DEPARTMENT OF COMMERCE

BUREAU OF STANDARDS

George K. Burgess, Director

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 256

[Part of Vol. 18]

SOME METHODS OF TESTING RADIO RECEIVING SETS

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Bureau of Standards

March 26, 1924

PRICE, 10 CENTS

$1.25 PER VOLUME ON SUBSCRIPTION

Sold only by the Superintendent of Documents, Government Printing Office

Washington, D. C.

WASHINGTON

GOVERNMENT PRINTING OFFICE

1924

SOME METHODS OF TESTING RADIO RECEIVING SETS.

By J. L. Preston and L. C. F. Horle.

ABSTRACT.

This paper describes some methods of measurement of electrical characteristics of a radio receiving set and formulates statements of features which may be learned by an inspection of the electrical and mechanical design of a set. In developing these methods it has been the aim to provide means for determining to what extent a receiving set embodies the following characteristics:

(1) Sufficient sensitivity to produce audible or loud sounds when tuned to receive from stations which may be located at a considerable distance.

(2) Selectivity or the ability to respond to signals of a given frequency without responding to signals of slightly different frequency.

(3) Convenience of operation and simplicity of manipulation in order that persons not highly trained nor conversant with the details of the circuits used may still be able to operate the receiving set satisfactorily.

(4) Effectiveness in covering the particular range of frequencies used by the transmitting stations which it is desired to receive.

(5) Substantial construction in order to remain in serviceable condition in spite of rough handling which may be received during shipment and use.

A summary of data from measurements of sensitivity and selectivity or sharpness of resonance of 28 receiving sets of various types, made by 15 manufacturers, using the methods described in this paper are also given.

CONTENTS.

I. INTRODUCTION.

The possibilities of radio as a means of broadcasting timely information, such as that collected from market centers and from the agencies whose duty it is to guard life and property, became more apparent as the art of radio became more established. Together with this service was the possibility of broadcasting to outlying districts, musical entertainment, the spoken drama, lectures, and many other classes of material which could entertain and educate audiences not within reach of the source. As these various services were broadcast for all who wished to hear, the number of listeners grew and is still growing. The increasing interest of the people has been reflected in a larger production of radio apparatus, which makes it more necessary than ever that methods be available for determining and definitely describing the characteristics and performance of such sets. The seller needed a laboratory method by which to test and describe his product and the buyer needed to know the characteristics which determine the usefulness of a radio receiving set.

The desire for such information was expressed by the Bureau of Agricultural Economics of the Department of Agriculture, representatives of radio manufacturing companies, testing laboratories, and other organizations who conferred with the Bureau of Standards in regard to this need for methods of testing radio receiving apparatus.

This paper describes some methods [1] of measurement of the electrical characteristics and formulates statements of features which may be learned by an inspection of the electrical and mechanical design of a set. In developing these methods it has been the aim to provide means for determining to what extent a receiving set embodies the following characteristics:

(1) Sufficient sensitivity to produce audible or loud sounds when tuned to receive from stations which may be located at a considerable distance.

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[1] Methods of measurement of properties of electron tubes and amplifiers are not included herein. Methods of measuring voltage amplification of amplifiers are given in Bureau of Standards Letter Circular No. 86, and methods of measuring properties of electron tubes are given in Bureau of Standards Letter Circular No. 87. Letter Circular No. 98 gives the results of measurements of the voltage amplification of audio-frequency amplifiers.

(2) Selectivity or the ability to respond to signals of a given frequency without responding to signals of slightly different frequency.

(3) Convenience of operation and simplicity of manipulation in order that persons not highly trained nor conversant with the details of the circuits used may still be able to operate the receiving set satisfactorily.

(4) Effectiveness in covering the particular range of frequencies used by the transmitting stations which it is desired to receive.

(5) Substantial construction in order to remain in serviceable condition in spite of rough handling which may be received during shipment and use.

It would be desirable, if possible, to know the number of miles over which a given receiving set can receive signals. It would greatly assist the average purchaser if he could go to the counter and buy a receiving set by specifying that it must be a 50-mile set. There are, however, a number of factors which make it impossible to rate receiving apparatus in this simple way. For example, all transmitting stations do not use the same power and the distance over which signals can be received depends upon the power employed at the transmitting end.

The loudness of received signals depends also upon the location and method of construction of the receiving antenna. The topography of the region through which the transmission takes place and across which the waves must pass in traveling from the transmitting to the receiving station influences the signal intensity. In the case of the transmission of signals over any considerable distance the weather conditions are a very important factor in determining the strength of received signals. There are so many variables involved in determining the relation between weather and radio transmission that this problem is far from solution. Transmission may be much better, though extremely variable, at night than in the daytime and in winter than in summer, but the effect of rain, clouds, wind, and barometric pressure have not yet been determined.

A receiving set which may be satisfactory in one location where there is little disturbance caused by the existence of a large number of nearby transmitting stations may be entirely unsuitable for use where it is necessary to use the maximum degree of selectivity possible in order to avoid hearing undesired stations. These considerations are in addition to the variable requirements of those

who listen to broadcast reception, some persons being satisfied when they can hear weak signals with the telephone receivers on their ears, while others require that the speech or music be amplified sufficiently to actuate a loud speaker.

Therefore, even after measurements of the performance of radio-receiving apparatus have been made in a laboratory under conditions which can be controlled and measured, it is not easy to apply the results of such measurements to actual transmitting conditions. It must be assumed, for example, in laboratory measurements that the signal which reaches the transmitting station has a certain magnitude and the laboratory apparatus is so arranged as to duplicate the effect of this received signal. The question then comes to the determination of the relation between the magnitude of the received signal and the power in the transmitting station for different distances and under the various conditions affecting reception which were enumerated above.

It is hoped that valuable information in this direction may result from a series of tests of the range of radio transmitting stations now in progress under the direction of the Bureau of Standards. The records which are being secured during these tests are such as to indicate the percentage of time when the signals are easily readable, readable with but little difficulty, just readable, or not readable. The reports received contain, in addition, information as to obstacles to reception which are found to be most serious. The results of tests of this kind, when continued over a period of several years so that proper averages can be obtained, and when coupled with quantitative measurements of the received signals at various distances from transmitting stations of known power, should serve to make laboratory measurements of the performance of receiving sets applicable directly in terms of radio broadcasting service.

Meanwhile measurements on the receiving sets themselves are of great value in enabling one to compare the performance of a number of receiving sets and in pointing out features in which the design of such apparatus can be approved.

It is hoped that the methods described in this paper and which were used by the bureau in 1921 and 1922 in testing a number of radio receiving sets[2] will be useful to manufacturers and com-

[2] The results of tests on 34 receiving sets made by 19 different manufacturers, using the methods herein described, are given in a series of four mimeographed letter circulars which have been issued by the Bureau of Standards. The particular receiving sets studied are referred to by arbitrary reference numbers rather than by a statement of the manufacturers' names and type or model numbers. Representative values of sensitivity and sharpness of resonance obtained are given in the appendix at the end of this paper.

mercial testing laboratories and will assist in bringing about a condition under which the actual testing of radio receiving apparatus will be quite common. This condition would be advantageous to the buyer also, as he could the more readily learn to specify the desired properties in receiving equipment about to be purchased.

It is appreciated that there are improvements to be made in these methods. Further work is particularly needed on the methods for measuring selectivity and sensitivity, these properties being especially significant. There are also other measurements which would be significant, an example being the determination of quality or exactness of reproduction of speech or music. It is desirable not only to make the methods applicable to all types of receiving sets but also to have the tests yield results that have definite significance to the nontechnical person as far as possible.

II. INSPECTIONS.

The first data noted in connection with a set are the several items specified by the manufacturer in respect to the frequency range of the set, antenna to be used, etc. These data are listed as follows:

(*a*) Manufacturer's name and address.
(*b*) Name of receiving set.
(*c*) Type and number of receiving set.
(*d*) Cost.
(*e*) Antenna specifications.
(*f*) Detector, batteries, and other auxiliaries with specifications for their operation.
(*g*) Telephone receivers.
(*h*) Photographs of receiving set.

Where an item specified is furnished with the set, as detector or telephone receivers, the fact is stated.

The next information given is the method of packing for shipment and observations on its effectiveness, under the following heads:

(*a*) Description of materials and carefulness of packing.
(*b*) Brief mechanical and electrical inspection of equipment on arrival from manufacturer.
(*c*) A short performance test to indicate whether the receiving set is in operating condition.

Circuit Diagrams.—Diagrams showing the electrical circuit of each receiving set are made. If diagrams have been submitted by the manufacturer, these are checked.

Circuit and Panel Arrangements.—Inspections are made of the interior and exterior arrangements of the set: The following data are listed:

(*a*) Type of electrical circuit employed.
(*b*) Type of inductors and condensers used.
(*c*) Panel:
  1. Size.
  2. Material.
  3. Finish.
(*d*) Type of frequency controls:
  1. Method used for fine adjustment of frequency.
  2. Method used for showing frequency calibration.
(*e*) Description of detector-control apparatus.
(*f*) Description of the method of making connections.
(*g*) Description of labeling of controls and terminals.

Structural Details.—The receiving set is examined with respect to the ruggedness, quality of materials and workmanship of component parts, ease of operation, and possible precision and permanence in adjustment of controls. In doing this the device is given a very close inspection to determine the absolute and relative grades of materials with particular reference to the materials under mechanical strain, the materials and parts which are likely to change owing to the effects of moisture and mechanical shock, and which are likely to wear in use. These are summarized under:

(*a*) Cabinet.
(*b*) Dielectric materials in—
  1. Panel.
  2. Condensers.
  3. Inductors.
  4. Detector.
(*c*) Type of mechanical construction used in the assembly of—
  1. Condensers and auxiliaries.
  2. Inductors and auxiliaries.
  3. Detector (electron-tube auxiliaries or crystal detector stand).
(*d*) Workmanship of assembly and wiring.
(*e*) Strength of metallic wiring, supports, and anchors.

Electrical Inspection.—The receiving set is examined to determine the electrical qualities of its component materials, the care taken in working up these materials into component parts, and their disposition relative to one another. This inspection is made with special attention to the materials that constitute the high-current parts of the circuit, the parts which are subject to relatively great voltage, and the protection of these parts from the effect of moisture. These inspections are summarized under:

(a) Type of circuit used.
(b) Electrical design of inductors and quality of materials used.
(c) Electrical design of condensers and quality of materials used.
(d) Method of rectification (type of detector circuit).
(e) Quality of component parts.
(f) Relative location of component parts.
(g) Method and location of interconnections.
(h) Method of shielding.

III. LABORATORY TESTS.

1. FREQUENCY RANGES.

The receiving set is connected to an antenna and ground and is used as in operation for the reception of signals. The antenna is that specified by the manufacturer of the receiving set or of a size most likely to be used. Where departure is made from the antenna specified by the manufacturer the constants of this antenna must be known and stated.

A phantom antenna may be used instead of an actual antenna. It is a series arrangement of capacity, inductance, and resistance, the combination being the equivalent of an antenna used in radio receiving. For measurements at a given frequency the condenser and resistor of the phantom antenna are set at the values of capacity and resistance of a typical antenna at that frequency. The inductance of the phantom antenna is the same as the inductance of the typical antenna, and was substantially a constant value over a considerable range of frequencies.

In this connection measurements were made on an antenna of a type much used for broadcast reception, and its equivalent capacity and reactance are given in the curves of Figure 1.[3] In making the measurements referred to in the footnote on page 206, using the methods described in this paper, the capacity of the phantom antenna at any frequency was the capacity values shown in Figure 1 for that frequency. The inductance of the phantom antenna in those measurements was approximately 4.25 microhenries and the resistance was approximately 16 ohms.

A buzzer-driven wavemeter [4] is placed so that it will excite only the antenna circuit, care being taken that no direct excitation of the receiving set except that through the antenna exists. A complete calibration of the receiving set is then obtained by

[3] By making measurements of the constants of a large number of antennas, it would be possible to establish an arbitrary set of standard values of the constants which could be used to secure more uniformity in the way in which receiving sets are tested.

[4] Where precision is required a modulated electron-tube generator with a separate wavemeter would be better than a buzzer-driven wavemeter.

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determining frequency in kilocycles (or wave length in meters) to which the receiving set is resonant at as many positions of the tuning controls as are required to determine the limits of frequency range of the several controls. If the receiving set is tuned by tapped inductors and variable condensers a minimum setting and a maximum setting of the condenser is used for each inductor tap. This applies to removable (plug) inductors as well.

If the receiving set is of a coupled type, employing a primary and secondary tuning system, each system is calibrated independently of the other; that is, a primary circuit calibration is obtained

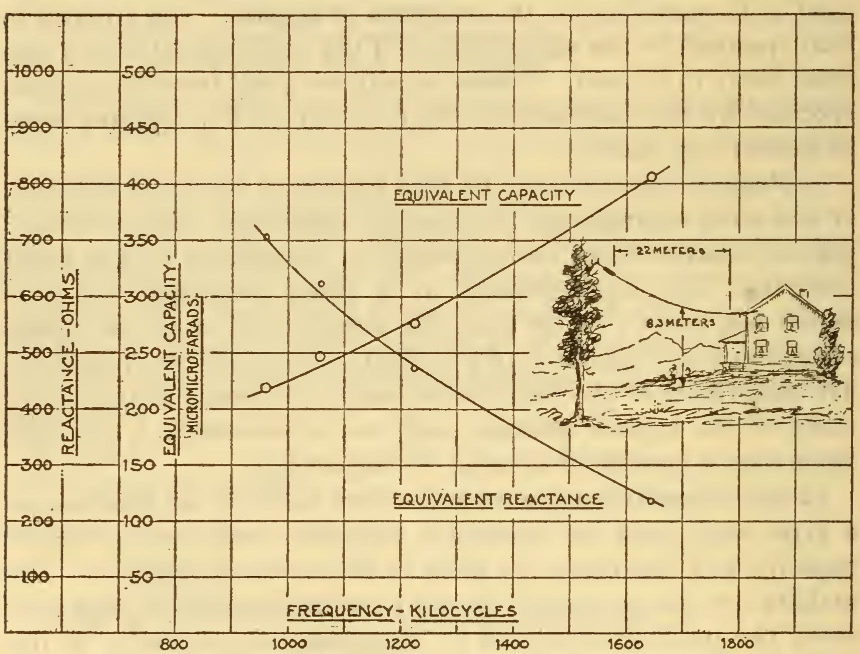

FIG. 1.—*Constants of typical antenna used for broadcast reception.*

for each tap or inductor with minimum and maximum condenser settings. A similar secondary circuit calibration is obtained, care being taken that interaction between these circuits is reduced to a minimum during the calibration.

For the single-circuit type of receiving set, the procedure for frequency calibration is the same as that of the calibration of the primary circuit of a coupled receiving set; that is, each tap or plug inductor is calibrated with minimum and maximum capacity of the antenna condenser. In all cases, indication of resonance is obtained by use of the detector and telephone receivers furnished or to be used with the receiving set.

The above methods of frequency calibration apply to all types of receiving sets, whether regenerative or not. The data show the range of frequencies to which the receiving set will respond for each of its several combinations.

For nonregenerative receiving sets the above frequency calibration is all that is necessary, but the regenerative types should receive some additional consideration. The method used to determine the generation range of a regenerative radio receiving set is: (1) For one extreme limit, vary the receiving set controls until current is just produced at the highest possible frequency, as determined by the click in the telephone receivers, or by placing an ammeter in the plate circuit and noting the point at which there is a sudden change in plate current. Having found the generation point, slightly vary the controls until the current just ceases, then (with a buzzer-driven wave meter) determine the frequency of the receiving-set circuit with that position of the controls; (2) for the other extreme limit vary the controls of the receiving set as described above until the receiving set generates current at the lowest possible frequency. Having found this point, slightly change the setting of the controlling device until the generated current just ceases. Determine the frequency of the receiving-set circuit with that position of controls by using a buzzer-driven wave meter. These two determinations indicate the frequency range over which the receiving set is regenerative.

2. VIBRATION TEST.

This test is designed to obtain information as to the mechanical strength of the receiving sets, particularly as it concerns their ability to withstand the shocks of transportation. These data are obtained by fixing the receiving set on a vibrating machine, which simulates the vibration and shocks in transit. The vibrating machine is operated for a period of 15 minutes. At the end of this time the receiving set is taken from the vibrator and carefully inspected as to mechanical condition. If parts of the receiving set have been displaced in any way, the condition is noted. Any displacement or alteration in the receiving set during this process indicates insufficient ruggedness to withstand the rigors of transportation. The construction of the vibrator and method of securing the receiving set to the vibrator table are shown in Figure 2 (facing p. 214).

A partial recalibration for frequency is made after the vibration test, at several different settings of the frequency controls, to note any effects on the electrical characteristics of the receiving set due to the vibration test.

3. SENSITIVITY.

(*a*) THEORY.—The practical usefulness of a radio receiving set depends primarily on its ability to convert a desired incoming radio signal into sound in the telephone receivers in as great volume as possible. The louder the signal, for a given voltage impressed on the antenna circuit of the receiving set, the more effective it is. Thus, the ratio of signal intensity as perceived by the ear to the voltage[5] impressed on the antenna circuit of the receiving set is a direct measure of its effectiveness in this regard and might well be termed its sensitivity. It is difficult, however, to make a direct measurement of signal intensity and we therefore resort to a more easily measured quantity which is related to signal intensity. Experience indicates that the value of the signal current in the telephone receivers is a satisfactory indication of signal intensity at constant audio frequency, and since the measurements made by the methods outlined in this report are made independent of the audio frequency, the telephone-receiver signal current is taken as a measure of signal intensity and the ratio of the telephone-receiver signal current to the voltage impressed on the antenna circuit of the receiving set is defined as the "sensitivity" of the receiving set.

The sensitivity may then be defined as the ratio of the telephone-receiver signal current to the voltage impressed on the antenna circuit of the receiving set. The telephone-receiver signal current in a crystal detector set is the total direct current flowing in the telephone-receiver circuit, while the telephone-receiver signal current in an electron-tube receiving set is determined by measuring the change in the direct current passing through the telephone receivers as a result of the signal voltage induced in the antenna circuit.

It has been found convenient in order to avoid values of sensitivity in numbers that are much less than unity to arbitrarily define sensitivity as

$$\text{sensitivity} = \frac{I_t}{E_a} \times 10^5 \qquad (1)$$

[5] See page 224 for the method of measuring the voltage impressed on the antenna circuit.

where I_t is the telephone-receiver signal current in amperes, and E_a is the radio-frequency voltage applied to the antenna circuit, in volts.

This definition of sensitivity gives a simple numerical expression and is normally independent of the absolute values of currents or voltages when the detector has a linear relation between applied voltage and telephone-receiver signal current. It has been found, as indicated on page 218, that crystal and electron-tube detectors do not have such simple rectification characteristics. In fact, the relation of the telephone-receiver signal current to the applied voltage is found to vary greatly with the magnitude of the applied voltage. It is necessary, therefore, if measurements of value for comparison are to be made on a group of different receiving sets, that these measurements be made at a number of different applied, voltages and that these voltages approximate those commonly met with in service.

Using an unmodulated radio-frequency generator operating at the desired frequency, the voltage impressed on the antenna circuit may be calculated from measurements of current and the constants of the apparatus. Determinations of the sensitiveness of crystal-detector receiving sets have been made with antenna voltages of 30, 50, and 100 mv. The sensitivity of electron-tube detector receiving sets has been determined at radio-frequency antenna voltages of 15, 30, and 50 mv. In these measurements the antenna resistance was determined in each case, and was between 5 and 40 ohms. It is desirable that measurements be made with a voltage as low as 1 mv in the antenna.

In these determinations the crystal detectors used on the receiving sets should be adjusted to average sensitive positions for each signal strength used. Electron-tube detectors should be used at their rated values of filament current and plate voltage. If soft detector tubes are used, adjust to the most sensitive condition as determined by the condition of maximum signal. None of the data secured in these measurements indicate the degree of distortion that accompanies the use of any of the receiving sets, but it can be said, in general, that the detector in which the relation between input voltage and output current is most nearly constant for a wide range of input radio-frequency voltages will probably give the least distortion.

(*b*) Determination of Sensitivity of Crystal-Detector Receiving Sets.—Figure 3 gives the arrangement of testing

apparatus as used in the determination of sensitivity. A photograph of the apparatus used is shown in Figure 4. The receiving set is operated in connection with a phantom antenna, having a capacity and resistance equal to that of the typical antenna. The desired radio-frequency voltage is induced in the phantom antenna. The detector is then adjusted to average sensitivity and the receiving set carefully tuned to resonance. The telephone-receiver signal current (I_t) is noted and compared with the induced voltage in the phantom antenna as shown by equation (1). These data

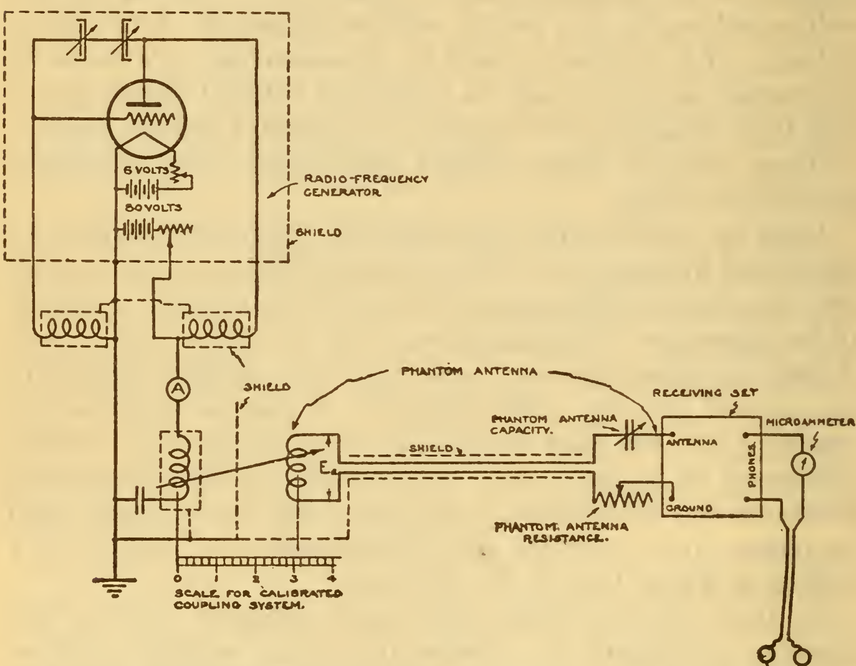

FIG. 3.—*Schematic arrangement of apparatus for sensitivity and selectivity determinations.*

are obtained at several frequencies and antenna voltages, and the results tabulated. For measuring the telephone-signal current it is convenient to use a quadruple scale milliammeter having 200, 20, 2, and 0.2 milliampere scales. The telephone receivers to be employed with the receiving set should also be used for these measurements, and, if possible, their impedance should be measured and recorded. In the case of coupled circuit receiving sets a record should be made of the coupling at which the measurements are made.

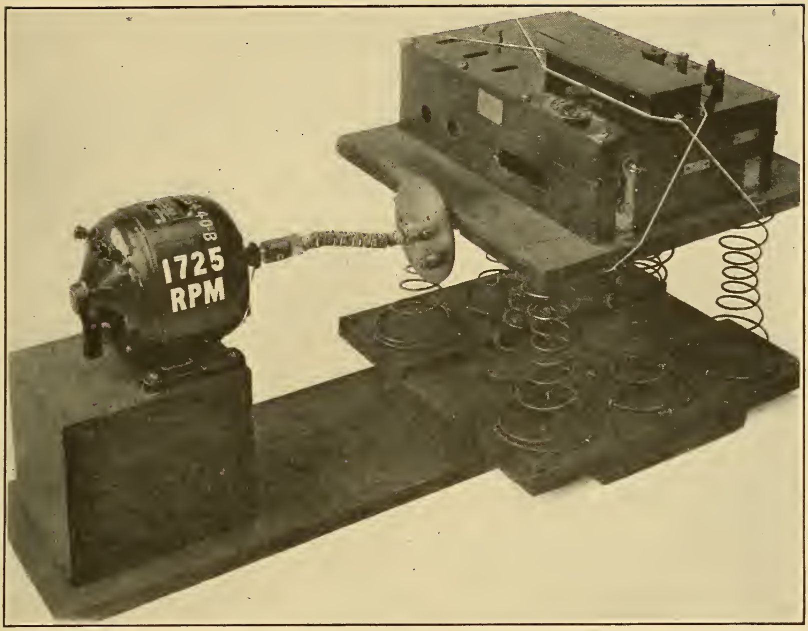

FIG. 2.—*Vibrating machine with receiving set attached for testing.*

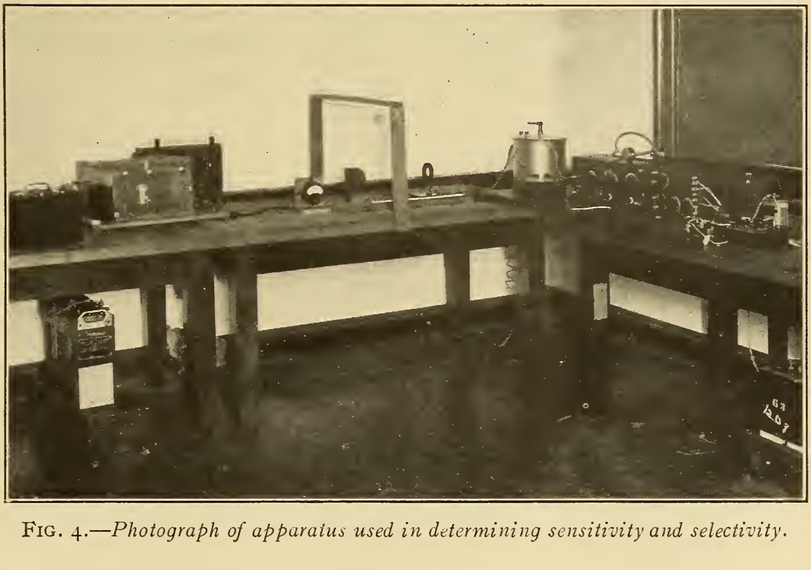

FIG. 4.—*Photograph of apparatus used in determining sensitivity and selectivity.*

(*c*) DETERMINATION OF SENSITIVITY OF RADIO RECEIVING SETS EQUIPPED WITH ELECTRON-TUBE DETECTORS.—The procedure for this determination is that given in 3(*b*) above for the case of crystal-detector receiving sets, the telephone-receiver signal current being given by the change of the plate current.[6]

In all measurements on receiving sets employing electron tubes it is important that record be made of the type of tube used or of its characteristics.

In the case of regenerative sets, however, regeneration is carried as far as possible without actually generating current in the local circuit. The point where generation begins is usually indicated by a sudden change in plate current or a very weak heterodyne signal. It should not be said that this degree of added sensitivity can be realized when obtaining faithful reproduction of voice-modulated continuous-wave signals because of the instability and distortion, but the point of maximum regeneration so defined gives the maximum sensitivity that it is possible to obtain from the receiving set when receiving damped-wave telegraph signals. A comparison of the values of sensitivity at minimum regeneration and maximum regeneration indicates the degree of regeneration possible in the receiving set under test as compared with the regeneration which is inherent in the set.

The above methods of determining sensitivity, as well as those following on selectivity, are applicable to receiving sets comprising a tuner and detector, and, if the input voltage is reduced accordingly, to receiving sets which include radio-frequency amplification.

4. SELECTIVITY.

(*a*) THEORY.—One of the primary requirements of any radio receiving set is that it shall be capable of tuning in a desired radio transmitting station to the exclusion of other stations transmitting on approximately the same frequency. That is, if two voltages of comparable magnitude but of slightly different frequencies be simultaneously or successively impressed on the same receiving antenna, the ideal receiving set, if properly adjusted, will be able to transform the signal voltage from the desired transmitting

[6] In the case of regenerative receiving sets, information regarding the fineness and ease of adjustment of regeneration may be obtained by measuring the telephone-signal current at various settings of the regeneration or tickler control, particularly as the point of generation is approached. A curve may be plotted having regeneration control plotted along the horizontal axis and corresponding telephone-receiver signal current along the vertical axis. Information regarding the necessity for readjusting the regeneration control when the tuning is changed may be obtained by determining, at various frequencies, the setting of the regeneration or tickler control which just avoids generation. This information may be plotted as a curve with frequency or wave length on the horizontal axis and regeneration or tickler setting on the vertical axis.

station into sound in the telephone receivers in very much greater volume than it does the signal voltage due to the undesired frequency with which it is not exactly in tune.

The degree in which a receiving set is capable of differentiating between signals of like magnitude but slightly different frequency is termed the *selectivity* and may be measured by means of the apparatus shown schematically in Figure 3. A photograph is given in Figure 4. The radio-frequency generator simulates the remote transmitting stations, while the phantom antenna simulates the antenna ordinarily used. Observation of the amount by which the telephone-receiver signal current changes as the frequency of the generator is changed from resonance with the receiving set to a nonresonant value makes possible the numerical evaluation of the selectivity.

In this paper selectivity is expressed in terms of a quantity called the "sharpness of resonance" (see Bureau of Standards Circular No. 74, Radio Instruments and Measurements, pp. 36, 187, and 195). For a simple radio-frequency circuit, sharpness of resonance is defined as follows:

$$\text{Sharpness of resonance, } S = \frac{\sqrt{\dfrac{I_r^2 - I^2}{I^2}}}{\dfrac{\pm(f^2 - f_r^2)}{f f_r}} = \frac{\sqrt{\dfrac{I_r^2 - I^2}{I^2}}}{\dfrac{\pm(\lambda_r^2 - \lambda^2)}{\lambda_r \lambda}} \qquad (2)$$

where

f_r = frequency of applied emf at resonance,

f = frequency of applied emf different from the frequency at resonance,

I_r = radio-frequency current in circuit at resonance,

I = radio-frequency current in circuit when applied emf has the frequency f,

λ_r = wave length corresponding to frequency f_r,

λ = wave length corresponding to frequency f.

When making measurements on a receiving set, the values of S obtained for different values of frequency off resonance, on any particular observed resonance curve, are not likely to be the same. Hence, no single observed value of S can be considered as the unique measure of the selectivity of the set for that particular frequency. It is convenient to arbitrarily select a value of frequency off resonance which makes the numerator of this fraction equal to unity; that is, I^2 equal to $\frac{1}{2} I_r^2$, the value of f or λ must be

taken to correspond. This particular value of sharpness of resonance may be designated as $S_{1/2}$.

It is found convenient in measuring the sharpness of resonance of receiving sets, to use the telephone-receiver signal current (see definition on p. 212) as a measure of the radio-frequency current in the set. This is desirable because the telephone-receiver signal current is a direct indication of the sound intensity of the signal produced when the input radio-frequency voltage is modulated. Assuming the telephone-receiver signal current to be proportional to the square of the radio-frequency current in the tuned circuit of the receiving set,

$$\text{Sharpness of resonance, } S = \frac{\sqrt{\dfrac{I_{t_r} - I_t}{I_t}}}{\dfrac{\pm(f^2 - f_r^2)}{f\,f_r}} \tag{3}$$

where I_{t_r} and I_t are the telephone-receiver signal currents at resonance and off resonance, respectively. The validity of the assumption of the square law is discussed later in this paper.

When the telephone-receiver signal current-frequency curve is not symmetrical with respect to the vertical line drawn through the apex of the curve, as is the case in Figure 7 below, two values of sharpness of resonance may be computed, one for either side of the vertical axis. In such cases it is desirable either to express sharpness of resonance as the average of the two or to state both values where the two are widely different.

To make the measurement of sharpness of resonance it is necessary to connect to the receiving set an antenna (real or artificial), detector, and such necessary accessory equipment as batteries, telephone receivers, etc., as in Figure 3, and to induce in the antenna a series of voltages of constant magnitude but of frequencies at, above, and below the resonant frequency, observing the several values of telephone-receiver signal currents and corresponding frequencies. The values of the frequencies are read directly from the radio-frequency generator supplying the signal voltage to the antenna circuit, or by measurement with a wave meter, while the telephone-receiver signal currents are determined by measurement of the direct current passing through the telephone receivers as a result of the signal voltage induced in the antenna circuit. The values of frequency and telephone-receiver signal current are then substituted in equation (3) and the sharpness of resonance calculated for that frequency. Similar

measurements and calculations are made over a wide range of frequencies.

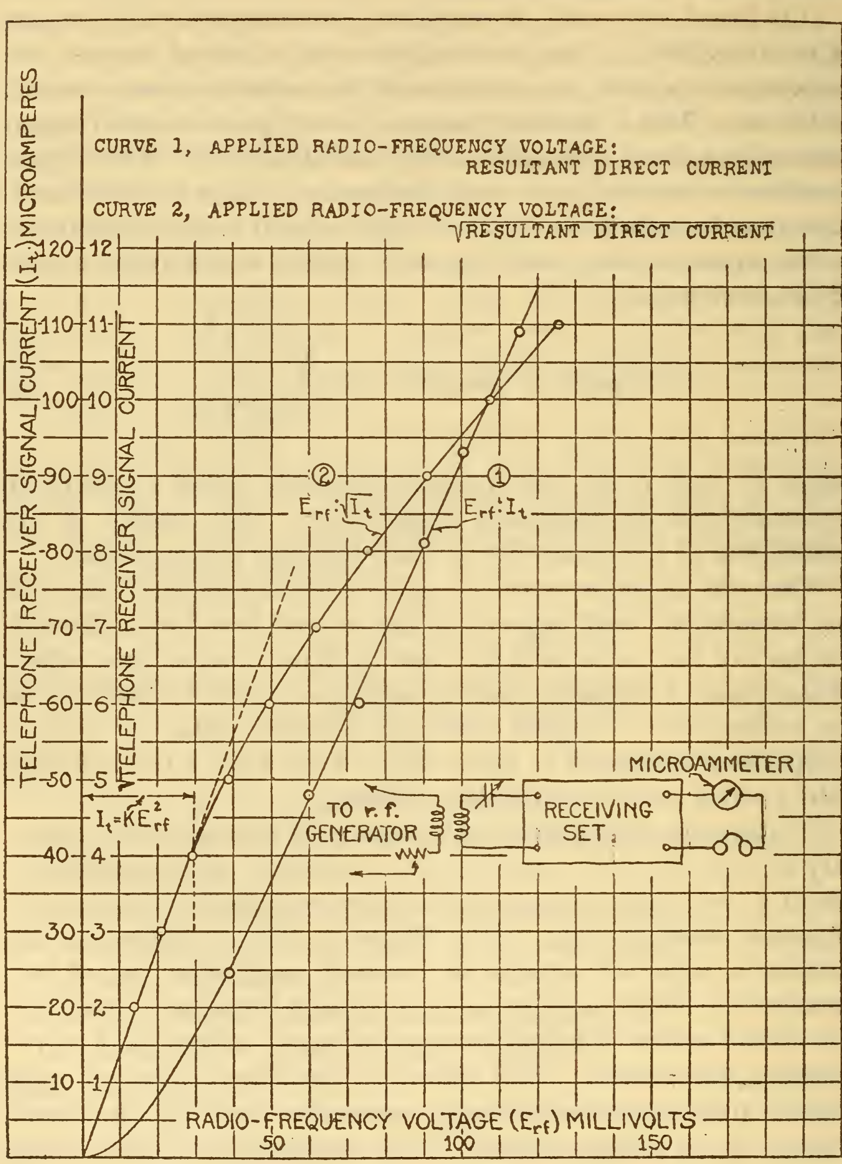

Fig. 5.—*Voltage-current characteristic of crystal detector.*

(*b*) Determination of Sharpness of Resonance of Radio Receiving Sets Equipped With Crystal Detectors.—For single-circuit radio receiving sets equipped with crystal detectors, the method outlined above is directly applicable; that is, a radio

frequency voltage of constant magnitude but of variable frequency is induced in the antenna circuit and the values of the telephone-receiver signal currents are observed by means of a microammeter in series with the telephone receivers. Where the telephone-receiver signal current is proportional to the square of the applied voltage the resultant sharpness of resonance is in strict agreement with equation (3), while if the square law obtains only approximately the value so obtained is not in strict agreement with equation (3).

In this connection it is of considerable interest to determine the relation between applied voltage and telephone-receiver signal current in the case of a typical crystal rectifier. This has been done by successively applying several known values of the radio-frequency voltage to the antenna circuit of a radio receiving set equipped with a crystal detector and noting the resultant telephone-receiver signal current. The results are given in Figure 5, from which it may be concluded, in the case of this particular receiving set and crystal detector, that if the telephone-signal current is not greater than 40 microamperes it varies as the square of the applied voltage, and the calculated sharpness of resonance, therefore, conforms to equation (3).

Figure 5 shows that when the telephone-signal current is greatly in excess of 40 microamperes, a great departure from the "square-law" action occurs in the crystal whose characteristics are given in this figure. This can be corrected for in the calculation of sharpness of resonance by the determination of the relation between applied voltage, E, and rectified current in the detector, I_t, and the substitution of the proper value of x in the numerator of equation (3) as modified below.

$$\sqrt{\frac{I_{t_r}^{\frac{2}{x}} - I_t^{\frac{2}{x}}}{I_t^{\frac{2}{x}}}} \text{ where } x \text{ is defined by equation } (I_t = E^x)$$

This correction is usually unnecessary, however.

In Figure 7 is given the signal-current frequency characteristic of a typical radio receiving set equipped with a crystal detector. The sharpness of resonance of this receiving set has been calculated and is shown in the figure.

(c) Determination of Sharpness of Resonance of Non-regenerative Electron-Tube Radio Receiving Sets.—When electron-tube detectors are employed for rectification in receiving

sets, the general method outlined above is applicable, with the exception, however, that a special method for the determination of the telephone-receiver signal current is necessary, since the

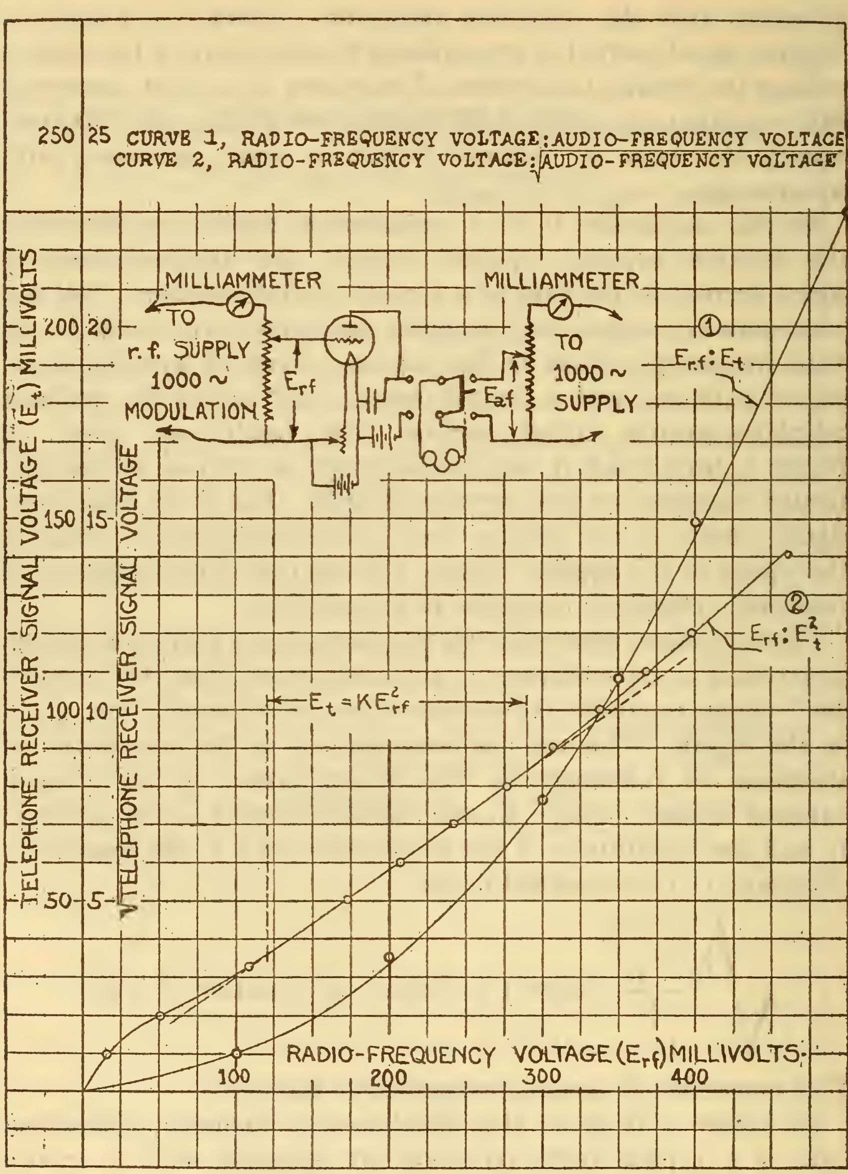

FIG. 6.—*Radio-frequency voltage, audio-frequency voltage characteristic of electron-tube detector.*

telephone-receiver current in such a receiving set has a continuous current component upon which is superimposed the alternating signal current.

The actual value of the plate current for any given fixed plate voltage and filament current depends upon the constant voltage between the grid and filament. Under normal conditions (no signal current in the antenna circuit) the potential of the grid is fixed and is determined by the voltage drop across the grid leak due to the current passing between the grid and filament. Thus, when no alternating current exists in the tuned circuit and hence no alternating voltage is applied to the grid, a certain fixed value of current (normal plate current) exists in the plate circuit. But when an alternating current exists in the tuned circuit and an alternating voltage is consequently applied to the grid, the current through the grid leak and the voltage drop across the grid leak increase, making the grid more negative, and the plate current is consequently reduced, the reduction being proportional to the square of the change in grid voltage, and, hence, proportional to the square of the current in the tuned circuit. The change in plate current is then a measure of the alternating telephone-signal current made available in the telephone receivers by the application of the incoming signal voltage to the antenna circuit, and it is ordinarily also a measure of the square of the alternating current in the main circuit.

The expression for sharpness of resonance in the case of the receiving set equipped with an electron-tube detector is then,

$$\text{Sharpness of resonance, } S=\frac{\sqrt{\dfrac{\Delta I_r-\Delta I}{\Delta I}}}{\dfrac{\pm\ (f^2-f_r^2)}{f\,f_r}} \tag{4}$$

where ΔI_r and ΔI both represent the differences between (*a*) the plate current with a radio-frequency signal voltage applied to the grid (that is, the normal plate current augmented by the incoming signal current) and (*b*) the normal plate current with no radio-frequency signal voltage applied to the grid, these measurements being made at the two frequencies f_r and f, respectively, as defined in connection with equation (2).

In receiving sets equipped with electron-tube detectors, as well as in crystal detector receiving sets, the applied radio-frequency voltages must be rather small if the detector is to operate as a "square-law" device. But in this case, as in the case of the crystal receiving sets, the sharpness of resonance may be determined by comparison between the telephone-receiver signal current and the frequency, without correction for the departure of the law of

the detector from the square-law relation. Figure 6 shows the relation between radio-frequency voltage applied to the grid and the resultant audio-frequency telephone-receiver voltage of a certain electron tube. It is interesting to note from this figure that in the electron-tube detector, unlike the crystal, there is a very marked departure from the square law both above and below the rather narrow range in input signal voltages in which the square law obtains strictly.

(*d*) PROCEDURE FOR THE DETERMINATION OF SHARPNESS OF RESONANCE OF HIGHLY REGENERATIVE ELECTRON-TUBE RADIO RECEIVING SETS.—In receiving sets employing the regenerative principle large values of sharpness of resonance may be obtained. This is sometimes explained as being due to the decrease by regeneration of the effective resistance of the circuit. In this type of receiving set it is difficult to make precise measurements of the small changes in frequency, f_r and f, required by the application of the above-described method.

Measurement is made possible in this case, however, by the fact that regeneration may be considered as effective in reducing the resistance of the input circuits of the electron-tube detector. It may be shown [7] that for a simple series circuit the sharpness of resonance may be expressed as,

$$S = \frac{1}{R}\sqrt{\frac{L}{C}}$$

where C, L, and R are the capacity, inductance, and resistance, respectively, of the radio-frequency circuit. Sharpness of resonance, therefore, varies inversely as the effective resistance (R) of the tuned circuit which supplies the signal voltage to the detector. The ratio of the effective circuit resistance with minimum regeneration to the effective circuit resistance with maximum regeneration is, therefore, equal to the ratio of the sharpness of resonance with maximum regeneration to the sharpness of resonance with minimum regeneration.

It remains, then, to determine the sharpness of resonance of the receiving set with minimum regeneration; then to determine the ratio of the effective resistance of the entire circuit with maximum regeneration to its resistance with minimum regeneration. The sharpness of resonance at maximum regeneration is then the product of this ratio and the sharpness of resonance

[7] See B. S. Circular 74, Radio Instruments and Measurements, p. 37.

with minimum regeneration. But since, at resonance, the current in the tuned circuit is inversely proportional to the resistance and proportional to the square root of the telephone-receiver signal current, then

$$S_{\mathrm{max.}} = S_{\mathrm{min.}} \sqrt{\frac{I_{t'}}{I_t}} \qquad (5)$$

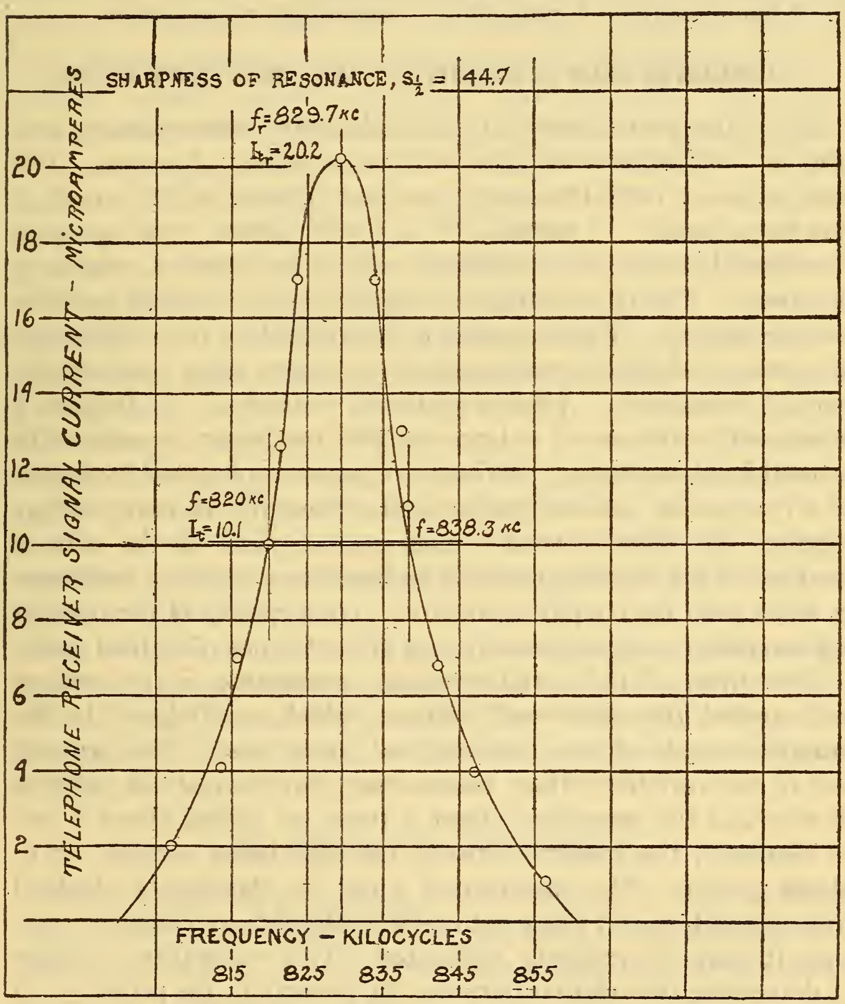

FIG. 7.—*Signal current, frequency characteristic of radio receiving set with crystal detector.*

where $I_{t'}$ is telephone-signal current at maximum regeneration and I_t is telephone-signal current at minimum regeneration.

In actual measurement the sharpness of resonance of the regenerative receiving set is first determined at minimum regeneration as described above. The telephone-receiver signal current is

carefully noted when the receiving set is adjusted for minimum regeneration and is in resonance with the frequency of the impressed voltage. Then the receiving set is adjusted to its highest state of regeneration, and the telephone-receiver signal current noted again. These values of telephone-receiver signal currents and sharpness of resonance are then substituted in equation (5) which gives the sharpness of resonance at maximum regeneration.

5. APPARATUS USED IN SENSITIVITY AND SELECTIVITY TESTS.

All of the above sensitivity and selectivity measurements employ a continuous-wave generator as a source of power. For this purpose a radio-frequency generator (shown in figs. 2 and 3) has been used. It consists of a 5-watt power tube operated considerably below its maximum output to insure a constancy of power. The plate voltage is supplied by an 80-volt portable storage battery. The frequency is determined by the inductances of a series of shielded interchangeable inductors and a continuously variable condenser. A fine-adjustment control of the frequency is secured by the use of a large variable condenser in series with a small fixed condenser. Variation of power is obtained by means of a 10,000-ohm variable resistance in series with the plate voltage supply. The direct-current supply to the plate of the tube is kept out of the coupling inductor by inserting a stopping condenser in series with the coupling inductor. The capacity of the insulating condenser is approximately 0.05 μf, and is not of critical value.

The object of the variable-voltage transformer is to produce and control the very small voltages which are induced in the antenna circuit of the receiving set under test. The primary coil of the variable-voltage transformer may have about 30 turns of wire and the secondary about 3 turns on tubing about 8 cm. in diameter, the spacing between the coils being variable up to about 50 cm. The transformer must be thoroughly shielded from capacitive and other not easily controlled couplings in order that it may be precisely calibrated. This calibration consists of determing the relation between the current in the primary coil and the voltage induced in the secondary coil over a wide range of frequencies and couplings. This calibration is made by passing large currents through the primary of the transformer and measuring the currents induced in the secondary coupling inductor, when the secondary coupling inductor is tuned to resonance with the exciting frequency. The induced voltage, E, is then

equal to the product of the resonant current, I, in the secondary and the resistance, R, of the secondary circuit at that frequency. The radio-frequency resistance of the secondary is measured by means of this same arrangement[8] and the voltage induced in the secondary calculated on the assumption that the coupling is sufficiently loose to eliminate reaction between secondary and primary. From a series of measurements made at different separations between primary and secondary a calibration curve of induced voltage against separation may be made. By means of a careful calibration so made, it is possible to have available for measurement purposes radio-frequency voltages of exceedingly small but precisely known values. For the measurements of sensitivity a variable-voltage transformer of this type is quite essential, and with proper care in calibration and operation affords an exceptionally simple and reliable device. It is of primary importance, however, that all capacity couplings be eliminated and that no great resistance be introduced into the circuits by the shielding methods. This can usually be accomplished by maintaining a large separation between conductors and shields and by thorough grounding of all shields. In using meters in any of the radio-frequency circuits it is essential that they be as near as possible to ground potential so that little tendency to capacitive coupling accompanies their presence. Accurate measuring instruments are essential.

The variable voltage transformer in connection with the radio-frequency generator gives a range of radio-frequency voltage across the coupling and inductor, between limits of 5 and 150 mv at frequencies of 1,500, 833, and 619 kilocycles per second (wave lengths 200, 360, and 485 m).

IV. NOTES ON OPERATION.

The receiving set is connected to an antenna of measured constants, and put into operation as specified by the manufacturer. The ease of operation and permanence of adjustments are noted under the following headings:

1. Arrangements of all controls with reference to their ease of operation.
2. Number of controls and performance of each in operating the receiving set.
3. Permanence of frequency adjustment as secured by shielding and electrical design of the receiving set.
4. Degree and stability of regeneration.
5. Ease of detector adjustment to effective operating condition.

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[8] The method is described in B. S. Circular No. 74, pp. 180–185, and in B. S. Sci. Paper No. 471, pp. 40–53.

It is very difficult to judge the performance of any particular receiving set on the basis of any one trial of its operation. This is largely due to the widely different types and conditions of service it may be required to render. The type of reception, the conditions under which it is to operate, and the skill or lack of skill of the operator very largely determine the degree of satisfactory operation possible in its use. This paper makes no attempt to outline the various possible performance tests that might be used to establish the value of a set in the actual work of receiving. It is probable that the influence of opinion of the operator can not be eliminated from such tests.

V. ACKNOWLEDGMENTS.

This work was done under the direction of Dr. J. H. Dellinger and L. E. Whittemore, chief and alternate chief of the radio section of the Bureau of Standards. The essential features of the methods here described were given in a preliminary report entitled, "Tentative Methods of Testing Radio Receiving Sets," by the present authors assisted by H. F. Harmon, whose services were made available by the United States Department of Agriculture. Assistance in the preparation of the paper in its present form was given by L. E. Whittemore, Dr. C. B. Jolliffe, and H. J. Walls, of the staff of the radio section. Useful criticisms and suggestions were made on the preliminary report referred to above by a number of people, especial acknowledgment being due to the following: Dr. L. W. Austin, radio physical laboratory, Bureau of Standards; M. C. Batsel and L. W. Chubb, Westinghouse Electric & Manufacturing Co; E. H. Colpitts and R. A. Heising, Western Electric Co.; C. J. Dow; Dr. A. N. Goldsmith, secretary Institute of Radio Engineers; J. D. Jones, chairman committee No. 12, radio and wire carrier systems, American Railway Association; Ray H. Manson, Stromberg-Carlson Telephone Manufacturing Co.; Telegraphentechnisches Reichsamt, Berlin. These and a number of other persons also gave suggestions for further work in developing and improving the test methods.

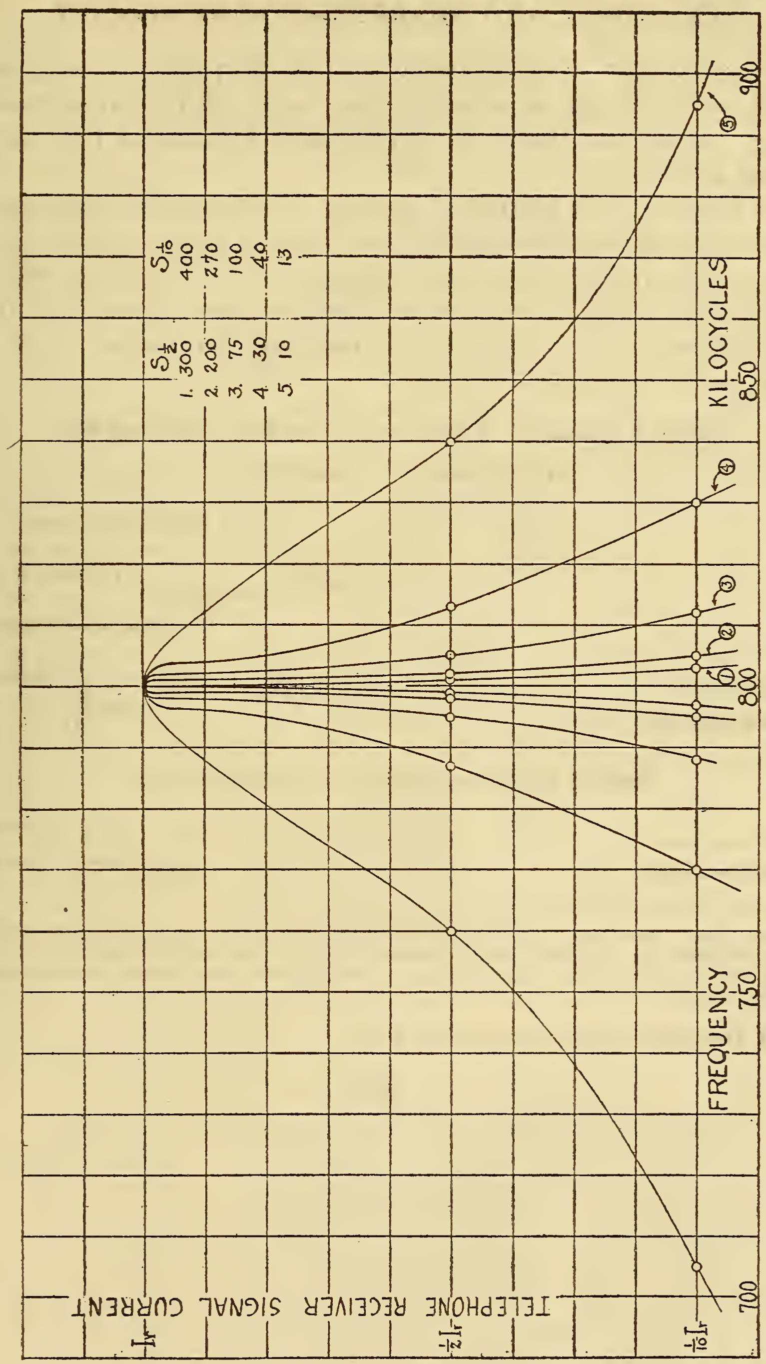

FIG. 8.—*Sharpness of resonance curves.*

VI. APPENDIX.—SUMMARY OF MEASUREMENTS OF SENSITIVITY AND SHARPNESS OF RESONANCE.

Measurements of the sensitivity and sharpness of resonance of 28 receiving sets of various types, made by 15 manufactures using the methods described in this paper have given the values shown in Table 1.

In Figure 8 are plotted a number of sharpness of resonance curves corresponding to values of $S_{1/2}$ from 10 to 300 and $S_{1/10}$ from 13 to 400. Inspection of these curves will show to what extent interference should be expected from stations differing in frequency from that to which the receiving set having a given sharpness of resonance is tuned.

TABLE 1.—Summary of Measurements on Radio Receiving Sets.

AVERAGE VALUES OF SENSITIVITY.

	Crystal detectors.	Electron-tube detectors.		
		Nonregenerative.	Regenerative.	
			Minimum.	Maximum.
Single-circuit sets	(9 to 100) 40	50	(1 to 120) 30	(180 to 610) 425
Coupled-circuit sets	....	6	(14 to 150) 70	(400 to 715) 600

AVERAGE VALUES OF SHARPNESS OF RESONANCE $S_{1/2}$.

	Crystal detectors.	Nonregenerative.	Regenerative, Minimum.	Regenerative, Maximum.
Single-circuit sets	(7 to 46) 20	(4 to 25) 15	(3 to 95) 25	(100 to 450) 240
Coupled-circuit sets	....	65	(17 to 90) 50	(222 to 380) 300

NOTE.—Figures given in parentheses show the extremes of the several values of which the average was taken. It should be borne in mind that these figures are the results of measurements on a limited number of receiving sets received during the years 1921 and 1922, and that lower values of antenna voltage than those used are frequently encountered in practice.

WASHINGTON, November 14, 1923.