spectrum should be of satisfactory quality for good results. The quantities to be measured are:

1. transmitter output power,
2. receiver sensitivity,
3. ringing time of auxiliary echo box (if available),
4. ringing time of test echo box,
5. meter reading of test echo box,
6. radar frequency.

While the order in which the measurements are to be made is flexible, the order listed is entirely satisfactory.

To measure the transmitter power, the power meter is coupled to the radar through the directional coupler. In general, additional attenuation between the radar and bridge is required to reduce the power level to a value that can be measured with the bridge. Average output power, expressed in dbm, is the bridge reading in dbm plus the attenuation of pads and cable, plus the directional coupler loss. Since the bridge reads average power, the duty cycle of the radar has to be taken into consideration if

[redacted]

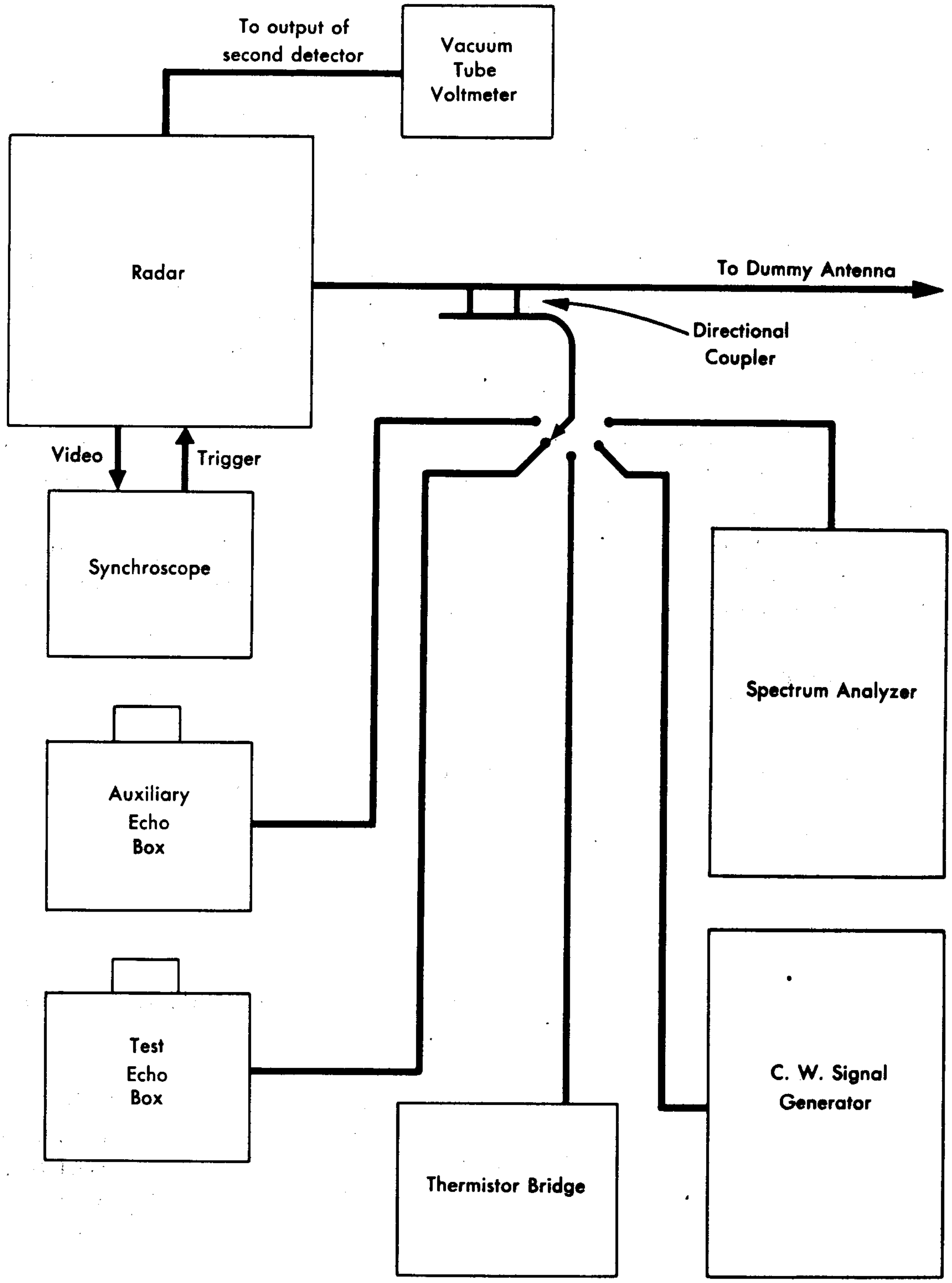

FIG. V A-3 LABORATORY SETUP FOR OBTAINING RINGING TIME CHARACTERISTICS the peak power output is to be recorded. It is not important, however, whether peak or average power is used, since the two differ only by a constant, provided the pulse width and repetition frequency remain constant. Measuring the receiver sensitivity is somewhat more involved. A CW signal at the radar frequency is fed into the directional coupler and measured by a vacuum tube voltmeter connected to the output of the second detector. The meter must be zeroed with the gain of the receiver at zero so that the zero-signal voltage of the detector is eliminated from the readings. In addition, a resistor of the order of 0.1 megohm must be placed in series with the meter lead at the second detector to prevent oscillations when the meter is in the receiver circuit. The measurement is made by increasing the receiver gain until the noise voltage measured by the meter is 0.7 volt. The signal generator output is then increased until the meter reading is one volt. When this has been done, the signal injected into the receiver is equal to the noise signal. The noise signal, although developed within the receiver, can be treated as a signal injected into the receiver. The receiver sensitivity can be defined as the magnitude of signal which, when injected into the radar receiver, is equal to the noise signal actually present in the receiver. It is advisable to measure the signal generator output externally rather than to trust the internal calibration. The amount of power injected into the radar for the condition of signal = noise is too small to give an indication on a thermistor bridge. The signal generator output must therefore be attenuated by a known amount before it is injected into the receiver, and the unattenuated power level measured on the bridge.

In case the radar proves to have low sensitivity, it should be "peaked up" before proceeding further.

The box under test is then connected and the ringing time measured, at least five readings being taken and averaged, and the output meter reading recorded. The ringing time of the auxiliary echo box is read, and the frequency measured either by an auxiliary wavemeter or one of the echo boxes.

The radar performance should be measured again to make sure nothing has changed, and finally the box under test is tuned slowly through its entire tuning range in a search for extraneous ringing and meter readings.

The foregoing series of measurements should be performed on each run as rapidly as possible, since the radar performance is continually changing and the radar frequency is subject to drift.

Measurements should be made at a sufficient number of different frequencies to provide adequate coverage over the tuning range of the echo box, and additional measurements should be made where there are crossing modes or where previous measurements indicate unexplained fluctuations in ringing time.

When the measurements are completed, the ringing time and resonance indicator meter readings are corrected to standard performances. Some convenient value, fairly near to the median performance level obtained in the experiment, is selected arbitrarily as the standard performance, and ringing time values are corrected to this level. This is done by multiplying the echo box sensitivity in yards per decibel by the difference between the standard performance level and the actual performance obtained for that run and adding or subtracting the resulting number of yards to the ringing time of the box.

In correcting the echo box resonance indicator reading to standard performance, it must be remembered it is the transmitter power only, rather than the radar performance, which affects this meter. Corrections on the observed meter readings, therefore, are made only for variations in transmitter output power. To make the correction, the manner in which the echo box meter reading varies with the input power to the echo box must be understood. The relation is a complicated one, since the crystal characteristic is non-linear, and the power level in the echo box as a function of time varies exponentially. If variation of input power is small (up to 20 per cent) the correction can be made by assuming the meter deflection to be proportional to the input power.

The corrected ringing time and meter readings can now be plotted as a function of frequency. In addition, the ratio of ringing time of the experimental box to the auxiliary box should be plotted as a function of frequency. This procedure aids in uncovering irregularities in the measurements. For example, if the corrected ringing time differs markedly from the measured ringing time due to a large correction for radar performance, but the ringing time of the two boxes and the ratio of ringing times are not much different from the usual values, the indication is that the performance measurement is in error.

The plotted points fall in a band across the tuning range. In general, two measurements made at the same frequency may differ from each other by 10 per cent or more. The reason for this difference is that there is experimental error in making the measurements. For example, ringing time measurements cannot, by their nature, be made precisely. Experimental error may be fairly large in the performance measurements, and of course, the performance can change while it is being measured or between the performance measurement and the ringing time measurements. A number of points should be plotted and a smooth curve drawn through the center of the distribution.

In the regions of crossing modes the ringing time may drop markedly. This phenomenon is called a "hole". The ringing time should be investigated thoroughly in this region. If holes are found or are anticipated at some region in the echo box tuning range, it will prove time-saving to investigate these regions by taking the ratio of ringing time of the echo box under test to that of the auxiliary echo box. Over the relatively small tuning range involved, the ringing time of the auxiliary box may be considered constant; hence, the ratio of ringing time for the two boxes is a measure of the corrected ringing time for the box under test. By simplifying the procedure in this way, a curve of ringing time vs. frequency with numerous points can be obtained in a short time and the behavior of the box in the region of the anomaly can be investigated in detail.

It is also useful to investigate the effect of tilting the end plate on ringing time. By so doing, an idea of the necessary tolerances on end plate alignment will be obtained, information which is needed in the production of the echo box. The test should be performed with the rubber gasket between the end plate and the cylinder removed (Sec. IVE).

VA.4 Adjustment of Coupling

Coupling loop or hole sizes must be adjusted empirically, preferably under conditions identical to those the box will meet in the field. A prototype box is generally constructed with the input and output couplings deliberately left somewhat smaller than is believed to be necessary, until ringing time measurements and meter readings are made. The first results should indicate that the coupling is, in fact, too loose. A slight increase in input coupling is then made, and the ringing time measured again on the same radar. Results should be corrected for radar performance as before, especially if considerable time elapses between tests. The input coupling should be adjusted first and the coupling hole or loop size should be plotted versus ringing time. Frequently it is desirable to continue the process slightly beyond the point of optimum coupling in order to determine this point. The meter coupling can then be adjusted until the meter reading is about half scale.

In case the radar used for the test differs from that for which the box is designed such that the level difference at the echo box is not the same, the input coupling should not be adjusted for maximum ringing time, but instead made slightly greater or slightly less than this value. Figure IIID-3 in Section IIID shows the variation in optimum coupling as F, the level difference, is varied. It can be seen from this figure that the greater the level difference, the looser is the coupling which gives maximum ringing time. Therefore, if the radar for which the box is to be used has a greater level difference than the one used for testing, the input coupling should be left slightly looser than that resulting in maximum ringing time on the test radar, and vice versa. It should be borne in mind that these differences in optimum coupling are rather small, and that too loose a coupling has a much more drastic effect on ringing time than too tight coupling.

VB PRODUCTION TESTING

It is necessary to make routine tests on newly manufactured echo boxes in order to keep the quality of the product up to specifications and to detect anomalies which may have crept into the product. It can be expected that more trouble will occur near the beginning of a production run from the measured ringing time due to a large correction for radar performance, but the ringing time of the two boxes and the ratio of ringing times are not much different from the usual values, the indication is that the performance measurement is in error.

The plotted points fall in a band across the tuning range. In general, two measurements made at the same frequency may differ from each other by 10 per cent or more. The reason for this difference is that there is experimental error in making the measurements. For example, ringing time measurements cannot, by their nature, be made precisely. Experimental error may be fairly large in the performance measurements, and of course, the performance can change while it is being measured or between the performance measurement and the ringing time measurements. A number of points should be plotted and a smooth curve drawn through the center of the distribution.

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VB PRODUCTION TESTING

It is necessary to make routine tests on newly manufactured echo boxes in order to keep the quality of the product up to specifications and to detect anomalies which may have crept into the product. It can be expected that more trouble will occur near the beginning of a production run than later, so a closer check should be made at this time. The diameters should be measured to ensure that the boring equipment has been properly set, and checks made on the perpendicularity of the end plates with the side walls.

Routine visual inspection of the interior surfaces of each box is made after the second machining operation in order to detect blow holes and sand holes in the castings, and a similar inspection is made just prior to silver plating.

Upon completion each echo box is checked for ringing time on a radar, usually at only one frequency. The ringing time is compared with that measured using the previously established "standard" box, and the percentage difference is then stamped on the meter housing. Boxes ringing longer than the standard are marked with a plus (+) sign; boxes ringing less, with a minus (-) sign.

In some echo boxes, such as the TS-545, a "standardization loop" is used to equalize the ringing of all boxes to that of the standard. In such cases this loop with its associated resistor is inserted at the time of the ringing check, and its coupling adjusted until the ringing time is decreased to that of the standard. It is, of course, necessary that the box under test be capable of ringing longer than the standard box; therefore, the ringing time of the standard should be sufficiently low for the majority of production boxes to be adjusted downward to it.

Echo boxes with abnormally low ringing time must be corrected. The most common cause of low ringing time is defective or insufficient silver plate, and the next most common cause is misalignment of the cavity end plates. In the case of coaxial or partial-coaxial cavities, a common cause is poor electrical contact at the spring fingers. Lack of perfect alignment of the end plates causes a great amount of trouble in some types of echo boxes. At X-band the tolerances are very small and a box with an end plate which is very slightly tilted, or not parallel to the opposite end plate, may show a considerable reduction in ringing time. These distortions are also likely to cause trouble by coupling to undesired modes. Extraneous modes, if they exist within the operating rectangle (and they usually do), can also be excited by any other lack of symmetry in the box, such as a movable end plate (tuning plunger) that is off center, or not concentric with the cavity axis. A detailed search for extraneous ringing or extraneous meter readings is ordinarily not performed on each box produced, and so the only check on the quality of the cylinder is made by adhering to close mechanical tolerances in manufacture and assembly.

On models in which rejections tend to be high, a pre-assembly ringing test will prove saving in time and money. In this test the cavity is tested for proper ringing before the tuning mechanism is assembled, tuning being accomplished by tapping the plunger gently with a mallet.

Meters should be checked electrically before installation. An occasional meter is found whose resistance differs from the usual value, and its performance, if installed, will not be the same as the normal meter.

Occasionally, difficulty has been encountered due to change in the electrical characteristics of crystal rectifiers. A crystal holder design suitable for a particular crystal may not produce enough meter indication when used with the same type of crystal obtained from the same manufacturer, but from a later production run. Since the use of crystals as rectifiers in echo box meter circuits is subsidiary to their prime function, which is to serve as mixers in radar receivers, presumably the changes which occur in crystal performance are in the interests of better performance as radar mixers. If the change in characteristics seriously alters the meter readings, the only recourse is to redesign the crystal mount so that it is suitable for use with the newer crystal. During the ringing check which each box receives, it is therefore desirable to record the meter reading also, so that such effects can be discovered, as well as defects in the tuning indicator circuit of particular boxes.

Some echo boxes are equipped with a motor driven plunger. The motor imparts to the plunger a reciprocating motion, so that the echo box is continually tuned across a small band. On such boxes, after assembly and calibration, the motors should be run for a time, during which the lubrication is checked and any tendency to overheat is discovered.

A test for backlash in the tuning mechanism is made on each box manufactured. This test is performed while the box is connected to a radar by approaching resonance first in one direction, then in the other. The dial readings corresponding to the same meter reading in each case are recorded, and the difference between them is a measure of the amount of backlash. The sensitivity of this test is increased enormously if, instead of tuning to the peak of the resonance curve, as indicated by maximum meter reading, a point on one side or the other is chosen; for example, one of the points where the meter reads two-thirds of its maximum value. This procedure avoids using the relatively flat top of the resonance curve whose exact frequency is somewhat indeterminate. For best results the test should be performed rapidly to minimize effects of radar frequency drift and power output variation.

CHAPTER VI

SPECIAL ECHO BOXES

VI A UNTUNED ECHO BOXES

The concept of an untuned ringing cavity is an attractive one. Eliminating the tuning control simplifies an already simple device, removes a possibility for incorrect adjustment, and makes it unnecessary to locate the box within reach of the radar maintenance man. The only adjustment needed is a means for switching energy into the cavity when required, and this means can be as simple as pointing the radar antenna in the direction of a pickup dipole connected permanently to the cavity. Although some of the disadvantages of such a device are very serious, for some applications the untuned echo box is entirely satisfactory.

A cavity which has a very large number of modes located very close together will be essentially "in tune" no matter what the excitation frequency is. This is the principle of the untuned cavity. It was stated in Section IIA. 5 that any cavity is capable of resonating at an infinite number of frequencies. This statement, while true for any cavity resonator, contains no information about the number of resonances to be expected within a finite frequency band. The corollary statement which is important here is that the resonances are closer together as the frequency increases, i. e., as the cavity dimensions become large compared to the exciting wavelength. Therefore, one way of making an untuned echo box is to make a very large one. This approach also results in a high Q, since Q increases with volume.[1]

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[1]The increase in ringing time with volume can be seen from the limiting case, the earth. In 1893, J. J. Thomson (Lord Kelvin), calculated that electromagnetic energy in a hollow copper sphere the size of the earth would decrease to 37 per cent of its initial value in about five million years (Ref. 10).

A more sophisticated approach is to choose a configuration which results in the required distribution of modes in the smallest possible volume. It may be possible to find a cavity shape which will support a large number of non-degenerate modes, and then to determine a cavity size which will allow a sufficient number of these modes to exist within the frequency band of interest. Since any symmetry about an axis allows the oscillations which occur in directions perpendicular to that axis to reduce to the same frequency, or to become degenerate, it is apparent that a resonator shape having little or no symmetry is desirable (Ref. 18). A rectangular prism is such a shape. The resonance of such a box is

$$f_r = \frac{c}{2}\sqrt{\left(\frac{\ell}{A}\right)^2 + \left(\frac{m}{B}\right)^2 + \left(\frac{n}{C}\right)^2}$$

where A, B and C are the cavity dimensions, and ℓ, m, and n define the mode. It turns out that if the dimensions A, B and C are incommensurate (i. e., no common factors) when examined in pairs, and in addition, differ from each other by approximately a quarter wavelength in the frequency band of interest, concentration of modes will occur in the desired frequency range. If the desired band width is narrow, a greater concentration of modes may be achieved by reducing the differences in the dimensions.

The number of modes can be increased still further by cutting off the corners of the parallelepiped and replacing the cut sections by triangular corner plates. The best results are obtained if opposite corner plates are parallel and if the cuts are made so that no two sides of any of the resulting triangles are equal, and in addition, no two of the eight resulting corner plates are identical. The input coupling means should be asymmetrically located and oriented. No output coupling device or resonance indicator is ordinarily employed.

As was mentioned above, the untuned cavity has serious drawbacks. One of these makes it unwise to attempt to tune a radar by reference to the ringing time from this type of cavity. Since many modes may be simultaneously excited within the frequency spectrum of the radar transmitter, the echo box will return echoes at all these frequencies after the transmitter has turned off. If all these modes had the same Q, there would be no trouble; but the range of Q among the different modes will probably be very large, with the result that some modes will ring much longer than others. The operator, in adjusting the radar local oscillator and TR cavity to maximize the ringing time, will automatically tune the radar receiver to give the best response at the frequency of that energized mode which has the longest ringing time, even though this frequency may be considerably removed from the peak of the magnetron spectrum. The result of such a procedure is, of course, that the radar is mistuned. In addition, two or more modes may lie so close together in frequency that very low-frequency beats can be observed between them (perhaps caused by mixing action in the crystal) and the ringing pattern on the scope will flutter. Other and more obvious disadvantages are that other measurements, such as frequency or spectrum, are not possible with the untuned cavity. Therefore, the untuned cavity is of dubious value as a radar test instrument, not to be compared with the tuned cavity.

VI B IF ECHO BOXES

The possibility of producing an "echo box" to operate at the intermediate frequency of the radar receiver is an intriguing one. It is understood by the authors that such a device was used by the Germans in the second World War. The advantages of an IF echo box are: 1) since nearly all radar IF frequencies are at 30 mcs or 60 mcs, only a few echo box designs would be required; 2) [redacted] the echo box would never require tuning; 3) since the necessary Q values at these low frequencies are only of the order of several hundred, the "box" might be made using lumped-circuit techniques, which would result in small size and weight and be very much less expensive than conventional cavities.

One method of using an IF echo box is illustrated in Figure VI-1. In this scheme the radar must be provided with the equivalent of an RF switch plus a dummy antenna, and two directional couplers connected in opposite directions, one on either side of the RF switch. The IF echo box is coupled into the system at a point beyond the crystal mixer, where it can be energized by pulses at IF frequency generated by the action of the mixer. In order to make a ringing time reading the radar transmitter is disconnected from the antenna and connected to the dummy load by means of the switch, and the IF echo box connected to the system. The two directional couplers serve to inject a small portion of the transmitted pulse into the antenna line in the proper direction to enter the receiving circuit. Ringing time is read on the radar scope as usual.

A much simpler scheme omits the RF switch and the two directional couplers, and utilizes the energy leaking through the TR cavity during the transmitted pulse in normal radar operation to energize the echo box. The disadvantage of this method is that no check on the tuning of the TR cavity can be made.

VI C ECHO LINES

In the case of radars operating in the frequency range above 16,000 mcs, the design and construction of echo boxes of the conventional type becomes difficult, and satisfactory boxes have not yet been produced for this frequency region. A device known as an echo line has been suggested as a substitute, and experimental models have actually been constructed and tested (Ref. 19). The principle of the echo line is illustrated by reference to Figure VI-2. The echo line consists simply of a low-loss transmission line connected to the radar system via an RF switch and a directional coupler. The line must have an electrical length greater than one-half the radar pulse length, so that the round trip time will be greater than one pulse length. It is terminated at the far end by a short-circuit and a mismatch is provided at the input end to reflect the pulse.

In use, a fraction of the radar pulse enters the echo line by way of the directional coupler and switch. Much of this energy is reflected back toward the radar by the reactance, but some will get past the reactance and into the line. This pulse travels to the short-circuit and is reflected back toward the input end. At the reactance a large portion of the pulse is reflected back again toward the far end of the line, but a small portion will get past the reactance and show up as a pulse on the radar scope. This process continues to repeat itself, each round trip producing a pulse on the radar scope, and each pulse being weaker than the last because of the loss of energy in and from the line. Finally, the pulses become so weak that the radar receiver cannot see them. By counting the number of visible pulses and estimating or measuring the strength of the last pulse, the operator can obtain a measure of radar performance.

[redacted]

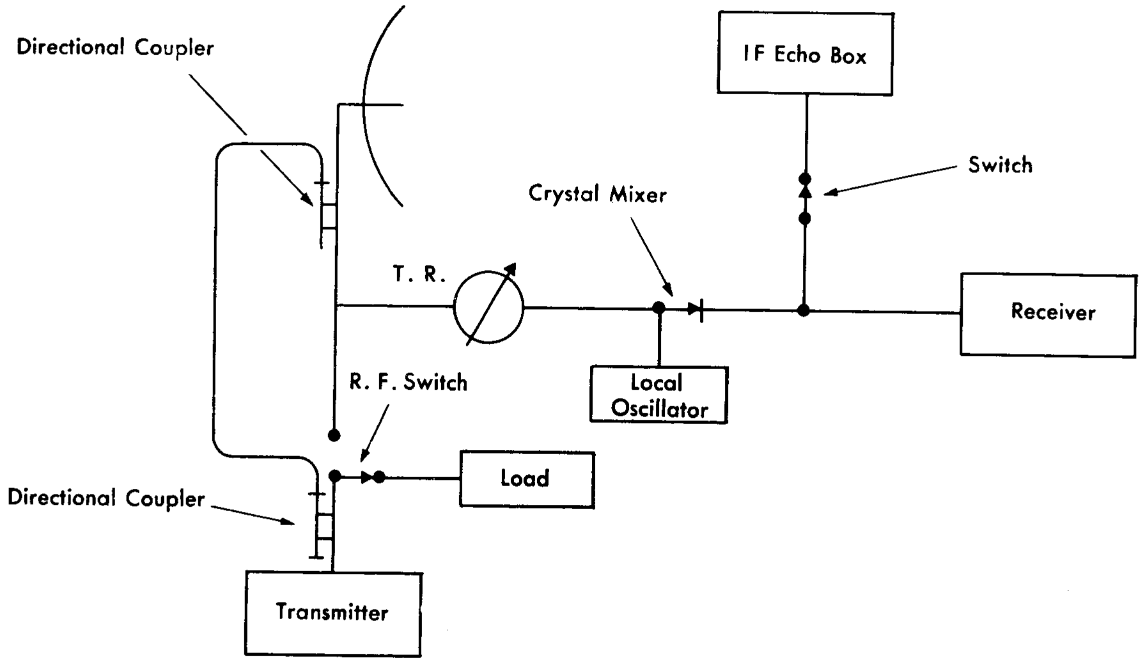


FIG. VI-1 SCHEMATIC OF RADAR WITH IF ECHO BOX

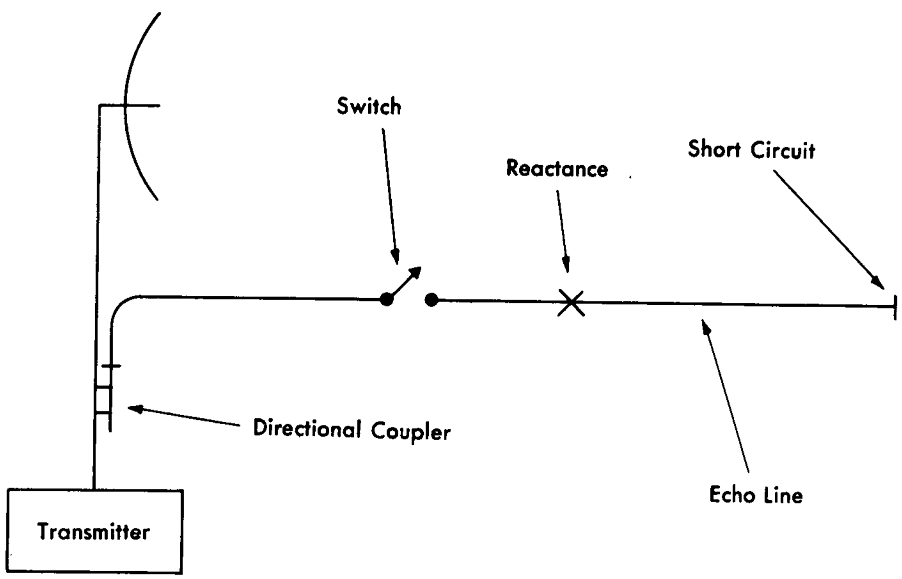


FIG. VI-2 SCHEMATIC OF RADAR WITH ECHO LINE

[redacted]

It is very difficult to construct a satisfactory echo line of small bulk and low attenuation using present materials and techniques, and for this reason the echo line at the present time appears to be practical only for short pulse lengths and high frequencies.

APPENDIX I

CAVITY PERTURBATION[1]

The modes of oscillation of the electromagnetic field in a cavity are dependent upon the geometry of the cavity, so that a perturbation, i.e., a small distortion of the cavity's shape, will result in a modification of both the spatial distributions and the frequencies of the modes.

The frequencies and spatial distributions for the new modes will be estimated separately, dependent upon the presence or absence of degeneracies. A system of modes is said to be degenerate if two or more modes have the same frequency of oscillation.

AI. 1 Non-Degenerate Modes

The frequency to which the *nth* mode transforms, as the result of a perturbation, can be obtained from the relation

$$f^2 \simeq f_n^2 \frac{\int_v \bar{E}_n \cdot \bar{E}_n \, dv}{\int_v \bar{H}_n \cdot \bar{H}_n \, dv} \qquad \text{(AI-1)}$$

where

f_n = unperturbed frequency,

f = perturbed frequency,

v = volume of the perturbed cavity,

[1]The material in this appendix is based on References 23, 24, 25, and 26.

$\bar{E}_n$ = electric mode vector for the n *th* mode[1], and

$\bar{H}_n$ = magnetic mode vector of the n *th* mode.

Equation AI-1 can be written in two forms, dependent upon whether the perturbed volume is greater or less than the unperturbed volume, as

$$\text{a)}\quad f^2 \simeq f_n^2 \, \frac{1 + \int_{v_A} \bar{E}_n \cdot \bar{E}_n \, dv}{1 + \int_{v_A} \bar{H}_n \cdot \bar{H}_n \, dv}$$

$$\text{b)}\quad f^2 \simeq f_n^2 \, \frac{1 - \int_{v_S} \bar{E}_n \cdot \bar{E}_n \, dv}{1 - \int_{v_S} \bar{H}_n \cdot \bar{H}_n \, dv} \qquad n = 1, 2, 3 \ldots\ldots \quad \text{(AI-2)}$$

---

[1]The mode vectors are defined by the following relations

$$\nabla \times \bar{H}_i = k_i \bar{E}_i \quad \text{and} \quad \nabla \times \bar{E}_i = k_i \bar{H}_i \text{ within the cavity,}$$

$$\bar{H}_i \cdot \bar{n} = 0 \quad \text{and} \quad \bar{E}_i \times \bar{n} = 0 \quad \text{on the boundary;}$$

and are normalized such that

$$\int_{v_o} \bar{H}_i \cdot \bar{H}_j \, dv = \int_{v_o} \bar{E}_i \cdot \bar{E}_j \, dv = \delta_{ij}, \quad \begin{cases} \delta ij = 0 \text{ if } i \neq j \\ = 1 \text{ if } i = j \end{cases}$$

where v_o is the original unperturbed cavity volume.

Their relation to the actual field vectors $\vec{E}$ and $\vec{H}$ is

$$\vec{E} = \frac{P}{\sqrt{\epsilon}} \bar{E} \sin\left(\frac{K}{\sqrt{\mu\epsilon}} t + \phi\right), \quad \vec{H} = \frac{P}{\sqrt{\mu}} \bar{H} \cos\left(\frac{K}{\sqrt{\epsilon\mu}} t + \phi\right)$$

where P is a unit constant with dimensions of energy.

where

v_A = volume added to the cavity by the perturbation,

v_S = volume subtracted from the cavity by the perturbation.

From the integrals, it is apparent that (a) is used when volume is added to the cavity, and (b) is used when volume is subtracted from the cavity.

The $\bar{E}_n$ and $\bar{H}_n$ of the perturbed cavity may be taken to be approximately equal, except for frequency, to the $\bar{E}_n$ and $\bar{H}_n$ of the unperturbed cavity.

AI. 2 <u>Degenerate Case</u>

If the system is degenerate, or if the n'th mode is one of a group of modes whose frequencies are close together in value, the above formulas may not be used. This is because the deformation of the cavity may cause the independent modes with frequencies close together in value, or coincident, to interact or interfere with one another, and the above formulas were derived without considering such interactions.

Suppose that f_1, $f_2, \ldots f_n$ are frequencies close to one another in value, or that some or all of them are of equal value. The perturbed frequencies into which these transform are obtained from the roots of the determinant.

$$\begin{vmatrix} A_{11} & A_{21} & \ldots & A_{n1} \\ A_{12} & A_{22} & \ldots & A_{n2} \\ \ldots & \ldots & \ldots & \ldots \\ A_{1n} & A_{2n} & \ldots & A_{nn} \end{vmatrix}$$ [1]

[1]See Reference 23 for a method of evaluating determinants.

where

$$A_{11} = K^2 \int_v \bar{H}_1 \cdot \bar{H}_1 \, dv - K_1^2 \int_v \bar{E}_1 \cdot \bar{E}_1 \, dv$$

$$A_{21} = K^2 \int_v \bar{H}_2 \cdot \bar{H}_1 \, dv - K_1^2 \int_v \bar{E}_2 \cdot \bar{E}_1 \, dv$$

$$\cdot \quad = \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot$$

$$A_{ij} = K^2 \int_v \bar{H}_i \cdot \bar{H}_j \, dv - K_j^2 \int_v \bar{E}_i \cdot \bar{E}_j \, dv$$

$$\cdot \quad = \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot$$

$$A_{nn} = K^2 \int_v \bar{H}_n \cdot \bar{H}_n \, dv - K_n^2 \int_v \bar{E}_n \cdot \bar{E}_n \, dv$$

and where

v = volume of perturbed cavity,

$$f_i = \frac{K_i}{2\pi\sqrt{\epsilon \mu}},$$

$$f = \frac{K}{2\pi\sqrt{\epsilon \mu}},$$

ϵ = permittivity of the dielectric, and

μ = permeability of the dielectric.

Approximate values $\bar{E}^*$ and $\bar{H}^*$ for $\bar{E}$ and $\bar{H}$ associated with one of the perturbed frequencies, f, may be obtained by solving the following set of equations:

$$\sum_{s=1}^{n} A_{s1}\,\alpha_s = 0$$

$$\sum_{s=1}^{n} A_{s2}\,\alpha_s = 0$$

$$\cdots\cdots\cdots$$

$$\sum_{s=1}^{n} A_{sn}\,\alpha_s = 0$$

for the values of α, and then substituting into the formulas

$$\bar{E}^{*} = \sum_{s=1}^{n} \alpha_s \bar{E}_s \quad \text{and} \quad \bar{H}^{*} = \sum_{s=1}^{n} \alpha_s \bar{H}_s$$

An alternative expression for A_{ij} is

$$A_{ij} = K_i \int_{\text{Cavity Surface (Perturbed)}} \bar{n} \cdot (\bar{E}_i \times \bar{H}_j)\,da - \delta_{ij}(K_j^2 - K^2)$$

where

$\bar{n}$ = unit vector normal to the surface

$\delta_{ij} = 0$ if $i \neq j$

$= 1$ if $i = j$

If the n'th mode is one of a group of modes whose frequencies are separated by such an amount as to make it questionable which method to use, apply the method for degenerate modes.

AI 3 Examples Of Perturbation

In practice a tunable echo box is essentially a circular cylindrical resonant cavity designed to operate on a particular member of the TE_{01n} family of modes. The normalized unperturbed fields for the $TE_{\ell mn}$ and $TM_{\ell mn}$ modes for a circular cylindrical cavity will be used in the example and are given below:

$TE_{\ell mn}$

$$\bar{E}_\rho = \mp A \frac{\ell D}{2r_{\ell m}\rho} J_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\sin\\ \cos\end{matrix}\ \ell\theta \sin\frac{n\pi}{L}\ \hat{z\rho}$$

$$\bar{E}_\theta = -AJ'_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\cos\\ \sin\end{matrix}\ \ell\theta \sin\frac{n\pi}{L}\ \hat{z\theta}$$

$$\bar{E}_z = 0$$

$$\bar{H}_\rho = A\frac{n\lambda}{2L} J'_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\cos\\ \sin\end{matrix}\ \ell\theta \cos\frac{n\pi}{L}\ \hat{z\rho}$$

$$\bar{H}_\theta = \mp A\frac{n\lambda\ell D}{2L\rho} \frac{J_\ell\left(\frac{2r_{\ell m}}{D}\rho\right)}{2r_{\ell m}} \begin{matrix}\sin\\ \cos\end{matrix}\ \ell\theta \cos\frac{n\pi}{L}\ \hat{z\theta}$$

$$\bar{H}_z = A\frac{r_{\ell m}\lambda}{\pi D} J_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\cos\\ \sin\end{matrix}\ \ell\theta \sin\frac{n\pi}{L}\ \hat{zz}$$

$TM_{\ell mn}$

$$\bar{E}_\rho = B\frac{n\lambda}{2L} J'_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\cos\\ \sin\end{matrix}\ \ell\theta \sin\frac{n\pi}{L}\ \hat{z\rho}$$

[redacted]

$$\bar{E}_\theta = \mp B \frac{n\lambda\ell D}{2L\rho} \frac{J_\ell\left(\frac{2r_{\ell m}}{D}\rho\right)}{2r_{\ell m}} \begin{matrix}\sin\\ \cos\end{matrix} \ell\theta \sin\frac{n\pi}{L} z \hat{\theta}$$

$$\bar{E}_z = - B \frac{r_{\ell m}\lambda}{\pi D} J_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\cos\\ \sin\end{matrix} \ell\theta \cos\frac{n\pi}{L} z \hat{z}$$

$$\bar{H}_\rho = \pm B \frac{\ell D}{2r_{\ell m}\rho} J_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\sin\\ \cos\end{matrix} \ell\theta \cos\frac{n\pi}{L} z \hat{\rho}$$

$$\bar{H}_\theta = B J'_\ell\left(\frac{2r_{\ell m}}{D}\rho\right) \begin{matrix}\cos\\ \sin\end{matrix} \ell\theta \cos\frac{n\pi}{L} z \hat{\theta}$$

$$\bar{H}_z = 0$$

where the upper sign and the upper trigonometric form go together and where the frequencies and the modes of oscillation are related by

$$\frac{4\pi^2}{\lambda^2} = \left(\frac{2r_{\ell m}}{D}\right)^2 + \left(\frac{n\pi}{L}\right)^2$$

and

$A = A_{\ell mn}$, the normalizing coefficient for the $TE_{\ell mn}$ modes

$$= \pm \frac{\sqrt{2(2 - \delta_{0\ell})}}{\sqrt{v_o}\, J_\ell(r_{\ell m}) \sqrt{1 - \left(\frac{\ell}{r_{\ell m}}\right)^2}}$$

[redacted]

$B = B_{\ell mn}$, the normalizing coefficient for the $TM_{\ell mn}$ modes

$$= \pm \frac{\sqrt{(2 - \delta_{0\ell})(2 - \delta_{0n})}}{\sqrt{v_o}\, J'_{\ell}\,(r_{\ell m})}$$

$J_{\ell}(x)$ = Bessel function (Ref. 26)

$$J'_{\ell}(x) = \frac{d\, J_{\ell}\,(x)}{dx}$$

D = diameter of circular cylindrical cavity

L = height, or length of the cylindrical cavity

ℓ, m, n = integers

ρ, θ, z = cylindrical coordinates as illustrated below

$r_{\ell m}$ = the m*th* root of $J'_{\ell}(x) = 0$ for the TE modes

$r_{\ell m}$ = the m*th* root of $J_{\ell}(x) = 0$ for the TM modes

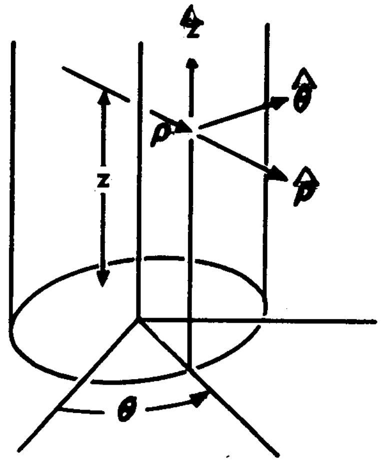
$\delta_{0\ell} = \delta_{0n} = 0$ if $\ell \neq 0$, $n \neq 0$

$\delta_{0\ell} = \delta_{0n} = 1$ if $\ell = n = 0$

λ = wavelength = $\frac{c}{f}$ where c = velocity of light

$\lambda_i = \frac{c}{f_i}$

v_o = volume of the unperturbed cavity



In the following examples the a *th* mode vectors will be taken as $\bar{E}_a = \bar{E}_\rho + \bar{E}_\theta + \bar{E}_z$ and $\bar{H}_a = \bar{H}_\rho + \bar{H}_\theta + \bar{H}_z$ where the ρ, θ, and z components are determined by the values of ℓ, m, and n for the a'th mode.

- - -

Example 1

For the non-degenerate mode TM_{010} the components of $\bar{E}$ and $\bar{H}$ are found from the general forms above merely by setting ℓ, m, n, equal to 0, 1, 0 respectively. Let λ be the wavelength corresponding to this mode. Then

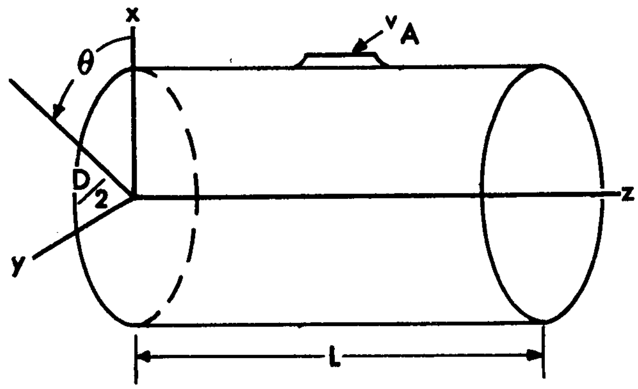
$$\bar{E}_\rho = \bar{E}_\theta = 0$$

$$\bar{E}_z = B \frac{-r_{01}\lambda_1}{\pi D} J_0\left(\frac{2r_{01}}{D}\rho\right)\hat{z}$$

$$\bar{H}_\rho = \bar{H}_z = 0$$

and

$$\bar{H}_\theta = B\, J_0'\left(\frac{2r_{01}}{D}\rho\right)\hat{\theta}$$



Suppose we wish to estimate the perturbed value of the corresponding frequency f_1, assuming it is not close to any other frequency of the cavity, due to a small increase v_A in volume at the point $\rho = \frac{D}{2}$, $\theta = 0$, $z = \frac{L}{2}$. For this case $\int_{v_A} \bar{E}_1 \cdot \bar{E}_1 \, dv \simeq 0$ so that, since v_A is small,

$$f^2 \simeq f_1^2 \left(1 - \int_{v_A} \bar{H}_1 \cdot \bar{H}_1 \, dv\right)$$

may be used. Upon substitution $f^2 = f_1^2 \left[1 - v_0 B^2 J_1^2(r_{01})\right]$ and to an equally good approximation, $f = f_1 \left[1 - 1/2 \; v_0 B^2 J_1^2(r_{01})\right]$

\- - -

<u>Example 2</u>

Determine the effect of adding a small volume v_A at the point $\left(\frac{D}{2}, 0, \frac{L}{2}\right)$ of a circular cylindrical cavity operating on the TE_{011} mode. This mode is degenerate with both the TM_{111} mode which varies as cos θ and the one which varies as sin θ. The common frequency of these modes does not coincide with or lie near any other mode, so there are no other degeneracies. Denote the common frequency by f_b and the corresponding wavelength by λ_b.

Choose the TE_{011} mode as the first mode, then the components of the first mode will be given as

$$\overline{E}_1 = -A\, J_0'\left(\frac{2r_{01}}{D}\rho\right) \sin\frac{\pi z}{L}\,\hat{\theta}$$

$$\overline{H}_1 = A\frac{\lambda_b}{2L} J_0'\left(\frac{2r_{01}}{D}\rho\right)\cos\frac{\pi z}{L}\hat{\rho} + A\,\frac{r_{01}\lambda_b}{\pi D}\, J_0\left(\frac{2r_{01}}{D}\rho\right)\sin\frac{\pi z}{L}\;\hat{z}$$

Let the even (cos θ) TM_{111} mode be designated as the second mode, with components

$$\overline{E}_2 = B\frac{\lambda_b}{2L}\; J_1'\left(\frac{2r_{11}}{D}\rho\right)\cos\theta\,\sin\frac{\pi z}{L}\hat{\rho} - \frac{B\lambda_b D}{4Lr_{11}\rho}\; J_1\left(\frac{2r_{11}}{D}\rho\right)\sin\theta\,\sin\frac{\pi z}{L}\,\hat{\theta}$$

$$- B\;\frac{r_{11}\lambda_b}{\pi D}\, J_1\left(\frac{2r_{11}}{D}\rho\right)\cos\theta\,\cos\frac{\pi z}{L}\;\hat{z}$$

and

$$\overline{H}_2 = B\,\frac{D}{2r_{11}\rho}\; J_1\left(\frac{2r_{11}}{D}\rho\right)\sin\theta\,\cos\frac{\pi z}{L}\hat{\rho} + B\, J_1'\left(\frac{2r_{11}}{D}\rho\right)\cos\theta\,\cos\frac{\pi z}{L}\,\hat{\theta}$$

and the odd (sin θ) TM mode be designated as the third mode, with components

$$\bar{E}_3 = -B\frac{\lambda_b}{2L} J_1'\left(\frac{2r_{11}}{D}\rho\right)\sin\theta \sin\frac{\pi z}{L}\hat{\rho}$$

$$-B\frac{\lambda_b D}{4Lr_{11}\rho} J_1\left(\frac{2r_{11}}{D}\rho\right)\cos\theta \sin\frac{\pi z}{L}\hat{\theta}$$

$$+ B\frac{r_{11}\lambda_b}{\pi D} J_1\left(\frac{2r_{11}}{D}\rho\right)\sin\theta \cos\frac{\pi z}{L}\hat{z}$$

and

$$\bar{H}_3 = B\frac{D}{2r_{11}\rho} J_1\left(\frac{2r_{11}}{D}\rho\right)\cos\theta \cos\frac{\pi z}{L}\hat{\rho} - B J_1'\left(\frac{2r_{11}}{D}\rho\right)\sin\theta \cos\frac{\pi z}{L}\hat{\theta}$$

Using the relations

$$-J_0'(x) = J_1(x)$$

and

$$J_1'(x) = J_0(x) - \frac{J_1(x)}{x}$$

the $\bar{E}$ and $\bar{H}$ vectors at the point $\left(\frac{D}{2}, 0, \frac{L}{2}\right)$ may be written as

$$\left.\begin{aligned} \bar{E}_1 &= 0 \\ \bar{H}_1 &= A\frac{r_{01}\lambda_b}{\pi D} J_0(r_{01})\hat{z} \end{aligned}\right\} \quad \text{for the } TE_{011} \text{ mode}$$

[redacted]

$$\left.\begin{aligned}\bar{E}_2 &= B\frac{\lambda_b}{2L} J_0 (r_{11})\hat{\rho} \\ \bar{H}_2 &= 0\end{aligned}\right\} \text{for the even } TM_{111} \text{ mode, and } \left.\begin{aligned}\bar{E}_3 &= 0 \\ \bar{H}_3 &= 0\end{aligned}\right\} \text{for the odd } TM_{111} \text{ mode}$$

Using the formula that

$$A_{ij} = (K^2 \int_{v_o} \bar{H}_i \cdot \bar{H}_j \, dv - K_j^2 \int_{v_o} \bar{E}_i \cdot \bar{E}_j \, dv)$$

$$= K^2(1 + \int_{v_A} \bar{H}_i \cdot \bar{H}_j \, dv) - K_j^2(1 + \int_{v_A} \bar{E}_i \cdot \bar{E}_j \, dv)$$

it follows that, for this case,

$$A_{11} = K^2(1 + \int_{v_A} \bar{H}_1 \cdot \bar{H}_1 \, dv) - K_b^2(1 + \int_{v_A} \bar{E}_1 \cdot \bar{E}_1 \, dv)$$

$$= K^2\left[1 + \left(\frac{Ar_{01}\lambda_b}{\pi D}\left[J_0(r_{01})\right]\right)^2 v_A\right] - K_b^2$$

$$A_{22} = K^2 - K_b^2\left(1 + B^2 \frac{\lambda_b^2}{4L^2}\left[J_0(r_{11})\right]^2 v_A\right)$$

$$A_{33} = K^2 - K_b^2 \qquad \text{and all other } A_{ij} \text{'s} = 0$$

Substituting into the determinant and setting it equal to zero yields the relation

$$A_{11} A_{22} A_{33} = 0$$

[redacted]

from which the perturbed frequencies are given approximately by

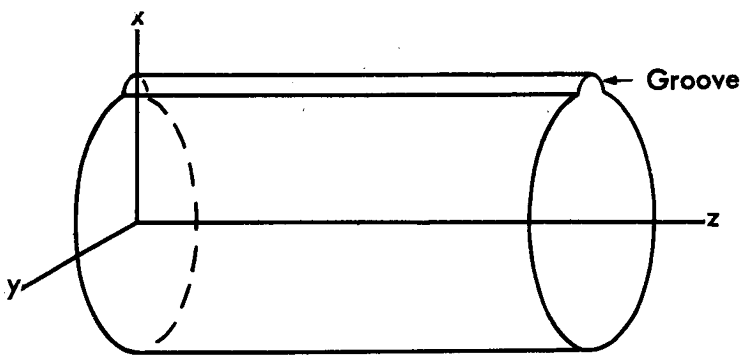
$$f_1^2 = \frac{f_b^2}{1 + \left[A \, \frac{r_{01} \lambda_b}{\pi D} \, J_0(r_{01}) \right]^2 v_A} , \qquad f_2^2 = f_b^2 \left[1 + \left(B \frac{\lambda_b}{2L} J_0(r_{11}) \right)^2 v_A \right]$$

and

$$f_3 = f_b .$$

Example 3

Determine the effect of introducing a small groove parallel to the z-axis on the side of the unperturbed cavity at $\Theta = 0$ in the previous example as shown in the figure below.



The modes are now

$$\bar{E}_1 = 0 \qquad \bar{H}_1 = A \frac{r_{01} \lambda_b}{\pi D} J_0(r_{01}) \sin \frac{\pi z}{L} \hat{z}$$

$$\bar{E}_2 = B \frac{\lambda_b}{2L} J_1' (r_{11}) \sin \frac{\pi z}{L} \hat{\rho} \qquad \bar{E}_3 = 0 .$$

$$\bar{H}_2 = B J_1' (r_{11}) \cos \frac{\pi z}{L} \hat{\Theta} \qquad \bar{H}_3 = 0$$

Proceeding as before

$$A_{11} = K^2 \left[1 + \left(A \frac{r_{01} \lambda_b}{\pi D} \left[J_1' \, (r_{01}) \right] \right)^2 \int_{v_A} \sin^2 \frac{\pi z}{L} \, dv \right] - K_b^2$$

$$A_{22} = K^2 \left[1 + B^2 \left[J_1'(r_{11}) \right]^2 \int_{v_A} \cos^2 \frac{\pi z}{L} \, dv \right]$$

$$-K_b^2 \left[1 + \left(B \frac{\lambda_b}{2L} \left[J_1'(r_{01}) \right] \right)^2 \int_{v_A} \sin^2 \frac{\pi z}{L} \, dv \right]$$

$$A_{33} = K^2 - K_b^2$$

The perturbed frequencies are determined by

$$f_1^2 = \frac{f_b^2}{1 + \left(A \frac{r_{01} \lambda_b}{\pi D} \right)^2 \left[J_1' \, (r_{01}) \right]^2 v_A}$$

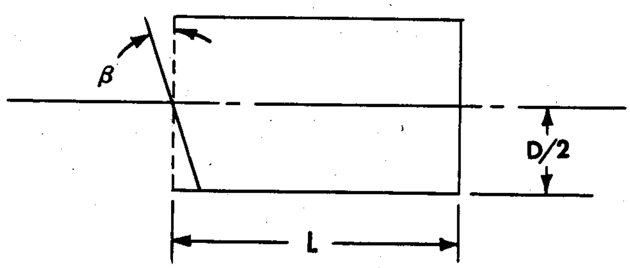
$$f_2^2 = f_b^2 \, \frac{1 + \left(B \frac{\lambda_b}{2L} \right)^2 \left[J_0 \, (r_{01}) \right]^2 v_A}{1 + B^2 \left[J_1' \, (r_{11}) \right]^2 v_A}$$

$$f_3 = f_b$$

and again the perturbed modes have essentially the same form as the unperturbed modes.

Example 4

Determine the effect of tilting an end plate of the right circular cylindrical cavity operating on the TE_{011} mode through a very small angle β about the line $\theta = 0$, as illustrated below.



Let the tilted end plate be at $z = 0$.

The A_{ij} 's are determined as in the previous example, yielding

$$A_{11} = A_{22} = A_{33} = K^2 - K_b^2$$

From the equation

$$A_{ij} = K^2 \int_v \bar{H}_i \cdot \bar{H}_j \, dv - K_j^2 \int_v \bar{E}_i \cdot \bar{E}_j \, dv$$

it follows that, since $K_i = K_j$, $A_{12} = A_{21}$, and $A_{13} = A_{31}$. By means of the alternative form for A_{ij} and, considering only the axial component of $\bar{E}_i \times \bar{H}_j$,

$$A_{12} = \frac{K_b \, AB \left(\frac{D}{2}\right)^3 \pi^2 \beta}{2 r_{11} L} \left[J_2 \, (r_{11}) \right]^2$$

To within the accuracy of this approximation

$$A_{13} = A_{31} = 0$$

$$A_{23} = A_{32} = 0$$

and

$$\begin{vmatrix} K^2 - K_b^2 & A_{12} & 0 \\ A_{12} & K^2 - K_b^2 & 0 \\ 0 & 0 & K^2 - K_b^2 \end{vmatrix} = (K^2 - K_b^2)\left[(K^2 - K_b^2)^2 - A_{12}^2\right] = 0$$

The new frequencies are

$$f_1^2 = f_b^2 + \frac{c^2 K_b AB \left(\frac{D}{2}\right)^3 \beta}{8 r_{11} L} \left[J_2 (r_{11})\right]^2$$

$$f_2^2 = f_b^2 - \frac{c^2 K_b AB \left(\frac{D}{2}\right)^3 \beta}{8 r_{11} L} \left[J_2 (r_{11})\right]^2$$

$$f_3 = f_b$$

The expressions for the new mode vectors for each frequency may be partially determined from the following simultaneous equations for a_1, a_2, and a_3:

$$A_{11} \; \alpha_1 + A_{12} \; \alpha_2 = 0$$

$$A_{33} \; \alpha_3 = 0$$

and the series representation for $\bar{E}^*$ and $\bar{H}^*$ near the beginning of this section.

APPENDIX II

EQUIVALENT CIRCUITS[1]

A circuit B is said to be equivalent to a circuit A if a differential equation for A is identical with that for B. In general, a circuit A can be equivalent to circuit B, to circuit C, and so on; the equivalence is not unique. In other words, B can be a circuit equivalent to A, but not the equivalent circuit.

In the study of a resonant cavity, it is assumed that the actual fields may be represented in terms of a set of orthogonal field vectors. These field vectors are used to determine the energy in the cavity which in turn is used to obtain the differential equation describing the current flow. An equivalent circuit may then be devised such that its current flow is described by this same differential equation.

If the equations of the equivalent circuit are to be solved by a network analyzer, an equivalent network must be devised which is physically realizable (Ref. 21). Even if a network analyzer is not used for obtaining a solution, an equivalent network can give the investigator an intuitive feeling for the significance of the various modes and design constants. On the other hand, if the differential equations for the response of the resonant cavity are to be considered only as a problem in mathematics, nothing is gained by introducing equivalent circuits.

The equivalent circuits which follow are for circular cylindrical cavity resonators with the end plates perpendicular to the axis of the cylinder. In using these circuits, one must not lose sight of the fact that while they may duplicate the response of a loss free cavity, they only approximate the response of an actual cavity. They are approximations because the resistance to the current flow is approximated, the field distortion due to the exciting loop is not considered, and the geometry of the actual cavity is not exactly that of a right circular cylinder.

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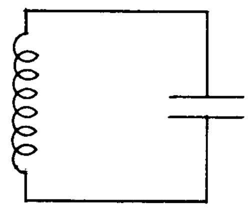
[1]The material in this appendix is based on References 20, 21, and 22.

AII. 1 Loss-Free Cavity

The equivalent circuit for a cylindrical cavity resonator is made up of a set of equivalent circuits, each one of which represents the cavity oscillating in one of its possible modes. Use of this representation implies that the equivalent circuit for the cavity varies as the number and type of modes of oscillation change.

An equivalent circuit for a loss-free cavity resonator oscillating in its a*th* normal mode may be given as in the figure, where



$$L_a = \mu_o K_a^2 V \text{ henrys}$$

$$C_a = \frac{\epsilon_o}{K_a^2 V} \text{ farads}$$

and

μ_0 = magnetic permeability } in cavity

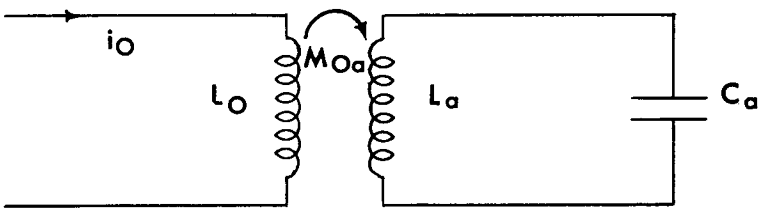
ϵ = dielectric constant } in cavity

$K_a = \frac{2\pi}{\lambda_a}$, λ_a = wavelength of a*th* mode, or wave number

V = volume of the cavity.

The equivalent circuit for a loss-free cavity, operating such that it has N normal modes, would consist of N such circuits with no coupling of any sort between these circuits.

Exciting the cavity by means of a coaxial line and loop input is equivalent to exciting the equivalent circuit as shown in next figure for the a*th* mode.



i_0 = current flowing through the input loop

M_{0a} = coefficient of mutual induction between the input and the equivalent circuit for the a*th* mode

$= \mu_0 K_a \Phi_a$ henrys

Φ_a = flux of the characteristic vector wave function through the net area of the coupling loop

$$= \sqrt{V} \int_{\text{net area of loop}} \bar{H}_a \cdot \bar{n}\, da$$

$\bar{n}$ = unit vector normal to the plane of the loop

$K_a = \frac{2\pi}{\lambda_a}$, the characteristic wave number

λ_a = wavelength of the a*th* oscillation

L_0 = total self-inductance of the input loop.

The Emf component, $(\text{Emf})_a$, arising from the effect of the external exciting current upon the a*th* mode is given by $(\text{Emf})_a = M_{0a} \frac{di_0}{dt}$

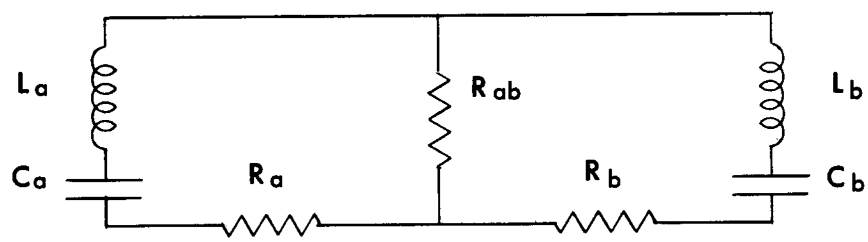
The coupling coefficient K corresponding to the normal inductance as obtained from the customary definition is

$$K = \frac{\mu_0 \Phi_a^2}{L_0 V},$$

Excitation of N modes corresponds to an equivalent circuit wherein each normal mode is inductively coupled to the input but where there is no direct coupling between the circuits representing the normal modes.

AII. 2 Dissipative Cavities

The equivalent circuits associated with the modes of a dissipative cavity are in general resistively coupled. The equivalent circuit for two modes in such a cavity may be represented as in the figure below.



For this circuit

$$R_{ab} = \frac{\sqrt{\omega_a \omega_b L_a L_b}}{Q_{ab}}$$

$$\frac{1}{Q_{ab}} = \frac{\sqrt{\delta_a \delta_b}}{2} \int_{\text{cavity surface}} \bar{H}_a \cdot \bar{H}_b \, da$$

$$\frac{1}{Q_a} = \frac{\delta_a}{2} \int_{\text{cavity surface}} \overline{H}_a \cdot \overline{H}_a \, da$$

$$\delta_a = \sqrt{\frac{2}{\sigma \mu \omega_a}}$$

$$\omega_a^2 = \frac{1}{L_a C_a} = \left(\frac{2\pi c}{\lambda_a}\right)^2$$

$$R_a = \frac{\omega_a L_a}{Q_a} \qquad R_b = \frac{\omega_b L_b}{Q_b}$$

σ = conductivity of the walls

Q_a = unloaded Q of the a*th* resonant mode

Q_{ab} = cross-coupling Q

c = velocity of light

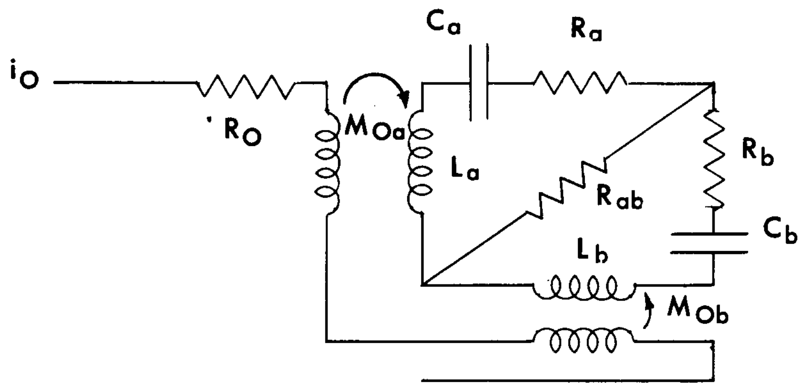
An equivalent circuit for a dissipative cavity excited by a coaxial line and loop input may be constructed such that each normal mode may be represented by a closed resonant circuit containing inductance, capacitance and resistance in series, and where the circuits for the modes are resistively coupled to all other modes of a set for which the mutual resistances are not zero, i.e., when the integral (App. I)

$$\int_{\text{cavity surface}} \overline{H}_a \cdot \overline{H}_b \, da$$

is non-zero.

The surface integral always vanishes in a cylindrical cavity between any $TE_{\ell mn}$ mode and any TM_{rst} mode unless $r = \ell \neq 0$, and $t = n$ regardless of the values for m and s. Between pairs of either TE or TM modes alone, it may be shown that the surface integral vanishes unless either $\ell = r$, $m \neq s$, and $n = t$, or $\ell = r$, $m = s$, and the difference between n and t is an even number greater than zero. That is, there is no mutual resistance between two TE or two TM modes unless both modes have the same first index and either two of the remaining indices coincide, with the provision that when $n \neq t$ their difference must be an even number.

Each mode is inductively coupled to the external exciting circuit, as shown in the figure



where the combined inductance of the input circuit is L_0 and where R_0 is the radiation resistance of the resonant cavity antenna if the resonant cavity is dipole-coupled to the source. These modes are not directly coupled inductively.

In addition to the loop and coaxial line type of excitation, a cavity may be excited by a waveguide input or by means of a probe. The associated equivalent circuits are seldom investigated.

AII. 3 Effect Of Cavity Distortion

If either the cross-section of the cavity is elliptical rather than circular, the end plates are not everywhere perpendicular to the axis of the cylinder, or the end plates are not concentric with the cylinder, there will be inductive and/or capacitive coupling between modes in addition to the resistive coupling R_{ab}[1].

Example: Development of an Equivalent Circuit

To construct an equivalent circuit for a circular cylinder cavity resonator operating on the TE_{011} mode where the cavity has the dimensions

radius = 2.78 in. = .07 meters

length = 3.93 in. = .0998 meters

and the wavelength is 10 cm, the cavity is excited by a coaxial line and loop, where the loop is located at the side of the cavity and lies in a plane perpendicular to the axis of the cylinder.

$$L_a = \frac{4\pi \times 10^{-7} \times 4\pi^2 \times \pi (0.0049)(0.0998)}{.01} = 76.2 \times 10^{-7}$$ henrys for all three modes

$$C_a = \frac{10^{-13}}{36\pi \times 16\pi^4 \times \pi (0.0049)(0.0998)} = 3.69 \times 10^{-16}$$ farads for all three modes

$$\epsilon_0 = \frac{1}{36\pi} \times 10^{-9}$$ approximately

$$\mu_0 = 4\pi \times 10^{-7}$$

Let a = 1 for the TE_{011} mode, a = 2 for the even TM_{111} mode, and a = 3 for the odd TM_{111} mode.

[1]The theoretical basis for these equivalent circuits may be found in References 21 and 22. The actual construction may be found in Reference 20. The effects of deviation from the circular cylindrical cavity with concentric and perpendicular end plates are treated in Reference 22.

Then

$$\bar{H}_1 = A \frac{\lambda_u}{2L} J_0'\left(\frac{2r_{01}}{D}\rho\right) \cos\frac{\pi z}{L} \hat{\rho} + A \frac{r_{01}\lambda_u}{\pi D} J_0\left(\frac{2r_{01}}{D}\rho\right) \sin\frac{\pi z}{L} \hat{z}$$

$$\bar{H}_2 = B \frac{D}{2r_{11}\rho} J_1\left(\frac{2r_{11}}{D}\rho\right) \sin\theta \cos\frac{\pi z}{L} \hat{\rho} + B J_1'\left(\frac{2r_{11}}{D}\rho\right) \cos\theta \cos\frac{\pi z}{L} \hat{\theta}$$

$$\bar{H}_3 = B \frac{D}{2r_{11}\rho} J_1\left(\frac{2r_{11}}{D}\rho\right) \cos\theta \cos\frac{\pi z}{L} \hat{\rho} - B J_1'\left(\frac{2r_{11}}{D}\rho\right) \sin\theta \cos\frac{\pi z}{L} \hat{\theta}$$

To calculate the coefficient of mutual induction between the external source and the 1st or TE mode it is necessary to evaluate the integral

$$\int_{\text{Loop Area}} \bar{H}_i \cdot \bar{i}_3 \, da = A \frac{r_{01}\lambda_u}{\pi D} \int_{\text{Loop Area}} J_0\left(\frac{2r_{01}}{D}\rho\right) da,$$

where the loop is at the point $\left(\frac{D}{2}, 0, \frac{L}{2}\right)$ If the area of the loop is small, then the integral is approximately equal to

$$A \frac{r_{01}\lambda_u}{\pi D} J_0(r_{01}) \pi \rho_0^2$$

where ρ_0 is the radius of the input loop. Assume a loop radius of 10^{-3} meters.

$$A = \frac{\sqrt{2}}{J_0(r_{01})}$$

$$\int_{\text{Loop}} \bar{H}_1 \cdot \bar{i}_3 \, da = \frac{\sqrt{2} r_{01} \lambda_u}{2D} \rho_0^2 = \frac{3.83 \times 0.1 \times 10^{-6}}{\sqrt{2} \times 0.07}$$

and

$$M_{01} = 4\pi \times 10^{-7} \frac{2\pi}{0.1} \frac{3.83 \times 0.1 \times 10^{-6} \times .0391}{2 \times 0.07}$$

which yields the result that $M_{01} = 1.20 \times 10^{-11}$ henrys. $M_{02} = M_{03} = 0$ because the plane of the loop is parallel to the transverse magnetic field.

The unloaded Q's depend upon the integral $\int_{\text{cavity surface}} \bar{H}_a \cdot \bar{H}_a \, da$. For the TE mode the integral may be written as

$$2\pi \left(\frac{\sqrt{2}\, r_{01} \lambda_u}{\pi D} \right)^2 \frac{D}{2} \int_0^h \sin^2 \frac{\pi z}{L} \, dz = \frac{r_{01}^2 \lambda_u^2 L}{\pi D}$$

$$\frac{1}{Q_1} = \frac{\delta_a}{2} \frac{r_{01}^2 \lambda_u L}{\pi D} = 1.95 \times 10^{-9}; \quad R_1 = \frac{\omega_1 L_a}{Q_1} = 2.80 \times 10^{-4} \text{ ohms}$$

In computing δ_a, σ for silver is taken as 6.14×10^7 mhos/meter, and μ is taken as μ_0. This is very nearly the case for high frequencies.

From the expressions for $\bar{H}_1$, $\bar{H}_2$ and $\bar{H}_3$ above, it follows that

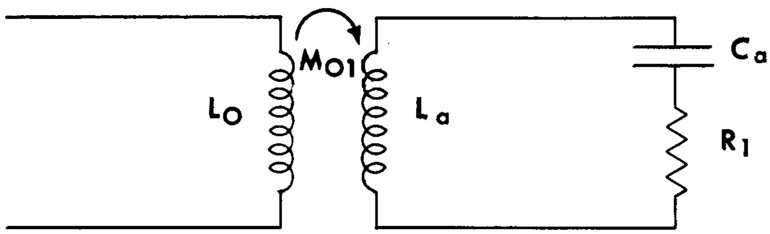
$$\int_s \bar{H}_1 \cdot \bar{H}_2 \, da = \int_s \bar{H}_2 \cdot \bar{H}_3 \, da = \int_s \bar{H}_1 \cdot \bar{H}_3 \, da = 0$$

where

s = surface of cavity

da = an element of area

Consequently, the equivalent circuit for this cavity is as shown below.



$L_a = 76.2 \times 10^{-7}$ henrys

$C_a = 3.69 \times 10^{-16}$ farads

$R_1 = 2.80 \times 10^{-4}$ ohms

$M_{01} = 1.20 \times 10^{-11}$ henrys

L_0 = self-inductance of input loop

In practice the TM_{111} modes may be coupled inductively to the input because of a tilted input loop, because the resonator is not a perfect right circular cylinder, or because the input loop will disturb the field in the immediate neighborhood, so that the equivalent circuit will differ from that assumed above.

APPENDIX III

FORMULAS FOR THE CYLINDRICAL CAVITY[1]

AIII. 1 Fields In A Cylindrical Cavity

For TE modes

$n > 0$

$m > 0$

$$\overline{E} = \frac{-\ell J_\ell (k_1 \rho)}{k_1 \rho} \operatorname{Sin} \ell \theta \operatorname{Sin} k_3 z \hat{\rho} - J_\ell' (k_1 \rho) \operatorname{Cos} \ell \theta \operatorname{Sin} k_3 z \hat{\theta}$$

$$\overline{H} = \frac{k_3}{k} J_\ell' (k_1 \rho) \operatorname{Cos} \ell \theta \operatorname{Cos} k_3 z \hat{\rho} - \frac{\ell k_3}{k} \frac{J_\ell (k_1 \rho)}{k_1 \rho} \operatorname{Sin} \ell \theta \operatorname{Cos} k_3 z \hat{\theta}$$

$$+ \frac{k_1}{k} J_\ell (k_1 \rho) \operatorname{Cos} \ell \theta \operatorname{Sin} k_3 z \hat{z}$$

For TM modes

$m > 0$

$$\overline{E} = \frac{-k_3}{k} J_\ell' (k_1 \rho) \operatorname{Cos} \ell \theta \operatorname{Sin} k_3 z \hat{\rho}$$

$$+ \frac{\ell k_3}{k} \frac{J_\ell (k_1 \rho)}{k_1 \rho} \operatorname{Sin} \ell \theta \operatorname{Sin} k_3 z \hat{z}$$

$$+ \frac{k_1}{k} J_\ell (k_1 \rho) \operatorname{Cos} \ell \theta \operatorname{Cos} k_3 z \hat{z}$$

[1]The symbols used in this appendix are defined in Section III B

$$\overline{H} = -\ell \frac{J_\ell(k_1\rho)}{k_1\rho} \operatorname{Sin} \ell\theta \operatorname{Cos} k_3 z \, \hat{\rho} - J_\ell'(k_1\rho) \operatorname{Cos} \ell\theta \operatorname{Cos} k_3 z \, \hat{\theta}$$

where

$$k_1 = \frac{2\, r_{\ell m}}{D}$$

$$k_3 = \frac{n\pi}{L}$$

$$k^2 = k_1^{\,2} + k_3^{\,2} = \left(\frac{2\pi}{\lambda}\right)^2$$

$r_{\ell m}$ = the m*th* root of $J_\ell(x)$ for TM modes

= the m*th* root of $J_\ell'(x)$ for TE modes

$\hat{\rho}$, $\hat{\theta}$ and $\hat{z}$ are unit vectors in cylindrical coordinates

AIII.2 Expressions For MS Factor In The Cylindrical Cavity

TM modes

$$\frac{Q\,\delta}{\lambda} = \frac{r_{\ell m}}{2\pi}\left[1 + p^2R^2\right]^{1/2} \frac{1}{1+R} \qquad \text{if } n > 0$$

$$\frac{Q\,\delta}{\lambda} = \frac{r_{\ell m}}{\pi(2+R)} \qquad \text{if } n = 0$$

TE modes

$$\frac{Q\,\delta}{\lambda} = \frac{r_{\ell m}}{2\pi}\left[1 + p^2R^2\right]^{3/2} \frac{1 - \left(\frac{\ell}{r_{\ell m}}\right)^2}{1 + p^2R^3 + p^2(1-R)R^2\left(\frac{\ell}{r_{\ell m}}\right)^2}$$

$$R = \frac{D}{L}$$

$$p = \frac{n\pi}{2r_{\ell m}}$$

AIII.3 <u>Currents And Fields In The Cavity End Plates</u>[1]

The magnetic field at the end plates is

TE modes

$$H_\rho = \frac{k_3}{k} J_\ell' (k_1 \rho) \cos \ell\theta \tag{1}$$

$$H_\theta = -\ell \frac{k_3}{k} \frac{J_\ell (k_1 \rho)}{k_1 \rho} \sin \ell\theta \tag{2}$$

TM modes

$$H_\rho = -\ell \frac{J_\ell (k_1 \rho)}{k_1 \rho} \sin \ell\theta \tag{3}$$

$$H_\theta = - J_\ell (k_1 \rho) \cos \ell\theta \tag{4}$$

where

$$k_1 = \frac{2r_{\ell m}}{D}$$

$$k_3 = \frac{n\pi}{L}$$

[1]The discussion in this subsection is based on Reference 6.

$$k^2 = k_1^{\,2} + k_3^{\,2} \text{ and } k = \frac{2\pi}{\lambda}$$

$$r_{\ell m} = m\,th \text{ root of } J_\ell(r) = 0 \text{ for TM modes}$$

$$= m\,th \text{ root of } J'_\ell(r) = 0 \text{ for TE modes}$$

The magnitude of the magnetic field is found from

$$H^2 = H_\rho^{\,2} + H_\theta^{\,2} \tag{5}$$

Let $x = k_1\rho$ and substitute the values for H_ρ and H_θ from (1) and (2) into (5), obtaining

$$H^2 = \left(\frac{k_3}{k}\right)^2 \left[J'_\ell(x)\right]^2 \cos^2 \ell\theta + \ell^2 \left(\frac{k_3}{k}\right)^2 \left(\frac{J_\ell(x)}{x}\right)^2 \sin^2 \ell\theta \tag{6}$$

This expression applies only to TE modes.

Because only the contour lines and relative magnitudes are of interest here, constants appearing in both H_ρ and H_θ may be dropped. Therefore, for TE modes

$$H^2 = \left[J'_\ell(x) \cos \ell\,\theta\right]^2 + \left[\frac{\ell}{x} J_\ell\,(x) \sin \ell\theta\right]^2$$

By use of the identities

$$J_\ell(x) = \frac{x}{2\ell}\left[J_{\ell-1}(x) + J_{\ell+1}(x)\right]$$

$$J'_\ell(x) = 1/2\left[J_{\ell-1}(x) - J_{\ell+1}(x)\right],$$

the expression for H reduces to

$$H^2 = (J_{\ell -} \cos \ell \theta)^2 + (J_{\ell +} \sin \ell \theta)^2$$

where

$$J_{\ell -} = J_{\ell - 1}(x) - J_{\ell + 1}(x)$$

$$J_{\ell +} = J_{\ell - 1}(x) + J_{\ell + 1}(x)$$

For TM modes

$$H^2 = \left[\frac{\ell}{x} J_{\ell}(x) \sin \ell \theta \right]^2 + \left[J'_{\ell}(x) \cos \ell \theta \right]^2$$

which is identical with the expression for TE modes. By setting H equal to successive constant values, contours of H may be obtained.

For TE modes, when $\theta = 0$, the field is entirely radial and is proportional to $J'_{\ell}(k_1 \rho)$. When $\theta = \frac{\pi}{2\ell}$, $H_{\rho} = 0$ and H_{θ} is proportional to

$$\frac{J_{\ell}(k_1 \rho)}{k_1 \rho}$$

AIII.4 Decrement Equation

For a simple RLC circuit in oscillation, the envelope of the voltage is given by:

$$e = E_o \exp. \left(-\frac{\omega t}{2Q}\right)$$

where e is the envelope voltage at a time t, E_o is the maximum voltage at the beginning of the decay, ω is $2\pi \times$ the frequency of resonance of the circuit, and Q has the usual meaning. After a time t, the voltage envelope has decreased in the ratio $\frac{E_o}{e}$, which is

$$\frac{E_o}{e} = \exp. \left(\frac{\omega t}{2Q}\right)$$

The loss in db is

$$20 \log_{10} \frac{E_o}{e} = 20 \log_{10} \exp. \left(\frac{\omega t}{2Q}\right)$$

$$= (20 \log_{10} \epsilon) \left(\frac{\omega t}{2Q}\right)$$

$$= 20\,(0.434) \times \frac{2\pi ft}{2Q} = 27.3 \frac{ft}{Q}$$

The decrement, in db per microsecond, is

$$\frac{20 \log_{10} \frac{E_o}{e}}{t} = \frac{27.3\, f}{Q}$$

where f is in mcs, and t in microseconds.

AIH. 5 Ringing Time Equation

Operating manuals for echo boxes frequently contain a ringing time equation of the form

$$R = C + D \left[10 \log_{10} \frac{Pt^2}{B} - 2A \right] + 164\, t \qquad (1)$$

where

R = ringing time in yards

C = a constant

D = sensitivity of the echo box in yards per db

P = radar peak power in kilowatts

t = radar pulse length in microseconds

A = coupling factor of directional coupler

B = receiver bandwidth in mcs

The constant C in this equation is determined empirically for each type of cho box; however, Equation (1) may be obtained from Equation (2a) in Section IIID. Multiplying this equation by 164 yards per microsecond yields the ringing time in yards

$$R = 164\ t + \frac{164}{d_L}\left\{\left[P_t - P_n\right] - 2\left[W_1 + W_2\right] + 20 \log_{10}\left[1 - \frac{Q_L}{Q_0}\right] + 20 \log_{10}\left[1 - \exp.\ (-0.115\ td_L)\right] + W_5\right\} \quad (2)$$

In Equation (1), W_2, the cable loss, is not considered, so it will be neglected also in Equation (2). The factor $\frac{164}{d_L} = D$, and therefore it is necessary only to convert the factor within the brackets in Equation (2) to the form of the factor within the brackets in Equation (1), and to obtain a value for the constant C.

The terms P_t, P_n, and W_5 can be combined as follows:

$$P_t - P_n + W_5 = 10 \log_{10} \frac{P' W'_5}{P'_n} \quad (3)$$

where

P'_n = noise power of receiver in watts

P' = peak transmitter power in watts

W'_5 = the ratio of the noise power of the receiver to the power of the ringing signal at the end of ringing time.

It can be shown that

$$P'_n = KTB' (NF)$$

where

K = Boltzmann's constant = 1.38×10^{-23} Joules per degree Kelvin,

T = absolute temperature (usually taken as $291^\circ K.$)

B' = bandwidth of receiver in cycles per second

(NF) = noise figure of receiver, expressed as a ratio.

If the power P' is expressed in kw, and if the bandwidth B is expressed in mcs, (3) becomes

$$P_t - P_n + W_5 = 10 \log_{10} \frac{PW'_5 \times 10^3}{KTB(NF) \times 10^6} \tag{4}$$

The logarithmic term can be written as

$$10 \log_{10} \frac{PW'_5 \times 10^{-3}}{KTB\,(NF)} = 10 \log_{10} \frac{W'_5 \times 10^{-3}}{KT\,(NF)} + 10 \log_{10} \frac{P}{T} \tag{5}$$

The first term on the right-hand side of (5) becomes part of C.

The term $20 \log_{10} \left[1 - \exp. \; (-0.115\, d_L t) \right]$ can be expanded in series form. Neglecting all but the first two terms of the series, it becomes

$$20 \log_{10}\left[1 - \exp\ (-0.115\, d_L t)\right] \cong 20 \log_{10} 0.115\, d_L t = 10 \log_{10} (0.115\, d_L t)^2$$

$$= 10 \log_{10} (0.115\, d_L)^2 + 10 \log_{10} t^2 \qquad (6)$$

Combining (6) with (5) yields

$$10 \log_{10} \frac{W'_5 (0.115\, d_L)^2 \times 10^{-3}}{KT\ (NF)} + 10 \log_{10} \frac{Pt^2}{B} \qquad (7)$$

(2) can now be written as

$$R = \frac{164}{d_L} 10 \log_{10} \frac{W'_5 (0.115\, d_L)^2 \times 10^{-3}}{KT\ (NF)} \left(1 - \frac{Q_L}{Q_0}\right)^2$$

$$+ \frac{164}{d_L} \left[10 \log_{10} \frac{Pt^2}{B} - 2W_1\right] + 164\, t$$

where

$W_1 = A.$

APPENDIX IV

ABSTRACTS

INDEX OF ABSTRACTS ON RESONANT CAVITIES AND ECHO BOXES

P - Patents
A - Articles
T - Reports and Technical Manuals
B - Books

INDEX OF ABSTRACTS ON RESONANT CAVITIES AND ECHO BOXES (Cont.)

INDEX OF ABSTRACTS ON RESONANT CAVITIES AND ECHO BOXES (Cont.)

PATENTS

P1 - Variable Capacity Cavity Tuning, by L. D. Smullin, U. S. Pat. 2,600,278, filed August 2, 1945, issued June 10, 1952.

A resonant cavity consisting of a cylindrical surface bounded by two flat end plates is tuned by means of a disc-shaped conductor mounted on a dielectric sleeve which projects into the cavity from the cylindrical wall. The cavity is operated with the electric field between the parallel walls and tuning is accomplished by moving the inserted piece toward the center of the cavity where the electric field is stronger.

P2 - Cavity Resonator, by A. Baños, Jr., U. S. Pat. 2,600,186, filed October 3, 1945, issued June 10, 1952.

A cylindrical cavity has a tuning plunger with spherical curvature instead of being flat; this innovation separates the TE_{omn} and TM_{1mn} modes, removing these degeneracies. The resulting cavity, then, has a Q and a ringing time which are not at all critical to minor departures from the ideal shape, for example, to non-parallelism of the end plates, slight departures from the circular of the cylindrical wall, etc.

P3 - Method of Forming a Cavity Resonator, by Daniel Alpert, et al, U. S. Pat. 2,584,717, filed November 28, 1945, issued February 5, 1952.

A cavity resonator is used for the testing of radar performance. This cavity embodies several novel features to produce stability. The cavity is evacuated, and compensated for temperature, humidity, and pressure changes. In addition, the mounting to the radar apparatus is done in a manner to eliminate stresses which would result in distortion of the cavity and cause a resonant frequency change. Not only is the cavity proper evacuated, but the space between the tuning piston and an outside plate is also evacuated. Over this whole apparatus is placed a cap which protects the cavity from external pressures, atmospheric and mechanical. An Invar rod projects into the cavity slightly, and compensates for the change in frequency resulting from thermal expansion of the cavity.

PATENTS (Continued)

P4 - Cavity Resonator and Charts for Design, by J. P. Kinzer, U. S. Pat. 2,541,925, filed April 13, 1945, issued February 13, 1951.

Kinzer has patented a tunable cylindrical cavity resonator which has been designed in accordance with certain considerations: the cavity is to operate in a TE_{01n} mode, is to have a pre-assigned Q at a given frequency, and the length and diameter, as well as n, are to be determined from a set of design equations. Such a cavity will have the smallest volume possible for the given Q, and in addition, have a relatively small number of unwanted modes. The patent write-up presents a set of three design curves which are useful in determining n, L (length), and D (diameter) when a given conducting material for construction of the cavity, a Q, and an operating frequency are specified.

P5 - Loading for Electrical Cavity Resonators, by J. M. Wolf, U. S. Pat. 2,566,050, filed April 12, 1949, issued April 28, 1951.

Resonant cavities of the hollow cylindrical and the coaxial type are provided with loading devices to alter the curve $Q = Q(f)$. A coaxial cavity an odd number of quarter-wavelengths long has two resistive loading devices coupled to the cavity through a loop or probe. One is located at a position where the coupling is independent of frequency, another to a position where the coupling is a function of frequency. By proper adjustment of the coupling, the curve $\frac{Q}{f}$ vs. f can be made substantially flat over a selected region. The same principle has been applied to a coaxial cavity an even number of quarter-wavelengths long and to a cylindrical cavity operating in the TE_{012} mode.

P6 - Tunable Cavity Resonator, by E. D. McArthur, U. S. Pat. 2,549,499 filed February 19, 1949, issued April 17, 1951.

A cylindrical cavity resonator with a wide tuning range is

PATENTS (Continued)

constructed as follows. Two end plates are connected by a multitude of resilient fingers of conductive material which form the cylindrical surface. These fingers are all secured to one of the end plates and are free to slide radially along the other. The fingers, being under tension, are bowed outward and have the tendency to move outward. An adjustable cylindrical shoe makes contact with the fingers, and movement of the shoe will cause the fingers to move inward or outward, thus varying the average radius of the cavity. By this means the cavity is tuned. This method of tuning preserves the cavity symmetry and requires a sliding contact only on one end plate. As a result, the cavity is efficient and is fairly free from higher order waves.

P7 - High-Frequency Wavemeter, by J. P. Hagen, et al, U. S. Pat. 2,544,674, filed August 27, 1943, issued March 13, 1951.

This is a wavemeter of the quarter-wavelength, coaxial type. Tuning is accomplished by movement of the inner conductor, which is a telescopic device consisting of two members, one of which slides over the other. The movable member is attached to an Invar bar whose length remains constant independent of the temperature. Hence, a change in length of the cavity due to temperature change causes the gap between inner and outer conductor to change so that the resonant frequency remains unchanged. Also there is a retainer built into the cavity wall and coupled to the cavity. The chamber is to contain a hygroscopic agent (e.g., silica gel) to absorb moisture from the cavity, thus preventing resonant frequency changes due to humidity changes.

P8 - Coupling Loop, by S. Sensiper, U. S. Pat. 2,543,809, filed January 8, 1946, issued March 6, 1951.

In usual cylindrical cavity resonators excited by coupling

PATENTS (Continued)

loops, the loops act to a certain extent like probes. Due to this effect, the loops tend to excite a companion mode (a mode which is oriented at right angles to the desired mode, but is otherwise the same) if the mode does not possess axial symmetry. This occurs because the loops, being in the form of a semicircle, do not lie in a direction circumferential to the cavity wall. In this invention, the loops, instead of being semicircular, have the shape of a right triangle, one leg of which lies circumferential to the cavity wall while the other extends, perpendicular to the cavity wall, into the center portion of the coaxial coupling line.

P9 - Object Locator System, by W. F. Kannenberg, et al, U. S. Pat. 2,537,139, filed July 14, 1944, issued January 9, 1951.

A resonant chamber is used as an echo box to test the performance of a radar. The resonator, of cylindrical shape, is provided with a movable end plate which, in conjunction with a motor and cam, is caused to vibrate in a direction normal to itself, thus rapidly changing the frequency of the cavity and enabling the cavity to be simultaneously resonant to a band of frequencies. The lever upon which the cam acts may be disengaged at will, whereupon the tuning piston will remain fixed in a position such that the cavity will be resonant to no frequency in the radar band, thus preventing the cavity from absorbing energy from the radar transmitter except when a test of performance is being made. The resonant band may be varied.

P10 - Clamped Cavity Resonator, by K. F. Niessen, U. S. Pat. 2,528,387, filed May 9, 1946, issued October 31, 1950.

High frequency resonant cavities are temperature compensated in the following manner. A spherical cavity, with an increase in ambient temperature, will increase its dimensions and thus lower its resonant frequency. However, if the cavity

PATENTS (Continued)

is constrained from expanding the same in all directions, for example, as it would be if clamped at diametrically opposite points, the cavity will be altered slightly in shape. The greatest expansion may be made to occur in regions where an expansion would change the resonant frequency only slightly, or even in a direction opposite to that toward which it would expand in the absence of a constraint. Thus, the cavity may change its resonant frequency only slightly or not at all under a temperature change. Cylinders and parallelepipeds are used in this manner as well as are spheres.

P11 - Cavity Resonator of Rectangular Prismatic Shapes, by K. F. Niessen, U. S. Pat. 2,512,368, filed January 21, 1948, issued June 20, 1950.

This cavity is in the shape of a rectangular prism whose base is a parallelogram with a 45° angle and adjacent sides in the ratio $1:\sqrt{2}$, the side walls being rectangles. This cavity has the advantage that, for the lowest natural frequency for which the electric field is not a function of the height, the Q of the circuit is very high, being higher than for the square prism of the same material, frequency, and height, and operating in the same mode. The Q is also higher than for the conventional cylindrical cavity of the same height and operating at the corresponding lowest natural frequency.

P12 - Electrical Resonator, by T. H. Turney, U. S. Pat. 2,507,426, filed May 16, 1945, issued May 9, 1950.

A cylindrical cavity resonator is constructed of a metal with low coefficient of expansion (Invar), but one of the end plates is of a metal with high thermal expansion. This end plate is secured to the cylindrical walls with screws fitting into slots running longitudinally so that the position of the end

PATENTS (Continued)

plate may be adjusted. A rise in temperature will cause a small increase in the cavity dimensions, but a larger increase in the end plate dimension, and the plate, which is under tension, will be bowed inward sufficiently to compensate for the change in volume resulting from the expansion of the cavity dimensions.

P13 - Frequency Selective Electrical Device, by J. P. Kinzer, U. S. Pat. 2,500,637, filed June 1, 1946, issued March 14, 1950.

In this invention, two resonant cavities are tuned by means of a coiled spring which may be wound from one cavity into another, and which changes the effective diameter of the cavities. The output from the two cavities may be fed into a modulator which produces a frequency equal to the difference of the two resonant cavity frequencies. Since, in tuning, the resonant frequency of one cavity is increased while the other is decreased, tuning may take place at a rapid rate.

One of the cavities may be used merely for a storage space for the excess spring, and the other used as a general resonant cavity. An advantage of this cavity is that moving walls for tuning have been eliminated.

This technique also provides an effective way of matching cavities of different dimensions.

P14 - Microwave Electrical Testing System, by W. A. Edson, et al, U. S. Pat. 2,498,073, filed May 11, 1946, issued February 21, 1950.

In this system, microwave energy may be detected either through a resonant or a non-resonant system, and switching from one condition to the other is easily accomplished. Microwave energy may be fed directly to a detector or to a tunable resonant cavity to which the detector may be coupled. This switching may be done without changing the apparent electrical length of the testing system. The couplings are made variable, and when coupling is to one system, the other may be completely disconnected.

PATENTS (Continued)

P15 - Electrical Apparatus, by G. G. Edlen, U. S. Pat. 2,479,222, filed September 21, 1945, issued August 16, 1949.

A resonant cavity is used as the basis of a spectrum analyzer. The output of the cavity is detected, amplified, and applied to the vertical plate of a C. R. T. The tuning piston is coupled to a resistance which causes the voltage on the horizontal plate to vary with the tuning piston. When the cavity is resonant to an applied frequency, the C.R.T. will give a vertical deflection. As the cavity is tuned throughout its range, an output vs. frequency curve will be traced on the C.R.T.

P16 - Resonant Wave Guide Switching, by W. F. Kannenberg, U. S. Pat. 2,466,439, filed April 27, 1944, issued April 5, 1949.

The invention utilizes a high Q resonant cavity and has adjustable coupling. This is accomplished by a retractable loop switch which projects through a slot in the end of the cavity and provides adjustable coupling to the TE_{01n} mode. The tuning may be varied without affecting the coupling. The coupling may be made ineffective at will.

P17 - Electrical Cavity Resonator, by T. C. Campbell, U. S. Pat. 2,475,778, filed October 17, 1946, issued July 12, 1949.

This resonant cavity permits tuning over a wide range with a linear relation between dial displacement and resonant frequency. This is accomplished by means of a movable plunger and piston coupled to the dial with a bell crank mechanism, and a cross head. The piston motion varies as a sine function of the dial movements which substantially gives the desired linearity.

P18 - Temperature Compensating Mechanism, by K. C. DeWalt, et al, U. S. Pat. 2,486,129, filed July 26, 1946, issued October 25, 1949.

[redacted]

PATENTS (Continued)

This invention employs a resonating cavity with a temperature compensating mechanism that has all interengaging parts of the same temperature coefficient, and which compensates for the change in resonant frequency with temperature change.

One of the end walls of a cylindrical cavity has an elongated hollow support made of the same material as the cavity extending from it, but with an intermediate section of material having a different coefficient of expansion. Connected with this elongated cylinder is an elongated member extending into the cavity. An increase of temperature tends to decrease the resonant frequency, but will at the same time move the elongated member outward, which has the effect of increasing the resonant frequency. With all interengaging parts having the same temperature coefficient, the movable parts remain well fitting and easy to adjust.

P19 - Frequency Selective Apparatus, by W. F. Kannenberg, U. S. Pat. 2,460,090, filed November 26, 1945, issued January 25, 1949.

A tunable cylindrical resonant cavity is offered which gives a wide tuning range with freedom from interfering modes. Tuning is accomplished by means of an end plunger and piston. When an interfering mode is approached, the diameter of the cavity may be altered. This alteration removes the desired frequency to a region free of interfering modes. Tuning with the piston may then continue. The change in diameter is obtained by using a slightly tapered conducting cylinder of greater length than needed for the cavity. By movement of the end walls relative to the cylinder, the effective diameter of the cavity may be changed.

P20 - Conformal Grating Resonant Cavity, by A. G. Fox, U. S. Pat. 2,476,034, filed July 16, 1945, issued July 12, 1949.

Wire gratings with conductive wires conforming to the direction of the electric field are placed in a wave guide at the

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PATENTS (Continued)

entrance to a resonant cavity which comprises a section of the wave guide. The wave guide is proportioned to conduct waves at higher modes at the frequencies used. Grating inhibits generation of modes of higher order up to $TE_{2n+1,0}$ mode, where n = number of grating wires. Conformal grating also acts as a shunt reactance of high Q, results in cavity having high Q.

P21 - Echo Box Resonance Tester, by J. W. Brannin, U. S. Pat. 2,405,814, filed May 16, 1945, issued August 13, 1946.

A glow tube is used with a tunable resonant cavity for a visual indicating device. The glow tube is mounted at the end of a half wave (or multiple thereof) coaxial shaft, the other end of which couples to the cavity. The glow tube is energized by the cavity, and indicates resonance in the cavity. The coupling to the cavity is by a loop extending into the cavity.

In one version the length of the shaft is fixed; in an alternate version the length can be altered by means of a screw adjustment.

P22 - Electrical Testing System, by W. A. Edson, U. S. Pat. 2,414,456, filed April 19, 1945, issued January 21, 1947.

This invention is a piece of microwave testing equipment with a tuned input and an untuned input. The tuned input leads to a resonating cavity coupled to which is a detector consisting of a crystal and a meter. The untuned input leads directly to the detector. The detector may be quickly coupled either to the resonant cavity or to the untuned input. The object is to provide a piece of test equipment which can be switched quickly from a frequency selective condition to a non-frequency selective condition, without varying the apparent electrical length of the apparatus.

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PATENTS (Continued)

P23 - Electrical Resonator, by J. P. Kinzer, U. S. Pat. 2,500,417, filed April 13, 1945, issued March 14, 1950.

The invention is a cavity resonator comprising a hollow cylinder of conducting material with means of exciting the TE_{013} mode. Details of design are discussed from the standpoint of mode chart, which is a graph of the equation

$$(f\,D)^2 = \left(\frac{cr}{\pi}\right)^2 + \left(\frac{cn}{2}\right)^2 \left(\frac{D}{L}\right)^2$$

D = diameter of cavity
L = length of cavity
f = frequency
r = root of Bessel function $J_1(x) = 0$
or the derivative $J_1'(x) = 0$
n = n in $TE_{\ell mn}$

Avoidance of extraneous modes is discussed. Also discussion of tuning range is given.

P24 - Cavity Resonator, by W. A. Edson, U. S. Pat. 2,465,639, filed January 31, 1945, issued March 29, 1949.

This resonant cavity is for use as an echo box, and is designed to give a ringtime independent of resonant frequency.

The ringtime of an echo box is a function of the Q and the resonant frequency. The Q is a function of the resistivity of the conducting walls. Increasing the resonant frequency is accomplished by increasing the size of the resonant cavity by means of an adjustable piston forming one of the walls. This tends to change the ringtime. By making different portions of the cavity surface of different materials, it is possible to have

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PATENTS (Continued)

the effective resistivity, and hence, the effective Q, vary with frequency in such a way that the ringtime is independent of the tuning. This has been accomplished here by coating the interior of the echo box with two substances, silver and cadium, so that as tuning is done, varying amounts of the cadmium surface are exposed, altering the effective Q of the cavity.

P25 - Cavity Resonator, by H. M. Bach, U. S. Pat. 2,463,472, filed March 16, 1945, issued March 1, 1949.

A conventional oscillating cavity has for one of its walls a piezo-electric crystal unit with plated electrodes on the opposite faces. This crystal also forms part of the grid circuit of an electron-tube oscillator. When the oscillator is in operation, the mechanical motion of the crystal causes the volume of the cavity, and hence, the resonant frequency of the cavity, to change periodically. In another version, the crystal forms one of the re-entrant faces of a toroidal cavity.

In this way, the cavity will receive a complete band of frequencies.

P26 - Cavity Resonator, by J. C. Schelleng, U. S. Pat. 2,453,760, filed March 2, 1945, issued November 16, 1948.

This cavity is made to discriminate against unwanted modes by virtue of a multiple feed system. A wave guide projects into the cavity and divides into four branches, each having a slot which couples to the cavity. The position of the slots is such that for the fields of the TE_{01n} mode, the four apertures excite the resonator in phase, thus tending to strengthen this mode at the expense of others.

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PATENTS (Continued)

P27 - Cavity Resonator Circuit, by P. S. Carter, U. S. Pat. 2,357,314, filed January 4, 1941, issued September 5, 1944.

Resonant cavities are used as filters. By employing resonant cavities excited in two or three modes whose resonant frequencies are close together, passbands of desired characteristics are obtained. In one embodiment a rectangular cavity of sides a, b, and c is used, the input and output probes being located in diagonally opposite corners and making equal angles with the three sides. This excites three fundamental modes whose wavelengths depend on a, b, and c. By placing the probes on opposite faces and oriented parallel to one of the dimensions, only two modes will be excited. Cylindrical and ellipsoidal cavities are employed in an analogous manner. This invention differs from a previous one of Carter (No. 2,357,313, filed October 1, 1940) in that here several frequencies, being close together, are excited simultaneously, and fundamental modes are employed, resulting in smaller cavity dimensions.

P28 - Cavity Tuning Device, by I. L. Stephan, U. S. Pat. 2,409,321, filed December 16, 1943, issued October 15, 1946.

An invention for compensating for temperature variations in tuned cavities is described. A resonant cavity changes its volume with change in temperature; this causes the resonant frequency to be changed. The resonant frequency will then not agree with the calibration. This invention keeps the resonant frequency constant. The top of the resonant cavity is a diaphragm mounted on a bridge-like structure. The expansion of this structure is designed to move the diaphragm in such a manner that the change in resonant frequency introduced by diaphragm movement will compensate for change in resonant frequency caused by expansion or contraction of the cavity. This can be accomplished by using substances of suitable coefficient of expansion for the bridge-like structure and accessory parts.

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PATENTS (Continued)

P29 - Tuning Apparatus, by E. O. Thompson, U. S. Pat. 2,405,277, filed December 2, 1943, issued August 6, 1946.

A mechanical method of effecting periodic variations in the motion of the tuning plunger of a resonant cavity is offered. The periodic motions are superposed on the long-range tuning sweep and are of relatively high frequency. The object is to avoid passing a given frequency or wavelength at a time when no signal is coming in, by introducing limited vibratory or reciprocatory motion while main sweep is continuing. The object is accomplished by use of D. C. motor for the drive, and a system of gears and eccentrics. When the desired frequency is reached, the over-all movement may be stopped while vibratory motion may continue.

P30 - Wavemeter for Centimeter Waves, by V. D. Landon, U. S. Pat. 2,423,506, filed November 29, 1943, issued July 8, 1947.

This wavemeter consists of an adjustable resonant cavity consisting of two telescopic cylindrical sections joined together and providing a means of varying the volume of the cavity. The cavity is coupled loosely by means of a coupling rod which extends into the cavity and into a wave guide transmission line. A crystal detector and meter also are coupled to the cavity and serve as an indicator.

The invention provides means for measuring wavelength of microwave energy and also means for measuring microwave power.

P31 - Device for the Frequency Modulation of the Resonant Frequency of Cavity Resonators, by J. O. H. Fredholm, et al, U. S. Pat. 2,436,640, filed November 24, 1943, issued February 24, 1948.

The devices used with the resonant cavity permit the resonant frequency of a resonant cavity to vary periodically about some average frequency. The frequency deviation is made large with

PATENTS (Continued)

relatively small change in volume by altering the volume of a relatively small cavity coupled to the main cavity.

In addition, frequency stabilization, whereby the average basic frequency is kept constant, is accomplished by arranging cavities in a bridge connection.

P32 - Tuner for Cavity Resonators, by E. Rostas, U. S. Pat. 2,444,066, filed June 3, 1943, issued July 29, 1948.

A resonant cavity has been developed which is tunable, not by the usual method of using a sliding piston as one of the walls to vary the volume, but by the insertion of adjustable, conducting, bent rods or loops into the cavity to change the configuration of the fields. These rods may be adjusted by altering their depth or rotating them axially. Illustrations show the application to cavities of toroidal or re-entrant shapes, but the method is presumably not restricted to cavities of a particular shape.

P33 - Pulse Echo Testing Apparatus, by N. Bishop, U. S. Pat. 2,489,075, filed April 17, 1943, issued November 22, 1949.

In this invention, the performance of a radar is evaluated by connecting the radar to an antenna located at the focus of a parabolic reflector. Facing this reflector is another parabolic reflector. This constitutes a reverberation device, which, when energized, will continue to reverberate for a time afterward. A portion of the energy in the reverberation device is returned to the radar and its effect is observed on a scope or other indicating device. The distance between the two reflectors is adjustable for maximum response, and the duration of the response gives a measure of radar performance.

P34 - Resonator Wavemeter, by W. W. Hansen, U. S. Pat. 2,439,388, filed December 12, 1941, issued April 13, 1948.

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This cylindrical wave meter has features for suppressing unwanted modes of oscillation. It is designed for high Q and for convenient shape and size. Mode suppression is obtained by (1) the introduction of a gap between piston and cylinder, and subsequent operation in a mode in which the electric lines of force are parallel to the resulting gap, (2) the presence of resistive wires within the cavity, so situated that the electric lines of force for the desired mode are everywhere perpendicular to the wires. The undesired modes will in general have a component of electric field along the wires, with a consequent lowering of the Q for the undesired mode and a slight change in resonant frequency.

P35 - Ultra High Frequency Circuit Conductor Member, by C. H. Foulkes, U. S. Pat. 2,356,044, filed July 1, 1942, issued August 15, 1944.

This invention is a method of polishing the inner surface of a hollow conductor. If the inner surface of a wave guide or other hollow conductor is burnished or polished in a direction parallel to the direction of current flow, all scoring marks and scratches inclined to the direction of current flow will be removed, with a considerable improvement in efficiency.

P36 - Tunable Oscillatory Circuit for Ultra-Short Waves, by K. Schüssler, U. S. Pat. 2,242,404, filed November 18, 1939, issued May 20, 1941.

A tunable resonant cavity is formed of two concentric conductors, the outer being shorted by a plate at one end. The inner conductor is composed of two parts of different diameter, the smaller part being located at the free end and being adjustable in length.

P37 - Wavemeter, by A. E. Harrison, U. S. Pat. 2,444,041, filed February 25, 1942, issued June 29, 1948.

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The wavemeter is of the cylindrical resonant cavity type. An adjustable plunger projects into the cavity and is used for tuning. The objects of the meter are (1) to give fairly uniform response over a variety of wavelenths, (2) to increase the over-all efficiency by having the indicating meter and crystal built integral into the equipment, and (3) to eliminate interfering modes.

P38 - Resonant System for Ultra-Short Waves, by W. Engbert, U. S. Pat. 2,250,096, filed September 14, 1940, issued July 22, 1941.

The invention consists of a tunable cylindrical cavity with a tuning piston and plunger. Electrical energy is fed into the cavity by means of a longitudinal slot in the side wall. At two opposite points in the slot are impressed the exciting potentials. The slot is roughly $\frac{\lambda}{2}$ in length, so that there is high impedance between the potentials, which prevents shorting of the potentials. No antenna or probe need be inserted into the cavity; excitation is from the surface of the chamber.

P39 - Cavity Resonator, by H. Buchholz, U. S. Pat. 2,315,313, filed July 12, 1940, issued March 30, 1943.

A cavity surrounded by conducting material is used as a resonant LC circuit. This type of circuit is especially suited for ultra-short waves, since for this region the physical dimensions of the cavities are conveniently small. The cavity has an infinite number of discrete resonant frequencies above some minimum resonant frequency which is determined by the dimensions and shape of the cavity. Electrical energy is introduced into the cavity by means of dipoles or loops projecting into the cavity. The shape of the cavity is arbitrary; cylindrical and rectangular shapes are most suitable because they may be easily analyzed theoretically.

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PATENTS (Continued)

P40 - Ultra-High Frequency Signaling, by G. C. Southworth, U. S. Pat. 2,106,771, filed April 11, 1936, issued February 1, 1938.

In this patent various cavity resonators and other apparatus for various purposes are described. A cavity with a variable piston tuning device is coupled to a wave guide through a coupling hole. Crystal and other detecting devices are shown in the resonant cavities. Barkhausen and other oscillators are suggested for use as sources of microwave energy. Resonant cavity designs are suggested for reception of electric waves and for the amplification of electric waves.

P41 - Electric-Circuit Element, by W. L. Barrow, U. S. Pat. 2,281,550, filed August 14, 1937, issued May 5, 1942.

Resonant cavities of various shapes and design are discussed. Their use as high frequency low-loss resonant LC circuits is indicated. Methods are discussed of coupling the cavities to sources of energy. The adjustment of the resonant frequencies by means of a tuning piston is mentioned. A discussion of the types of fields possible in such cavities is given.

P42 - Temperature Compensated Resonant Cavity, by A. D. Ehrenfried, U. S. Pat. 2,600,225, filed March 29, 1946, issued June 10, 1952.

This cavity is compensated for change of frequency due to temperature changes. The apparatus accomplishing this also can be used to tune the cavity.

The cavity is of cylindrical shape with flat end plates. Around the cylindrical wall is an annular portion of the cavity. On either side of the annular ring are clamping rings which make contact with the annular cavity ring through ring-shaped fulcrums concentric with the cavity axis. The clamps have a very small temperature coefficient of expansion, so that the distance between

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the two clamps does not vary with temperature. An expansion of the cavity wall will tend to increase the height of the annular ring section of the cavity. This will cause a distortion of the annular ring such that the inner portion will be compressed, and the total cavity length will be unchanged, if the proper adjustments are made. The clamps may be moved and will result in the alteration of the cavity length, which enables the cavity to be tuned.

P43 - Cavity Resonator Mode Suppression Means, by H. B. Brehm, U. S. Pat. 2,593,095, filed June 29, 1946, issued April 15, 1952.

This cavity is designed to suppress TE modes. To accomplish this, radial slits are placed in the end plates and longitudinal slits are placed in the cylinder wall.

P44 - Cavity Resonator, by I. G. Wilson, U. S. Pat. 2,593,234, filed May 12, 1945, issued April 15, 1952.

A resonant cavity with movable end plates for tuning is constructed to operate in a TE_{0mn} mode, and embodies suppression techniques to inhibit undesired modes. Movable end plates with back cavities are provided at both ends of the cylinder. In one case the periphery of the end plate is tapered so as to reduce the capacitance between the end plate and cylinder wall. This causes a relatively large change in the resonant frequency of those modes, most notably the companion TM modes, that have electric field existing across the gap. In another instance, the end plate has a rearward-extending annular flange whose length is such that the energy leakage for the desired mode will be minimum. Also the end plates may have annular slots concentric with the axis to inhibit current flow for non-TE_{0mn} modes. In another case, small holes arranged along circles concentric with the axis are used to suppress the undesired modes.

PATENTS (Continued)

P45 - Electrical Cavity Resonator for Microwaves, by R. W. Marshall, U. S. Pat. 2,587,055, filed December 6, 1946, issued February 26, 1952.

A high-Q cavity resonator operates in the TE_{01n} mode, and has a crystal and meter to detect the presence of microwave energy. The instrument has both a tuned and untuned input, the latter conducting the microwave energy directly to the detector. A resistive attenuator projects from the cylinder wall of the cavity and is designed to lower the Q for extraneous modes, but affects only slightly the Q of the desired mode. The tuned input is an input transducer consisting of a section of waveguide coupled to the cavity by an orifice and is excited by a probe input. The untuned input leads to a similar waveguide section, but which is loaded at one end by its characteristic impedance, giving the effect of an infinite line. This guide is coupled by a directional coupler to a chamber in which the crystal detector is situated. The directional coupler is needed because the cavity also is connected to this detector chamber and it is desired to avoid exciting the cavity from the untuned input.

P46 - Method and Means for Measuring Microwave Frequencies, by R. L. Sproull, U. S. Pat. 2,580,968, filed November 28, 1945, issued January 1, 1952.

In this invention, the resonant frequency of a resonant cavity may be obtained by comparison with the resonant frequency of a standard cavity. In essence, a frequency-modulated microwave signal generator has its output fed into the two cavities, and the output of each, after detection by crystals, is viewed on an oscilloscope. These potentials are applied to the vertical plates, while the horizontal sweep is obtained with the modulation voltage. Two resonance curves, one for each resonator, are seen on the oscilloscope. When the two resonance curves coincide, the two resonant cavities are at equal frequencies.

PATENTS (Continued)

P47 - Tunable Resonance Chamber, by W. F. Kannenberg, U. S. Pat. 2,573,148, filed April 3, 1945, issued October 30, 1951.

A tunable resonant cavity is used to test radar equipment. This cavity operates in the TE_{01n} mode and has concentric circular slits in the end plates to suppress the extraneous modes, particularly the companion TM_{11n} mode. Microwave energy is coupled to the cavity by means of a probe-excited waveguide which is coupled to the cavity at the stationary end plate by means of a coupling orifice. Each end plate has a gap between its periphery and the cylinder wall, which leads into a back cavity containing absorbing material. This aids in the suppression of undesired modes. The stationary end plate has adjustments to align it parallel to the movable end plate.

The feed section wave guide has an electrical wavelength $m \frac{\lambda}{4}$, where m is an even integer. The guide has a switch which can cut off the energy flow to the cavity; this switch is located a distance $n \frac{\lambda}{4}$ from the input end of the guide where n is an odd integer. In order that this electrical distance always be $n \frac{\lambda}{4}$, regardless of the resonant frequency, provision is made to depress the waveguide wall to alter the wavelength in the guide. This depressing mechanism operates with the tuning mechanism.

P48 - Variable Frequency Cavity Resonator, by E. G. Martin, U. S. Pat. 2,562,323, filed April 24, 1945, issued July 31, 1951.

This cavity resonator has for its walls a series of overlapping plates which make contact with each other and, in conjunction with a pair of end plates, form a completely enclosed cavity. The plates are constructed to move radially while still making contact with each other, which alters the size of the cavity but does not change the shape of the cross-section. In this manner, the resonant frequency can be varied.

PATENTS (Continued)

P49 - Cavity Resonator, by A. E. Kerwien, U. S. Pat. 2,560,353, filed March 16, 1945, issued July 10, 1951.

The cavity resonator of this invention is of the cylindrical type and operates in a TE_{0mn} mode. The energy is fed into the cavity through radial slits in the end plates, symmetrically arranged about the axis of the plate; the cavity thus has a multiple feed system.

P50 - Constant Frequency Cavity Device, by R. L. Carnine, et al, U. S. Pat. 2,553,811, filed November 23, 1949, issued May 22, 1951.

This invention is a coaxial cavity which is designed for use as a resonator. The cavity consists of two pairs of concentric conductors, each pair consisting of an inner and an outer conductor. These pairs overlap and provision is made for movement of one of the pairs relative to the other. This permits changes in the cavity length. The cavity is mounted on a series of rods joining the end plates; the rods have a relatively low coefficient of expansion and keep the cavity length constant under changes of temperature. The expansion of the cylinder walls is accompanied by a sliding of the coaxial rod pairs over each other, while the cavity length remains unchanged.

P51 - High-Frequency Electrical Resonator, by N. L. Harris, et al, U. S. Pat. 2,551,672, filed January 22, 1947, issued May 8, 1951.

A cavity of toroidal shape has flat end plates and a tubular side wall. The side wall is designed to move radially by sliding its edges along the surface of the end plates. In this manner the volume of the cavity may be altered and the cavity tuned.

PATENTS (Continued)

P52 - Radar System Test Equipment, by W. W. Hansen, et al, U. S. Pat. 2,539,511, filed July 8, 1942, issued January 30, 1951.

This test equipment is an echo box with a pickup dipole and meter detector. The cavity may be either cylindrical or rectangular. The input coupling devices may be probes, loops, or orifices. Tuning is accomplished for the cylindrical cavities by movement of the end plate plunger. The resonant cavity may support more than one mode, and resistance wires may be mounted in the cavity so that they are perpendicular to the electric lines for the desired mode, but extraneous modes will have a component of electric field parallel to the wires. This will tend to damp out the unwanted modes without affecting the operating mode.

P53 - Resonant Electrical Arrangement, by B. A. Bels, U. S. Pat. 2,533,912, filed December 4, 1946, issued December 12, 1950.

This invention is a tunable concentric line resonant cavity in which temperature compensation is achieved by the use of three metals with different temperature coefficients of expansion in the construction of the cavity. The metals are so distributed that the depth of insertion of the central conductor (which does not extend the full cavity length) does not change with temperature.

P54 - Electrical Resonator and Mode Suppressor Therefor, by H. B. Brehm, et al, U. S. Pat. 2,527,619, filed August 1, 1946, issued October 31, 1950.

The cavity described herein is a high Q resonator operating in a desired TE_{01n} mode and having thin plates of lossy material placed at electric nodal planes for the desired mode. These plates are to be in a region of high electric intensity for the undesired mode. If necessary, a movable support may be had for

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these plates, so that as the cavity is tuned by movement of the end plate, the absorption plate may remain in a nodal region for the desired mode.

P55 - Variable Coupling Tunable Microwave Resonator, by E. G. Linder, U. S. Pat. 2,524,532, filed February 27, 1946, issued October 3, 1950.

In this invention, the coupling to a resonant cavity may be made to vary with the tuning of the cavity in some prescribed manner. In one embodiment of the invention a probe projects through a tuning piston (axial movement of which varies the cavity frequency) and into a narrow recess in the opposite wall. As the plunger is moved inward, the probe moves with the piston, more of the probe moving into the recess on the opposite wall and leaving less of the probe to excite the cavity. In various other embodiments of the invention, a coupling loop may alter its area as the cavity is tuned, or the loop may change its orientation, or the size of a coupling orifice may change with position of the tuning plunger.

P56 - Capacitively Tuned Concentric Line Resonator, by A. A. MacDonald, et al, U. S. Pat. 2,523,128, filed March 13, 1948, issued September 19, 1950.

This cavity is a concentric line resonator which is tuned, not by a movable end plate as is the case with conventional cavities, but by two pairs of plates located at one end of the cavity which capacitively load the cavity. One pair is adjustable which enables the cavity to be tuned by altering the capacitance between these plates.

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PATENTS (Continued)

P57 - Multi-Resonant Cavity Resonator, by S. A. Schelkunoff, U. S. Pat. 2,518,383, filed August 1, 1945, issued August 8, 1950.

An untuned cavity is used for an echo box. It is desired that the cavity have a large number of resonant frequencies very close together in the frequency range for which it is to be used. To accomplish this, the cavity, which is in the form of a rectangular prism, is built so that its three dimensions are all different. This design eliminates degeneracies, which gives more resonant frequencies. In addition, if some corners be cut off from the prism through a region near the corner of the prism, the number of resonances will be further increased, particularly if the lengths of the corners cut off are not equal and if the triangular faces of the new sections have no two sides equal.

P58 - Ultra-High Frequency Wavemeter, by E. L. Ginzton, et al, U. S. Pat. 2,503,256, filed January 29, 1943, issued April 11, 1950.

This wavemeter, in one embodiment, consists of a concentric line cavity. A sleeve separates this cavity from a back cavity. The coupling between the cavities consists of a gap between the sleeve and the inner conductor. The gap is $\lambda/4$ in length, which gives zero impedance looping from the main to the back cavity. This device permits the central conductor to be adjustable (for tuning purposes) without the necessity of providing electrical contacts between the movable center conductor and the cavity end wall.

P59 - Tuning Mechanism for Resonant Cavities and the Like, by E. G. Martin, U. S. Pat. 2,501,728, filed May 25, 1944, issued March 28, 1950.

This tuning mechanism comprises a flexible diaphragm in

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PATENTS (Continued)

one end of a cavity, and secured at the edges. Movement of a tuning knob imparts motion to a threaded screw which presses against the diaphragm causing it to be forced inward, altering the cavity volume.

P60 - Tuning Mechanism for Hollow Electrical Resonators, by N. C. Barford, U. S. Pat. 2,501,303, filed September 15, 1945, issued March 21, 1950.

This tuning mechanism is used with a resonant cavity and accomplishes tuning by movement of the cavity wall. The adjustable element is arranged to pivot about two axes; movement about one of the axes constitutes coarse tuning, while movement about the other constitutes fine tuning.

P61 - Cavity Resonator, by W. E. Bradley, U. S. Pat. 2,496,772, filed July 12, 1944, issued February 7, 1950.

In this invention a resonant cavity is designed to resonate in two different modes with different frequencies; one of these modes may be tuned while the frequency of the other remains unchanged. This is done by inserting into the cavity a sheet of conducting material which is always parallel to the magnetic field and normal to the electric field for the constant frequency mode, but which is not so oriented in the case of the tunable mode. Varying the depth of insertion of the conducting sheet changes the frequency of the latter mode, but not that of the former.

P62 - Electrical Cavity Resonator, by G. L. Usselman, U. S. Pat. 2,487,619, filed November 16, 1943, issued November 8, 1949.

A resonant cavity has curved vanes arranged symmetrically about the cavity axis. These vanes overlap one another, and the extent of overlap determines the resonant frequency of the cavity.

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By a tuning arrangement the vanes may be drawn inward, increasing the amount of overlap, and decreasing the volume of the cavity, thus increasing the resonant frequency. The cavity end plates are flat and stationary.

P63 - Resonant Circuits for Ultra-High Frequencies, by Fernand Bac, French Pat. 960.764, filed February 22, 1944, issued November 7, 1949.

This patent purports to be a hybrid cavity and describes a tuning mechanism which, in addition to tuning, aids in inhibiting unwanted modes. The resonant frequency of the dominant mode is determined by the diameter of the cylinder.

P64 - Ultra-High Frequency Measuring Device, by W. E. Bradley, U. S. Pat. 2,483,802, filed June 20, 1944, issued October 4, 1949.

This invention employs an untunable resonant cavity as a wavemeter. The output of a sweeping oscillator is applied to a multiple-resonant cavity, and the output of this cavity is detected and applied to the vertical plates of a cathode ray oscilloscope. The sweep of the oscilloscope is synchronized with the sweep of the oscillator. Hence, the cavity output spectrum is seen on the scope. An unknown frequency is applied to another detector, which also receives the output of the sweeping oscillator. These two signals beat and the difference frequency is applied to the cathode ray tube, this signal being superimposed on the cavity spectrum. The position at which the beat frequency is zero can be seen on the scope and its position relative to the cavity spectrum can also be seen. Since the cavity spectrum is known, the frequency of the unknown signal is then found by noting its position on the cavity spectrum.

PATENTS (Continued)

P65 - Improvements in or Relating to Cavity Resonators, British Pat. 627,513, filed October 10, 1946, issued August 10, 1949.

See U. S. Patent No. 2,593,234, filed May 12, 1945, issued April 15, 1952.

P66 - Temperature Compensated Microwave Device, by E. G. Linder, U. S. Pat. 2,475,035, filed November 8, 1944, issued July 5, 1949.

A resonant cavity is filled with a gas whose dielectric constant is an inverse function of temperature. This arrangement is used to compensate for frequency changes due to change of temperature. An increase of temperature will tend to reduce the resonant frequency by altering the cavity dimensions and will tend to increase the resonant frequency by decreasing the dielectric constant of the gas. The gas and the pressure to be used are selected so that these two tendencies will cancel each other, making the resonant frequency independent of temperature.

P67 - Tunable Resonant Cavity with Adjustable Walls, by W. A. Edson, et al, U. S. Pat. 2,471,419, filed July 7, 1944, issued May 31, 1949.

This device is a resonant cavity used for testing radars. One of the end plates is movable, by which means the cavity is tuned. This end plate is moved by means of a motor, imparting to the plunger a reciprocating motion over a small range. This effectively makes the cavity tuned to a small but definite band of frequencies rather than to a single frequency, so that if the frequency of the radar under test shifts somewhat, the resonant cavity will yet be tuned to the radar.

The energy enters the system through a pickup dipole and the dipole is coupled to the cavity through coaxial cable and a coupling loop situated at the stationary end plate. This coupling loop is retractable and does not project into the cavity except when the cavity is in operation.

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PATENTS (Continued)

The stationary end plate is backed by a pivot and leveling screws to bring it into accurate parallelism with the other end plate.

P68 - Variable Cavity Resonator, by J. T. Beechlyn, U. S. Pat. 2,473,777, filed May 17, 1945, issued June 21, 1949.

This cavity may be tuned by altering its shape. In one embodiment the cavity consists of an inner and outer conductor concentric with the cavity axis and octagonal in cross-section. The two end walls are parallel. The cavity shape is changed by application of pressure to the end plates, which results in the side wall plates being bowed, the outer wall plates being bowed inward and the inner wall plates outward.

P69 - Electrical Apparatus, by J. Halpern, U. S. Pat. 2,473,426, filed September 6, 1945, issued June 14, 1949.

The cylindrical cavity of this invention may be tuned by means of an end plate plunger. The other end plate is a diaphragm which may be forced to vibrate, thus periodically altering the resonant frequency and frequency modulating the cavity output.

P70 - Tunable Cavity Resonator, by F. A. Record, U. S. Pat. 2,463,423, filed December 17, 1945, issued March 1, 1949.

The cavity described here is elliptical in cross-section and has extruding folds across the center. Pressure applied to the ends of the cavity will cause an increased extrusion of the folds, altering the shape of the cavity and its resonant frequency. This permits a wide tuning range for the cavity.

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PATENTS (Continued)

P71 - Improvements in or Relating to Electrically Resonant Cavities, by Philips Lamps, Ltd., British Pat. 613,479, filed May 31, 1946, issued November 29, 1948.

See U. S. Patent No. 2,528,387, filed May 9, 1946, issued October 31, 1950.

P72 - Electric Resonance Chamber, by Western Electric, French Pat. 939.451, filed December 24, 1946, issued April 19, 1948.

Same as English Patent No. 605,300.

P73 - Cavity Resonator, French Pat. 943.059, filed March 12, 1947, issued September 27, 1948.

See U. S. Patent No. 2,527,619, filed August 1, 1946, issued October 31, 1950.

P74 - Wavemeter for Ultra-Short Waves, by Thomson-Houston Company of France, French Pat. 936.708, filed April 16, 1946, issued February 3, 1948.

This patent described a cylindrical type wavemeter operating on TE_{01n} mode with an air or dielectric 1/4 wavelength gap at the end wall. This gap is intended to suppress undesired modes.

P75 - Improvements in or Relating to Electrical Resonance Chambers, by Western Electric Company, British Pat. 605,300, filed December 19, 1945, issued July 20, 1948.

This device is a cylindrical cavity with a gap at the tuning plunger. Dielectric rings are introduced for suppressing unwanted modes.

PATENTS (Continued)

P76 - Cavity Resonator Circuit, by P. S. Carter, U. S. Pat. 2,444,152, filed July 15, 1944, issued June 29, 1948.

The cavities of this invention are used as passband filters. It is desired to obtain a wide passband without lowering the Q of the cavity. This is accomplished by exciting the cavity in two or three of its lower modes, and designing the cavity so that the resonant frequencies for these modes will lie close together, sufficiently close so that the passband for each mode will overlap that of the adjacent mode. There are several embodiments of this invention; the cavity may be a rectangular prism with two or all three sides unequal, or it may be an elliptical cylinder.

P77 - Tuning Device for Cavity Resonator, by Telefunken Co., Swedish Pat. 114,731, filed June 10, 1943, issued June 28, 1945.

A cavity resonator, formed by a cylinder and two flat end plates has a coaxial cable connected to it. This cable is so arranged that the outer conductor goes to one of the end plates while the inner conductor extends across the cavity interior to the opposite end plate. A movable shorting plunger in the coaxial cable permits the cavity to be tuned. The point of connection of the coaxial cable and the wave resistance of the resonator are chosen so that the tuning rate for the tuning plunger will be that desired, and the tuning curve will be linear.

P78 - Improvements in or Relating to Electrically Resonant Cavities, by Philco Radio and Television Corp., British Pat. 603,119, filed October 24, 1945, issued June 9, 1948.

This patent describes mode suppression techniques in resonant cavities. Either one of the two following conditions may be obtained:

PATENTS (Continued)

1. One TE_{1mn} mode may be sustained and all other such modes suppressed,

2. TM modes may be favored and all TE modes inhibited. This suppression is accomplished by means of rings or by slots of nonconducting material in the cavity wall, which interrupt the flow of current for undesired modes.

P79 - Resonant Cavity Tuning Device, by H. E. Tompkins, U. S. Pat. 2,442,671, filed February 29, 1944, issued June 1, 1948.

In this invention, a resonant cavity is constructed of conductive stationary walls and is tuned over a relatively wide range by means of a rotatable tuner within the cavity. The axis of the tuner is transverse to both electric and magnetic fields. Movement of this tuning piece causes change in resonant frequency because of both the effect on the electric and on the magnetic field. Hence, a greater range of tuning is possible than if but one of these fields were affected.

P80 - Improvements in or Relating to a Resonator Wavemeter, by Sperry-Gyroscope Co., British Pat. 599,487, filed March 3, 1943, issued March 15, 1948.

See U. S. Patent No. 2,439,388, filed December 12, 1941, issued April 13, 1948.

P81 - Tuning Arrangement for Concentric Transmission Line Resonators, by A. M. Gurewitsch, U. S. Pat. 2,435,442, filed December 23, 1943, issued February 3, 1948.

This resonant cavity of the concentric transmission line type comprises an outer and an inner conductor. Tuning is accomplished in a novel way. Instead of varying the cavity length by means of an adjustable end plate, the cavity is capacitively tuned. Two concentric rings are attached at the end of

PATENTS (Continued)

the cavity, one to the inner conductor and one to the outer. A third ring is placed in the cavity and makes no contact with either ring, but is in close proximity with them. Movement of this ring varies the capacitance between the movable ring and the two stationary ones and changes the resonant frequency of the cavity.

P82 - Method and Apparatus for Tuning Cavity Resonators, by Rudolph A. Dehn, U. S. Pat. 112,066.

This device is an open inductive loop having its ends capacitively coupled. The loop is introduced into the cavity and provision is made for tuning the loop, which in turn tunes the cavity.

P83 - Electrical Resonator, by C. P. Carlson, et al, U. S. Pat. 2,426,177, filed June 10, 1944, issued August 26, 1947.

This resonator is a cylindrical cavity with a movable end plate, and is used as an echo box for radar test purposes. The movable end plate has a reciprocating motion and is motor driven. This enables the cavity to be resonant to a much wider frequency band than would be the case if the end plate had no reciprocating motion. Energy is coupled to the cavity by means of a pickup dipole and coaxial cable terminating in a coupling loop in the resonant cavity.

P84 - High Frequency Resonator and Circuits Therefor, by P. S. Carter, U. S. Pat. 2,424,267, filed May 16, 1944, issued July 22, 1947.

Here resonators in the forms of rectangular prisms, right elliptical cylinders and oblate spheroids are used as band-pass filters. The cavities are constructed so that there are two resonant frequencies lying close together. This gives a wider bandpass and yet maintains a high Q. These cavities are excited by a loop or probe and another loop or probe is used to couple the load to the cavity.

[redacted]

PATENTS (Continued)

P85 - Wavemeter, by S. D. Lavoie, U. S. Pat. Re. 22,894, original filed September 24, 1941, issued July 1, 1947.

The wavemeter described here consists of a hollow cavity with metal portions extending from opposite walls toward each other, but not making contact. These two metal portions form a condenser which supplies capacitance to the cavity. The cavity is tuned by varying the width of the gap between these two metal portions. Means are provided for the introduction of energy into the cavity.

P86 - Wide Range Tuner for Cavity Resonators, by R. S. Julian, U. S. Pat. 2,418,839, filed May 12, 1943, issued April 15, 1947.

This cavity, which is in the shape of a cylinder, is tuned by means of a rod extending into the cavity, this rod having its axis parallel to the end plates.

P87 - Variable Cavity Resonator, by J. C. Schelleng, U. S. Pat. 2,410,109, filed February 13, 1943, issued October 29, 1946.

A resonant cavity of rectangular shape is tuned by movement of one or two end plates. The end plates here instead of being flat have a more complex curvature. This is done so that an oscillator tube projecting into the cavity will not limit the minimum closure of the end plates. The end plates are shaped so that the cavity volume may be made extremely small without the tubes obstructing the end plate movement.

P88 - Frequency Adjustment of Resonant Cavities, by D. H. Ring, U. S. Pat. 2,406,402, filed September 3, 1941, issued August 27, 1946.

A resonant cavity may be tuned by the insertion of a metallic plug or screw into the cavity. If this screw be of dielectric

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PATENTS (Continued)

material, the frequency change will be in the opposite direction to that of the metallic screw inserted at the same place. The use of both metallic and dielectric screws will give an increased tuning range.

P89 - Cavity Resonator, by D. E. Branson, U. S. Pat. 2,477,232, filed March 28, 1945, issued July 26, 1949.

This invention consists of three concentric conducting cylinders, closed at the ends by conducting plates, thus forming two concentric coaxial cavities. Movement of one of the end plates enables the cavities to be tuned. Good electrical contact between the movable plates and the cavity wall is obtained by constructing these plates of a fabric-like conducting material on the outside, with an interior cushion of resilient non-conductive material.

P-90 - Improvements in Electric Resonant Chambers, by E. B. Moullin, British Pat. 572,781, filed April 30, 1943, issued October 23, 1945.

This invention is a coaxial cylindrical cavity into which a fixed and a rotating radial surface are introduced. The central cylinder rotates with the rotating radial surface so as to vary the ~~radial~~ resonant frequency continuously. Methods for suppressing unwanted modes in the device are included.

P91 - Low Loss Tuning Apparatus, by W. L. Carlson, U. S. Pat. 2,363,641, filed April 1, 1942, issued November 28, 1944.

In this coaxial resonant cavity, the empty space between inner and outer conductor contains another pair of concentric lines as an additional tuning section, permitting a reduction in the over-all size of the cavity. This multi-cavity tuner has all the advantages of a single cavity tuner without any substantial increase in size.

PATENTS (Continued)

P92 - High Frequency Resonator and Circuit Therefor, by P. S. Carter, U. S. Pat. 2,357,313, filed October 1, 1940, issued September 5, 1944.

These resonant cavities are used as band-pass filters. The cavities are arranged to be excited in two different modes whose frequencies differ by a predetermined percentage. In one case, the resonator is in the form of a hollow rectangular prism while in another, the resonator is in the form of an elliptical cylinder.

P93 - Tunable Resonant Cavity Device, by E. G. Linder, U. S. Pat. 2,356,414, filed February 26, 1941, issued August 22, 1944.

The cavity of this invention may be in the shape of a toroid or any one of numerous other shapes. The invention consists of the use of a conductive reed suspended from the cavity wall and hinged so that rotation of the reed is possible. In this manner, the resonant frequency and the cavity Q can be varied.

P94 - Tuning of Resonant Cavities, by C. Lorenz Aktiengesellschaft, French Pat. 894.787, filed May 18, 1943, issued March 20, 1944.

A method of tuning a resonant cavity is as follows: a small piece of material with a large dielectric constant is inserted into a cavity. The form and the position (which is variable) of this material is contrived so that its movement will alter the resonant frequency.

P95 - Tuned Circuit and Associated Devices Therefor, by P. S. Carter, U. S. Pat. 2,323,201, filed January 7, 1939, issued June 29, 1943.

A high frequency resonant cavity has the outer conductor in the shape of a sphere, and has two re-entrant cone-shaped portions, so that the cavity somewhat resembles an hour-glass. The apices of the cones are flattened to increase the capacitance between the cones.

PATENTS (Continued)

P96 - A Hollow Conductor for Ultra-High Frequency Oscillations, by Julius Pintsch, Kommandit Gesellschaft, French Pat. 880.564, filed March 26, 1942, issued January 4, 1943.

This patent deals with coaxial and parallelepiped cavities. The cavities are used as mixers, filters, and selectors. A signal and the local oscillator excite the cavity in two modes, which are independent of each other. Each mode is dependent on a certain dimension or ratio of dimensions of the cavity. The detection of beat frequencies is accomplished by coupling to diodes.

P97 - Tuning Arrangement for Cavity Resonators, by A. L. Samuel, U. S. Pat. 2,306,282, filed June 28, 1941, issued December 22, 1942.

The tuning arrangement described herein is used for cavities supporting an electron beam. The cavity, which is of cylindrical shape, has a slot in the wall parallel to the cavity axis and a plate slides through this slot into the cavity to accomplish tuning. By coupling the plate to a motor driven cam, the cavity may be frequency modulated.

P98 - Tuned Oscillatory Circuit, by S. Koch, et al, U. S. Pat. 2,292,880, filed May 17, 1941, issued August 11, 1942.

This invention consists of a cylindrical resonant cavity with central rods extending from the end plates along the cylinder axis, and separated by a gap in the center of the cavity. A conducting disk is situated in the cavity between the two conductors and is designed to move from regions of large electric field to regions of large magnetic field. In this manner the resonant frequency of the cavity may be adjusted.

PATENTS (Continued)

P99 - Concentric Resonant Line, by C. W. Hansell, U. S. Pat. 2,286,408, filed April 17, 1938, issued June 16, 1942.

This concentric line resonator is designed to overcome two defects inherent in previous line resonators: (1) the end plate where the two conductors are joined will be distorted as the temperature changes, but it will not be known whether the plate will bow outward or inward; (2) the region where the central conductor contacts the end plate will vary as the end plate is distorted. The first defect is overcome by bowing the end plate, so that the direction of additional warping will be known. The second defect is overcome by having the end plate contact the central conductor through a wedge shaped conductor, which enables the point of contact between conductor and end plate to be accurately known for all temperatures.

P100 - Tuning Device, by I. E. Mouromtseff, et al, U. S. Pat. 2,263,184, filed October 9, 1940, issued November 18, 1941.

This tuning device is used to tune a cavity in which a beam of electrons passes. The resonant frequency of the electron discharge will depend upon the width of the gap across which the beam passes. The gap distance is varied by depressing the cavity wall in the region of the gap. To accomplish this, the cavity wall in this region is made slightly flexible and a mechanical means of forcing the cavity inward is contrived.

P101 - Frequency Stabilization at Ultra-High Frequencies, by F. B. Llewellyn, U. S. Pat. 2,262,020, filed January 15, 1938, issued November 11, 1941.

The resonant cavity described here is cylindrical with flat end plates and has a length of at least 1/4 of its diameter.

PATENTS (Continued)

Through the center of one of the end plates projects a conducting rod which is insulated from the cavity wall. This conductor terminates on a conducting disk within the cavity which has a diameter of about 1/5 the cavity diameter, and is situated about L/5 or less from the end plate through which the conducting rod projects, where L is the cavity length. This device constitutes the coupling to the cavity, through which microwave energy is introduced.

P102 - Short Electromagnetic Wave Oscillatory Circuit, by J. M. Unk, U. S. Pat. 2,251,085, filed March 9, 1940, issued July 29, 1941.

A resonant cavity consists of two concentric cylindrical conductors, joined together at one end and the inner one designed to move relative to the outer one, to accomplish tuning. Electrically connected to the other end of the central conductor and to the outer conductor is a diaphragm. The diaphragm serves to capacitively couple the inner and outer conductor.

P103 - Wavemeter, by D. D. Zottu, U. S. Pat. 2,245,138, filed January 21, 1937, issued June 10, 1941.

This wavemeter consists of a cylindrical cavity into which extends a conducting rod. Movement of the end plate to which the conducting rod is attached results in the tuning of the cavity. In another form of the invention the central rod has a metallic disk at its free end, providing capacitance between the disk and end plate, which permits the cavity to be shorter than would otherwise be the case.

P104 - Frequency Indicator, by W. H. C. Higgins, U. S. Pat. 2,235,521, filed July 26, 1939, issued March 18, 1941.

This frequency indicator is a concentric line cavity with a

PATENTS (Continued)

central conducting rod extending along the cavity axis, but not the full cavity length. Mounted within the cavity is a diode which is used as a detector.

P105 - Temperature Cycling, by C. W. Hansell, U. S. Pat. 2,205,851, filed April 1, 1938, issued June 25, 1940.

Resonant line cavity resonators tend to alter their resonant frequency over a period of years due to the fact that the metal composing the cavity has stresses introduced during the manufacture of the cavity. These stresses cause a slow alteration of the cavity shape. This invention constitutes a method of reducing these dimensional changes by subjecting the resonator, after manufacture, to extremes of heat and cold.

P106 - Ultra-Short Wave Apparatus, by H. O. Peterson, U. S. Pat. 2,201,199, filed April 2, 1934, issued May 21, 1940.

This apparatus consists of two cylindrical cavities, one residing within the other. These cavities are used as oscillatory circuits, generally with the surface of the inner cavity and that of the outer connected to different elements of a vacuum tube used as an oscillator.

P107 - Electromagnetic Resonator, by W. Dällenbach, U. S. Pat. 2, 199, 045, filed January 29, 1937, issued April 30, 1940.

The resonator described herein is in the shape of a torus. Energy is admitted to this cavity by means of a gap on the inner equator of the torus, which couples the cavity to a line which extends through the center of the torus.

P108 - Wavemeter, by A. E. Bowen, U. S. Pat. 2,106,713, filed April 21, 1936, issued February 1, 1938.

PATENTS (Continued)

This wavemeter is a coaxial line with a shorting end plate at one end, the position of which is adjustable. At the other end a probe projects into a waveguide for the purpose of abstracting a convenient, but negligibly small, amount of energy from the guide. The depth of insertion of the probe can be adjusted. A meter and detecting crystal are coupled to the coaxial line and detect the presence of standing waves. Wavelength is measured by moving the shorting end plate outward and finding the positions of resonance. Resonance will occur every time the line is increased by $\lambda/2$. Frequency is found from the relation $f = c/\lambda$.

P109 - Low Power Factor Line Resonator, by J. W. Conklin, et al, U. S. Pat. 2,103,515, filed August 31, 1935, issued December 28, 1937.

A line resonator consists of an inner and outer conductor, with shorting plates on the ends of the outer conductor. The inner conductor is electrically connected to the outer conductor through one of the end plates, while the other end of the inner conductor is free. At this end there is an adjustable element consisting of a bellows or a sliding part, which permits adjustment of the length of the central conductor. This permits the cavity to be tuned. The movable element is fastened to the end plate by means of a rod which extends through the central conductor and which has a very low temperature coefficient of expansion. This causes the length of the inner conductor, and hence, the resonant frequency, to be independent of temperature fluctuations.

P110 - High Frequency Wavemeter, by G. L. Grundmann, U. S. Pat. 2,086,615, filed April 9, 1936, issued July 13, 1937.

The wavemeter described herein is a cylindrical resonant cavity with a central conductor extending along the axis throughout

PATENTS (Continued)

a portion of the cavity. Tuning is accomplished by varying the depth of insertion of the rod. The rod is removable and rods of various lengths may be substituted, each rod making possible a different range of frequencies.

P111 - Electromagnetic Resonator, by Julius Pintsch Aktiengesellschaft, French Pat. 817.017, filed January 29, 1937, issued May 15, 1937.

Same as U.S. Patent No. 2,199,045, filed January 29, 1937, issued April 30, 1940.

P112 - Oscillation Circuit for Electric Waves, by H. O. Roosenstein, U. S. Pat. 1,955,093, filed July 7, 1930, issued April 17, 1934.

This oscillatory circuit is of the concentric line type, enclosed at both ends by end plates. At one end are two sets of plates, one movable and one stationary, which serve as a variable capacitor for tuning purposes.

P113 - Electromagnetic Cavity Resonator with High Q, by N. V. Philips Gloeilampenfabrieken, Swiss Pat. 270,382, filed July 27, 1948, issued August 31, 1950.

This cavity is designed so as to give high Q without lowering the frequency or operating in higher modes. In general, the Q of a cavity is increased by increasing the size. This, however, lowers the resonant frequency unless one goes to higher modes. In this invention the frequency is maintained while still operating in the lower mode. To do this, the cavity is constructed of a number of congruent figures with plane surfaces, in which bordering figures each share jointly a whole side surface and are so arranged that the cavity cannot be constructed from larger multilaterally congruent figures. The cavity will then be resonant to a frequency equal to the resonant frequency for one of the constituent geometric figures. Frequencies lower than this will be inhibited.

PATENTS (Continued)

P114 - A Tunable Electromagnetic Resonant Cavity, N. V. Philips Gloeilampenfabrieken, Swiss Pat. 250,195, filed May 31, 1944, issued August 15, 1947.

This cavity resonator is in the shape of a rectangular prism. The cavity is tuned by altering one of the cavity dimensions. By selecting the longest direction as the one of variable length, the cavity tuning rate may be made small, which will result in more exact tuning. The cavity is characterized by the fact that the excitation frequency is not more than 15 per cent greater than the cutoff frequency. This aids in decreasing the tuning rate. The invention is not restricted, however, to cavities of the above mentioned shape.

REPORTS AND TECHNICAL MANUALS

T1 - Development of an Echo Box for 130-150 MC/S Band, Report No. WLEAE-1-101, Watson Laboratories, A.M.C., Red Bank, N. J., 46 pages, September 1948. (Unclassified)

A design has been submitted for the development of an echo box for the 130 to 150 mcs band. A theoretical discussion of the design procedure is given. The desired characteristics are stated and their attainment discussed. It was decided to use a coaxial quarter wave length resonant cavity, operating on the TEM mode. This decision arose because hollow cavities without central conductors are too large at this low frequency band. A half wave coaxial cavity was also considered and regarded as somewhat less desirable because of its larger size and greater plunger motion required for tuning. Expressions for loaded Q and expected ring-time are developed and applied. In addition, there is contained in the appendix the development of a mode chart, and of expressions for power loss in the cavity, and for coupling by means of a coupling loop. Graphs and bibliography also are given.

T2 - Requirements for Echo Box for 130-154 MC/S Band, Exhibit No. WLENG-1167, Watson Laboratories, A.M.C., Red Bank, N. J., 12 pages, November 19, 1948. (Restricted)

A detailed list of the specifications for the 130-154 mcs echo box is given. The Joint Army-Navy Standard Specifications listed in AESA List No. 100, entitled "List of Approved Electronic Standards", apply to this exhibit wherever applicable. Other specifications also form a part of this exhibit. The specifications cover detailed requirements, inspection and test procedures, packing and marking.

T3 - Echo Box Application, by J. M. Wolf, Report 1040, Radiation Laboratory, Massachusetts Institute of Technology, 59 pages, April 18, 1946. (Unclassified)

REPORTS AND TECHNICAL MANUALS (Continued)

Echo boxes have been found the simplest tool for field measurement of absolute radar performance on all radars for which their use is suited. Needed are a reliable echo box, simple means for coupling to the radar, suitable means in the radar for measuring ringtime, and provision for predicting ringtime. Tests have been made to determine observation errors in ringtime measurements. These tests include ability of observer to repeat his measurements, agreement of different observers, effect of experience in reading ringtime, and the effect of factors such as pulse repetition frequency, presentation time, and scope persistence. The use of directional couplers is suggested. Criteria of good echo boxes and methods for testing echo boxes are discussed. Means for predicting "expected ringtime" are developed. Echo box tests include measurement of TR-box recovery, measurement of receiver band pass, spectrum and pulse length determination, and the localization of "jitter". (Author's abstract)

T4 - Instruction Book for Echo Box, Radar Test Equipment, Navy Model OBU-3, Ships 308(B), U. S. Navy Dept., Bureau of Ships, Johnson Service Co., Milwaukee, Wisconsin, May 21, 1945. (Restricted)

A general description of the OBU-3 echo box is given, along with directions for its installation, operation, adjustment, and maintenance. Topics include ringing time and its measurement, correlation with radar performance, and spectrum analysis with the echo box. Tests for over-all performance, transmitter power, frequency and frequency pulling, erratic transmitter operation, automatic frequency control performance, TR - box and receiver recovery, and transmission line loss are discussed. A brief, non-mathematical discussion of the basic theory is given. There are numerous graphs, diagrams, and illustrations, including sample radar test sheets.

REPORTS AND TECHNICAL MANUALS (Continued)

T5 - Echo Boxes TS-270/UP and TS-270A/UP, TM-11-1086, War Dept. Technical Manual, about 40 pages, June 14, 1945. (Unclassified)

A general description of the TS-270/UP echo box is given, along with directions for its installation, operation, adjustment, and maintenance. Topics include ringing time and its measurement, correlation with radar performance, and spectrum analysis with the echo box. Tests of over-all performance, transmitter power, frequency and frequency pulling, erratic transmitter operations, automatic frequency control performance, TR - box and receiver recovery, and transmission line loss are discussed. A brief, non-mathematical discussion of the basic theory involved is given. There are numerous graphs, diagrams, and illustrations, including sample radar test sheets.

T6 - Calculation of Expected Ringtime and Policy for Setting Rated Values and Maintenance Limits for Ringtime, Report 554, Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., 8 pages, July 28, 1945. (Unclassified)

An "intuitive" derivation for the ringing time of an echo box is given. Ringing time is taken to be proportional to:

1. Level difference between transmitter peak power and receiver sensitivity.
2. Twice the attenuation loss between echo box and radar.
3. Decrement of echo box.
4. Charging constant for echo box.

The results are applied to calculation of expected ringing time for the SS radar, and a rated peak ringing time of 5800 yards was obtained.

T7 - Review of Information on Resonant Cavities, Bell Telephone Laboratories, Case 23458-5, 3510, JPK-WY, about 70 pages, January 8, 1943. (Unclassified)

REPORTS AND TECHNICAL MANUALS (Continued)

The theory of resonant cavities is given, and formulas for the different modes of oscillation in terms of cavity parameters are derived. An extensive bibliography is contained. Curves and tables are presented to permit the calculation of the resonant frequencies and Q values of electrical cavity resonators of three simple shapes: the rectangular prism, the perfect cylinder, and the full coaxial formed by two coaxial cylinders.

T8 - Tuned Ringing Cavities Theory, Bell Telephone Laboratories, Case 23458-5, 3510, JPK-HS, 44 pages, December 2, 1943. (Unclassified)

An equation for the ringing time of a tuned resonant cavity is derived and experimentally verified. In another approach, the cavity is treated as a series resonant RLC circuit. The cavity is assumed to be representable by a two-mesh loosely-coupled circuit in which the Q of the primary is small compared to that of the secondary and the applied pulse is rectangular and of the same frequency as the reradiated frequency of the cavity. The use of Fourier series and the Fourier integral in analyzing the response of the cavity to a pulse is discussed, but because of the difficulties involved, a transient approach is indicated as preferable. Both lead to the same results. A bibliography is included.

T9 - The Resonant Echo Box, Report 55-1, Pamphlet by W. H. Fenn, Radiation Laboratory, Massachusetts Institute of Technology, 26 pages, September 4, 1942. (Unclassified)

The echo box described here consists of a high Q resonant cavity so coupled to the radar system as to produce an artificial echo signal extending two to three miles beyond the transmitted pulse. It is shown that the length of this signal can be used as a measure of system performance. With the resonator described, which has a Q greater than 20,000, a change of echo signal length

REPORTS AND TECHNICAL MANUALS (Continued)

of one microsecond is shown to result from a change of system performance of 4 db provided that the signal length is greater than the time taken for the T-R box to recover. Experimental results are given together with a description of echo box installations on airborne radar systems. (Author's abstract)

T10 - K-Band Echo Line, Report 974, by J. M. Wolf, Radiation Laboratory, Massachusetts Institute of Technology, 14 pages, January 1, 1941. (Unclassified)

An echo line is a long wave guide in which the radar pulse re-echoes, producing a series of pulses on the indicator for test purposes. The fabrication and testing of an 18" helix of oversize K-band wave guide 150' long is discussed. Tests showed the attenuation to be .029 db/ft, which suggests the use of such oversize wave guides for radar transmission lines.

T11 - Optimum Operation of Echo Boxes, by W. M. Hall and W. L. Pritchard, Raytheon Mfg. Co., Newton 58, Mass., 14 pages. (Unclassified)

The parameters determining ringing time for an echo box in a radar system are examined, and the conditions for optimum ringing time established. Two specific arrangements, namely, the echo box coupled through a directional coupler and through a test dipole, are treated in detail.

Representative curves of ringing time as functions of various parameters and curves of power extracted by the echo box are included. It will be seen that simply increasing the loaded Q of a cavity will not increase the ringing time past a certain maximum, and that there is an optimum value of loaded Q which is a function of the radar power, receiver sensitivity, pulse length, and the method of coupling the cavity to the radar. (Author's abstract)

REPORTS AND TECHNICAL MANUALS (Continued)

T12 - Final Engineering Report for Echo Box FR-41(xw-1)/U and FR-41 (xw-2)/U, Polarad Electronics Corp., July 31, 1951. (Restricted)

Part I of this report consists of four sections each of which provides technical data for the development of the mechanical and electrical parts of the equipment. Each phase of the echo box equipment is discussed in detail. Special emphasis is given to the mechanical construction and design. Conclusions are derived and listed from the theoretical considerations and final experiments of the echo boxes.

Part II consists of recommendations for future mechanical and electrical construction of the equipment.

In Part III, 23 illustrations and schematics are provided for reference material.

Part IV, an appendix, is the instruction manual for the engineering model of the echo box FR-41(xw-2)/U. This instruction manual is provided to illustrate how well the purpose of the contract has been translated into equipment. (Author's abstract)

T13 - A Treatment of Echo Box Problems by Lagrangian Procedures, Part II, Report No. 696, Radiation Laboratory, Massachusetts Institute of Technology. (Unclassified)

The two sections included in this report are additional applications of Lagrangian procedures to echo box problems and supplement those of RL Report 629. A knowledge of the latter is essential to an understanding of the material presented here. The first section shows that the gap is not a small perturbation and that the superposition of it with ellipticity of the cylinder introduces an interaction effect. The resultant additions to the equivalent network are tabulated. The second section gives a means of handling the question of gap geometry to a first approximation. The end result is a simple equation for the electrical reluctance of the gap. (Author's abstract)

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REPORTS AND TECHNICAL MANUALS (Continued)

T14 - Field Strength Measurements in Resonant Cavities, by Leonard C. Maier, Jr., Tech. Report 143, Massachusetts Institute of Technology, Research Laboratory for Electronics, November 2, 1949. (Unclassified)

Perturbations are discussed. The perturbation effects of metallic spheres and circular metallic needles (ellipses rotated about the major axis) are given. There is an experimental verification of the theory. Field strengths have been measured where the fields could not be found analytically. Cylindrical cavities are not considered.

T15 - Microwave Field Measurements II, Cavity Resonators for Continuous Axial and Rotary Movement of Modes, by Beverly C. Dunn, Jr., N5ori-76, Task I, Cruft Laboratories, Harvard University, October 3, 1949, 31 pp. (Unclassified)

The resonator is used for studying the response of conducting loops to electromagnetic fields. The method employed is to compare calculated field characteristics in the cavity with measurements of these characteristics as made with the loops being investigated. A loop to be studied is placed in a field rotary mounted along a 5-3/4" diameter tube. A given resonant mode can be moved axially and rotated with respect to the loop mount by means of corresponding motions of identical pistons, on which are mounted the necessary exciting and monitor antennas, polarizers, etc. The mechanical and electrical features of the resonator are discussed and illustrated together with associated equipment and experimental methods. At 3000 mcs, the resonator can sustain six modal series: TE_{11n}, TM_{01n}, TE_{01n}, TM_{11n}, TE_{21n}, and TE_{31n}. The mode spectra for these series are displayed and discussed with respect to choosing suitably pure modes for study. A comparison between measured and theoretically calculated field characteristics at the cylindrical surface of the cavity

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is illustrated for the TE_{118} mode. The comparison extends to all characteristics of the surface fields or the equivalent surface densities, that is, to the amplitude and phase of surface charge and to the direction, amplitude and phase of surface current. The measurements were made with both small and large filaments and loops in order to examine the effect of the over-all perturbation of cavity fields (by the loop under test) upon the experimental methods. Within a moderate range of cavity loading the results indicate the feasibility of the technique of mode-movement; that is, the negligibility of depolarization effects, contact variations, off-resonant mode levels, and the effects of the over-all perturbation upon the phase constancy of cavity fields, amplitude monitoring, and the specification of mode location. (Author's abstract)

T16 - Shunt Resistance of Tunable Cavity Resonators, by Richard Honey, Stanford University Electronics Research Laboratory, Contract N6-onr-251, Consolidated Task 7, Report No. 9, August 15, 1949, 12 pp. (Unclassified)

This paper is an attempt to explain the wide variation in shunt resistance often encountered in tunable cavity resonators. These variations are found to be due to the field configurations resulting from mode intersections. The data were obtained largely with the aid of two Kron Network Analyzers at Stanford Electronics Research Lab. (Author's abstract)

T17 - A Survey of Methods of Determining the Shunt Resistance for Klystron Resonant Cavities, by V. B. Westburg, Tech. Rept. No. 11, Stanford University Electronics Research Laboratory, Contract N6-onr-251, Task 7, November 30, 1948. (Unclassified)

The definition of shunt resistance is presented and the basis

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and application of various types of circuit analogies to a general resonant cavity are discussed. There is an explanation of several different ways of measuring the shunt resistance, some being more direct than others, but all involving a meticulous use of experimental techniques. The measured values of a given resonant cavity by certain of the methods are presented and the results evaluated. A good discussion of equivalent circuits is given. (Author's abstract)

T18 - Circumferential Resonances in Concentric Line Cavities, by E. G. Goddard, Stanford University Electronics Research Laboratory, Tech. Report No. 3, November 1, 1947. (Unclassified)

The tuning characteristics for a coaxial type cavity may be calculated approximately for simple gap configurations, but when the gap is altered to any degree, as is the case in cavities for oscillators, such calculations become very laborious. A study has been made of a large number of cavities to determine the effect of changes in the cavity characteristic impedance and gap configurations upon tuning characteristics. Of particular interest have been the interference regions of the 3 $\lambda/4$ and 5 $\lambda/4$ TEM principle modes with the TE_{111} circumferential mode. Non-dimensional tuning curves which may be used for the design of cavities at other frequencies are given. (Author's abstract)

T19 - A Treatment of Echo Box Problems by Lagrangian Procedures, Radiation Laboratory, Massachusetts Institute of Technology, Report 629, January 13, 1945, 65 pp. (Unclassified)

In this report procedures are applied to the following echo box problems: coupling loops, dissipation in the walls, deviation of the planes of the ends of the box from perpendicularity to the axis, the presence of an air gap between the piston and the cylindrical wall, eccentricity of the piston, and the presence

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of a back cavity and of bakelite in this cavity. The results are placed in the form of matrices, which show how the equivalent network is affected and how the various meshes of this network are coupled by the above structural peculiarities. Experimental data are given which are in agreement with the theory obtained. (Author's abstract)

T20 - Perturbation Theory for Cavities, by H. A. Bethe and J. Schwinger, D1-117, National Defense Research Committee Contractor's Report, Cornell University, March 4, 1943. (Unclassified)

A perturbation theory is developed which permits one to calculate the change of resonant frequency of a cavity caused by some small change of the cavity. It is first applied to the effect of the insertion of a dielectric of small volume on the frequency and Q value, e.g., the effect of the glass in a TR-box. A method is described by which cavity resonators can be used to measure the dielectric constant and the magnetic permeability of a small sample of material. The effect on the frequency of small changes of shape or volume of the cavity (small plugs) and that of windows in the cavity walls is calculated. (Author's abstract)

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A1 - Electromagnetic Resonant Behavior of a Confocal Spheroidal Cavity System in the Microwave Region, by J. C. Simons and J. C. Slater, J. Applied Physics, 23, 29-30, January 1952.

The resonance of a small spheroidal object in a large spheroidal cavity is investigated. This approximates the case of a thin needle-like aerial in a large cavity. It is shown that this needle, if thin enough, shows marked resonant properties, in that when the cavity is tuned to a resonant frequency defined by the needle, the magnetic field on the surface of the needle is greatly enhanced. This property can be used in a practical way in measuring surface impedance of the material of which the needle is composed; at resonance most of the loss in the cavity is located at the surface of the needle and depends on the material of which it is composed.

(From Electrical Engineering Abstracts, 1913, 1952.)

A2 - Resonance Frequency of Spheroidal Cavity Resonator, by T. Nimura, Science Report of the Research Institute of Tôhoku University, B, 1-2, 73-90, January 1951.

Using spherical coordinates and a spheroidal wave function, the electromagnetic fields of oblate and prolate spheroidal cavity resonators are analyzed and their resonance frequencies are given when they have rotational symmetrical fields.

(From Electrical Engineering Abstracts, 922, 1952.)

A3 - A High Power Attenuating Tuner for a High Q 10 cm Cavity, by R. R. Perron, Note in Rev. Sci. Instrum. 22, 116-117, February 1951.

A water-filled polystyrene attenuating segment is mounted on a carriage such that it can be positioned longitudinally in a slotted section of waveguide. The attenuator can pivot about one end for the control of the attenuation.

(From Electrical Engineering Abstracts, 2848, 1951.)

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A4 - A Cylindrical Cavity Filled with a D.C. Discharge, by G. W. Stuart, Jr., and P. Rosen, Letter in J. Applied Phys., 22, 236, February 1951.

Expressions are given for resonant frequency and Q-factor. (From Electrical Engineering Abstracts, 2004, 1951.)

A5 - On the Theory of Electromagnetic Waves in Resonant Cavities, by H. B. G. Casimir, Philips Research Reports, 6, 162-182, June, 1951.

The theory of standing electromagnetic waves in resonant cavities is surveyed. The formal analogy between the modes of vibration of a cavity, the modes of vibration of a network of discrete elements, and the vibration of a simple LC circuit is emphasized. Special attention is given to the theory of perturbations, and this theory is then applied to a number of examples, including the determination of the high frequency properties of magnetic materials by means of cavities into which small spheres of the material are introduced, and the coupling of two identical cavities by a small hole in a dividing wall. The zero-point energy of empty space is considered.

(From Electrical Engineering Abstracts, 3503, 1951.)

A6 - Optimum Operation of Echo Boxes, by W. M. Hall and W. L. Pritchard, Proc. Inst. Radio. Engrs., 39, 680-684, June, 1951.

The parameters determining ringtime for an echo box in a radar system are examined and the conditions for optimum ringtime established. Two specific arrangements, namely, the echo box coupled directly to the guide and the echo box coupled through a directional coupler are treated in detail. Merely increasing the loaded Q-factor of a cavity does not increase the ringing time past a certain maximum, and there is an optimum value of loaded Q which is a function of the radar power, receiver sensitivity, pulse length and the method of coupling the cavity to the transmitter.

(From Electrical Engineering Abstracts, 3504, 1951.)

ARTICLES (Continued)

A7 - Design and Construction of Cavity-Wavemeters for Centimeter Waves, by M. L. Toppinga, Tijdschrift van het Nederlandsch Radiogenootschap, (Baarn), 16, 185-207, July, 1951. In Dutch.

The wavemeter described can be used in the 5-7 cm wave-length band. Attention is paid to the method of excitation and detection: also to a method of suppression of unwanted modes. A graph shows the position of the wanted and unwanted modes, relative to each other.

(From Electrical Engineering Abstracts, 4224, 1951.)

A8 - Microwave Filters Employing a Single Cavity Excited in More than One Mode, by W. G. Lin, J. Appl. Phys., 22, 989-1001, August 1951.

A cavity resonator with input and output couplings represents a two-terminal pair network with an infinite number of natural modes of oscillation. In some cavities of special shape, a number of degenerate modes with identical natural frequencies can be found. In a single cavity, various numbers of these degenerate modes can be coupled together to form a chain of coupled circuits by perturbing the otherwise ideal geometrical configuration of the cavity. The filter behavior is described, and the two-terminal-pair network realizing this is obtained by a process of synthesis.

(From Electrical Engineering Abstracts, 3910, 1951.)

A9 - Artificial Dielectrics for Microwaves, by W. M. Sharpless, Proc. Inst. Radio Engrs., 39, 1389-93, November, 1951.

A theory of parallel strip dielectrics is developed. It is possible to introduce strip loading into a cylindrical coaxial cavity without introducing edge effects. The effective dielectric properties of the strips are deduced from the readings of a slotted line connected to the cavity through a coned section. Experimental data at 3 and 7 cm are tabulated.

(From Electrical Engineering Abstracts, 1912, 1952.)

ARTICLES (Continued)

A10 - On the influence of Circular Holes in Cavity Resonators, by W. Klein, Zeitschrift für angewandte Physik., 3, 253-9, November 7, 1951. In German.

When two or more cavity resonators are coupled directly through holes in mutually separating walls, coupled circuits exist. The theory and influence of coupling on the behavior of cavity resonators are described. The experimental investigations were carried out at 10 cm and 25 cm.

(From Electrical Engineering Abstracts, 1911, 1952.)

A11 - Present Position of Centimeter-Wave Technique, by H. Döring, Hochfrequenztechnik und Weltraumfahrt. Stutgart, S. Hirzel Verlag, 19-35, 1951. In German.

A brief survey of modern centimeter-techniques, covering coaxial lines, waveguides cavity resonators, and amplifying and oscillating tubes such as magnetrons, klystrons and traveling-wave tubes.

(From Electrical Engineering Abstracts, 1280, 1952.)

A12 - Theory of Slotted Cylindrical Cavities with Transverse Electric Fields, by K. Fujisawa, Technical Report, Osaka University, 1, (No. 1-9), 69-87, 1951.

A theory of transverse electric fields is developed which is applicable to the slotted cavities of magnetrons and aerials. Green's function is calculated for typical shapes of cross-section. Equivalent parallel circuits can be derived and the frequency limits of their validity is discussed. The theory has been confirmed for cross-section squares, rectangles, full circles, and segments of circles. Some relations of the roots of Bessel functions are derived.

(From Electrical Engineering Abstracts, 3896, 1951.)

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A13 - Dynamic Measurement of Q-Factors and Natural Frequencies of Cavity Resonators Possessing a Single Coupling Element, by M. Denis and S. Couybes, Annales de Radioélectricité, 5, 54-61, January 1950. In French.

The method is analyzed theoretically and a description given of the equipment. The method enables the resonant frequency, Q-factor, and equivalent shunt impedance of a rhumbatron loaded by an electron beam, and their alteration with varying parameters to be determined.
(From Electrical Engineering Abstracts, 1050, 1950.)

A14 - The Perturbation of the Resonant Frequencies of Concentric Spherical Resonators, by Displacement of the Inner Sphere, by J. Broc, Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences, 230, 285-6, January 16, 1950. In French.

The calculation was carried out by both analytical and perturbation methods. Good agreement is obtained in particular cases.
(From Electrical Engineering Abstracts, 1559, 1950.)

A15 - Effect of the Deformation of a Cylindrical Cavity Resonator on the Wavelength of the E_{010} and E_{011} Modes, by R. Müller, Zeitschrift für Naturforschung, 5a, 332-4, June, 1950. In German.

The effect is discussed mainly in connection with Essen and Gordon Smith's measurements of the velocity of light. (See Abstract 2887, 1948.) It vanishes for the E_{010} mode, and therefore results obtained by using this mode are more accurate.
(From Electrical Engineering Abstracts, 4298, 1950.)

A16 - The Transmission Characteristics of a Cavity Resonator as a Coupling Transformer, by A. Käch, Archiv der Elektrischen Übertragung, 4, 301-8, August, 1950. In German.

The transmission characteristics of a cavity resonator with

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loss-free quadripoles inserted in the input and output coaxials are calculated. Formulae are given for the bandwidth, loss and resonant frequency, including effects due to loss in the cavity. Tests made at 2000 mcs support the theory.
(From Electrical Engineering Abstracts, 298, 1951.)

A17 - Some Perturbation Effects in Cavity Resonators, by A. Cunliffe and L. E. S. Mathias, Proc. Inst. Elec. Engrs., Pt. III, 97, 367-75, September 1950.

An investigation, partly theoretical and partly experimental, has been made of some effects which occur when the boundary of a cavity is deformed slightly. First, the theory of natural electromagnetic oscillations inside lossless cavities is summarized. Then a general theory, on the lines of first-order perturbation theory is given. The theory has been applied to the perturbation of a right-circular cylindrical cavity. Two cases have been considered: the E_{010} mode, a non-degenerate case; and the H_{011} and E_{111} modes, a triply degenerate case. These two cases have also been investigated experimentally. Theory and experiment are in reasonable agreement, even for quite large deformations, when the deformation is applied gradually over a large area of the cavity wall. For sharp changes in the geometry of the cavity wall, however, it appears that the first-order perturbation theory can be applied only for very small distortions. The general results obtained show that from the frequencies of other modes, a deformation of the boundary changes only the frequency of the operating mode and not its electromagnetic field configuration. If the frequency of the operating mode is near to the frequencies of other modes, a slight deformation of the cavity boundary, as well as changing the frequency of the operating mode, may also change its electromagnetic field configuration. "Lossy" material or resistance wires, introduced into a cavity to damp out unwanted modes, may

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also affect the desired resonance if certain types of deformation are present.
(From Electrical Engineering Abstracts, 4297, 1950.)

A18 - Detection of Small Variations in the Quality Factor of a Resonant Cavity, by R. Malvano and M. Panetti, Alta Frequenza, 19, 231-43, October-December, 1950. In Italian.

A dynamical method for detecting small variations of the Q-factor of a cavity resonator is described. The microwave energy feeding the cavity is frequency-modulated and part of it is transmitted to a detecting circuit. The relative variations of the average output voltage are proportional to $\frac{\Delta Q}{Q}$. The errors caused by variations in the characteristics of the generator and the detector are negligible owing to the frequency modulation. As an example, the method is applied to examine the absorption spectra of paramagnetic substances observed by the magnetic resonance method and directly recorded on an oscillograph screen.
(From Electrical Engineering Abstracts, 1576, 1951.)

A19 - Separation of Degenerate Modes of Oscillation in Perturbed Rectangular Cavities, by F. Bosinelli, Alta Frequenza, 19, 244-58, October-December, 1950. In Italian.

Slater's general theory is applied to determine the relative frequency shifts $\frac{\Delta k}{k}$ of the originally degenerate TE- and TM-modes of a rectangular prismatic cavity, one face of which is slightly rotated about one of its edges. The theory also applies where the degeneracy arises from dimensional symmetry, and is illustrated for such a case. A useful bibliography is included.
(From Electrical Engineering Abstracts, 1575, 1951.)

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A20 - Forced Oscillations in a Hollow Spherical Resonator, by A. A. Piotrovskii, J. Technical Physics, USSR; 20 (No. 3), 282-94, 1950. In Russian.

This paper deals with the excitation of oscillations by a turn situated at the center of the resonator, the derivation being based on the case of a resonator with an ideally conducting envelope, proceeding to finite conductivity of the material of the resonator. The two limiting cases considered are those of infinite input resistance of the exciting winding (parallel resonance) and minimum input resistance (series resonance).

(From Electrical Engineering Abstracts, 3918, 1950.)

A21 - On Avoiding Low Frequencies in a Rectangular Cavity Resonator Used as Part of a Triode Generator, by K. F. Niessen, Applied Scientific Research, B1 (No. 5), 325-40, 1950.

If the bottom and the top plate of a rectangular cavity resonator are increased, so that a "sideroom" is added to the original resonator, its natural frequencies will be changed. Special attention is paid to fields independent of the height. The sideroom can be chosen so that all lower frequencies are changed except one (the frequency required), the corresponding nodal figure remaining unchanged. A means is indicated of eliminating the unwanted vibrations and of increasing the quality of the resonator for the required frequency at the same time.

(From Electrical Engineering Abstracts, 1949, 1950.)

A22 - On Some Results in the Theory of Coupled Electromagnetic Cavity Resonators, by E. Ledinegg and P. Urban, Acta Physica Austriaca, 4 (No. 2-3), 186-96, 1950. In German.

The method and results of a previous paper (Abstracts 2228, 1949) (cf No. A44) are extended and a general theory is now given

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for the oscillations of a system of coupled resonators which are of interest in cm-wave technique. The coupling frequencies are calculated and compared with experimental results, and the influence of damping in the resonator is considered. An analysis is made of the oscillations of a system consisting of two circular cylinders coupled by a concentric cell.
(From Electrical Engineering Abstracts, 1574, 1951.)

A23 - On The Representation of the Complete System of Resonances of Arbitrary Cylindrical Cavity Resonators with Horizontal Stratification of the Dielectric Medium, by E. Ledinegg and P. Urban, Acta Physica Austriaca, 3 (No. 4), 320-41, 1950. In German.

It is shown that, as in a resonator with only a single dielectric constant, the fields are either TE or TM. The TEM modes occur if the section of the resonator is multiply connected. General expressions for the fields are given. The case of a dielectric constant which varies over the section in such a way that the second derivative is continuous is applied to a discontinuous boundary between two media, by Fourier analysis. The expressions for the last case are given in some detail because of their utility in dielectric measurement.
(From Electrical Engineering Abstracts, 3533, 1950.)

A24 - On Driving and Coupling Electromagnetic Cavities, by J. Bernier, Annales de Radioélectricité, 4, 3-11, January 1949. In French.

The results of Bethe (Abstract 524, 1945), for coupling by means of holes in the walls of the cavity are compared with the results for coupling by loops and probes. The hole acts as a combination of loop and probe and can give coupling in either sense according to the relative direction of the fields.
(From Electrical Engineering Abstracts, 2582, 1949.)

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A25 - Microwave Modulation by Variable Circuit Elements Comprising Waveguides or Cavity Resonators, by A. N. Bhattacharyya, Indian Journal of Physics, 23, 175-83, April, 1949.

A driving mechanism similar to that of an electrodynamic loud-speaker is utilized for varying the dimensions of a wave-guide or cavity resonator according to the voice frequency signals so that microwaves passing through the guide may either be amplitude- or phase-modulated and the microwave output of the cavity resonator may be amplitude-modulated. The same mechanism is also applied for varying the length of a probe inside a guide resulting in load impedance modulation.
(From Electrical Engineering Abstracts, 4081, 1949.)

A26 - Design of an Echo Box, by J. H. Vogelman, Radio-Electronic-Engineering, 13, 16-18, 31, November, 1949. (Also in Report No. WLEAE, 1-101.)

Describes the design of a quarter-wave echo box for the measurement of radar performance. Five references are given to papers describing the operation and application. To meet the requirements of decay rate, a Q-factor of 4000 is necessary, but for the required band pass the Q-factor must be 20000. The actual dimensions of the box to cover a tuning range of 130-154 mcs are 43 inches x 23 inches diameter with a plunger movement of 3.5 inches. Formulae are given for calculating the dimensions of the box, the tuning dial calibration and compensation and the ringtime. The tuning after correction is accurate to 0.1 mcs. The ringing time is 336 microseconds and variation 1 per cent. Tables of values for this particular box are given.
(From Electrical Engineering Abstracts, 1051, 1950.)

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A27 - Analogue Studies of Losses in Reflex Oscillator Cavities, by F. W. Schott and K. R. Spangenberg, Proc. Inst. Radio Engrs., 37, 1409-18, December, 1949.

Describes the application of a network analogue to the determination of loss in resonant cavities. The expressions for the cavity shunt resistance, Q-factor and dielectric loss are developed, the method of measurement described and some typical results are discussed . Particular attention is given to the avoidance of zero shunt resistance in resonators capable of covering an extended tuning range.
(From Electrical Engineering Abstracts, 1560, 1950.)

A28 - Design of Tunable Resonant Cavities with Constant Bandwidth, by L. D. Smullen, Proc. Inst. Radio Engrs., 37, 1442-3, December, 1949.

(No abstract given. Electrical Engineering Abstracts, 1211, 1950.)

A29 - Impedance of Resonant Transmission Lines and Waveguides, by W. W. Harman, J. Appl. Phys., 20, 1252-5, December, 1949.

The relations of the Q-factor to the impedance of a resonant transmission line is clarified. Universal curves relating Q-factor and resonant impedance of capacitively terminated transmission-line and waveguide sections are presented and discussed. Their use in cavity resonator design and as a method for measuring resonator shunt resistance is considered.
(From Electrical Engineering Abstracts, 1151, 1950.)

A30 - Nodal Planes in a Perturbed Cavity Resonator, II, by K. F. Niessen, Applied Scientific Research, B1 (No. 4), 251-60, 1949.

Starting from a field with one nodal plane, parallel to one

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of the walls of the original resonator, a combination of functions analogous to that described in Part I is obtained, fulfilling the conditions in the perturbed resonators. It appears that two of these functions must be multiplied by coefficients of the order of δ. For the ratio of the coefficients of the order of 1, two values are found, and consequently, two solutions for the perturbed field with two different frequencies. Neither of these solutions return to the original unperturbed functions for $\delta \rightarrow 0$. A brief discussion is given of the behavior of the nodal plane.
(From Electrical Engineering Abstracts, 2899, 1949.)

A31 - Nodal Planes in a Perturbed Cavity Resonator, III, by K. F. Niessen, Applied Scientific Research, B1 (No. 4), 284-98, 1949.

In choosing in the unperturbed resonator a vibration having two nodal planes (one parallel and one perpendicular to the movable wall) the mathematics required is quite different from that of Part II. Again a combination of functions is chosen, the coefficients of which have to be determined. It appears that all these coefficients, except that belonging to the original function, must be of the order of δ, as found in I. There is only one possible solution and its nodal figure is permanent, being no function of the time. Instead of the two intersecting nodal planes $y = \frac{a}{2}$ and $z = \frac{a}{2}$ existing for $\delta = 0$, are obtained for $\delta > 0$ two sheets, the intersection of which with a plane perpendicular to the x-axis resembles an orthogonal hyperbola and the difference between the new and the original nodal system is relatively large in the neighborhood of the central axis of the resonator. The use of this effect for the construction of special resonators containing a "sideroom" and a bar is shown.
(From Electrical Engineering Abstracts, 2900, 1949.)

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A32 - Perturbation of the Boundaries of Special Types of Electromagnetic Cavity Resonators, by H. L. Knudson, Transactions of the Danish Academy of Technical Sciences, (No. 2), 5-28, 1949.

The following perturbation problems are discussed in detail: (1) Variations in the curved surface of a long cylinder; (2) Variation of the end surfaces of a short circular cylinder for the TM_{0n0} mode; (3) Variation of the radial surfaces in a spherical resonator.

(From Electrical Engineering Abstracts, 2343, 1950.)

A33 - Perturbation Calculations on Electromagnetic Resonators with Multiple Eigen-values, by E. Ledinegg, Osterreichisches Ingenieur Archiv., (Vienna) 3 (No. 3), 215-21, 1949. In German.

The perturbation theory of cavities in which degeneracy is eliminated by a small deformation of the boundary is developed: first, for the case of n-fold degeneracy and then for two-fold degeneracy.

(From Electrical Engineering Abstracts, 556, 1950.)

A34 - Phenomena in Electromagnetic Resonators Near the Coincidence Points of the Natural Frequencies, by V. B. Steinschläger, Doklady Akademii Nauk, USSR, 65 (No. 5), 669-72, 1949. In Russian.

Circular cylindrical resonators, using the H_0-wave, are widely used, mainly for measuring purposes, for two reasons: (1) the quality factor of the H_{01}-wave resonator is the highest one; (2) the H_0-wave is free of an axial current component. Therefore the unwanted resonances of the other waves may be considerably attenuated without impairing the quality factor of the H_0-resonance. Only at such positions of the piston where

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the suppressed wave and the resonator's H_0-wave have equal natural frequencies, a serious drop in the quality of the resonator occurs. This hitherto unexplained phenomenon is analyzed theoretically.

(Electrical Engineering Abstracts, 3407, 1949.)

A35 - On the Calculation of the Mistuning of Electromagnetic Cavities with Applications to the Experimental Determination of Dielectric Constants in the Centimeter Wave Region, by E. Ledinegg, Osterreiches Ingenieur Archiv., 3, (No. 2), 128-39, 1949. In German.

A mathematical discussion of the effects of a thin plate of dielectric material in a cylindrical cavity. Exact analysis is difficult; approximations are derived by the integration of Maxwell's equations and their application to the measurement of permittivity is discussed.

(From Electrical Engineering Abstracts, 558, 1950.)

A36 - The Experimental Measurement of Resonant Impedance in Electromagnetic Resonators, by F. Borgnis, Helvetica Physica Acta, 22 (No. 5), 555-78, 1949. In German.

The theory of several methods of measurement, by perturbing the capacitance, the inductance, or the parallel resistance is given. Experimental results for several resonators at 14 cm wavelength measured by a variety of methods are given. The results are considered to be accurate within 10 per cent. The methods described are only applicable to resonators in which the electric field is homogeneous in an area big enough to contain the perturbing element.

(From Electrical Engineering Abstracts, 557, 1950.)

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A37 - A General Theory of Ultra Short-Wave Circuits, I and II, by S. Tomonaga, J. of the Physical Society of Japan, 2, 158-71, November-December, 1947, 3, 93-105, March-June, 1948. In English.

The matrix theory of waveguide and concentric line networks is developed. The general theory is discussed and the characteristic matrix for the network is introduced and its properties examined. Some examples of the application of the theory to waveguide tees are given. In Part II the matrix equivalent of the load is introduced and problems of cylindrical cavities are discussed and formulae for the transmission and reflection given.

(From Electrical Engineering Abstracts, 3744, 1949.)

A38 - Calculation of the Equivalent Circuits of a Cavity Resonator, by N. N. Malov, Journal of Technical Physics, USSR, 18, 421-30, April, 1948. In Russian.

Complexity of the field of cavity resonators makes determination of the equivalent circuits difficult. However, rigorous analysis shows that the following four conditions lead to a reasonable definition of "electric" equivalence between resonator and substituted circuit: (a) Equality of the electric energy, (b) equality of charges, (c) equality of the "goodness", (d) isochronism of the oscillations. A similar set of four conditions has to be satisfied for the magnetic equivalence. The method is used for finding the equivalent circuit of a cylindrical resonator in which a standing wave of the type H_{011} has been set up.

(From Electrical Engineering Abstracts, 4076, 1949.)

A39 - Some Bessel Equations and Their Application to Guide and Cavity Theory, by M. Kline, J. Math. Phys., 27, 37-48, April, 1948.

The existence of roots of the equation given in Abstracts

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2581, 1949, is established for values of k near zero. It is shown that as $k \longrightarrow 0$ the roots approach roots of $J_n(x) = 0$ and $J'_n(x) = 0$, respectively. This result is applied in several ways to the theory of waveguides and cavities.
(From Electrical Engineering Abstracts, 2901, 1949.)

A40 - Table of Roots for Natural Frequencies in Coaxial Type Cavities, by H. B. Dwight, J. Math. Phys., 27, 84-9, April, 1948.

The roots of the equations, $J_n(x)\ N_n(Kx) - J_n(Kx)\ N_n(x) = 0$, $J'_n(x)\ N'_n(Kx) - J'_n(kx)\ N'_n(x) = 0$ are tabulated for a set of values of k ranging from 1.0 to 50.
(From Electrical Engineering Abstracts, 2581, 1949.)

A41 - The Method of Feeding Microwave Power into a Resonator Having a Fine-Mode Structure, by G. R. Newbery, and W. E. Willshaw, Nature, London, 161, 519-20, April 3, 1948.

Details are given of the method of feed into a resonator designed for a linear electron accelerator (Abstract 3120, 1947) with 24 cavities and a separation in frequency between adjacent modes of only 0.2 per cent (6 mcs at 3000 mcs). The power absorbed by the resonator (390 kw) was 60 per cent of the power output of the magnetron when fed into a matched load. The frequency stability achieved indicated that a considerably longer resonator, with correspondingly finer mode structure, can be satisfactorily fed.
(From Electrical Engineering Abstracts, 2268, 1948.)

A42 - Study of Transient Conditions in Waveguides and Electromagnetic Cavities, by T. Kahan and L. Colombo, Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences, Paris, 226, 2060-1, June 21, 1948. In French.

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Fourier transforms are applied to Maxwell's equations for a dipole excited guide or cavity. A formal solution for the admittance to the step function is obtained, indicating how spectrum analysis can be applied to the solution of response to transients from the known solution for study sinusoidal oscillation.

(From Electrical Engineering Abstracts, 3071, 1948.)

A43 - On The Forced Electromagnetic Oscillations in Spherical Resonators, by O. E. H. Rydbeck, Phil. Mag., 39, 633-44, August, 1948.

A mathematical analysis of the oscillations is presented. Their dependence on the exciting source is examined, and the solutions obtained show the degree of excitation of the various modes and orders. Transverse electric and transverse magnetic waves are treated separately, and the equivalent circuit for a resonator with two current loops is given. The impedances of the coupling loops are calculated.

(From Electrical Engineering Abstracts, 3089, 1948.)

A44 - The Theory of Coupled Oscillations of Cavity Resonators, by E. Ledinegg, and P. Urban, Acta Physica Austriaca, 2, 198-214, September 1948. In German.

The general equations for a set of coupled cavities are set up and solved by means of perturbation theory, so that the resonances appear as the roots of a secular determinant. The results are applied to two coaxial lines with a coaxial coupling and two inductively coupled quasi-stationary circuits.

(From Electrical Engineering Abstracts, 2228, 1949.)

(cf No. A22)

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A45 - On the Measurement of Cavity Impedance, by W. W. Hansen, and R. F. Post, J. Appl. Phys., 19, 1059-61, November, 1948.

The cavity impedance is measured by determining the changes in resonant wavelength caused by the introduction of small cylinders into the cavity. The cylinders are chosen to have the same diameter, but are of various heights. If a screw plunger be used, "negative cylinders" can be introduced, and so the rate of change of resonant wavelength to height of cylinder can be determined for the case of a cylinder of zero height. It is shown that a simplified expression applies to this special case, because a cylinder of zero height does not disturb the field distribution within the cavity. An experimental check has been made using calculable cavities. The accuracy is about $\pm$ 5 per cent. The method has been extended so as to give a simple means of comparing the impedances of cavities.
(From Electrical Engineering Abstracts, 2425, 1949.)

A46 - Pot Circuits as Resonators in Decimeter Wave Technique, by G. Megla, Electrotechnik, Berlin, 2, 305-12, November, 1948. In German.

Circuits derived from quarter-wave coaxial lines are discussed. Methods of coupling, building in planar grid valves and increasing the wavelength of physically small circuits are considered. Equivalent circuits are derived and the resonance conditions obtained. Approximations for the parallel impedance are given.
(From Electrical Engineering Abstracts, 2229, 1949.)

A47 - The Design and Use of Resonant Cavity Wavemeters for Spectrum Measurements of Pulsed Transmitters at Wavelengths Near 10 cm., by H. R. Allan and C. D. Curling, J. Inst. Elec. Engrs., 95, Part II, 473-85, November 1948.

The H_{011} mode of resonance is employed and the resonant

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frequency is varied by the axial movement of a rod through one of the end walls of the cylindrical cavity. The most suitable dimensions of the cavity and rod are found by calculation. The effects of surface irregularities and of plating and coating the surface with polystyrene are calculated. The nature of the response of the wavemeter and diode detection to pulsed oscillations is discussed.

(From Electrical Engineering Abstracts, 447, 1949.)

A48 - Microwave Breakdown of a Gas in a Cylindrical Cavity of Arbitrary Length, by M. A. Herlin, and S. C. Brown, Phys. Rev., 74, 1650-6, December 1, 1948.

It is possible to consider breakdown in a cylindrical microwave cavity whose radius is much greater than its length as approaching the condition of parallel plate breakdown. This assumption has been used to measure high frequency ionization coefficients. The paper investigates the corrections to be made when the length is increased. Numerical results are given for cavities whose ratios of radius to length are as low as 0.5, and show that the method is applicable to any cylindrical cavity. The breakdown data in these longer cavities are used to extend to the high frequency ionization coefficient curves for air by a factor of 10.

(From Electrical Engineering Abstracts, 2230, 1949.)

A49 - The Analogies Between the Vibrations of Elastic Membranes and Electromagnetic Fields in Guides and Cavities, by E. C. Cherry, Instn. Elect. Engrs., Paper 734, December, 1948, 13 pages.

The electromechanical analogies between inductances and capacitances in lumped circuits on the one hand, and masses and springs on the other, are commonly known, and are extremely useful in many ways. In the paper the analogies are

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extended to distributed elements, the detailed relations being shown between the electromagnetic fields in cavities, waveguides, etc. (with or without discontinuities) and the mechanical vibrations of elastic sheets having similar boundaries. The conclusions reached are quite general and apply to plane sections of these electromagnetic fields, having any conducting boundaries, and with either TE or TM modes. The equivalent lumped circuits, whereby such fields may be represented to any degree of accuracy desired, are considered and illustrated by experimental examples. It is shown that these circuits result from applying the method of relaxation to the distributed field calculation. It is shown that, although two sets of electromechanical analogies are commonly applied to circuits of one dimension (such as transmission lines and filters), only one of these sets is at all applicable to distributed systems, namely that in which velocity corresponds to voltage (or E vector), and force corresponds, nearly, to current (or H vector). This latter analogy is strictly true only for regions with circular boundaries. Again, mass corresponds to capacitance (or to T) and elastic constant to inverse inductance (or to $1/\mu$). The possible applications of such analogies fall into two classes. In the first, elastic membranes are stretched over frames of suitable shape, and a study of their vibration patterns may assist in the design of microwave components, such as valve anode blocks, resonators, etc. In the second, the development of the lumped equivalent circuits, which are essentially two-dimensional circuits, is a contribution to the general study of periodic structures. The selectivity and impedance properties of these lumped circuits are examined in relation to the properties of conventional constant-k filter structures.

(From Electrical Engineering Abstracts, 526, 1949.)

A50 - A Method of Approximate Calculation of Self Resonances of Electr - magnetic Cavity Resonators of Irregular Shape, by G. V. Kisunko, Radioteknika, 3, (No. 5), 24-35, 1948. In Russian.

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The resonator is split up into component regular bodies whose characteristic functions are established. The limiting zones are then investigated and replaced by approximated regular boundaries to satisfy the demand of continuous Poynting vector penetrating these boundaries. The case of uniform isotropic dielectric spaces surrounded by infinitely conductive cylindrical boundaries is analyzed in detail; as a practical example, free oscillations in a system of parallel cylinders connected with each other by longitudinal slots are calculated.
(From Electrical Engineering Abstracts, 1856, 1949.)

A51 - Electronics Including Fundamental Emission Phenomena. II. Non-radiating Electromagnetic Systems, by R. Honerjäger, R. Müller and H. Meinke, FIAT. Rev. German Science, 1939-46, (Off. Mil. Govt. Germany), 31-64, 1948. In German.

A survey of German work on electromagnetic waves in waveguides, on cavities and on circuit elements for v.h.f. undertaken during the war. A systematic analytical treatment of wave propagation and excitation by electrical and magnetic dipoles is presented for three waveguide types (rectangular, circular and annular cross-sections). Transmission damping due to finite conductivity of walls and reflection and refraction effects are treated in detail. Waveguide elements are described, required for non-reflective connectors, couplers, bifurcations, changeovers from symmetrical to assymetrical transmission, attenuators, etc.
(From Electrical Engineering Abstracts, 3363, 1949.)

A52 - Nodal Planes in a Perturbed Cavity Resonator, I, by K. F. Niessen, Applied Scientific Research, B1 (No. 3), 187-94, 1948.

The perturbed cavity resonator under consideration is generated from a prismatic cavity with square cross-section

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by rotation of one of its walls through a small angle δ about its edge. The electric field vector is assumed to be everywhere parallel to that edge. Part I deals with the fundamental vibration only. The change in resonance frequency and the distortion of the electromagnetic field due to the perturbations are calculated. In Part II (to be published), two fields, each with one nodal plane, are considered separately. Part III will deal with the case of two nodal planes perpendicular to each other. In II and III the change in resonance frequency is calculated and special attention is paid to the distortion of the nodal planes.

(From Electrical Engineering Abstracts, 1178, 1949.)
(cf No. A30, A31)

A53 - On the Variation of the Resonant Wavelength and Attenuation of Hollow Circular Discs Containing Dielectric Rings, by E. M. Philipp, Acta Physica Austriaca, 1, (No. 3), 246-58, 1948. In German.

Systems with axial symmetry are considered. These are (1) a disc of given thickness and radius, containing a dielectric ring of given thickness, the position of which may be varied (by varying the radii of the ring); (2) a disc, whose thickness is constant from the center up to a given radius, and then is constant but of greater value to the extreme radius; the disc contains a dielectric ring, as before. Expressions for the electric and magnetic field components in the various spaces are obtained and these are used to derive expressions for the resonant wavelength and attenuation. The variation, with position of the ring, is exhibited graphically.

(From Electrical Engineering Abstracts, 2567, 1948.)

A54 - Radiation of Cavity Oscillations through a Hole as Analogue of the Tunnel Effect, by P. E. Krasnushkin and E. R. Mustel, J. of Tech. Phys., USSR, 18, (No. 11), 1378-93, 1948. In Russian.

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Investigation of the emission of electromagnetic waves set up in a cavity resonator connected with outer space by a neck. It is shown that the emission of the resonator may be treated as an analogue of the tunnel effect of quantum mechanics. Theory is confirmed by a series of experiments in the cm-wave band.
(From Electrical Engineering Abstracts, 1463, 1949.)

A55 - End Plate and Side Wall Currents in Circular Cylinder Cavity Resonators, by J. P. Kinzer and I. G. Wilson, Bell Syst. Tech. J., 26, 31-79, January, 1947.

Formulae are given for the calculation of the current streamlines and intensity in the walls of a circular cavity resonator. Tables are given which permit the calculation to be carried out for many of the lower order modes. The integration of $\int_0^x \frac{J_l(x)}{J_l'(x)} dx$ is discussed; the integration is carried out for ℓ = 1, 2, and 3 and tables of the function are given. The current distribution for a number of modes is shown by plates and figures.
(From Electrical Engineering Abstracts, 2578, 1947.)

A56 - Cavity Resonators for Measurements with Centimeter Electromagnetic Waves, by B. Bleaney, J. H. N. Loubser, and R. P. Penrose, Proc. of the Phys. Soc., London, 59, 185-99, March, 1947.

A wavemeter for wavelengths of $\sim$1 cm , with an accuracy of 1 to 2 parts in 10,000, is described, based on a new system of coupling to the H_0 mode in resonant cavities, which avoids the excitation of other modes. An indirect effect due to simultaneous resonance in two different modes is discussed in relation

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to the measurement of absorption by resonant cavities. The permittivities of six non-polar liquids have been determined by means of wavemeters of this type, at wavelengths of 3.2 and 1.35 cm. The values obtained at the two wavelengths agree in all cases within three parts in 10,000, and do not differ appreciably from the accepted l.f. values. The temperature coefficient of the permittivity is compared with that calculated from the dilatation of the fluid. The power-factors vary between 10^{-4} and 2×10^{-3}; the higher values may be due to traces of polar impurity.

(From Electrical Engineering Abstracts, 1983, 1947.)

A57 - A Graphical and Numerical Design Method For Cavity Resonators, by M. Abele, Alta Frequenza, 16, 174-91, June-August, 1947. In Italian.

A new method for calculating the parameter of the oscillating resonator is described. The resonator is assumed to be axially symmetric. Lines of electric force within the cavity may be determined, as well as the fundamental resonant frequency and the Q-factor. Two examples are given: (1) a cylindrical cavity with circular cross-section, (2) the same cavity with a second, coaxial cylinder of smaller length introduced.

(From Electrical Engineering Abstracts, 380, 1948.)

A58 - Some Results on Cylindrical Cavity Resonators, by J. P. Kinzer, and I. G. Wilson, Bell Syst. Tech. J., 26, 410-45, July, 1947.

The following results are derived: -- an approximation formula for the total number of resonances in a circular cylinder; conditions to yield the minimum volume circular cylinder for an assigned Q; limitation of the frequency range of a tunable circular cylinder as set by ambiguity; resonant frequencies of an elliptic cylinder; resonant frequencies and Q of a coaxial resonator in its higher modes. A brief discussion is given of fins in a circular cylinder.

(From Electrical Engineering Abstracts 379, 1948.)

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ARTICLES (Continued)

A59 - Approximate Methods Regarding Electromagnetic Waves in Hollow Pipes and Cavities, by T. J. Kihara, Journal of the Physical Society of Japan, 2, 65-70, July-August, 1947. In English.

The following questions are discussed: - the application of the variation principle to the calculation of resonances; radiation from a dipole in a guide; iris diaphragms; the use of the W. B. K. method; perturbation theory for curved pipes.
(From Electrical Engineering Abstracts, 3733, 1949.)

A60 - Charts for Resonant Frequencies of Cavities, by R. N. Bracewell, Proc. Inst. Radio Engrs., N. Y., 35, 830-41, August, 1947.

Six charts are given for designing cylindrical resonant cavities whose cross-sections are circles, concentric circles, squares, or rectangles. A new method called the "mode lattice" is used for representing multiple-resonance phenomena. The mode lattice is an alignment chart which relates the size and shape of a cavity with resonant wavelength for a larger number of modes. Points distributed on a lattice represent the modes. A set of equations has been derived for calculating the effect of small changes in dimensions or wavelength for resonators of all the above shapes.
(From Electrical Engineering Abstracts, 2849, 1947.)

A61 - Approximate Equivalent Circuit for a Resonator Transducer, by W. R. MacLean, Proc. Inst. Radio Engrs., N. Y., 35, 1095-6, October, 1947.

The equivalent circuit of a high-Q resonator transducer is given as a set of unit transducers connected in series on both ends. Each unit is a tank circuit with $\sqrt{L/C} = 120\pi$, and two ideal transformers whose turns ratios are given for loops or probes in terms of electrode geometry and a quantity called relative volume.
(From Electrical Engineering Abstracts, 155, 1948.)

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A62 - Electromagnetic Cavity Resonators, by G. DeVries, Philips Tech. Rev., 9 (No. 3), 73-84, 1947.

The modes of oscillation of resonators whose dimensions in the direction of one axis are small compared with the other dimensions are discussed in elementary terms. The treatment is extended to the cube, and Q-values are considered. A final section deals with the coupling between similar resonators obtained by a hole in a common wall; this uses the results of Bethe (Abstracts 524, 1945).
(From Electrical Engineering Abstracts, 733, 1948.)

A63 - On A Cavity Resonator of High Quality for the Fundamental Frequency, by K. F. Niessen, Applied Scientific Research, B1 (No. 1), 18-34, 1947.

The quality of a cavity resonator, the cross-section of which is a parallelogram of a very special shape, is evaluated. The resonator is very suitable where good quality is required without the possibility of lower frequencies occurring when the resonator is used as part of a triode generator.
(From Electrical Engineering Abstracts, 1018, 1948.)

A64 - Remarks on the General Theory of Electrical Cavity Resonators, by K. Simonye, Publications of the University of Technical Science, Budapest, (No. 2), 181-6, 1947. In German.

The vector equation satisfied by the Hertzian vector is derived and expressed as three scalar equations in a general orthogonal coordinate system. The equations are solved in some special cases and the expressions for the magnetic and electric field components are given.
(From Electrical Engineering Abstracts, 1537, 1948.)

A65 - The Problem of Forced Oscillations in Cavity Resonators, by A. L. Drabkin, J. of Tech. Phys., USSR, 17 (No. 1), 103-10, 1947. In Russian.

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Cavity resonators excited by coupling loops or probes and with or without loads are analyzed with regard to input impedances, forced emf amplitude and power loss at resonance. A practical example of a cylindrical cavity is calculated.

(From Electrical Engineering Abstracts, 1538, 1948.)

A66 - Boltzmann's Law of Slow Transformations and the Theory of Electromagnetic Resonators, by T. Kahan, Compte Rendus Hebdomadaire des Séances de l'Académie des Sciences, Paris, 222, 70-1, January 2, 1946. In French.

The law is used to calculate the change in energy of the field in the resonator when the resonator volume, and the permittivity and magnetic permeability of the medium within the resonator, undergo infinitesimal changes δV, $\delta\epsilon$, and $\delta\mu$. For a constant volume ($\delta V = 0$) the change in resonant frequency, $\delta\omega$, is given by

$$\omega^{-1} d\omega = \frac{\left(\int \delta\epsilon \, E^2 dV + \int \delta\mu \, H^2 dV \right)}{2\int \epsilon \, E^2 dV}$$

(From Electrical Engineering Abstracts, 2423, 1946.)
(cf. No. 77)

A67 - Characteristic Oscillations of Solid Conductors and Electromagnetic Resonators, by P. Nicolas, Annales de Radioélectricité, Paris, 1, 189-90, January, 1946. In French.

(From Electrical Engineering Abstracts, 182, 1947.)

A68 - The Transverse Electric Modes in Coaxial Cavities, by R. A. Kirkman and M. Kline, Proc. Inst. Radio Engrs., N. Y., 34, 14-17 P, January, 1946.

The transverse electric modes in resonant coaxial cavities

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labeled TE_{010}, TE_{102}, TE_{301}, by Barrow and Mieher (Abstracts 1446, 1946) suggested several implicit conclusions. The notation and diagrams of the electric field configurations of these modes, as given there, have caused confusion. The transverse electric modes with zero middle subscript do not exist. They are limiting cases and are approached by the fields of the coaxial modes TE_{111}, TE_{112}, TE_{211}, TE_{311}, etc., respectively, as the ratio of the radii of the inner and outer conductors approaches one. Several facts about the behavior of these modes for varying values of this ratio are presented. For a given mode, the resonant frequency of a coaxial cavity decreases as the ratio increases. In the case of a cavity of infinite length (i.e., a waveguide) the corresponding wavelengths (the critical wavelengths of the guides) approach the circumference of the cavity divided by the first subscript of the mode. Physical and mathematical arguments confirm these conclusions and show to what extent the Barrow and Mieher diagrams of the modes TE_{101}, TE_{102}, etc., are representative of actual coaxial modes. The practical importance of the transverse electric coaxial modes in u.h.f. work is emphasized.
(From Electrical Engineering Abstracts, 1203, 1946.)

A69 - Flat Cavities as Electrical Resonators, by G. C. A. Von Lindern, and G. DeVries, Philips Tech. Rev., 8, 149-60, May, 1946.

Starting from the transmission line equations for the parallel Lecher wire system, equations are derived for the tapered line case where inductance and capacitance per unit length vary according to a power relationship. These equations are then applied directly to cavities formed by rotating a closed tapered transmission line about an axis, and expressions obtained for the wavelengths of the different modes of resonance

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of hollow cavities of various shapes. Voltage and current distribution, Q-factor, and shunt impedance are also derived. The improvement in Q-factor obtained by increasing the thickness of a flat cylindrical resonator is illustrated by considering a number of thin resonators stacked together. Examples are given of the use of flat cavity resonators for stabilizing the frequency of a triode oscillator and for the input and output electrodes of short-wave values.

(From Electrical Engineering Abstracts, 2913, 1946.)

A70 - Resonant-Cavity Measurements, by R. L. Sproull, and E. G. Linder, Proc. Inst. Radio Engrs., N. Y., 34, 305-12, May, 1946.

Microwave measurements require the use of a sweep frequency generator modulated at 60 c/s and connected by line to a probe inserted into the cavity investigated. A second probe connects the cavity to a crystal detector, and its amplified output is fed to the Y plates of a c.r.o., the X plates being synchronized with the sweep frequency. The traced pattern indicates the frequency response of the cavity. The limitations and accuracy are discussed. Resonant frequency comparisons are possible by superimposing c.r.t. traces of cavity and generator, the frequency of the latter being adjustable by a calibrated plunger; an improved method leads to a null reading when the sign of one resonance curve is reversed. Q is measured similarly, by reading half-power points v. frequency deviation. The shunt resistance of a cavity is defined as a voltage difference between two points, divided by twice the power dissipated in the cavity. The "resistance insertion" and the "capacity insertion" methods of measuring it are described. The resistor consists usually of a rod of lossy dielectric; it is placed between the two points, i.e., opposite points on the axis of a doughnut-shaped cavity, and its effect on Q is observed. The capacitor is inserted similarly, and its effect on the resonant frequency noted.

(From Electrical Engineering Abstracts, 2326, 1946.)

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A71 - High-Q Resonant Cavities for Microwave Testing, by I. G. Wilson, C. W. Schramm, and J. P. Kinzer, Bell Syst. Tech. J., 25, 408-34, July, 1946.

The theory of right circular cylindrical cavity resonators is considered with special reference to the tunable resonators used in radar testing in which the length of the cylinder is varied. A mode chart and mode-shape factor charts are given; the TE_{01n} mode gives the smallest volume for an assigned Q value. The determination of the best cross-sectional area and other methods of reducing the effects of unwanted modes are dealt with. Coupling to the TE_{01n} mode resonator must be by magnetic loop or by an orifice from a waveguide. Details of designs for the 3000 and 9000 mcs band are given.
(From Electrical Engineering Abstracts, 1284, 1947.)

A72 - On Electromagnetic Resonators, by J. Bernier, Onde Electrique, 26, 305-17, August-September, 1946. In French.

Perfect resonators are first considered. The wave equation is given explicitly in the case of resonators whose boundaries are surfaces of revolution and in the case of cylindrical and sphero-conical resonators; and the various possible types of electric and magnetic waves are classified. The method of matching, in the case of a compound resonator, is described. Next, non-perfect resonators are considered. A formula is derived for the change in frequency when the boundary of a resonator is slightly deformed, and the effects of a finite conductivity in the walls of the resonator are analyzed. Formulae for the Q of a resonator are derived. Lastly, forced oscillations of a cavity are analyzed mathematically and formulae are obtained for the self-inductance, capacitance and shunt-resistance of a resonator.
(From Electrical Engineering Abstracts, 780, 1947.)

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A73 - Calculation of the Electromagnetic Field, Frequency and Circuit Parameters of High-Frequency Resonator Cavities, by H. Motz, J. Instn. Elect. Engrs., Part III, 93, 335-43, September, 1946.

A method for the calculation of the field components of free electromagnetic oscillations in metal cavities of any shape with reference to klystron oscillators. The present paper is concerned with the wave equation $\Delta \Phi + \frac{\omega^2}{c^2} \Phi = 0$. The differential equation is replaced by a system of difference equations, which in the case of free vibrations are homogeneous and soluble only for certain values of the parameter $\frac{\omega^2}{c^2}$, the proper values. A method for finding the lowest value of $\frac{\omega^2}{c^2}$ without solving a determinantal equation is described. The boundary of klystron resonators contains sharp corners, often feather edges, and to obtain the necessary accuracy for the circuit parameters the analytic behavior of the fields near the sharp corners must be considered. The relaxation method of solution of the equations is applicable and much computation is thereby saved. Once the field components and the resonant frequency are found, the beam impedance and the damping constant are easily determined.

(From Electrical Engineering Abstracts, 181, 1947.)

A74 - New Graphical-Numerical Method for Integration of Resonant Cavities, by M. Abele, Ricerca Scientisico Ricostruzione, 16, 1249-54, September, 1946. In Italian.

Briefly describes a new method, partly graphical and partly numerical, of integrating Maxwell's equations for a stationary alternating regime, with special reference to the determination of resonance frequencies of cavities possessing axial symmetry.

(From Electrical Engineering Abstracts, 179, 1948.)

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A75 - Theory of a Microwave Spectroscope, by W. E. Lamb, Jr., Phys. Rev., 70, 308-17, September 1 and 15, 1946.

(From Electrical Engineering Abstracts, 510, 1947.)

A76 - Universal Optimum-Response Curves for Arbitrarily Coupled Resonators, by P. I. Richards, Proc. Inst. Radio Engrs., N. Y., 34, 624-9, September, 1946.

The circuit analyzed consists of a set of resonators B_1, B_2, $\cdots$ and a set of coupling elements A_1, A_2, ..., where A_i connects B_i to B_{i+1}. Optimum response is obtained when the loss in the pass-band is less than a given value and the off-band rejection is as high as possible. Matrix Algebra is used in the circuit analysis and optimum response curves are given for 1, 2, 3, 4, 5, or 6 arbitrarily coupled resonators. The response depends only on the number of resonators, and not on the type of coupling or resonator.

(From Electrical Engineering Abstracts, 149, 1947.)

A77 - Perturbations and the Pressure of Radiation in Electromagnetic Cavities, by T. Kahan, Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences, Paris, 223, 785-6, November 13, 1946. In French.

A formula established previously (Abstracts, 2423, 1946), is used to calculate the relative change in resonant frequency of a resonator which either changes its shape slightly or is modified by the introduction of small pieces of metal. Under certain conditions the formula may be written in the form

$\frac{\delta w}{w} = w^{-1} \int_{\delta V} P dV$ where P is the pressure of the radiation.

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Two applications are made. One relates to the effect of an iris in a waveguide.
(From Electrical Engineering Abstracts, 3796, 1949.)
(cf No. A66)

A78 - Apertures in Cavities, by J. H. O. Harries, Electronics, 19, 132-5, December, 1946.

Size and positioning of orifices in cavity resonators for coupling purposes, and experimental methods for obtaining Q and η (efficiency) are described. H-slots cut into the wall at the current (magnetic) antinode and round E aperture at the electric antinode are used, the first being preferable as then the antinode can be used for beam injection. Lowest excitation frequency (H_{011} mode) is always assumed. The selectivity factor is defined as $Q = \omega W_F/P_R$ where $\omega = \frac{2\pi C}{\lambda}$, with C = velocity of the electromagnetic wave, W_F = the maximum instantaneous value of stored energy, and P_R = loss in the internal surface of the resonator. With an external load, dissipating P_L, $Q = \omega W_F/(P_R + P_L)$ and $\eta = P_L/(P_L + P_R)$. The case of a dipole aerial with its current point placed near the aperture is treated.
(From Electrical Engineering Abstracts, 1584, 1947.)

A79 - Resonant Frequencies of the Nosed-In Cavity, by E. Mayer, J. Appl. Phys., 17, 1046-55, December, 1946.

The resonant frequency is studied as a function of the cavity dimensions. Maxwell's differential equations and boundary conditions are converted into an integral equation which is solved approximately by the Ritz variational method. The size and shape of the cavity are fixed by specification of the dimensions

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r_1 and r_2, the inner and outer radii; ϵ', the post length, and ϵ'', the gap space. If the cavity is to resonate to the wavelength λ, only three of its dimensions can be given independently; the fourth is a function of the given three and the wave number $k = \frac{2\pi}{\lambda}$. For fixed $\frac{r_1}{r_2}$ the dependence of $k\epsilon'$ on $k\epsilon''$ is calculated with a precision of 1 per cent.
(From Electrical Engineering Abstracts, 1285, 1947.)

A80 - A Q-factor Comparator for Echo Boxes in the 10-cem. Band, by L. W. Shaw and C. M. Burrell, J. Instn. Elec. Engrs., Pt. IIIA, 93 (No. 9), 1443-6, 1946.

The instrument described compares the Q of echo boxes, or any similar high-Q cavities with two independent couplings, at any wavelength between 9.5 and 11 cm. With special precautions the accuracy is $\pm$ 2 per cent.

A81 - Calculation of a Specific Cylindrical Endovibrator, by V. L. Patrushev, J. Tech. Phys., USSR, 16 (No. 1), 35-8, 1946. In Russian.

A cylindrical cavity resonator is considered as a concentric line, and the equations for the electric and magnetic fields are solved. A practical example is given, the dimensions of the cavity are calculated and the field distribution curves presented.
(From Electrical Engineering Abstracts, 514, 1947.)

A82 - Coupling of Cavity Resonators Through Small Orifices, by V. B. Brodski, Bulletin de l'Académie des Sciences, USSR, Moscow, Ser. Phys., 10 (No. 1), 17-22, 1946. In Russian.

It is assumed that the coupling orifice is very small compared with wavelength, and that the field distribution of standing

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waves is affected only in its immediate neighborhood. Maxwell's equations are applied and the results shown to correspond to Kirchoff's equations for coupled tuned circuits. The physical interpretation suggests that maximum coupling is achieved when the magnetic field vectors on the surfaces around the orifice are parallel.

(From Electrical Engineering Abstracts, 2912, 1946.)

A83 - Self-Excitation of an "Endovibrator" Penetrated by an Electron Current, by S. Gvozdover and V. M. Lopukhin, Bulletin de l 'Académie des Sciences, USSR, Moscow, Ser. Phys., 10 (No. 1), 29-36, 1946. In Russian.

The "endovibrator" is any device converting the kinetic energy of entering electrons into h.f. energy of electromagnetic waves. Stationary conditions only are considered, and possible regions of self-oscillations and their amplitude and frequency are calculated. Two cases are treated in detail: the straightforward capacitor and a "monitron" (single cavity Klystron). (See Abstract 2701, 1946.)

(From Electrical Engineering Abstracts, 779, 1947.)

A84 - Simplified Design of Endovibrators, by V. M. Lopukhin, Bulletin de l 'Académie des Sciences, USSR, Moscow, Ser. Phys., 10 (No. 1), 111-16, 1946. In Russian.

A general mathematical treatment of some basic cavity resonators is given, and several characteristic values calculated, such as the shunt-impedance indicating the thermal losses, Q, the lowest natural resonant frequency and self-inductance. The toroid, quasi-toroid, cylindrical (fully closed) and cylindrical (one side open) endovibrators are treated; the possible errors are estimated to be under 30 per cent.

(From Electrical Engineering Abstracts, 2701, 1946.)

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A85 - The Resonator Action Theorem, by W. R. MacLean, Quart. Appl. Math., 2, 329-35, January, 1945.

The theorem states that in a lossless electromagnetic resonator, the action of each mode, i.e. the product of total energy and period, is invariant against an adiabatic deformation. A proof of the theorem is given and a possible application in the design of equipment is indicated.
(From Electrical Engineering Abstracts, 2660, 1945.)

A86 - The Electromagnetic Field in a Resonant Cavity, by M. Abele, Alta Frequenza, 14, 96-116, March-June, 1945. In Italian.

Considers a perfectly conducting resonant cavity having axial symmetry. The electromagnetic field is limited to one having no meridianal nodal points of either the electric or magnetic field. There are neutral points in the electric field, and the behavior of the lines of force in the neighborhood of such points enables the lines of force to be quickly traced. The fundamental resonance frequency is derived for two cases: (1) a toroidal cavity, (2) a nearly cylindrical cavity.
(From Electrical Engineering Abstracts, 2074, 1947.)

A87 - A Method for Computing the Resonant Wavelength of a Type of Cavity Resonator, by L. S. Goddard, Proc. Cambridge Philosophical Society, 41, 160-175, June, 1945.

The Hahn method (Abstract 630A, 1941) is replaced by a mathematical procedure in which certain slowly convergent series are summed by replacing Bessel function, appearing in the terms of the series, by their asymptotic expansions. Tables of the resonant wavelength are given for various values of the resonator parameters and an asymptotic formula is developed for the wavelength when the gap-width of the resonator is small.
(From Electrical Engineering Abstracts, 2658, 1945.)

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A88 - Electromagnetic Field Inside a Cylinder with a Gap, by C. C. Wang, J. Appl. Phys., 16, 351-66, June, 1945.

(From Electrical Engineering Abstracts, 2661, 1945.)

A89 - The Reactance Theorem for a Resonator, by W. R. MacLean, Proc. Inst. Radio Engrs., N. Y., 33, 539-41, August, 1945.

The Foster reactance theorem which states that in any loss-free network, $\frac{dX}{d\omega}$ is positive, is proved for any loss-free resonator. To establish the existence of an input impedance, the resonator is fed with a coaxial (or other suitable) transmission line. The proof is based upon an extension of Helmholtz's theorem of adiabatic invariants. The variation of frequency is attained by a slow (adiabatic) movement of a short-circuiting plug in the transmission line while the cavity is oscillating.

(From Electrical Engineering Abstracts, 2179, 1945.)

A90 - The Perturbation Method Applied to the Study of Electromagnetic Cavity Resonators, by T. Kahan, Compte Rendu Hebdomadaire des Séances de l 'Académie des Sciences, Paris, 221, 536-8, November 5, 1945. In French.

(From Electrical Engineering Abstracts, 1202, 1946.)

A91 - Calculation of the Perturbed Resonant Frequency of an Electromagnetic Cavity (Deformation of the Boundary), by T. Kahan, Compte Rendus Hebdomadaire des Séances de l 'Académie des Sciences, Paris, 221, 694-6, December 3, 1945. In French.

(From Electrical Engineering Abstracts, 1423, 1946.)

ARTICLES (Continued)

A92 - Mathematical Theory of Hollow Cylindrical Resonators Excited by a Hertzian Dipole, by F. DeSimoni, Commentations Pontificia Academia Scientiarum, Vatican City, 9 (No. 12), 491-513, 1945. In Italian.

(From Electrical Engineering Abstracts, 3795, 1949.)

A93 - On the Forced Electromagnetic Oscillations in Spherical Resonators, by O. E. H. Rydbeck, Arkiv for Matematik Astronomi och Fysik, (Stockholm), 32A (No. 3), Paper 11, 18 pp., 1945.

The oscillations in spherical resonators are studied as functions of the exciting source and the results show the degree of excitation of the various modes and orders. TE-waves and TM-waves are treated separately, and the impedances of the coupling loops are calculated. This involves a separation of the "primary" and "secondary" fields. The equivalent network for a resonator with two current loops is given.

(From Electrical Engineering Abstracts, 1916, 1946.)

A94 - On The Spherical and Spheroidal Wave Functions, by O. E. H. Rydbeck, Transactions of the Chalmers University of Technology, Gothenburg, (No. 43), 32 pp., 1945.

(From Electrical Engineering Abstracts, 509, 1947.)

A95 - New Methods for Calculating the Properties of Electromagnetic Resonators, by P. Grivet, Compte Rendu Hebdomadaire des Séances de l 'Académie des Sciences, Paris, 218, 71-3, January 10, 1944. In French.

It is often possible to construct a function which represents approximately the electric field, E, or the magnetic field, H, inside a resonator. Then the resonant wavelength may be

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found by means of the formula

$$\frac{4\pi^2}{\lambda^2} = \int_V (\text{curl } E)^2 \, d\tau \Big/ \int_V E^2 \, d\tau = \int_V (\text{curl } H)^2 \, d\tau \Big/ \int_V H^2 \, d\tau$$

Differentiation of this formula leads to one giving the variation of the wavelength for small deformations in the shape of the cavity.

(From Electrical Engineering Abstracts, 1657, 1946.)

A96 - A Matching Method for the Calculation of Electromagnetic Cavity Resonators, by J. Bernier, Compte Rendu Hebdomadaire des Séances de l 'Académie des Sciences, Paris, 218, 186-8, January 31, 1944. In French.

The method is useful for calculating the field within a resonator which is of such a shape that a boundary Σ may be drawn which divides the interior of the resonator into two spaces, S_1 and S_2, within each of which Maxwell's equations may be solved analytically to satisfy all the boundary conditions except those relating to Σ. Then a series of wave functions is taken in each of the spaces S_1 and S_2 and matched along the boundary Σ. An example is given relating to a type of nosed-in resonator. The lines of force and their orthogonal trajectories are drawn and the lines of equal amplitude of the electric and magnetic field are also given. For another example of the method see Abstracts, 630, 1941, and 2568, 1945.

(From Electrical Engineering Abstracts, 882, 1946.)

A97 - On The Resonant Wavelengths of Certain Electromagnetic Resonators, by P. Grivel, Compte Rendu Hebdomadaire des Séances de l 'Académie des Sciences, Paris, 218, 183-5, January 31, 1944. In French.

Using the methods of a previous paper (Abstracts, 1657, 1946), approximate formulae are deduced for the resonant

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wavelengths of (1) a cylinder, (2) a torus of rectangular section, (3) a rhumbatron, (4) a sphere. The rhumbatron consists of the space between an external cylinder of radius b and height ℓ and an internal cylinder of radius a and height ℓ-d. The resonant wavelength is λ where

$$\left(\frac{\lambda}{4\ell}\right)^2 = 1 + 2a^2 (b - a) / \left\{ k\ell d \; (b + a) \right\},$$

k being an adjustable constant. Taking k = 0.5 this represents the experimental results to within 5 to 12 per cent in the region $b < 6a, \ell > 3d$.

(From Electrical Engineering Abstracts, 1658, 1946.)

A98 - Representation of Impedance Functions in Terms of Resonant Frequencies, by S. A. Schelkunoff, Proc. Inst. Radio Engrs., N. Y., 32, 83-90, February, 1944.

Impedance and admittance functions of systems with an infinite number of natural frequencies are found as infinite series. Modifications of these are suitable for numerical computation. The approach is function-theoretic, assuming that the driving-point impedance and the transfer impedance are analytic functions of the oscillation constant. Several examples are given and there are calculations of the input impedance across the terminals of a loop in a cavity resonator, and the transfer impedance across a cavity transducer (2 loops inside a resonator). The results hold approximately for slightly dissipative systems. The paper ends with a discussion of cavity resonators considered as sections of waveguides.

(From Electrical Engineering Abstracts, 1540, 1944.)

A99 - Network Analyzer Studies of Electromagnetic Cavity Resonators, by J. R. Whinnery, C. Concordia, W. Ridgway, and G. Kron, Proc. Inst. Radio Engrs., N. Y. 32, 360-367, June, 1944.

Studies are described in which equivalent circuits for the

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Maxwell field equations are set up on an a.c. network analyzer. These correspond to several simple electromagnetic cavities for which results are known. Comparisons made between the known theoretical results and field distributions measured from the equivalent circuits are used for verification of the equivalent circuits, for evaluation of usefulness of present network analyzers in h.f. field problems, and for suggestions of desirable features for analyzers constructed especially for the study of field problems.

(From Electrical Engineering Abstracts, 1903, 1944.)

A100 - Transmission Line Theory Applied to Waveguide and Cavity Resonators - I, by D. Middleton, and R. King, J. Appl. Phys., 15, 524-35, July, 1944.

Hollow metal waveguides of arbitrary cross-section are analyzed in terms of scalar and vector potential and stream functions. Completely hyperbolic solutions analogous to those given in the usual theory are obtained for the E and H modes; these yield general relations for the stream and potential distributions. Terminal, input, and characteristic impedances are defined for the waveguide or cavity resonator. The propagation constant is discussed, and it is demonstrated that the attenuation (constant) due to imperfect metal walls of the pipe and the dielectrics in the guide are additive if the materials have low loss. The characteristic impedances for the two types of mode are considered; and general formulae for the practical conditions of operation are included. The analogy between this theory and that of the conventional line is discussed.

(From Electrical Engineering Abstracts, 1984, 1944.)

A101 - Transmission Line Theory Applied to Waveguide and Cavity Resonators, II, by D. J. Middleton, J. Applied Physics, 15, 535-44, July, 1944.

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Practical applications are considered. Formulae for power transfer, efficiency of transmission, standing wave ratios, and insulating discs are given, and the experimental determination of the line and terminal parameters is treated briefly. Examples: (1) a rectangular waveguide terminated by a section of pipe containing a horizontal slit at one end and a flat horn of 45° aperture at the other, (2) the same guide terminated by a section of tube with horizontal slit at one end and opening into space at the other, (3) the rectangular guide with a variable horizontal and vertical slit, in either case followed by a closed quarter-wave section of pipe, (4) a closed cylindrical section of tube containing several transverse slabs of imperfect dielectric material.
(From Electrical Engineering Abstracts, 1985, 1944.)

A102 - Cylindrical Cavity Resonators, by C. F. Davidson and J. C. Simmonds, Wireless Engr., 21, 420-24, September 1944.

Starting from the attenuation constant of an infinite guide and the impedance of a conducting end, the resonance conditions for a closed guide are simply derived. The variation of total impedance with frequency is calculated, and thereby the Q of the resonator is derived. The method, which is applicable to cavities of any cross-section, shows clearly the physical analogy with transmission-line phenomena.
(From Electrical Engineering Abstracts, 173, 1945.)

A103 - Theory of Diffraction by Small Holes, by H. A. Bethe, Phys. Rev., 66, 163-82, October 1 and 15, 1944.

A complete solution for a circular hole in a perfectly conducting plane screen is found, satisfying Maxwell's equations and the boundary conditions everywhere. The method is based on the use of fictitious magnetic charges and currents in the diffracting hole. The charges and currents are adjusted so as

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to give the correct tangential magnetic, and normal electric field in the hole. The result is different from that of Kirchhoff's method, giving diffracted electric and magnetic field values which are smaller in the ratio $\frac{\text{(radius of the hole)}}{\text{wavelength}}$. The diffracted field can be considered as caused by a magnetic moment in the plane of the hole, and an electric moment perpendicular to it. The theory is applied to the problem of mutual excitation of cavities coupled by small holes. This leads to equations similar to those for ordinary coupled circuits. The problem of stepping up the excitation from one cavity to another is treated.

(From Electrical Engineering Abstracts, 524, 1945.)

A104 - Comments on Bethe's Theory of Diffraction of Electromagnetic Waves by Small Holes, by C. L. Pekeris, Phys. Rev., 66, 351, December 1 and 15, 1944.

See Abstract 524, 1945.
(From Electrical Engineering Abstracts, 1290, 1945.)

A105 - Resonant Frequencies of E-Type Waves in a Capacitance-Loaded Cylindrical Resonator, by F. Lüdi, Helvetica Physica Acta, 17 (No. 6), 429-36, 1944. In German.

The differential equation satisfied by the field of a type of resonator used in the klystron is solved approximately and the frequency equation is obtained. A graph is given of the solution of the latter for certain ranges of values of the circuit parameters. The energy losses in the resonator are also calculated and an expression (somewhat involved) is obtained for the shunt impedance. A numerical case for a 10 cm resonator is studied.

(From Electrical Engineering Abstracts, 879, 1946.)

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A106 - Resonance Phenomena with Electromagnetically Excited Cavities, by F. Borgnis, Zeitschrift für Physik, 122, (Nos. 5-8), 407-12, 1944. In German.

Investigates the performance of cavity resonators for u.h.f. waves in the neighborhood of their natural frequency. The resonance curve for cavity resonators with perfectly conducting walls and dielectric of small conductance is mathematically derived and found similar to that of RC networks with lumped constants and losses. The amplitude of the field oscillations inside the cavity resonator are proportional to $\frac{1}{\text{conductance}}$ of the dielectric.

(From Electrical Engineering Abstracts, 1536, 1948.)

A107 - Elementary Theory of Spherical Resonators Excited by a Hertzian Dipole, by F. De Simoni, Alta Frequenza, 12, 163-82, April, 1943. In Italian.

Maxwell's equations are written down and solved by means of the Hertzian vector potential, expressed in spherical polar coordinates. Expressions are found for the field components and a calculation is made of the fundamental resonant frequency (ω) and the attenuation coefficient (b). The former varies as x, where x is a root of $\tan x = x(1 - x^2)^{-1}$, and this equation is solved graphically. A graph of b is given for wavelengths from 20 to 100 cm.

(From Electrical Engineering Abstracts, 1204, 1946.)

A108 - Ultra-High Frequency Oscillations of Cylindrical Cavity Resonators Containing Two and Three Dielectric Media, by D. Middleton, Phys. Rev., 63, 343-51, May 1 and 15, 1943.

(From Electrical Engineering Abstracts, 1921, 1943.)

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A109 - A Principle of Equivalence Between a Cavity Resonator and a Circuit Having Lumped Constants, by J. Bernier, Compte Rendu Hebdomadaire des Séances de l 'Académie des Sciences, Paris, 217, 424-6, November 3, 1943. In French.

A cavity resonator is equivalent to a chain of lumped circuits in series, each circuit consisting of a resistance, R, inductance, L, and capacitance, C, in parallel. Expressions for R, L, and C are given. These involve volume and surface integrals of the electromagnetic field vectors. If the resonator is coupled by means of a loop to some external circuit, the equivalent circuit has a mutual inductance component. An expression for this is also given.

(From Electrical Engineering Abstracts, 624, 1946.)

A110 - The Electric Fundamental Wave of the Circular Cylindrical Double-Layer Cavity, by F. Borgnis, Hochgrequenztechn. und Elektroakust, 59, 22-26, January 1942.

(From Electrical Engineering Abstracts, 2129, 1943.)

A111 - Excitation of Cavity Resonators by Relaxation Oscillations, by W. Ludenia, Elektrische Nachrichten-Technik., Berlin, 19, 7-15, January-February, 1942.

The influence of time of discharge and of pressure on the internal resistance and efficiency of gas-discharge relaxation oscillators is investigated. With high gas pressure and "in vacuo", higher outputs are obtainable than with atmospheric pressure. Using cavity conductors as resonators and as high-pass filters, the fundamental wave excited in the 2-pole may be effectively undamped. This is proved experimentally with an 8 cm transmitter.

(From Electrical Engineering Abstracts, 1925, 1943.)

ARTICLES (Continued)

A112 - The Mean Frequency Stability of Resonators, by K. F. Niessen, Physica, 's Gravenhage, 9, 145-573, February, 1942. In German.

A continuation of previous work (Abstract, 511, 1947). It is observed that if the dimensions of a cube and a sphere be varied in a certain manner the stability of the cube is greater than that of the sphere, i.e. there is less frequency change; but for another type of variation the sphere is more stable. A change in the dimensions is found such that the frequency stability for the sphere and the cube are very little different.

(From Electrical Engineering Abstracts, 512, 1947.)

A113 - Electromagnetic Oscillations in Cavity Resonators. General Theory, by M. Jouguet, Revue Générale d 'Électricité, 51, 318-23, June, 1942.

A resonator which is a figure of revolution is considered. It defines a curvilinear coordinate system, and Maxwell's equations referred to this system are shown to reduce essentially to a single scalar equation. A study of the latter leads to the electric and magnetic types of oscillations. The possible oscillations within a spherical resonator are studied in detail. Diagrams are given of various modes of vibration and the resonant frequencies are calculated.

(From Electrical Engineering Abstracts, 411, 1946.)

A114 - On The Frequency Stability of Some Resonators for Electrical Oscillations, by K. F. Niessen, Physica, 's Gravenhage, 9, 539-46, June 1942. In German.

The stability is defined and expressions for it are found in the case of the cube and the sphere for simultaneous variations of the dimensions parallel and perpendicular to the direction of the electric field.

(From Electrical Engineering Abstracts, 513, 1947.)

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A115 - Practical Suggestions for Maintaining Constant the Frequency of Spherical Hollow Cavity Resonators, by K. F. Niessen, Physica, 's Gravenhage, 9, 768-72, July, 1942. In German.

In order to suppress frequency changes due to expansion of the resonator as a result of Joule heat dissipation in the walls it was recommended: (1) mounting of the sphere between two diametrically opposite supports, the distance between which should not vary with temperature and the electric poles arranged in a radial direction; (2) fixing the sphere in a ring of diameter independent of temperature, with the dipoles arranged in a radial direction and diametrically in the plane of the ring.

(From Electrical Engineering Abstracts, 1917, 1946.)

A116 - Electromagnetic Oscillations in Ellipsoidal Cavities, by M. Jouguet, Revue Générale d 'Électricité, 51, 484-7, November, 1942. In French.

An extension of the results of a previous paper (Abstract 410, 1946) on spherical cavities. Maxwell's equations governing the oscillations are solved and curves are drawn showing the variation of the resonant wavelength with the eccentricity for the simplest types of vibrations.

(From Electrical Engineering Abstracts, 883, 1946.)

A117 - The Magnetic Fundamental Oscillation of the Cylindrical Cavity with Circular Cross-Section, by F. Borgnis, Hochfrequenztechn. und Elektroakust., 60, 151-55, December, 1942.

(From Electrical Engineering Abstracts, 2130, 1943.)

A118 - The Laws of Similitude of the Electromagnetic Field and Their Application to Cavity Resonators, by H. König, Wireless Engineers, 19, 216-17, (No. 1304), 1942.

The laws of similitude have strict validity only if a reduction

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in dimensions by the factor $\frac{1}{m}$ is accompanied by an increase in the conductivity of the walls by the factor m.
(From Kinzer, B.S.T.J., 1947, also appeared in Hochfrequenztech., December, 1941.)

A119 - On the Eigenschwingung of the Electromagnetic Hohlraum (A Note on Resonators and Wave Guides), by M. Watanabe, Electrotechn. J., 5, 7-10, January, 1941.

It is shown that Bromwich's method can be applied to elliptic cylinders, hexahedrons, coaxial cylinders, coaxial rectangular tubes and concentric spheres, in investigating their properties as resonators and waveguides. Formulae are derived for the natural oscillations of such resonators.
(From Electrical Engineering Abstracts, 1623, 1941.)

A120 - Elementary Theory of the Spherical-Cavity Resonator, by T. G. O. Berg, Hochfrequenztechn. u. Electroakust, 57, 56-60, February, 1941.

(From Electrical Engineering Abstracts, 196, 1944.)

A121 - Forced Oscillations in Cavity Resonators, by E. U. Condon, J. Appl. Phys. 12, 129-32, February, 1941.

Formulae are developed for calculation of the impedance of a cavity resonator when excited by a coupling loop or by a capacitive coupling.
(From Electrical Engineering Abstracts, 607, 1941.)

A122 - Electromagnetic Similarity Laws and Their Application to Cavity Resonators, by H. König, Hochfrequenztech. u. Elektroakust., 58, 174-80, December, 1941. In German.

The laws are derived from Maxwell's equations and are

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applied to geometrically similar cavity resonators. If a second resonator is a 1:m scaled-down replica of a first one, the conductivity of the smaller resonator becomes m times higher, self-resonance frequency ω' becomes $m\omega$ and Q and field distribution remain the same. If, however, the conductivity is the same, which is the normal case, then Q drops by $\sqrt{m}$ and the field distribution changes slightly inside the cavity and considerably in the metal.
(From Electrical Engineering Abstracts, 1659, 1946.)

A123 - On the Frequency Stability of Some Resonators, by K. F. Niessen, Physica, 's Gravenhage, 8, 1077-93, December, 1941. In German.

The variations in the resonant frequencies of a hollow metal cube and sphere are investigated in two cases: (1) when the dimensions are kept constant in one direction and varied slightly in the other two; (2) when there is a lengthening in one direction and a shortening in the other two directions, subject to the total surface area remaining constant. It is found that in case (1) the sphere is about eight times as stable as the cube, and in case (2) that the cube is about 3.6 times as stable as the sphere.
(From Electrical Engineering Abstracts, 511, 1947.)

A124 - A New Method for the Calculation of Cavity Resonators, by W. L. Hahn, J. Appl. Phys. 12, 62-68, 1941.

Series approximation for certain circularly symmetric resonators.
(From Kinzer, B.S.T.J., 1947.)

A125 - Damped Electromagnetic Waves in Hollow Metal Pipes, by A. W. Melloh, I.R.E. Proc., 28, 179-83, April, 1940.

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Simple apparatus for the production of damped waves in hollow-pipe waveguides is described. The results of some measurements at free-space wavelengths down to 4.59 cm in circular air-filled pipes as small as 2.86 cm in diameter show that such apparatus can be successfully employed for the investigation of the properties of hollow-pipe waves. Some data are given which confirm part of a previous theoretical analysis of the behavior of electromagnetic waves in a pipe of elliptical cross-section, and a possible method of detecting small deformations in a supposedly circular pipe is discussed.
(From Electrical Engineering Abstracts, 1447, 1940.)

A126 - Natural Oscillations of Electrical Cavity Resonators, by W. L. Barrow and W. W. Mieher, I.R.E. Proc., 28, 184-91, April, 1940.

Resonance phenomena in cavity resonators of coaxial and hollow-pipe types are described and the transition from a resonator of one type to the other is discussed. Measured curves of resonance frequencies for the first 12 modes are reported. The principle of similitude is proved and other aspects of these resonant circuit elements are considered.
(From Electrical Engineering Abstracts, 1446, 1940.)

A127 - Dielectric Resonators, by R. D. Richtmyer, J. of Applied Physics, 10, 391-7, June 1939.

Suitable shaped objects made of dielectric material can function as electrical resonators for h.f. oscillations. The theory of such resonators is developed very briefly and their resonant frequencies and losses computed in some very simple cases. The paper concludes with an observation on the behavior of dielectric waveguides.
(From Electrical Engineering Abstracts, 1730, 1939.)

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A128 - Fundamental Electric Oscillations of a Cylindrical Cavity, by F. Borgnis, Hochfrequenztechn. und Elektroakustik, 54, 121-8, October, 1939. In German.

A mathematical investigation of the lowest frequency of resonance of a regular cylinder of dielectric bounded by a perfectly conducting sheath. Three cases are considered, (a) circular, (b) rectangular, (c) elliptical cross-section. Formulae for the fundamental frequencies in terms of linear dimensions, and for the equivalent resistance, capacitance and inductance of the enclosure are worked out, and all results are illustrated with curves.

(From Electrical Engineering Abstracts, 343, 1940.)

A129 - Investigation on Electromagnetic Cavities, by J. Müller, Hochfrequenztechn. und Elektroakustik, 54, 157-61, November, 1939. In German.

By electromagnetic cavities are meant spaces limited by good conducting metal walls. In consequence of their low loss such cavities are of practical importance for frequency stabilization with short waves, as oscillatory circuits and for various other purposes. Zobel's law for cavities of this type is extended and a relation is obtained between the loss factor and the half-value width of the resonance curve. Variation of the natural frequency of cavities by changes in the constants of the medium is discussed and a method is given for determining the distribution of the electric and magnetic field in any given cavity.

(From Electrical Engineering Abstracts, 857, 1940.)

A130 - Ultra-Short Waves in Coaxial Cables and Cavity Resonators of the Pot Type, by H. Buchholz, Hochfrequenztechn. und Elektroakustik, 54, 161-73, November 1939. In German.

Theory is given of the radiation of electromagnetic waves

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by axially symmetrical transmitters within the cavity of a coaxial conductor. The different types of transmitters may be arranged in two groups. The first group generates magnetic transverse waves while the second group generates electric transverse waves. The fundamental form of the second group is the circular ring of electric dipoles. In the radiation field of such transmitters no principal wave occurs. The current losses which these waves undergo owing to the finite conductivity of the inner and outer conductors have, for each of the harmonies, the property that they decrease towards zero with increasing frequency according to a power law of 3/2. An investigation is made of the field in a cavity resonator of the pot type. For both principal types of transmitter analytical expressions for the wave field are given and also formulae for the various resonance frequencies.

(From Electrical Engineering Abstracts, 858, 1940.)

A131 - Frequency Distribution of Eigentones in a Rectangular Chamber at Low-Frequency Range, by Dah-Yow-Maa, J.A.S.A., 10, 235-38, 1939.

Another method of deriving an approximation formula. (From Kinzer, B.S.T.J., 1947.)

A132 - Frequency Distribution of Eigentones in a Three-Dimensional Medium, by R. H. Bolt, J.A.S.A., 10, 228-34, 1939.

Derivation of better approximation formulas than the asymptotic one; comparison with calculated values.

(From Kinzer, B.S.T.J., 1947.)

A133 - A Type of Electrical Resonator, by W. W. Hansen, J. Appl. Phys., 9, 654-63, October, 1938.

The theory of the use of certain shapes of "hohlraums" as

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electrical resonators is developed. In many respects they are equivalent to lumped constant circuits with properly chosen circuit constants. Suitable values for these circuit constants are found. The theory of coupling on to these hohlraum type of resonators is developed approximately.
(From Electrical Engineering Abstracts, 3334, 1938.)

A134 - A Loop-Excited Resonator Formed by Two Confocal Parabolic Caps, by H. Buchholz, Arch. Elekt. Übertragung, 6, 6-16, January, 1952; 67-72, February, 1952. In German.

Treats a resonator formed by two confocal paraboloids of revolution, joined at a plane of cross-section. It is excited by a loop located on the axis of revolution. The solution is developed from the eigen-functions for the parabolic horn. The eigen-frequencies for the symmetrical case are given. Part II details the generalized field coordinates and gives expressions for time-averaged energy. The magnetic field is drawn for the fundamental and first harmonic modes, and values of Q are deduced.
(From Electrical Engineering Abstracts, 2550, 1952.)

A135 - Mode Conversion Losses in a TE_{01} Type Cavity Resonator with Tilted End-Plate, by K. Shimoda, J. Phys. Soc. Japan, 6, 378-83, September-October, 1951.

A cylindrical cavity resonator of TE_{013} mode was constructed and its Q-value was measured at the frequency of 3075 mcs. The Q-value was reduced, when the end-plate was slightly tilted. The optimum Q-value ($Q_o = 7.53 \times 10^4$) agrees well with that calculated from the d.c. conductivity of the wall material (copper). It may be considered that some other modes (TE_{11}, TE_{12}, and TM_{11} modes) of waves are generated from

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the primary TE_{01} mode and they are lost as heat and radiation, when the end plate is tilted. The resonance of the TE_{01} mode is thereby damped by mode conversion which is calculated assuming the deformation of the cavity wall to be small. The calculated result agrees well with the observed Q-value of the cavity with tilted end-plate.

(From Electrical Engineering Abstracts, 2269, 1952.)

A136 - Cavity Resonator Regarded as a Transmission Line, Wireless Engr., 29, 29-30, February, 1952.

The simple pill-box cavity resonator is considered as a disc transmission line short-circuited by the cylindrical wall. The voltage distribution is given by a Bessel function. It is shown that the "3rd harmonic" is 2.3 x the fundamental frequency.

(From Electrical Engineering Abstracts, 2270, 1952.)

A137 - Two Similar Cylindrical Cavities Which are Arranged in Contact End to End and Are Coupled Through a Window Opened on Their Common wall, by S. Sonoda and T. Makimoto, Mem. Sci. Industr. Res. Osaka University, 7, 34-41, 1950.

The resonant frequencies are found by considering the system as a uniform resonant line loaded reactively at its mid-point. The general conclusions of the theory and experiment described are similar to those of the case treated in Abstract 759. Experimental curves are given relating slot and cavity dimensions in the 20 cm region.

(From Electrical Engineering Abstracts, 760, 1953.)

A138 - On the Resonance of a System of Two Cavities Coupled to Each Other Through a Two-Wire Line, by S. Sonada and T. Makimoto, Mem. Inst. Sci. Industr. Res. Osaka University, 7, 26-33, 1950.

Formulae relating the parameters of a cavity with n loosely

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coupled two-wire line outputs are quoted. The solution of the problem of two coupled cavities follows directly from these formulae. The case where the cavities have the same natural frequency is treated in detail, and it is found that as the tightness of coupling increases, the resonance curve develops two peaks equally spaced on either side of the resonance frequency of either uncoupled cavity. The method used for the experimental verification of the formula ($\lambda \simeq 20$ cm) is described. It is suggested that the "over-coupled" case may be applicable in the design of broad-band tank circuits or band-pass filters.

(From Electrical Engineering Abstracts, 759, 1953.)

A139 - Band-pass Cavities for Centimeter Waves, by H. Döring and W. Klein, Arch. Elekt. Übertragung, 6, 47-57, February, 1952. In German.

Discusses filters formed by cylindrical boxes coupled by holes in a common wall. The fundamental TM-mode is used. The application of filter theory is considered, and the reaction of the coaxial input and output coupling devices discussed. Experimental results, in good agreement with the theory, are included.

(From Electrical Engineering Abstracts, 2524, 1952.)

A140 - The Tuned Echo Box as a Radar Test Set, by R. G. Loughlin, Sperry Engineering Review, Vol. 3, No. 6, November- December, 1950.

A brief explanation of the operation of tunable echo boxes is given and the features which make them unique to radar testing are described. Special emphasis is given to the characteristics which govern the design of the cavity resonator and their effects in limiting the operation and decrement of the echo box.

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The ringtime equation is presented and those factors external to the echo box which affect the measuring accuracy are discussed.

A141 - Theory of Ringing Time of Tunable Echo Boxes, by A. Banos, Report 630, 40 pages, Radiation Laboratory, Massachusetts Institute of Technology, November 3, 1944. (Unclassified)

The equivalent circuit of a cavity resonator is first set up by inspection of the differential equations governing the behavior of its normal coordinates as here established. Explicit formulas are given for the computation of the self and mutual parameters of the equivalent circuit. The case of the circular cylinder echo box is next discussed by means of a numerical example. The ringing time equation is established for a single mode and for two resonant modes. It is shown that the ringing time of a circular cylinder echo box, operating on a given TE_{01n} mode and its companion degenerate TM_{11n} mode, decreases materially and may become even lower than the recovery time of the TR-box if sufficient coupling between these two modes is brought about as by tilting of the end plates. The appendices include a summary of pertinent information on cylindrical resonators and the solution of the complete two mode transient problem.

(Author's abstract)

A142 - Design of an Improved X-Band Echo Box, by A. Banos, Report 631, Radiation Laboratory, Massachusetts Institute of Technology 30 pages, December 7, 1944.

It is recalled that, in present day X-band echo boxes, the ringing time is a critical function of the degree of parallelism between the end plates, as observed experimentally, due to the presence of the intrinsic degeneracy associated with the usual

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ARTICLES (Continued)

operating mode of the right circular cylinder resonator. It is next shown theoretically that this anomalous behavior of ringing time can be eliminated through a suitable circularly symmetric deformation of at least one of the end plates. An experimental echo box operating on the TE_{01-12} mode is described which is equipped with three removable piston end plates comprising a flat disc of conventional design and two spherical caps of different depths which was designed and built for the purpose of testing the foregoing theory of end plate deformations. Extensive continuous wave transmission and ringing time measurements furnish adequate confirmation of the theory and show that an echo box has been produced with the spherical cap, whose ringing time is quite insensitive to moderate tilts of the fixed end plate within the most generous mechanical tolerances. The appendix contains a detailed account of the theory of end plate deformations.

(Author's abstract)

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BOOKS

B1 - Cavity Resonators, General, by August Hund, Short Wave Radiation Phenomena, 1st Ed., McGraw-Hill Book Co., N. Y., Vol. II, pp. 1233-1236, 1952.

A general discussion of resonant cavities is given. Expressions are given for the cutoff wavelength in a rectangular cavity and for the resonant frequency. The same is done for cylindrical cavities.

B2 - Resonant Cavities, by S. A. Schelkunoff, Electromagnetic Waves, D. VanNostrand, N. Y., pp. 267-272, 298-303, 437-440, 1951.

Oscillations in cylindrical cavity resonators are treated using scalar and vector potentials. Expressions for the field within the cavity, change on the cavity surface, energy content, impedance and cavity Q are given. A cylindrical cavity of toroidal shape is next examined. The case of electric waves inside a hollow sphere is then discussed.

B3 - Cavity Resonators, by J. C. Slater, Microwave Engineering, D. VanNostrand, N. Y., pp. 57-168, 1950.

The theory of resonant cavities is developed by an approach different from the usual. The field in a hollow cavity is expanded in orthogonal functions, the electric field functions being of two kinds, one of which is irrotational and the other solenoidal. Expressions for the field in terms of these functions are obtained in the form of integral equations. The input impedance of a cavity is treated. The effect of perturbing the cavity boundaries is considered. The resonant cavity with one, two, or several outputs is examined at length. The tuning of the resonant cavity by altering its length is discussed, as well as other measurable properties such as the Q, losses, and power flow. Coupling to cavities by means of irises, probes, and loops is considered. A discussion of the cavity as a transformer is presented.

BOOKS (Continued)

B4 - Cavity Resonators, by H. E. Penrose and R. S. H. Boulding, Principles and Practice of Radar, VanNostrand, N. Y., 3rd Ed., pp. 671-679, 1950.

Gives a brief discussion of resonant cavities, including classification as reëntrant or non-reëntrant, the latter being subclassified into cavities of spherical, cylindrical and rectangular shape. Also given is a brief discussion of the modes of cavity resonators.

B5 - Cavity Resonators, by H. M. Barlow and A. L. Cullen, Microwave Measurements, Constable and Co., London, pp. 74-98, 1950.

The resonant cavity is compared to a tuned circuit. Formulas are given for input impedance and Q-factor. Two theorems useful in connection with resonant cavities are presented: (1) If the surface is pushed in at a point of strong magnetic field, the resonant frequency is increased; if pushed in at a point of strong electric field, the resonant frequency is decreased. (2) If the input reactance of a transmission line coupled to a cavity is plotted as a function of frequency the slope will always be positive. A general discussion is then given of cavities of the waveguide type, expressions for the wave impedance, shunt impedance and transfer impedance being given, along with expressions for Q. The coupling to cavities is also treated.

B6 - Resonant Cavities, by Simon Ramo and John R. Whinnery, Fields and Waves in Modern Radio, Wiley and Sons, New York, pp. 378-417, 1944. Sixth printing, 1949.

Cavities of simple shapes and their lumped circuit analogies are discussed. Various physical pictures of waves in cavities are given. There is a mathematical treatment of the field within rectangular, cylindrical and spherical cavity resonators. Following this is a brief treatment of coaxial and reëntrant cavities of various shapes, and finally, a discussion of coupling to cavities.

BOOKS (Continued)

B7 - Resonant Cavities, Bell Laboratory Staff, Radar Systems and Components, VanNostrand, pp. 909-1020, 1949.

Formulae and charts are given which aid in the design of right circular cavity resonators operating in the TE_{01n} mode, which yields the highest Q for a given volume. The application of these to the design of an echo box radar test set is shown, and practical considerations arising in the construction of a tunable cavity are discussed. Formulas are given for the calculation of the current streamlines and intensity in the walls of a circular cylindrical cavity resonator. Tables are given which permit the calculation to be carried out for many of the lower order modes. The integration of

$$\int_0^x \frac{J_\ell (x)}{J_\ell '(x)} \quad \text{is discussed;}$$

the integration is carried out for ℓ = 1, 2, and 3, and tables of the function are given. The current distribution for a number of modes is shown by plates and figures.
(Author's abstract)

B8 - Principles of Microwave Circuits, by C. G. Montgomery, R. H. Dicke, and E. N. Purcell, Radiation Laboratory Series, McGraw-Hill Book Co., N. Y., Vol 8, Ch. 7, pp. 207-239, 1948.

Resonant Cavities as Microwave Circuit Elements.

Resonant cavities are treated from the equivalent circuit stand-point, representing the cavities as R.L.C. circuits. The resonant cavity is first regarded as a single-line, loss-less system. Next, an equivalent circuit of a single-line cavity-coupling system with loss is made. In both uses recourse is made to Foster's reactance theorem. An equivalent circuit

BOOKS (Continued)

is constructed for a loop-coupled cavity. This is done by solving the field problem for the cavity coupled system, using the Lagrangian method. The iris-coupled, short circuited waveguide is dealt with, and finally, cavity coupling systems with two emergent transmission lines.

B9 - Microwave Transmission Design Data, by Theodore Moreno, McGraw-Hill Book Co., N. Y., Ch. 13, pp. 210-241, 1948.

The resonant cavity can be regarded as a parallel R.L.C. circuit and treated mathematically as such. The resonant frequency, Q, and shunt impedance of a resonant cavity are treated. A discussion of the various modes and their characteristics is given for resonators of rectangular, cylindrical, and spherical shapes, as well as for cavities of the reëntrant type, cavities of the coaxial line type, and ellipsoidal hyperboloid resonating cavities. In addition, the effects of loading, of temperature and humidity, and of coupling between resonators and transmission lines are briefly mentioned. The use of a resonant cavity as a filter is given. There are numerous graphs for use as design curves.

B10 - Resonant Cavities, by Louis D. Smullen, and C. G. Montgomery, Microwave Duplexers, Radiation Lab. Series, McGraw-Hill Book Co., N. Y., Vol. 14, pp. 14-35, 1948.

The resonant cavity is discussed in connection with TR tubes. The resonant frequency and shunt resistance of the cavities are found, and also the Q and voltage transformation ratio. Loop-coupled and iris-coupled cavities are compared, and methods of tuning are given. Equivalent circuits of cavities are discussed. Other topics are tuning temperature compensation, cavity couplings.

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BOOKS (Continued)

B11 - Resonant Cavities, by Ernest C. Pollard, and Julian M. Sturtevant, Microwaves and Radar Electronics, John Wiley and Sons, N. Y., pp. 44-55, 1948.

A brief discussion is given of the rectangular cavity, and various other shapes are indicated. Brief and relatively non-mathematical discussions are made of energy storage in cavities, voltage and shunt resistance, and cavities in practice.

B12 - Resonant Cavities, by W. H. Watson, The Physical Principles of Waveguide Transmission and Antenna Systems, Oxford, Clarendon Press, 1st Ed., pp. 168-171, 1947.

A brief general, non-mathematical discussion of resonant cavities is given.

B13 - Cavity Resonators, by M. J. O. Strutt, Ultra and Extreme Short Wave Receptions, D. VanNostrand Co., N. Y., pp. 151-157, 1947.

Resonant cavities are discussed as an extension of wave-guide theory. The cavity Q is dealt with briefly, and finally, the resonant cavity as a coupling element to antennas and electron tubes is mentioned.

B14 - Resonant Cavities, by Louis N. Ridenour, Radar System Engineering, Radiation Lab. Series, McGraw-Hill Book Co., Vol. 1, pp. 405-409, 1947.

Resonant cavities are described, Q is defined.

B15 - The Measurement of Wavelength Using Resonant Cavities, by Carol G. Montgomery, Technique of Microwave Measurements, Radiation Lab. Series, McGraw-Hill Book Co., N. Y., Vol. II, pp. 285-342, 375-448, 1947.

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BOOKS (Continued)

The resonant cavity considered as a circuit element may be regarded as a system of coupled R.L.C. circuits of various forms. Equations for the normal field modes in cavities of rectangular, cylindrical, and spherical shapes are presented but not derived. The same is done for coaxial cylinders. Various practical wavemeter circuits are examined. Following this is a discussion of measurements of transmission, standing waves, phase, and decrement of cavities.

Resonant cavities are also used as secondary frequency standards. TE_{011} mode cavities for the purposes are discussed at length. The resonant frequency of cavities, however, is a function of the temperature and humidity, and these effects are treated. Various actual frequency measurement techniques are discussed. Resonant cavities are also used for measurement of frequency spectrum and pulse shape. The theory is given and following is an examination of various spectrum analyzers using resonant cavities. Other instruments using resonant cavities are presented briefly, including echo boxes.

B16 - Resonant Cavities, by Donald G. Fink, Radar Engineering, McGraw-Hill Book Co., N. Y., 1st Ed., pp. 205-217, 1947.

Resonant cavity theory is approached by contrasting the resonant cavity to a parallel resonant circuit. The theory of parallel L.C. circuits with resistance is reviewed. Expressions are given for the energy in and Q of a resonant cavity: also for the shunt resistance and energy dissipation. A discussion is given of the modes in cavity resonators in the shape of rectangles, cylinders, spheres, and for coaxial resonators. Their excitation is treated briefly.

B17 - Resonant Cavities, Harvard University, Radio Research Lab. Staff, Very High-Frequency Techniques, McGraw-Hill Book Co., N. Y., 1st Ed., Vol. II, pp. 611-626, 769-795, 878-939, 1947.

BOOKS (Continued)

An extensive discussion is given of equivalent circuits for resonant cavities. Several equivalent circuits are given for the resonant cavity and its coupling. The measurement of various quantities associated with cavity resonators is considered. Methods of calculating the parameters are then presented. An analytical justification of the methods is made.

The coaxial cavity as a tuning device is discussed, including coupling problems and extraneous responses. Multicavity resonators are dealt with briefly, and also the rectangular-waveguide cavity. Coaxial line resonators are treated in connection with oscillators, the topics including: TEM, TE, and TM modes, application to reflex tubes, condition for oscillation, reactances, effect of cavity dimensions, desirable modes, eliminations of mode interference and output coupling methods. Plunger design is considered at length.

B18 - Cavity Resonators, by L. G. H. Huxley, A Survey of the Principles and Practice of Waveguides, MacMillan Co., N. Y., pp. 218-246, 1947.

Cavity resonators are introduced by considering a waveguide with conducting end plates. The field configurations are then mentioned briefly. Expressions are derived for the resonant wavelength in the cavity. Mention is made of the charges and currents on the cavity walls, the method of exciting a cavity resonator, and the Q-factor. The uses of resonant cavities as wave meters, echo boxes, and oscillators is then discussed. Other topics briefly treated are the measurement of power factor and Q of dielectrics, the equivalent circuit of a resonator, and the resonator method for measurement of waveguide discontinuities.

B19 - Resonant Cavity, by V. J. Young, Understanding Microwaves, Rider Publishing Co., N. Y., pp. 170-198, 1946.

An elementary and non-mathematical discussion is given

BOOKS (Continued)

which includes: determination of frequency in resonant circuits; the development of a cavity from a wire loop, the forms of various cavities, the modes in these cavities, method of coupling to cavities, cavity Q, shunt resistance of, and energy storage in, the cavity. The dependence of Q on volume is indicated. The tuning of a cavity by adjustable slugs is mentioned, and the treatment is concluded with applications of cavity resonators.

B20 - Cavity Resonators, MIT Radar School Staff, Principles of Radar, McGraw-Hill Book Co., N. Y., pp. 10-46 to 10-81, 1946.

The phenomenon of resonance in cavities is discussed, and the mode of oscillation for rectangular and cylindrical cavities. The Q-factor, power loss, input impedance of cavities, and coupling to transmission lines are treated. Following this is a survey of the use of resonant cavities for velocity modulated tubes, wavemeters, TR boxes, and echo boxes.

B21 - Resonant Cavities, by R. I. Sarbacher and W. A. Edson, Hyper and Ultra-High Frequency Engineering, John Wiley and Sons, Inc., N. Y., pp. 364-399, 1943.

Formulae are developed for the field components in a rectangular cavity, treating the cavity as a waveguide with reflecting end walls. Expressions are given for the resonant frequency, and for cutoff wavelength, power loss and Q. Formulae are derived for the power in a cavity with walls of finite conductivity. Cylindrical cavities are treated similarly, and a briefer treatment of coaxial cylinders and spherical resonators is made. Brief mention is made of cavity coupling and equivalent lumped constant circuits. The above shapes of cavities are compared.

BOOKS (Continued)

B22 - Cavity Resonators, by F. E. Terman, Radio Engineer's Handbook, McGraw-Hill Book Co., N. Y., 1st Ed., pp. 264-273, 1943.

The various types of cavity resonators are listed and a description of the kinds of modes is given. A brief treatment is made of cavity Q, resonant frequency, shunt impedance, and coupling to cavity resonators.

B23 - Resonant Cavities, by J. C. Slater, Microwave Transmission, McGraw-Hill Book Co., N. Y., 1st Ed., pp. 300-304, 1942.

A dipole in a waveguide closed at both ends is discussed, giving input impedance and Q.

B24 - Resonant Cavities, by R. L. Lamont, Waveguides, Methuen and Co., London, pp. 69-82, 1942.

The following topics are discussed: energy relations in cavity resonators; cavities of rectangular, spherical, cylindrical and coaxial shapes; and comparison of resonators.

B25 - Cavity Resonators as Waveguide Filters, by George L. Ragan, Microwave Transmission Circuits, Radiation Lab. Series, McGraw-Hill Book Co., N. Y., 1st Ed., Vol. 9, pp. 645-688, 1941.

Resonant cavities may be used as band-pass filters in microwave transmission lines. The filter characteristics are examined by use of equivalent circuits for the cavity, consisting of a number of resonant circuits coupled together. The design of cavity filters is discussed. The coupling is important, since it determines the band width. Resonant cavities may be coupled together to give a sharp cutoff characteristic. These cavities may be direct coupled, but it is advantageous to couple the cavities with quarter-wavelength lines.

APPENDIX V

CHARACTERISTICS OF EXISTING ECHO BOXES

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
14 AAL	3200 - 3400	R.T. 28 μs.	$8\frac{3}{8}'' \times 9\frac{3}{8}'' \times 5\frac{5}{8}''$	Yale & Towne	Obsolete; part of 0AJ echo box test set (Philco); uses 66 AUL antenna; used with SO-1, -2, -8, -9, -13.
14 AAM	3200 - 3400	R.T. 31 μs.	$7\frac{1}{4}'' \times 8\frac{7}{8}'' \times 11\frac{5}{8}''$ 22 lb.	Yale & Towne	Obsolete; replaced by TS-61/AP; part of OAJ-1 echo box test set (Philco); uses 66 ADM antenna; used with SO-1, -2, -8, -9, -13.
14 AAN 14 AAN-1 14 AAN-2	2900 - 3100	R.T. 11 - 22 μs.	$5\frac{1}{2}'' \times 9\frac{1}{2}'' \times 13''$ 5 lb.	Raytheon	Obsolete; uses 66 ADO antenna; used with SO-1, -2, -8, -9, -13. Navy Contract NXsr-96835.
14 AAQ	X-BAND ~~[illegible] - [illegible]~~	Untuned	Wood box with copper lining. 450 lb. $37\frac{5}{8}'' \times 39\frac{13}{16}'' \times 40\frac{5}{16}''$	G-E	Obsolete; used with ASD, AIA.
14 AAR	9200 - 9530	R.T. 10 μs. Untuned. Has parabolic reflector	$13'' \times 13\frac{1}{2}'' \times 14\frac{1}{8}''$ 13 lb.	Sperry	Obsolete; used with ASD, AIA, AN/APS-4; Navy Contract NXsa-17457. Replaced by TS-62/AP
14 AAT	X-band	R.T. 10 - 13 μs.	$10\frac{1}{4}'' \times 7\frac{3}{4}'' \times 10\frac{1}{4}''$ 20 lb.	Raytheon	Obsolete; motor tuned; used with SO-3, -4, -12 M/N; Navy Contract NXsr-93933. Has neon tube indicator.
14 AAW	S-band		$12'' \times 10\frac{5}{8}'' \times 10\frac{3}{4}''$		Obsolete; used with SP, SP-1M.

CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
14 AAX	10,000	Gas tube enclosed in cavity. HV supply to keep gas near ionization	$16\frac{1}{4}'' \times 18\frac{7}{8}'' \times 15''$ 40 lb.		Obsolete; Used with ST.
14 AAY	2830 - 3170	Q: 47,000 Sens: 90 yd./db.	$14\frac{5}{8}'' \times 9\frac{7}{16}'' \times 10\frac{11}{16}''$	Maguire Industries	Obsolete; part of OBU-1 and OBU-2 echo box test sets; uses 66 AAV antenna; used with SE, SG, SJ, SL, mk. 8.
14 ABA } 14 ABA-1 }	2830 - 3170	Q: 47,000 Sens: 90 yd./db.	$10\frac{3}{4}'' \times 11\frac{1}{4}'' \times 7\frac{5}{8}''$	Johnson Service Company	Part of OBU-3, OBU-4 and AN/UPM-7 test sets; used with 66 AJG antenna; 47 AAN directional coupler; used with SJ-1, SO, SO-a, -b, -1, -13, SG-a, SG-1, SL, SL-a, SL-1, SF, SF-1.
14 ABE	8740 - 8890	Untuned	Copperweld steel $14\frac{5}{8}'' \times 14\frac{1}{4}'' \times 13\frac{11}{16}''$ 40 lb.	Western Electric	Obsolete.
14 ABG	3400 - 3900	R.T. 2.5 stat. mi. with 50 kw radar	$15\frac{1}{8}'' \times 7\frac{1}{8}'' \times 7\frac{1}{2}''$ 12 lb.	Western Electric	Part of SV radar.
14 ABN	280 - 320		$8'' \times 6\frac{1}{8}'' \times 5\frac{1}{2}''$. $2\frac{1}{4}$ lb.	Johnson Tool Engr. Co.	Used to tune RF line in AN/ART-22 receiver.

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CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
14 ABS	1250 - 1350		$10\frac{7}{8}'' \times 9\frac{1}{4}'' \times 17\frac{1}{8}''$		Tuned by plunger inserted through hole; used with SR-3.
14 ACF	6250 -	Coupled directly to waveguide	$8\frac{3}{4}'' \times 10'' \times 11\frac{1}{2}''$	Philco	Motor tuned; used with SO-6, SO-10.
CXGU	2850 - 3150	R.T. 2.5 mi. with 50 kw radar Q: 30,000 - 40,000	$11\frac{3}{4}'' \times 8'' \times 10\frac{5}{8}''$ 10 lb.	Western Electric	Obsolete; uses AS-107/AP antenna; Navy Contract NXsr-48371.
FR-7/UP	5450 - 5825	R.T. greater than 4000 yds.		Johnson Service Company	Used with AN/SPS-4 radar; Contract NObsr-39185.
FR-41/U	130 - 154		Quarter-wave coax; outer conductor diam. 20"; inner conductor diam. 5.555"; 42.9" long; over-all 43" long × 20" wide × 20" high	Polarad	USAF Spec. No. Exhibit WLENG-1167. Has built-in Q compensator.
FR-58	3400 - 3700	R.T. 5200 yds.	4" long × 5" dia. 27 lb.	Johnson Service Company	Motor tuned plunger at one end, manual at other. Part of AN/SPN-6. NObsr-49010.
FR-66	6275 - 6575	R.T. 4000 yds.	$8'' \times 16\frac{1}{2}'' \times 8''$	Johnson Service Company	Motor tuned plunger at one end, manual at other. Part of AN/SPS-5.

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CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
FR-72/UP	8500 - 9000		19" × 7" × 12" 30 lb.	Hughes Aircraft	AF Exhibit WCEG - 411.
OAA series	150 - 240	R.T. 5000 yds. Includes VTVM	$13\frac{1}{2}$" × $10\frac{1}{2}$" × $5\frac{3}{4}$" 35 lb.	RCA	Wavemeter; incidental use as echo box; Navy Contract NOs-96554.
OAF	105 - 125	Includes VTVM	$6\frac{5}{8}$" × 12" × 12"	RCA	Obsolete; wavemeter; incidental use as echo box; Navy Contracts NXs-3487, NXss-27552.
OAJ series	2700 - 3400	R.T. 25 μs. Uses ~~new~~ neon lamp indicator	$11\frac{5}{8}$" × $8\frac{7}{8}$" dia. 22 lb.		Obsolete; uses 66 ADM antenna for airborne radars.
OAO series	105 - 125	R.T. 50 μs. Includes VTVM	$6\frac{3}{8}$" × 12" × 12"	RCA	Obsolete; wavemeter; incidental use as echo box; Navy Contract NXsa-53325.
RF-3/AP RF-3A/AP	9275 - 9460	R.T. 2.5 mi. with 25 kw radar	$5\frac{3}{8}$" dia. × $25\frac{1}{2}$" 8 lb.	Western Electric	Obsolete; wobble-tuned ±10 mcs by motor-driven plunger; uses AS-15/AP antenna.
RF-4/AP	3200 - 3400	R.T. 2.5 mi. with 50 kw radar Q: 35,000	$6\frac{1}{2}$" × $6\frac{1}{2}$" × $13\frac{1}{2}$" 7 lb.	Western Electric	Obsolete; used 72 ohm connector; wobble-tuned ±5 mcs by motor; uses AS-14/AP.

CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
RF-4A/AP	3200 - 3400	R.T. 2.5 mi. with 50 kw radar Q: 35,000	$6\frac{1}{2}'' \times 6\frac{1}{2}'' \times 13\frac{1}{2}''$ 7 lb.	Western Electric	Obsolete; same as RF-4/AP except uses 50 ohm connector and AS-14A/AP antenna; wobble-tuned ±5 mcs by motor. Contract No. NXs-33816.
TS-4/AP	3200 - 3400	R.T. about 2.5 mi. on SCR-517 or SCR-520 radar Q: 35,000 - 40,000	Cylinder 4 " long $5\frac{1}{2}''$ ID	Western Electric	Obsolete; wobble-tuned ±5 mcs by motor. Replaced by RF-4A/AP.
TS-38/AP	9275 - 9460		Diameter 10". 10 lb.	Western Electric	Obsolete; replaced by RF-3/AP.
TS-48/AP	2915 - 3335	R.T. 40 μs. with 40 kw peak power, 1 μs. pulse length. Receiver Sens. 10^{-12} watts, 17 db. coupling sensitivity; 4 μs. per db.	$9\frac{1}{2}'' \times 8\frac{3}{4}'' \times 6''$ 10 lb.	Marathon	Obsolete; Navy Contract NXsa-25890. Replaced by TS-61/AP. Used AS-23/AP antenna.
TS-61/AP	3140 - 3460	R.T. 2.5 mi. with 50 kw radar	$10\frac{5}{8}'' \times 11\frac{3}{4}'' \times 8''$ 10 lb.	Western Electric	Used with AN/APG-1, 2. Uses AS-107/AP antenna.
TS-62/AP	9200 - 9530 Nos. 1 - 100 9320 - 9420 Nos. > 100	R.T. 2 stat. mi. for 25 kw radar. Q: 50,000 - 80,000 decrement: 40 yds/db.	18" × 10" × 6" 10 lb.	Western Electric	Used with MK 22, 29, APQ-7, 10, 13; Navy Contract S & A-20849. Uses AS-106 antenna. Replaced by TS-488/UP.

CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
TS-66/AP	X-band			Philco	Wobble tuned; Sig. Corps. No. 3F4325-66. Used with AN/APS-15.
TS-91/TPS-1	1050 - 1110	R. T. 10 stat. mi. with 100 kw radar	$21'' \times 19\frac{1}{2}'' \times 21''$ 85 lb. (in wooden case)	Western Electric	Used with AN/TPS-1, MK 20.
TS-110/AP	2400 - 2700	R. T. 2.5 stat. mi. with 50 kw radar	$12'' \times 10\frac{5}{8}'' \times 8''$ 12 lb. with case, 24 lb.	Western Electric	Used with AN/APG-5, 8, 13, 13A, 14, 15. Uses AS-159/AP antenna.
TS-110A/AP					Similar to TS-110/AP, but improved mechanically.
TS-114/APS-2F	3200 - 3336	R. T. 3 stat. mi.	$25\frac{1}{2}'' \times 5\frac{5}{8}''$ dia. 9.5 lb.	Philco	Motor tuned; used with AN/APS-2F. Uses TS-115/APS-2F antenna.
TS-172/UP	1220 - 1350	R. T. 10 stat. mi. with 100 kw radar	$15'' \times 15'' \times 18\frac{1}{2}''$ 21 lb.	Western Electric	Used with TPS-1B & AN/CPS-5.
TS-184/AP	410 - 470	Decay rate 4.52 db/μs. Q about 2500	$12'' \times 6'' \times 10''$ 30 lb.	RCA	Coaxial resonator; used with AN/APS-13 radar; uses AS-123/AP antenna.
TS-184A/AP	400 - 430		$12'' \times 6'' \times 10''$ 28 lb.	RCA	Used with AN/APS-13 radar; uses AS-123/AP antenna; same as TS-184/AP except for frequency range and attenuator rack and pinion drive.

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CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
TS-207/UP	2700 - 2900	3 stat. mi.	$9\frac{1}{8}$" × 6" dia. 5 lb.	Marathon	Used with SCR-584A or B, SCR-545A, SCR-582, SCR-682, AN/MPM-2.
TS-217/MPM-1	2700 - 2900	3 stat. mi.	19" × $7\frac{1}{8}$" × 6" 10.5 lb.	Marathon	Used with AN/MPM-1; designed for permanent installation.
TS-218/UP	8920 - 9250	Decay rate 4.5 to 6 db./μsec. R.T. 2.5 stat. mi. with 25 kw radar; Q varies between 50,000 & 80,000	$18\frac{1}{4}$" × $11\frac{3}{8}$" × 6" 10 lb.	Western Electric	Used with AN/MPM-1 radar. Uses AS-106/AP antenna.
TS-218A/UP	8994 - 9174	Decay 4.5 to 6.0 db per mcs. R.T. 4000 yds with 20 db coupler to 25 kw radar	18" × 6" × 10". 10 lb.	Western Electric	Same as TS-218/UP except for frequency range, type antenna, and method of suppressing unwanted modes. Uses AS-299/AP antenna.
TS-218C/UP	8920 - 9250	Decay 4.5 to 6.0 db per microsecond	18" × 6" × 10". 10 lb.		Similar to TS-218A/UP.
TS-219/UP	2660 - 2950	R.T. 2.5 stat. mi. with 50 kw radar	$10\frac{5}{8}$" × $13\frac{1}{2}$" × 8". 12 lb.	Western Electric	
TS-225/MPN-1	X-band		10" × 6" × 18". 10 lb.	Gilfillan Bros.	Part of AN/MPN-1. Same as TS-218/UP.
TS-228/UP	510 - 540		6" × 10" × 12"	Maguire Industries	

[redacted]

CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
TS-238/GP	2700 - 2900	R.T. 3 stat. mi.	14" × $8\frac{1}{2}$" × 8" 25 lb.	General Electric	Contract No. W-2279-ac-31 and W-2279-sc-106; used with SCR-584 and SCR-784-( ) radar; similar to TS-207/UP.
TS-255/AP	23,660 - 24,285	R.T. 3000 yds with 20 db. coupler to 25 kw radar	10" × 10" × 10" 12 lb.	Western Electric	Used with AN/APQ-39 radar and others; consists of two CG-344/6 waveguides.
TS-270/UP	2700 - 2900	Sensitivity: 90 yds/db. Q 47,000	9" × 12" × 12" 19 lb.	Johnson Service Company	Used with SCR-615, SCR-584, AEW, SM, and SD series, radars; similar to 14-ABA and TS-275 except for frequency range.
TS-270A/UP	2700 - 2900	Same as TS-270/UP			Similar to TS-270/UP.
TS-270B/UP	2630 - 2970	Same as TS-270/UP	Cavity is silver plated magnesium.		Similar to TS-270/UP except for frequency range and magnesium construction of cylinder. AAF Contract No. W-28-099-ac-47.
TS-275/UP	3400 - 3700	R.T. 4000 yd. loaded Q; 4700 sens: 50 yd/db.	11" × 8" × 11" 18 lb.	Johnson Service Company	Used with SG-3 and AN/CPS-6.

CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
TS-280/TPS-3	600		$10'' \times 15\frac{1}{4}'' \times 16''$ 20 lb.	Zenith Radio	Used with AN/TPS-3 radar; Signal Corps drawings No. SC-D-15073-15082.
TS-310/UP	8500 - 9000		$16\frac{7}{16}'' \times 7\frac{5}{16}'' \times 11\frac{1}{16}''$ 10 lb.	Western Electric	Navy Contract No. NXsr-51503.
TS-311/UP	8730 - 8910	R.T. 4000 yds. with 25 kw radar		Western Electric	Code No. X 63629A; wobble-tuned similar to TS-311A/UP.
TS-311A/UP	8730 - 8910	R.T. 4000 yds. when connected to 25 kw radar through 20 db. directional coupler	$16\frac{7}{8}'' \times 7\frac{15}{16}'' \times 11\frac{1}{16}''$ $18\frac{1}{2}$ lb.	Western Electric Gen. Comm. Co.	Same as TS-311/UP except has crystal checker; Navy Contract No. NObsr-30172.
TS-334/UP	3400 - 3900	R.T. 2.5 stat. mi. with 50 kw radar	$7\frac{1}{8}'' \times 15\frac{3}{32}'' \times 7\frac{1}{2}''$ 12 lb.	Western Electric	Part of Navy Model SV Radar Equipment; Navy Contract NXsr-66745.
TS-344/UP	3400 - 3900		$12'' \times 18\frac{5}{8}'' \times 9\frac{1}{4}''$ 18 lb.	Western Electric	Similar to Echo Box CW-14 ABG.
TS-349/UP	910 - 980	R.T. 6000 yds. with MK 12 radar sens. 65 yds./db.	$11'' \times 10\frac{1}{2}'' \times 7''$ 74 lb.	Johnson Service Company	$\lambda/4$ coaxial cavity; used with MK 12 radar.

[redacted]

CHARACTERISTICS OF EXISTING ECHO BOXES (Continued)

DESIGNATION	FREQUENCY RANGE (MCS)	ELECTRICAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	MFR.	REMARKS
TS-398/UP	150 - 240		16" × 11" × 8" 15 lb.	Cole Instrument Company	Used with SA, SC, SK, SR, and other radars; λ/4 coaxial cavity; Navy Contract No. N5sr-8592.
TS-488/UP	9000 - 9600	R. T. 4000 yds. with 25 kw radar and 20 db. coupler	$10\frac{1}{2}$" × $8\frac{7}{8}$" × $17\frac{3}{16}$"	Western Electric Fairchild	USAF Contract No. W-33-038-ac-21315. Replaces TS-62/AP, TS-218/UP, TS-311/UP.
TS-501/UP	6250 - 6900	4000 yds. with 25 kw radar, 20 db. coupler	12" × 12" × 8" 17 lb.	Western Electric Barlow Engineering	Navy Contract NObsr-39218, NRL-N-1736, NRL-10185.
TS-544/UP	580 - 620	7500 yds.	$8\frac{1}{2}$" × 13" × $10\frac{1}{2}$" 12 lb.	Johnson Service Company	λ/4 coaxial cavity; USAF Contract No. W-28-099-ac-181.
TS-545/UP	1150 - 1350	Sensitivity 50 yds./db.; decay 3.5 db./μs.	9" × 16" × 9" 15 lb.	Johnson Service Company	Navy Contract No. NObsr-39392. Replaces TS-172/UP.
TS-576/UP	2700 - 2900		$12\frac{1}{2}$" × $8\frac{3}{4}$" × 19" 50 lb.	Gilfillan Bros.	Similar to TS-270/UP. Part of AN/MPN-3 radar. NXsr-93195.

[redacted]

GLOSSARY OF SYMBOLS AND TERMS USED FREQUENTLY IN THIS REPORT

Mode (cavity)	A standing wave pattern of electric and magnetic fields within a cavity, always associated, in a cavity of a particular shape and size, with a particular resonant frequency.
Ringing time	The length of time, measured in microseconds (or its equivalent, radar range) during which an echo box signal can be detected by an operator observing the signal on the radar scope.
Sensitivity of an echo box	A number expressing the relation between a change in ringing time and the corresponding change in radar performance. Usually expressed in yards per decibel.
TE mode (Transverse Electric)	A type of mode in which the electric field is always perpendicular to a designated axis. Sometimes called "M" mode.
TEM mode (Transverse Electro-Magnetic)	A type of mode existing in transmission lines and coaxial cavities, in which both electric and magnetic fields are always perpendicular to the axis.
TM mode (Transverse Magnetic)	A type of work in which the magnetic field is always perpendicular to a designated axis. Sometimes called "E" mode.
A	Referring to a particular mode, the intercept on the vertical mode chart axis of the line representing this mode.
B	Referring to a particular mode, the number which when multiplied by n^2 gives the slope of the mode line ($= 0.34799 \times 10^{20}$ if the cavity dimensions are in inches and frequency is in megacycles).

C	Capacitance (farads).
D	Inside diameter of echo box cavity (inches).
D	Radar performance (measured at the echo box input, decibels).
E	Electric field intensity (volts per meter).
F	Function of.
F	Level difference; the ratio of the voltage at the input to an echo box measured during the transmitted pulse to that at the end of ringing.
H	Magnetic field intensity (ampere - turns per meter).
I	Surface current density (amperes per meter).
J_ℓ J'_ℓ	Bessel function of the first kind; derivative of Bessel function of the first kind.
K, k	Constants of proportionality.
L	Inductance (henrys).
L	Inside length of echo box cavity (inches).
M	Mutual inductance (henrys).
MS	"Mode Shape" factor, $\frac{Q\delta}{\lambda}$. A quantity used to describe the relative merit of a particular cavity shape.
P	Power (watts, milliwatts, or microwatts). Also expressed in decibels above milliwatts (dbm.) or decibels above 1 watt (dbw.).
Q	Quality factor of cavity. Analogous to the Q for a resonant LRC circuit.
Q_L	"Loaded" Q, the effective value of Q of a cavity coupled to an external circuit.

[redacted]

Q_o	"Unloaded" Q; that value of Q which a particular cavity would have if it were not coupled to an external circuit.
Q_T	"Theoretical" Q; a value of Q computed on the basis of ideal cavity shape and the conductivity of silver.
T	Radar pulse length, microseconds.
V	Potential difference (volts).
V	Volume of resonant cavity.
W	Energy (joules), or ratio of energies (decibels).
Y_ℓ, M_ℓ'	Bessel function of the second kind; derivative of Bessel function of the second kind.
Z	Distance measured along a cavity axis.
$\hat{z}$	Unit vector directed along cavity axis.
c	Velocity of electromagnetic radiation ([redacted]meter per second).
d	Decrement; the number of decibels decrease per microsecond of the power re-radiated from a cavity during ringing.
d.	In a partial coaxial cavity, the length which must be added to the physical length of the center conductor in order to obtain the electrical length.
2d	Diameter of inner conductor of coaxial cavity (inches).
f	Frequency (megacycles).
ℓ, m, n	Subscripts designating a particular cavity mode. ℓ, m, and n are always integers.
$r_{\ell m}$	The m*th* root of the Bessel function of order ℓ, or the m*th* root of the derivative of the Bessel function of order ℓ.
t	Time (seconds).

[redacted]

α	Temperature coefficient of resistivity (ohms per ohm per degree Centigrade).
δ	Skin depth (centimeter).
ϵ_o	Permittivity of free space.
θ	Angle measured about a cavity axis.
$\hat{\theta}$	A unit vector directed perpendicularly to the radius of an angle θ.
λ	Wavelength (centimeters).
μ_o	Permeability of free space.
ρ	Resistivity (ohm - centimeters).
ρ	Distance measured radially from a cavity axis.
$\hat{\rho}$	A unit vector directed radially.
ϕ	Flux (webers).
ω	$2\pi f$.
$\propto$	is proportional to.

[redacted]

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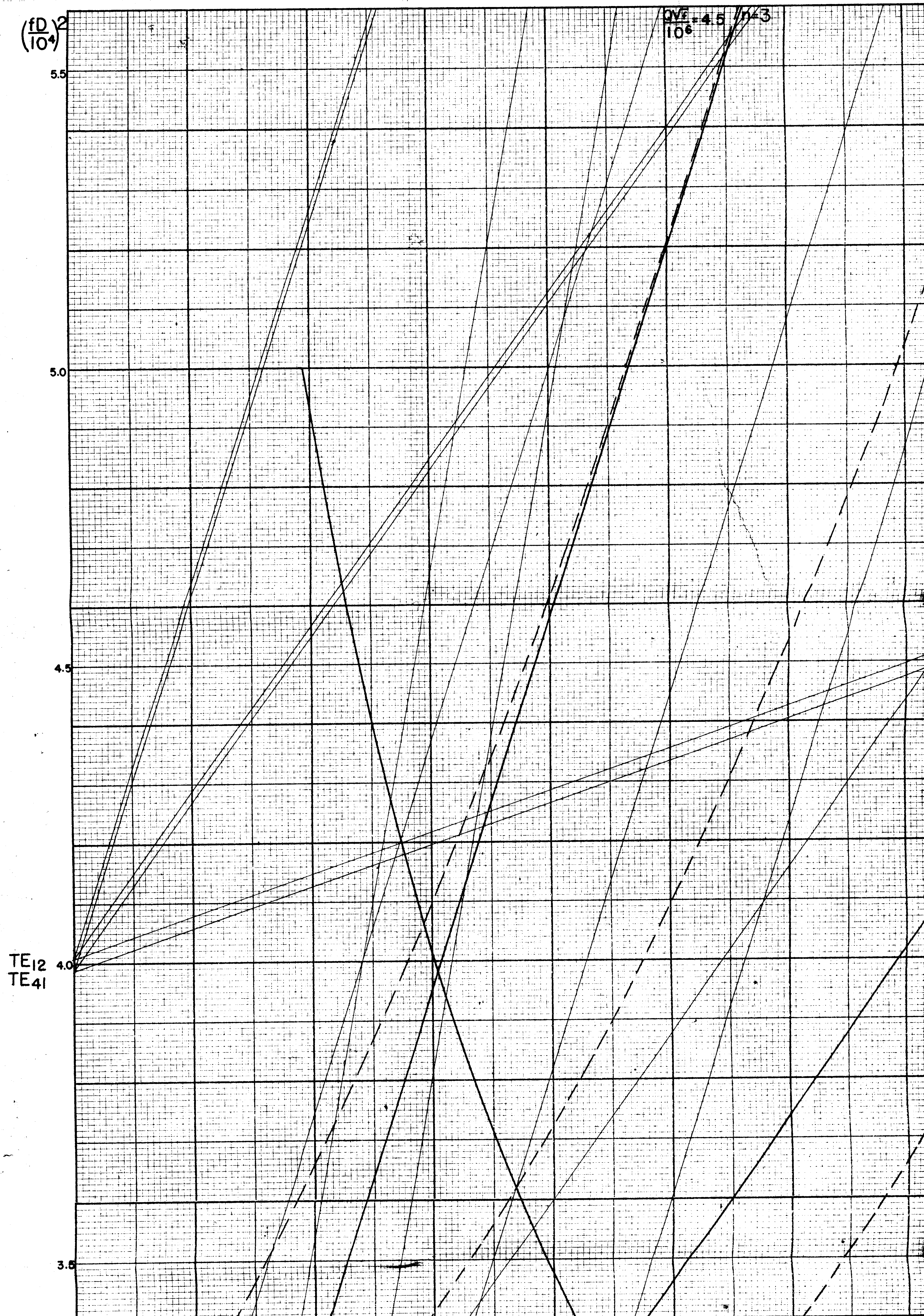
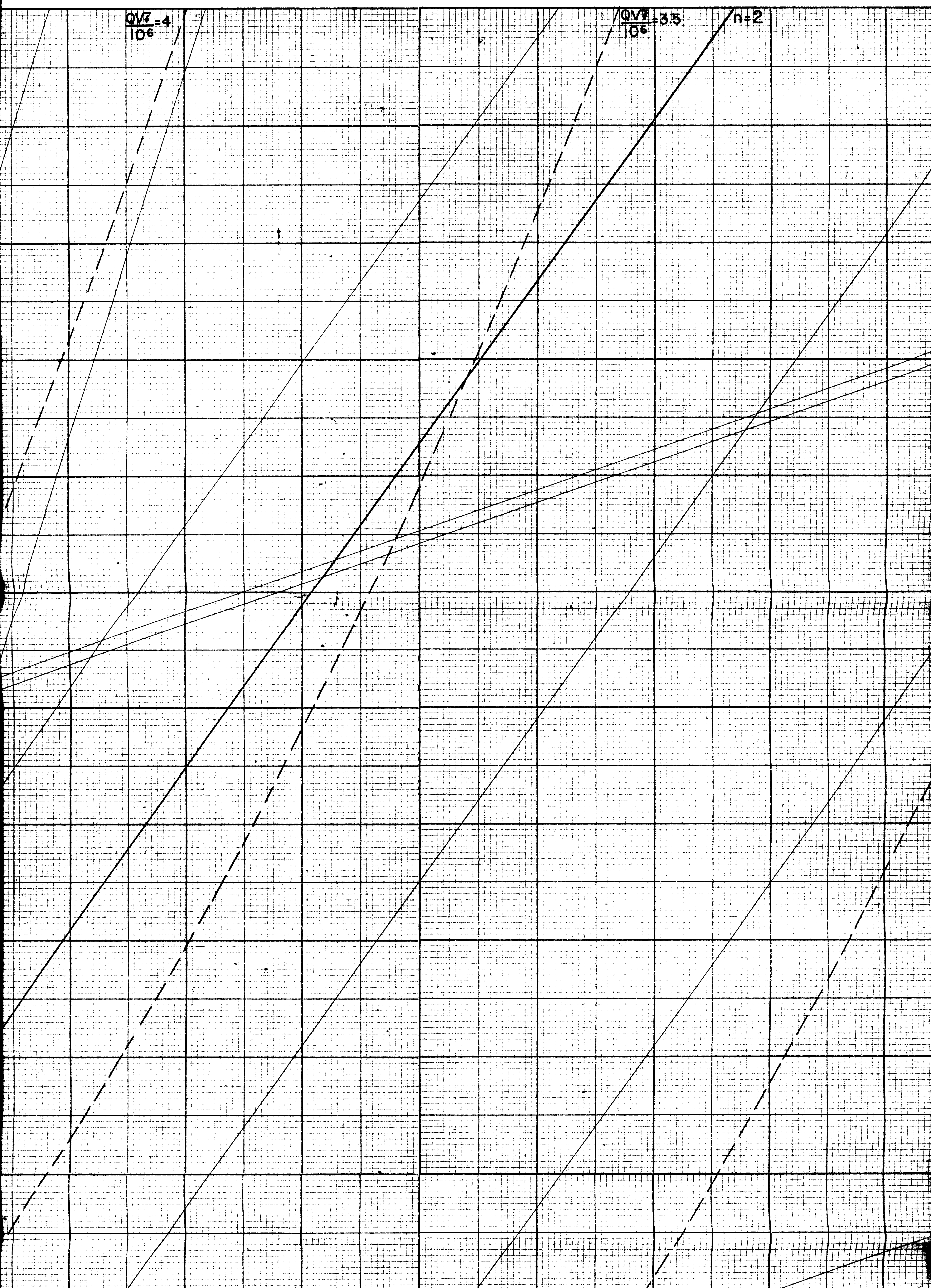
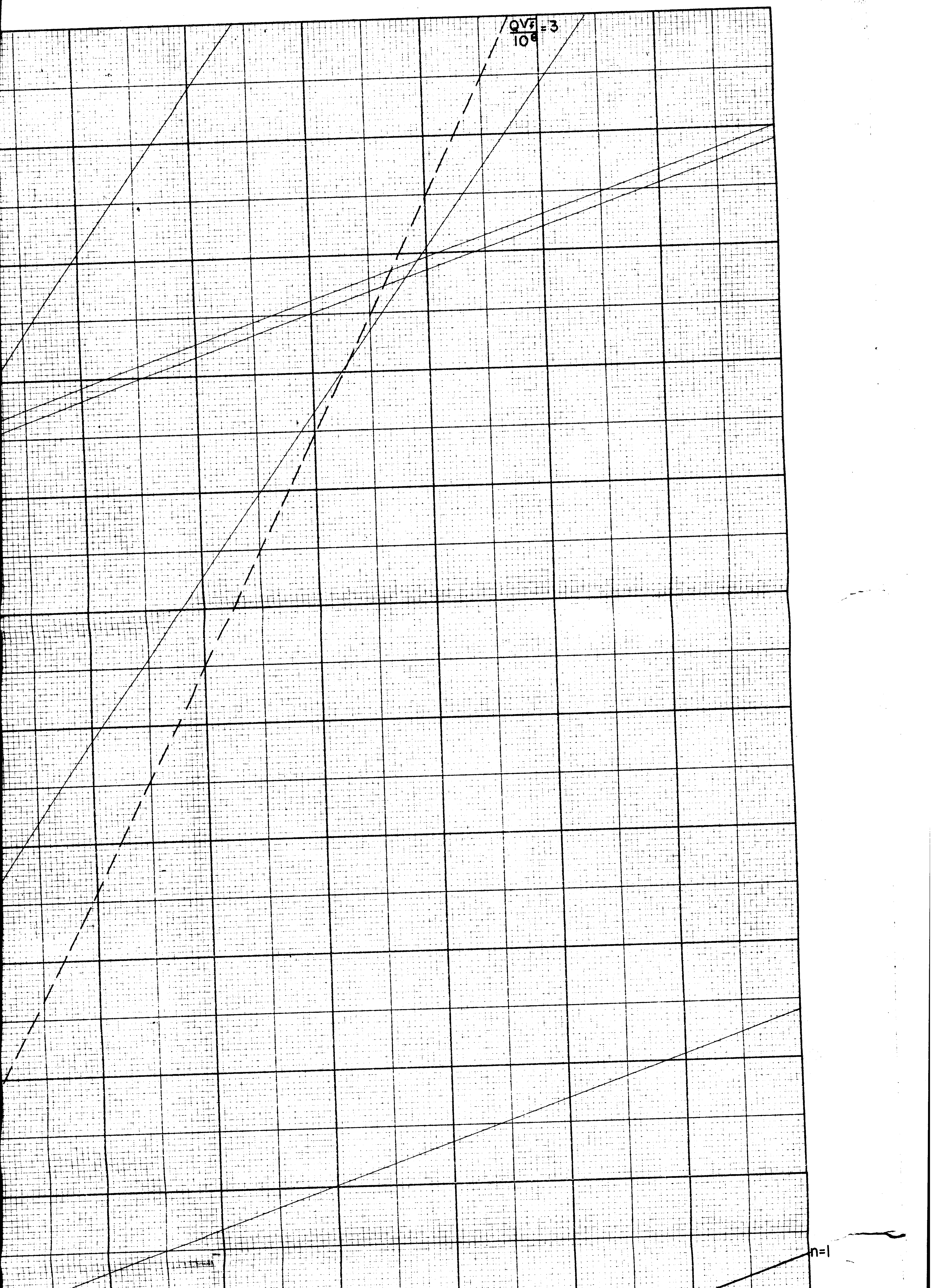


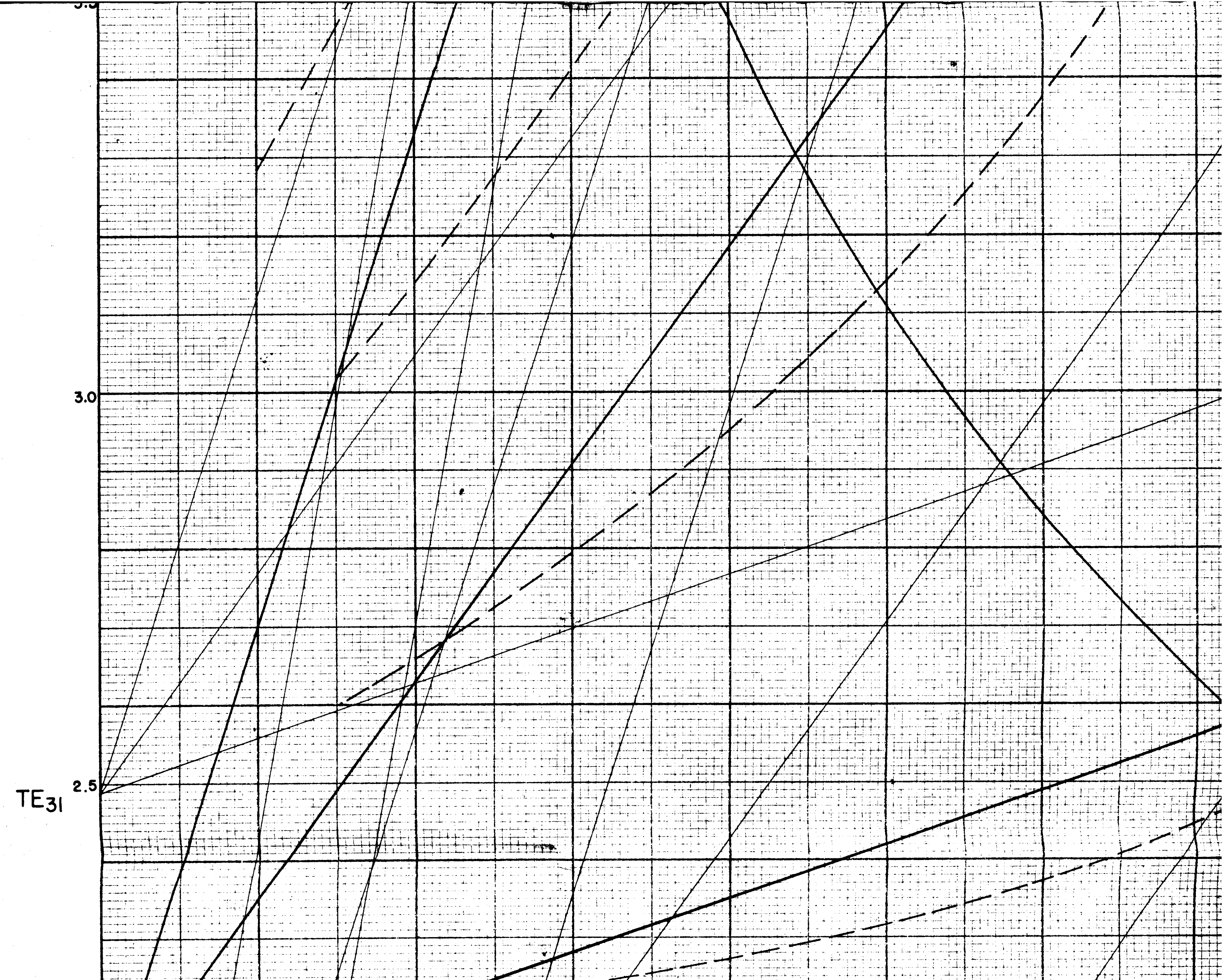
(fD/10⁴)²
5.5
5.0
4.5
4.0
3.5
TE12
TE41
QVf/10⁶ = 4.5
n=3



QV√T/10⁶ = 4
QV√T/10⁶ = 3.5
n = 2



$\frac{QV_F}{10^6}=3$
n=1



3.0
2.5
TE31
TE01
2.0
TE21
TE11
TE214
TE213
TE114
TE212
TE113
TE112
TE211
0.5
1.0

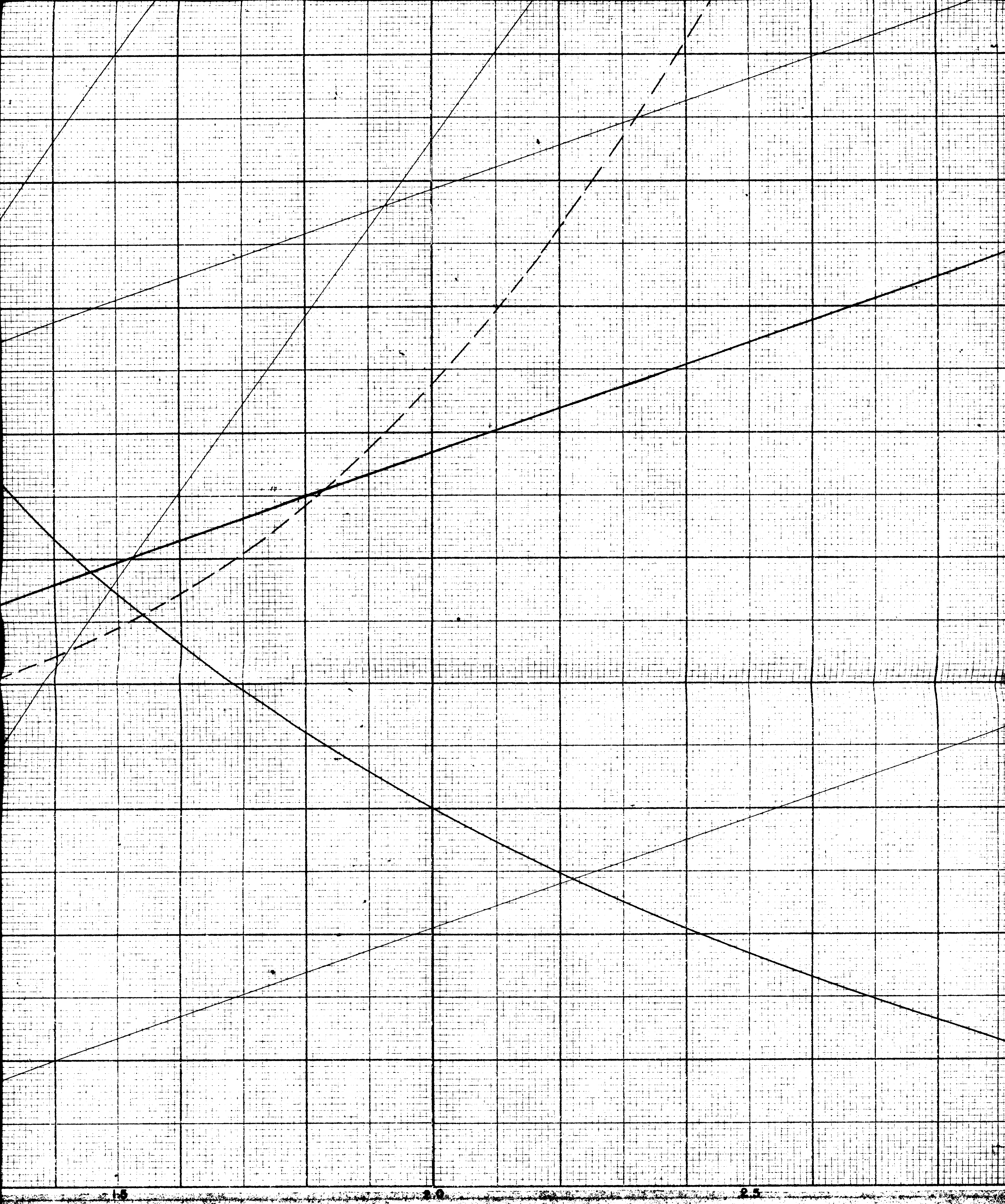
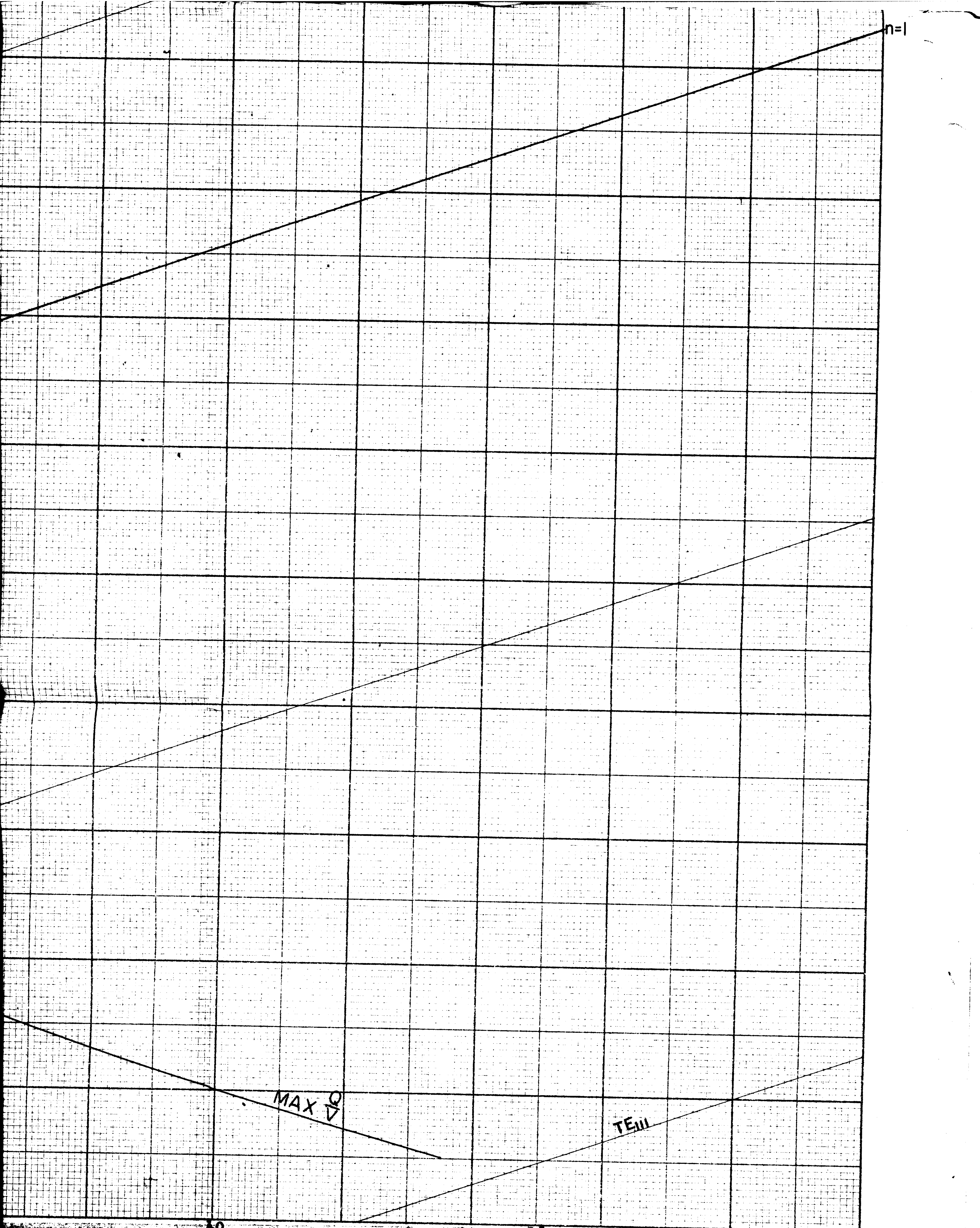


CHART NO. 1

MODE CHART FOR THE RIGHT CYLINDRICAL CAVITY



TE MODES ONLY ARE SHOWN
DASHED LINES SHOW CONTOURS OF $QV^{\frac{2}{3}}/10^6$ = CONSTANT (FOR SILVER PLATED CAVITIES)
D = CAVITY DIAMETER IN INCHES
L = CAVITY LENGTH IN INCHES
f = FREQUENCY IN MEGACYCLES
NOTE THAT VERTICAL SCALE STARTS AT $\left(\frac{fD}{10^4}\right)^2 = 1.6$