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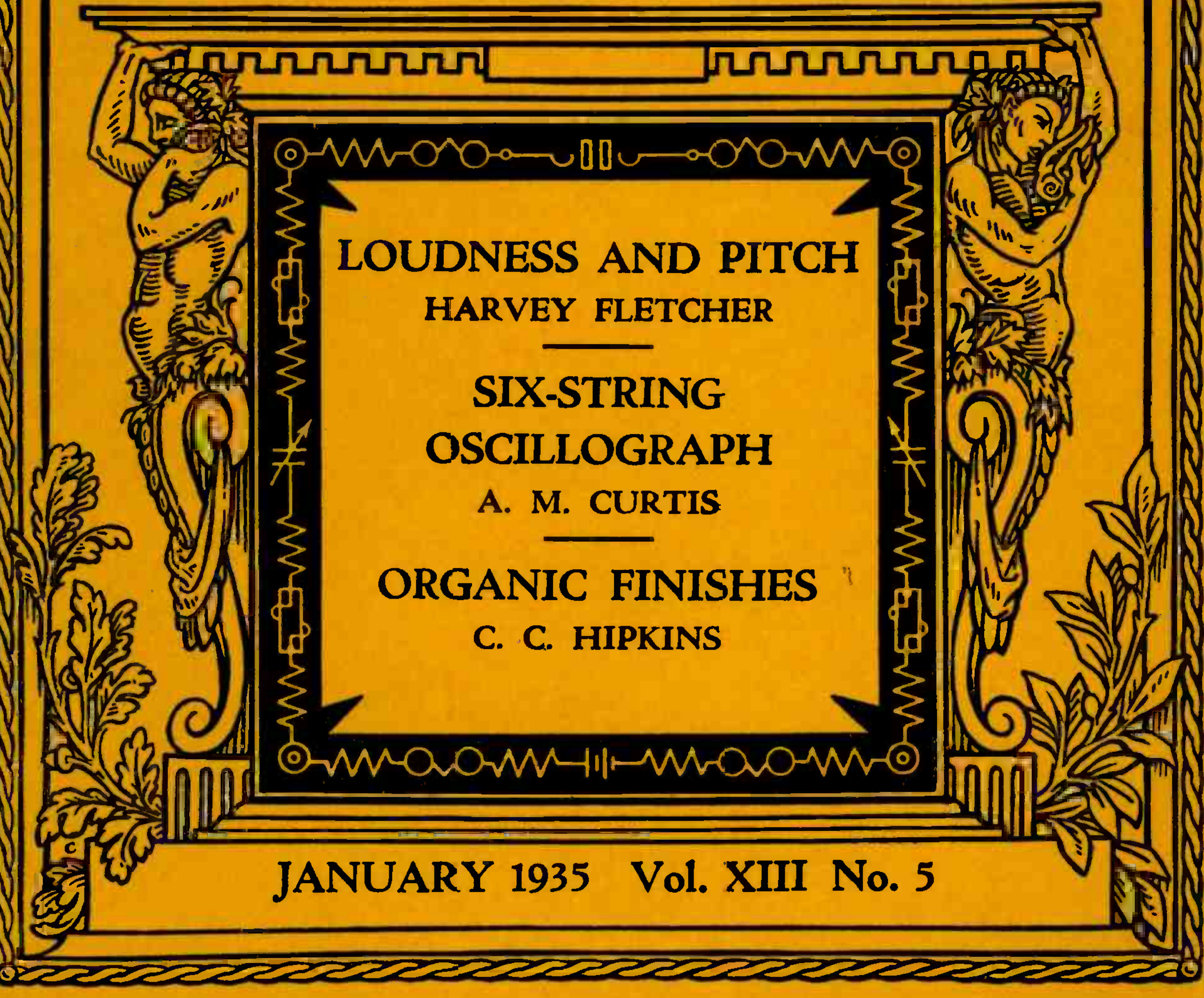

LOUDNESS AND PITCH
HARVEY FLETCHER

SIX-STRING OSCILLOGRAPH
A. M. CURTIS

ORGANIC FINISHES
C. C. HIPKINS

JANUARY 1935 Vol. XIII No. 5

BELL LABORATORIES RECORD

Published Monthly by BELL TELEPHONE LABORATORIES, INC.

SUBSCRIPTIONS are accepted at $2.00 per year; foreign postage $0.60 extra per year. Subscriptions should be addressed to Bell Laboratories Record, 463 West Street, New York City

In this Issue

BELL LABORATORIES RECORD

Northeast from the Laboratories' West Street building

VOLUME THIRTEEN—NUMBER FIVE

for

JANUARY

1935

Loudness and Pitch

By HARVEY FLETCHER

Director of Physical Research

MUSICIANS employ three terms to describe different aspects of the sensation they experience when listening to musical tones. These are pitch, loudness, and timbre, although the term quality, or tone color, is sometimes substituted for timbre. Most textbooks on physics have taught that these psychological characteristics are related in a simple way to three corresponding physical quantities: frequency, intensity, and overtone structure. The relationship between pitch and frequency, and between loudness and intensity, has been thought to be one of direct correspondence: the pitch of each note corresponding to a definite frequency, and the loudness of each note to a definite intensity. The relationship between harmonic structure and timbre has had no such simple formulation, but at least the timbre has been thought to depend on overtone structure alone. Studies in these laboratories, however, have shown that no such simple relationships exist, that each of the psychological quantities—although depending chiefly on the corresponding physical quantity—actually depends on all three. That there has not been a strict one-to-one correspondence between loudness and intensity has been known for some time, but only recently has accurate quantitative data been obtained. Between pitch and frequency, on the other hand, it is still generally thought that there is a strict one-to-one correspondence.

Frequency is the number of vibrations per second made by the sound source, such as a tuning fork or a violin string. Most musical tones, however, are composed of a series of frequencies which are multiples of the lowest or fundamental. For such tones the frequency of the fundamental is considered as the frequency of the tone, while the number and magnitude of the harmonics produce the overtone structure that results in the perception of a definite timbre. The intensity of the tone is the power content of the air vibrations at the position where the listener hears the tone.

Among musicians loudness is roughly gauged in seven steps running from *ppp* to *fff*. Such a scale is entirely inadequate for scientific studies, both because the steps are too large and because there is no definitely established reference loudness. To provide a more suitable measuring scale, it has been the practice for some time in these laboratories to measure loudness in terms of the power intensity of a pure tone at a frequency of 1000 cycles per second. Because of the wide range of intensities to which the ear responds, it has been convenient to use a logarithmic scale of values. The use of such a scale is further justified because the minimum change in intensity that the ear can detect seems to follow more nearly a logarithmic than an arithmetic law. Moreover, since it is convenient to establish the zero of the scale near the lowest loudness that can be detected, zero loudness is taken as that caused by the smallest audible intensity at a frequency of 1000 cycles, which is 10^{-16} watts per square centimeter in a free air wave.

At 1000 cycles the loudness level of a tone is defined as the logarithm of the ratio of the intensity of the tone to the basic intensity of 10^{-16} watts per square centimeter. Thus if L is the loudness level of a 1000-cycle tone and I its intensity in watts per square centimeter, $L = \log I - \log(10^{-16})$ or more briefly $L = [\log I + 16]$. For an intensity of 10^{-14} watts per square centimeter at 1000 cycles, therefore, the loudness level would be +2, and for one of 10^{-4} watts it would be +12, which is about the greatest intensity that the ear can tolerate without pain. Since the loudness level is defined as the logarithm of the ratio of two powers, the unit is the bel, and thus the loudness scale runs from 0 to 12 bels, or from 0 to 120 decibels.

Intensity level is measured in exactly the same manner, and at 1000 cycles, intensity level and loudness level are, by definition, the same. At any other frequency, the loudness level is defined as equal to the intensity level of a 1000-cycle tone that would be judged equally loud by the average listener. Some of the relationships between loudness and intensity levels for pure tones, which have been determined during the recent studies, are shown in Figure 1.

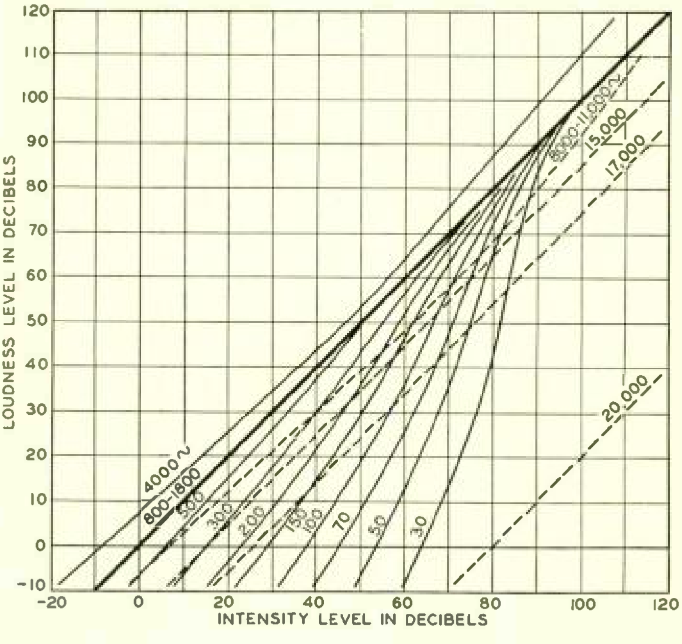

Fig. 1—Relationship between loudness and intensity levels for pure tones of various frequencies

The heavy straight line running up at an angle of 45° to the right represents a tone of 1000 cycles where by definition loudness level and intensity level are the same. This equality also holds very closely for all frequencies between 800 and 1800, and for frequencies from 500 to 6000 cycles there is no very great difference between the loudness level and intensity level. At 30 cycles, however, the intensity must be raised to 64 db before the tone is audible, and above this the loudness increases rapidly—a 36 db increase in intensity causing a 100 db increase in loudness.

To study the relationship between pitch and frequency, scales of pitch and frequency levels were established somewhat analogous to those of loudness and intensity. There is no natural scale of intensity, and thus logarithms to the base ten were employed, with the result that an intensity of level 4 represents 10 times the power of one

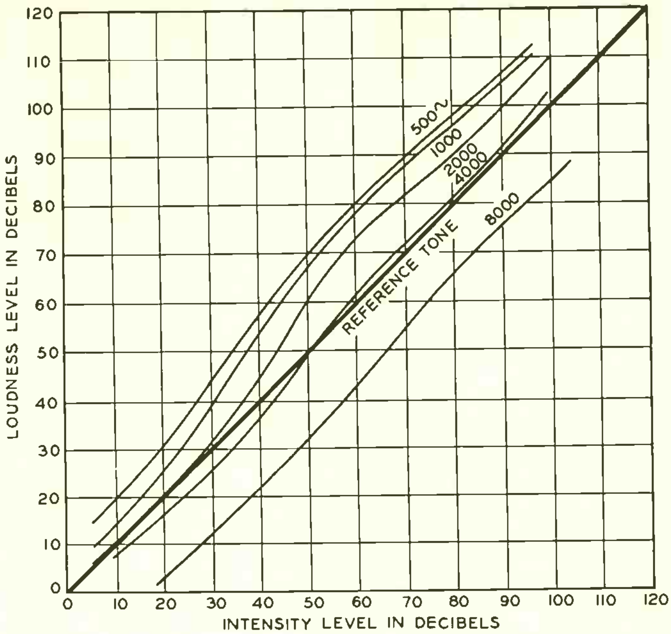

Fig. 3—The loudness of a group of harmonic tones of equal loudness is found to be greater than the sum of the loudnesses of the individual tones

of level 3. With pitch the situation is different, because there is a natural pitch scale—the octave. Two pure tones of the same loudness will be judged to be an octave apart when one frequency is double that of the other. Thus for these scales it seemed desirable to use logarithms to the base 2. As in defining loudness a constant frequency was selected for the reference tone, so in defining pitch a constant loudness level, that of 40 db has been selected. In selecting a zero level of loudness, the lowest audible intensity of the test tone was chosen, and a similar procedure seemed desirable with pitch. It is also desirable to have the pitch scale based on international pitch, which assigns a frequency of 440 cycles to A above middle C, and since a tempered scale is almost universally used, C is the natural starting point. The zero of the pitch scale was thus taken as C four octaves below middle C, which corresponds to a frequency of 16.35 cycles per second. The pitch level of a tone of loudness level 40 is thus defined as the logarithm to the base 2 of the ratio of the frequency of the tone to 16.35 cycles; or if P stands for the pitch level of a tone of loudness level 40, then $P = \log_2 f - \log_2 16.35$.

Frequency level, F, is defined in a similar manner; $F = \log_2 f - \log_2 16.35$. As loudness level at a frequency of one thousand cycles is defined as equal to the intensity level, so pitch level at forty db loudness level is defined as equal to the frequency level. At any other loudness level, pitch level is defined as the frequency level of a tone of 40 db, loudness level, that is judged equal to it in pitch. Since for both the frequency and pitch scales, logarithms to the base 2 are employed, the

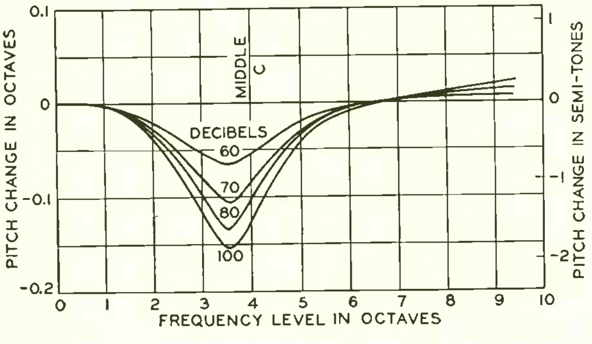

Fig. 2—Relationship between pitch change and frequency level for pure tones of various loudness

unit is the octave rather than the bel, and the audible scale covers a range of about ten octaves.

Until recently accurate studies of pitch at high loudness levels have been handicapped by the lack of suitable apparatus for producing very pure tones of high intensity. Such studies are now possible, however, by use of the apparatus developed for stereophonic, or auditory perspective, reproduction.* Some of the results obtained are shown in Figure 2. Here the abscissas are frequency level and the ordinates, the difference between the pitch and frequency levels. Curves are drawn for tones of various loudness; the curve for 40 db loudness would by definition lie along the line of zero pitch change.

The pitch changes indicated here are rather startling to those of us who have been accustomed to think of a definite frequency always corresponding to the same pitch. If for example middle C is sounded at a loudness level of 40, the frequency, on the international pitch scale we are using, would be 262 cycles. If this frequency were held constant but the loudness increased from 40 to 80 db, the pitch level would drop 0.1, more than a half tone, or to a pitch that at 40 db loudness level would require a frequency of 238.7 cycles. The greatest changes occur at a frequency level of about 3.5 or what roughly corresponds to a pitch of F sharp below middle C. At this frequency an increase in loudness of 50 db lowers the pitch almost a full tone. For very low notes and for those at a frequency level between 6 and 7 (corresponding to frequencies from 1050 to 2100) the changes in pitch with increasing loudness become negligible. For very high notes, however, for frequency levels above 8 (frequencies above 4200) the pitch level increases slightly with increase in loudness.

The results discussed above pertain to pure tones, but studies were also made of complex tones of various types. The relationships between intensity level and loudness level for complex tones having ten equally intense harmonic components are given in Figures 3 and 4. The curve labelled 1000, of Figure 3, for example, represents the results for a tone having a fundamental frequency of 1000 c.p.s. and overtones having frequencies of 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10,000 c.p.s., all having the same intensity. The intensity level of the combined components is given by the abscissas and the resulting loudness level by the ordinates. By adding the nine overtones to the 1000-cycle pure tone the intensity

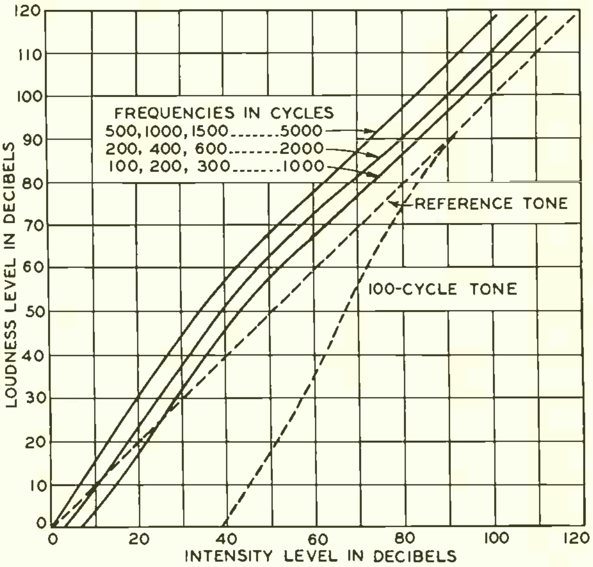

Fig. 4—Relationships between loudness and intensities of groups of ten harmonic tones

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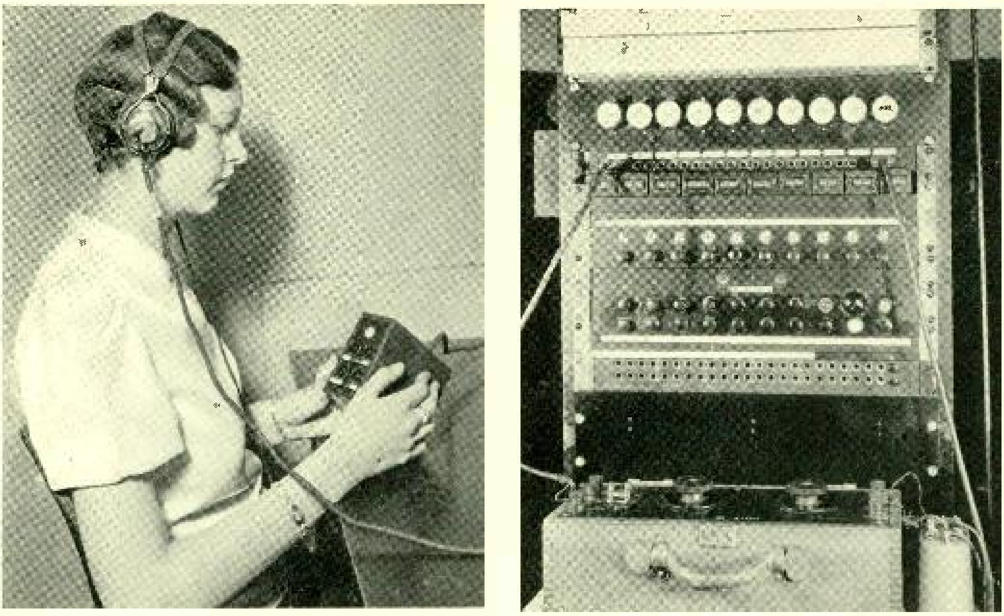
*Record, *May*, 1933, *p.* 254.



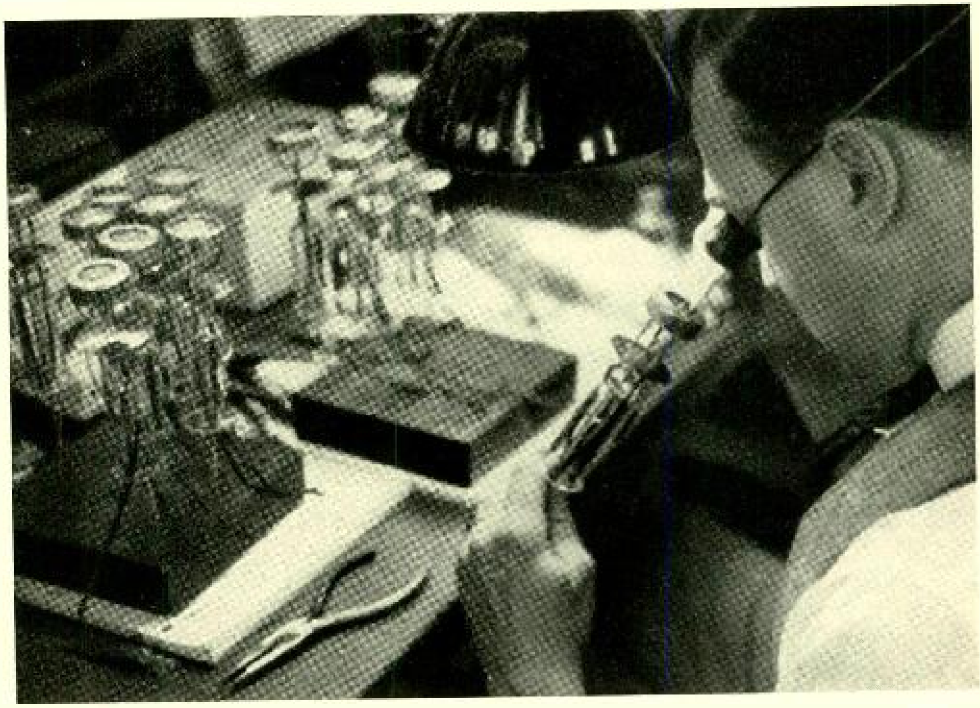
The apparatus at the right automatically presents a sound to be measured and a thousand-cycle comparison tone; the observer, Miss F. Torpadie, records her judgment as to which of the two sounds is the louder

level is raised 10 db, but the loudness level, it will be noticed, is increased nearly 30 db. In other words, increasing the overtone content of such a musical tone increases its loudness level much faster than one would expect from the increase produced upon its intensity level. It is interesting to note from Figure 4 the very large increase in the loudness level of the 100-cycle pure tone when an overtone structure is added to it. At an intensity level of 60 db, for example, the loudness level of the pure tone is slightly over 35 db. With the addition of nine overtones, however, the intensity level is increased ten db but the loudness level becomes 77 db—an increase of over 40 db. These results show why it is easy to increase the loudness of a musical tone by increasing its overtone content, a practice which is common in producing musical tones.

Another fact that becomes evident from these curves is that the loudness is greater the greater the separation between the harmonic frequencies. This is plainly evident in Figure 4, but in Figure 3 the higher harmonics become less important when all are of equal intensity because of the decrease in loudness at the higher frequencies as shown by the dotted curves of Figure 1.

Many interesting phenomena in connection with the pitch of complex tones were also discovered. It was found, for example, that while the pitch level of a pure tone of 200 cycles—a frequency level of 3.6—was lowered .15 octaves as the loudness level was raised from 40 to 100 db (as shown in Figure 2), the pitch level of a complex tone composed of tones of frequencies of 200, 400, 600, 800 and 1000, dropped only .03 octave. At 100 db loudness level, therefore, the pure tone was at a pitch level of 3.46 octaves and the complex tone at a level of 3.58 octaves—¾ of a tone higher, and when the two were sounded successively this difference was plainly noticeable. With this difference in pitch it would be expected that if the two were sounded together they would be discordant, but such was not found to be the fact. The effect is to strengthen the fundamental, and to lower the pitch of the resultant tone to a level of 3.54 octaves. Whether or not two tones will be harmonious when sounded together depends therefore on the frequency rather than on the pitch of the components.

Although no quantitative measurements have been made upon the timbre of a musical tone, we know that it depends not only upon the overtone structure but also upon the intensity. If a violin tone, for example, is reproduced at a very much higher intensity than that at which it is usually heard, it will be very evident that the timbre is changed. A scale for representing timbre is now being worked out and it will be interesting to see if some quantitative measurements similar to those reported under loudness and pitch can be made to describe the quality aspects of the tone. It is sufficient to say here that there is no doubt but that the results will show that timbre is dependent not only upon the overtone structure but also upon the intensity and the pitch of the tone. It is thus a safe conclusion that each of the three psychological characteristics of a tone is dependent on all three of the physical characteristics, although the influence of one is predominant in each case.



Inspecting the cathode of a mercury rectifier tube before sealing-in ferent values for different frequencies.

Such a resistor, if used for measurements on alternating current, therefore, would have a different value of resistance at each frequency, even though L and C might compensate each other so that the phase angle would remain small. If, for example, R were 1000 ohms (d-c value), L were 20 microhenrys, and C, 20 micro-microfarads, the phase angle of the network would remain negligibly small although at one kilocycle its resistance would be 1000 ohms and at 1000 kilocycles, it would be 1016 ohms. To avoid such effects it is necessary to make the associated inductances and capacitances so small that at the frequencies for which the resistor will be used their effects are negligible. These effects of alternating current had all been considered in the previous standard to make it suitable for frequencies in the audible range, but to make the standard suitable for the higher radio frequencies, a completely new design has been required.

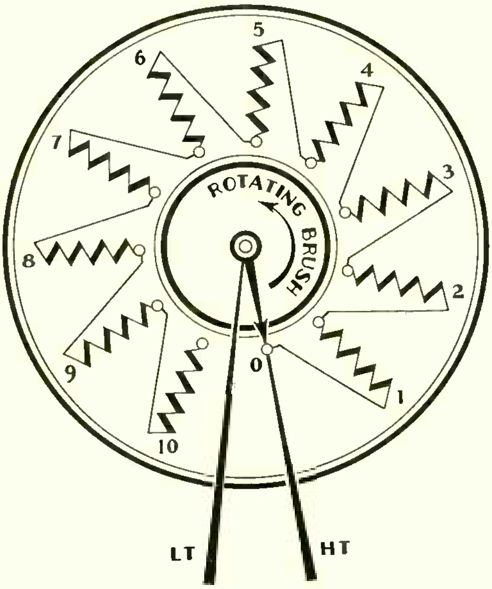


Fig. 3—Arrangement of resistance units in the "claw" type decade

Size is an important factor when a resistor is to be used on alternating current since both inductance and capacitance are proportional to the amount of conductor used. The possible reduction in size is limited, however, by the requirements for heat dissipation and mechanical strength, and the new resistors were reduced in size as far as was consistent with these limitations.

In the new standard the low resistance elements consist of short strips of resistance material only 1¼ inches long, and the higher value resistors are of the woven-wire type shown in the headpiece. With this construction the resistance wire is woven back and forth through a warp of silk fibers. Since the current flows in opposite directions through adjacent strands of the wire woof, the inductance is

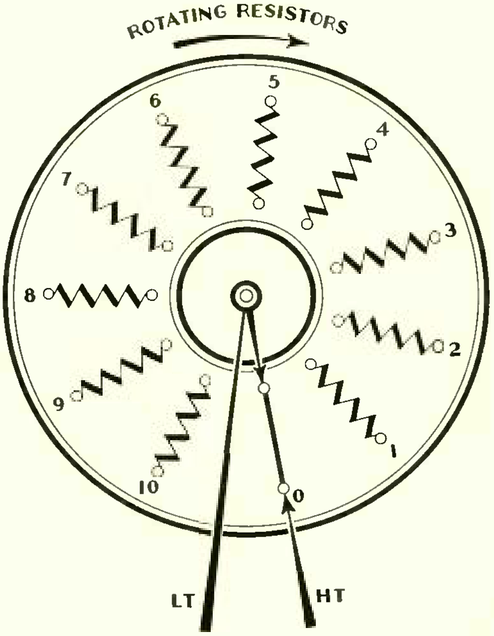


Fig. 4—In the "rotor-decade" only one unit is in the circuit at a time

kept to very small values. Also the equivalent capacitance effective across the entire resistor is greatly reduced because the voltage across the capacitance between adjacent strands is only a small fraction of that across the entire resistor. When mounted in the complete standard these woven resistors are wrapped around a central spindle.

Although these changes in the resistors have considerably improved the standard, the greatest gains have come from the use of a new switching arrangement known as the "rotor-decade" switch. Previous decade switches have employed ten resistors connected in series and all of the same resistance. A schematic of the arrangement is shown in Figure 3. As the contact arm is moved, the units are cut in or shorted out of the circuit as desired. The inductance and capacitance characteristics of this decade, however, are not satisfactory for use at high frequencies. Since each unit has an inductance, the total inductance introduced by the decade varies from step to step and may become quite high when most of the units are in the circuit. For precise high-frequency measurements, it is very desirable not only to have the total inductance low, but to have the change from step to step negligibly small. Moreover since the units are electrically connected together at all times, the capacitance to ground of such a decade is the sum of the capacitances to ground of all the individual units, and is thus relatively great compared to that of any one unit.

In the "rotor-decade" switch, these disadvantages are eliminated by the construction shown schematically in Figure 4. With this arrangement each unit is of different value, but only one is in the circuit at a time. The inductance of all units of a decade are made as nearly the same as practicable and since there is never more than one unit in the circuit for each decade, the overall inductance and capacitance is kept small. In a six-decade box, therefore, such as shown in Figure 2, the total inductance is not only very small but remains very nearly constant regardless of the positions of the individual dials. Because of its low overall inductance, this standard may be used for high-frequency measurements of ordinary precision without calibration, that is without applying corrections depending on the settings of the various decades. For very precise work, however, corrections must be applied for each setting of each of the six decades.

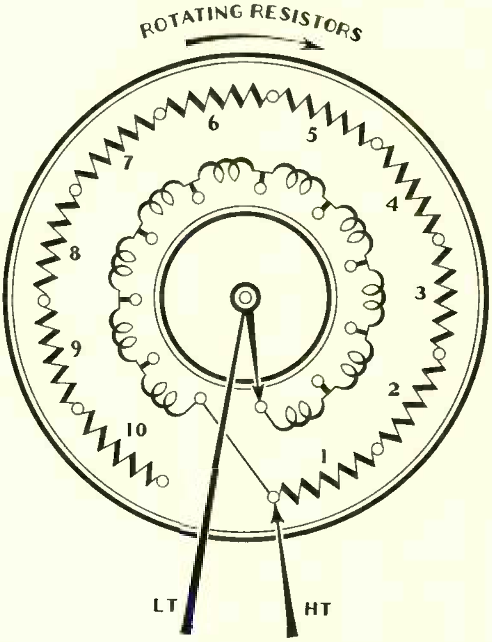


Fig. 5—In the compensated decade, the overall reactance remains the same for all settings of the dial

These corrections, although essential for very precise measurements, retard the measuring procedure. To

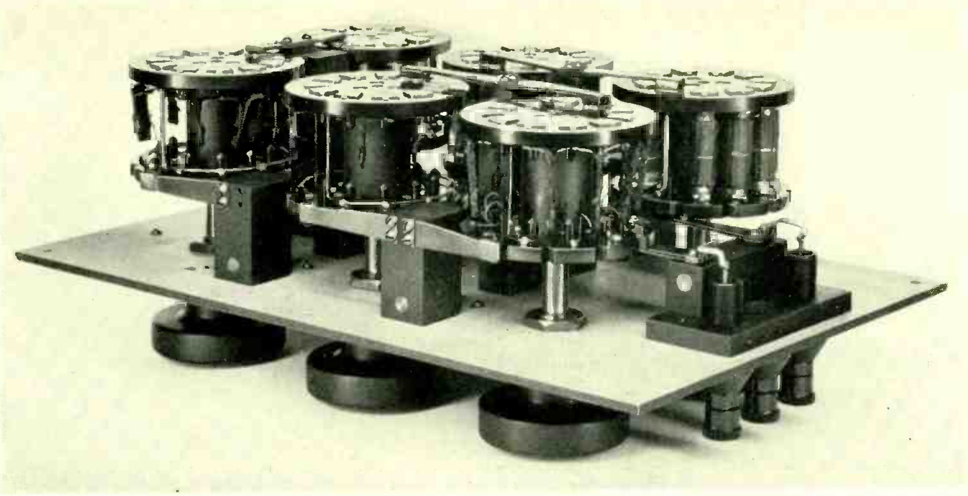


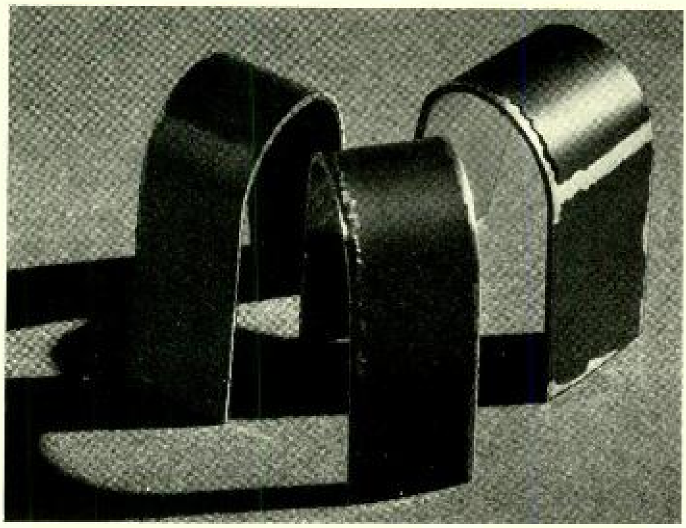
Fig. 6—In the compensated decade each resistance unit is of the same size, shown pendant from the upper section of the unit. The compensating inductances are shown around the lower part of the decade

simplify the calibration, a modification of the rotor-decade resistance box was developed which eliminates the necessity of applying a calibration to the three lower resistance decades. The total inductance of the box, however, is greater than that of the straight rotor-decade box, but for many purposes a somewhat greater total inductance can be tolerated.

In the modified rotor-decade box, the three higher resistance decades are identical with those of the straight rotor-decade, and a calibration for them is required. The three lower resistance decades are arranged as shown in the schematic of Figure 5. The appearance of this compensated box is shown in Figure 6.

The units are all of the same resistance and are connected in series as in the earlier type decade with the claw switch. In series with the resistance units is an equal number of small coils of negligible resistance but each with an inductance equal to that of one of the resistance units. When all of the resistance units are in the circuit, all of the inductance units are out, and thus the total inductance is equal to that of the ten resistance units. When one of the resistance units is removed, one of the inductance units is inserted to compensate for the inductance taken out by the removal of a resistance unit. With this arrangement therefore not only is the total inductance of the decade always the same but the change from step to step is negligible. The field of use for this modified unit is where the nature of the work requires a calibration to be made, and where a slightly greater overall inductance is of no great detriment. Under these conditions, the operation of this resistance box is simplified because no calibration is needed for the three lower units.

As a result of this new development two new types of resistance boxes have been made available for precise high-frequency work. Each has a range of from 0 to 11,111.10 ohms. Their desirable characteristics have caused them to find many applications in the field of high-frequency measurements.



Evaluation of Organic Finishes

By C. C. HIPKINS
Chemical Laboratories

AS a rule, the standard finishes employed on telephone apparatus are of relatively high quality, particularly in respect to durability and resistance to mechanical stress, for the requirements placed upon them are often severe. Usually a finish must afford enduring protection against corroding environments, and provide the desired appearance as well. Some are also required to resist a particular deteriorating influence. Finishes on parts which are frequently handled must be unaffected by the action of perspiration. Equipment in battery rooms must be protected by finishes which resist the attack of acid. Soil stresses and constant immersion in water must be prevented from deteriorating equipment installed underground. Some finishes must furthermore maintain high electrical resistance under prolonged conditions of high humidity. It is startling to realize that the finishes, called upon to compensate for many of the inherent deficiencies of the base materials by satisfactorily fulfilling these requirements, are usually no more than one-thousandth inch thick.

To give a satisfactory account of itself in service, each of these finishes, no matter what its special requirements may be, must adhere well to its base and resist the abrasion, impact, bending and stretching that it suffers in its normal service. In evaluating a finish, it is these properties that must usually be most accurately determined. Moreover, it is especially important to make certain that a finish will retain these desirable properties over a long time.

During the past few years, tools have been developed by which most of these properties may be quantitatively measured. With their aid, even when the complex chemical changes which constitute the aging of a finish remain unknown, the accompanying physical changes can be closely followed. By a systematic scheme of employing these tools, it is now possible to combine speed with reliability, and to predict the failure of a finish long before failure becomes visible, by extrapolation of curves showing the rate of change of each property measured.

To accomplish this, several precautions must be observed. The thickness of the test coating of finish must be controlled and known, and the tests must be performed under controlled conditions of temperature and humidity. If the aging of the finish is artificially accelerated, as is usually the case, the exposure conditions between the occasions of test must be reproducible. Under exposure conditions so controlled, observations of the rate of change in physical properties with time gives a complete picture of the deterioration. The time axis of degradation can be made flexible by using aging conditions which are either drastic or mild.

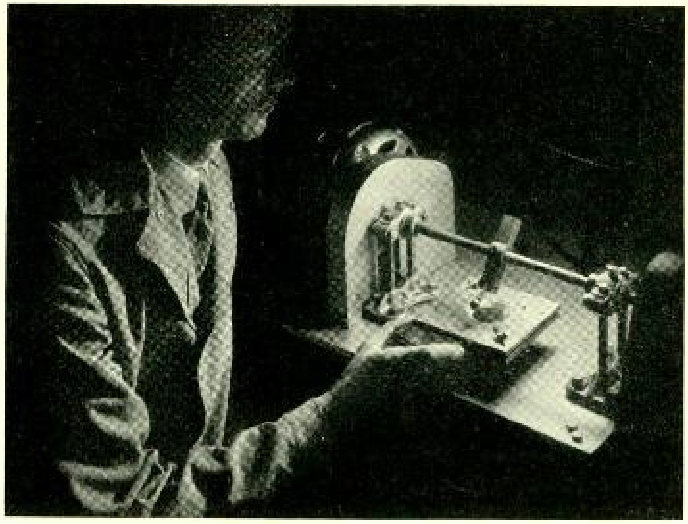


Fig. 2—A. Mendizza determines the "impact value" of the finish by slowly turning a coated panel and subjecting it to successively harder blows by a steel ball

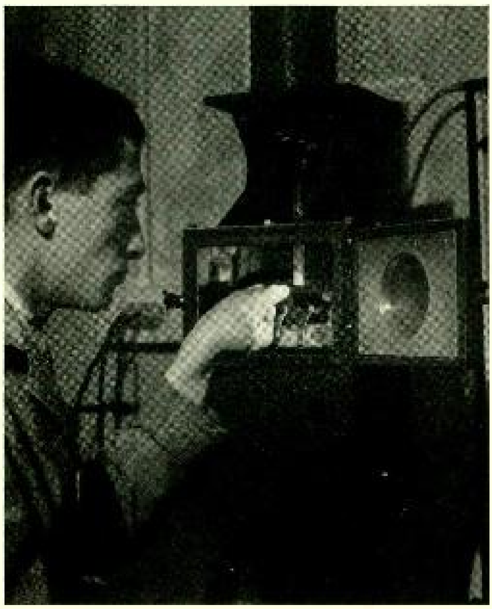


Fig. 1—To determine its resistance to mild abrasion, a film of finish is exposed to a blast of carborundum particles. H. C. Theuerer is removing a coated panel for examination after the test

The procedure which was followed in evaluating a number of black lacquer enamels, to be used for refinishing desk-stand telephone bases, is illustrative. Several panels were finished to the same thickness with the various enamels by "spin-coating" them on a centrifugal device which rotates the panels so as to throw off the excess of newly applied, unset enamel. The finishes were then dried under the proper conditions and allowed to mature for a time. Since the materials finally selected must withstand perspiration attack, those not resistant to this influence were eliminated by a simple "body-contact" test, in which the finishes were held in contact with the skin for one week by means of a belt worn next to the body. The remaining enamels were subjected to a series of physical tests, at various times in the course of aging under controlled exposure conditions.

The tests were performed at the same temperature and humidity, and twenty-four hours were allowed for the panels to reach equilibrium with the test conditions. The properties measured include hardness, flexibility, and resistance to impact and abrasion. After an initial set of tests, the panels were exposed to a severe aging environment. At stated intervals duplicate sets of panels were equilibrated with the same test conditions and subjected to the same tests. Almost invariably the various materials showed large differences, not only in their initial levels of quality but in their rates of decline from the starting levels. The materials could then be selected for finishing telephone mountings on the basis of their levels of qualities and their aging characteristics.

The resistance of finishes to mild abrasion is determined by the instrument shown in Figure 1. A definite velocity is imparted to carborundum particles of a certain size by a controlled air stream flowing through a nozzle in which the air and the particles are thoroughly mixed. The blast of particles is directed against the finish under test, and the total weight of particles required to wear through the film is taken as a measure of the abrasion resistance of the finish. The weight of carborundum necessary to wear through one-thousandth inch of the finish is then calculated so as to furnish a quantitative "abrasion value."

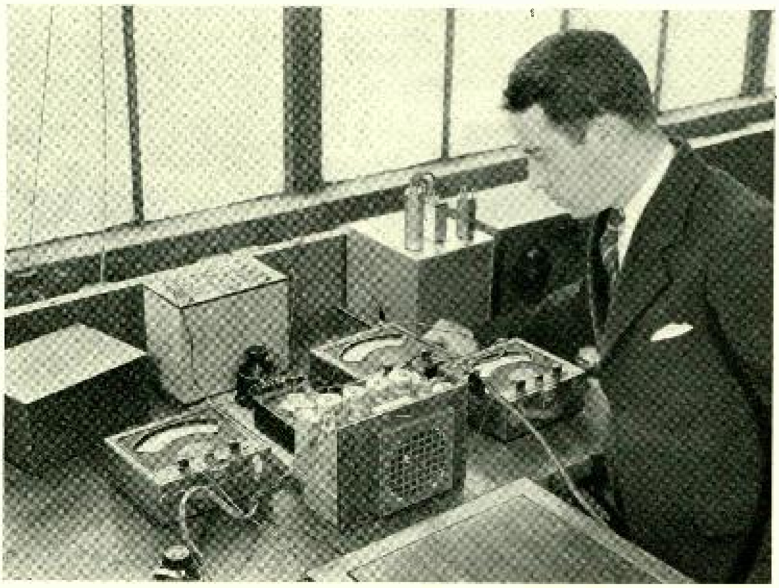
In the impact test, the panel is secured to a horizontal base, as shown in Figure 2, and is subjected to blows by a case-hardened steel ball on a short arm, which pivots on the end of a longer arm rotating at a constantly increasing speed. The "impact value" is taken as the r.p.m. of the ball at the point where the finish is first removed from the panel.

Fig. 3—The mandrel test, in the refined form here being used by H. E. Van Siclen, is a valuable means for determining the flexibility and adhesion of a finish

The behavior of coatings under the impact test may be characterized as brittle or plastic. Brittle materials are worn away by pulverization; if, in addition, the adhesion is poor, large flakes of the coating are shattered off when the end point is reached. Plastic materials, on the other hand, do not fail so distinctly; the coating gradually flows away from the point of impact, and the end point depends on the malleability of the coating and its adhesion to the base material.

To measure flexibility, the commonly used "mandrel" test has proved valuable when refined to give quantitative results. In this test the coated panel is clamped at one end so that the free end may be bent about a cylinder of a definite radius. The instrument shown in Figure 3, constructed in these Laboratories, permits metal panels of thicknesses up to one-sixteenth inch to be bent closely around any one of six mandrels with diameters ranging from one-eighth to one inch. By this means an area of the finish is elongated by an amount depending upon the size of the mandrel and the thickness of the panel. The distensibility of a finish is expressed as the maximum per cent elongation which it will withstand without cracking or flaking. This test also indicates the degree of adhesion of the coating to the base metal, as shown in the headpiece. Some finishes, when stretched to the point of cracking, entirely loosen from the base, others may be removed with ease by the finger nail, and still others can be removed only with difficulty or not at all.

Since this general method of evaluating finishes was adopted, it has been found that finishes rated as superior by these tests are the most durable in actual service. This relation makes possible a quicker and more informative evaluation of finishes than can be obtained by exposing them to the elements. Evaluations which might otherwise require years of observation can now often be made in as many months.



Laboratory measurements being made by J. J. Scanlon of Special Products Development on ultra-high frequency police car radio receiver which covers a frequency band from 30 to 42 megacycles.

I

Gangs of shielded coils and condensers, in a Western Electric radio receiver.

II

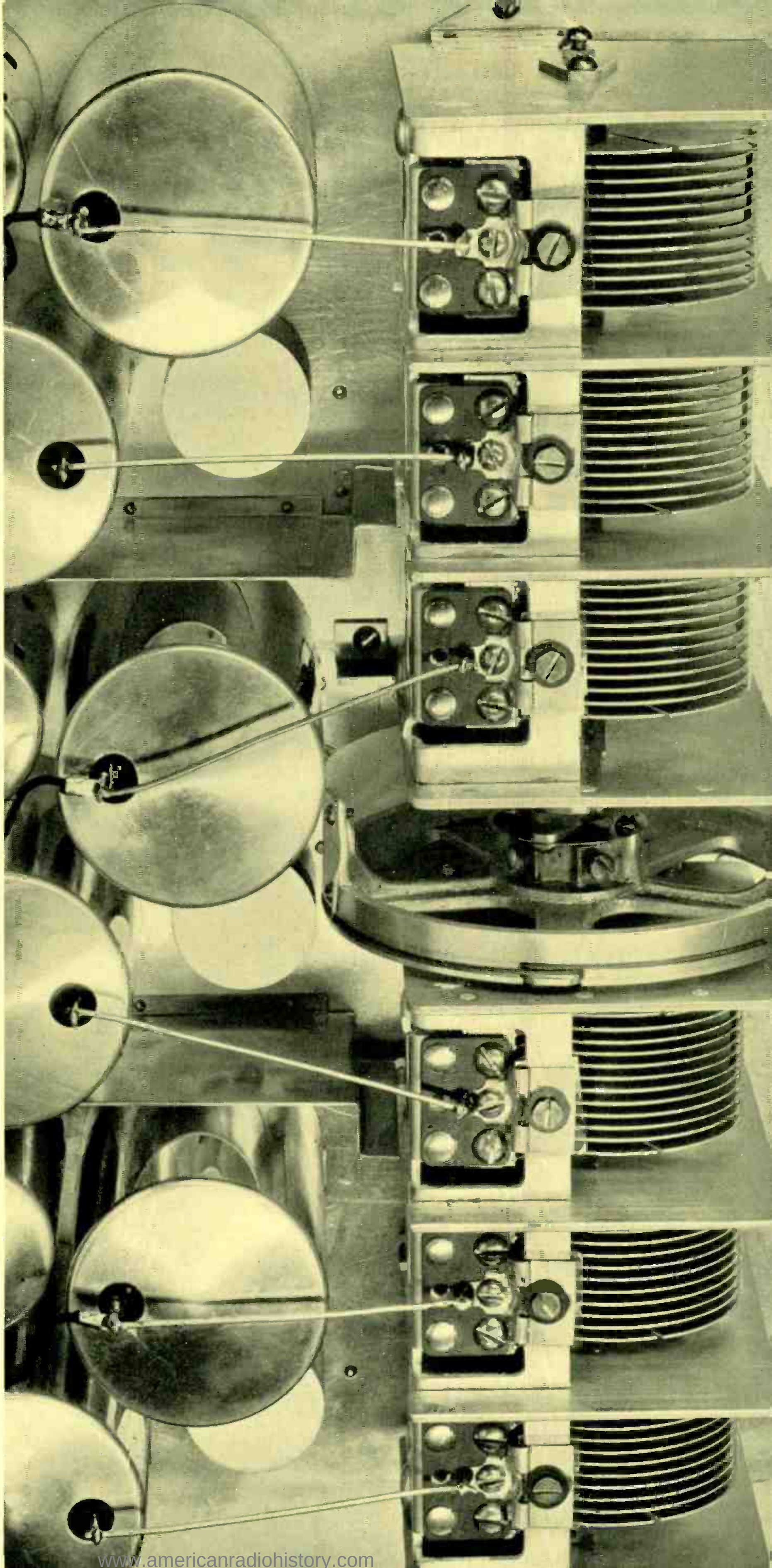
Types of paired wire used to furnish small adjustable capacitances.

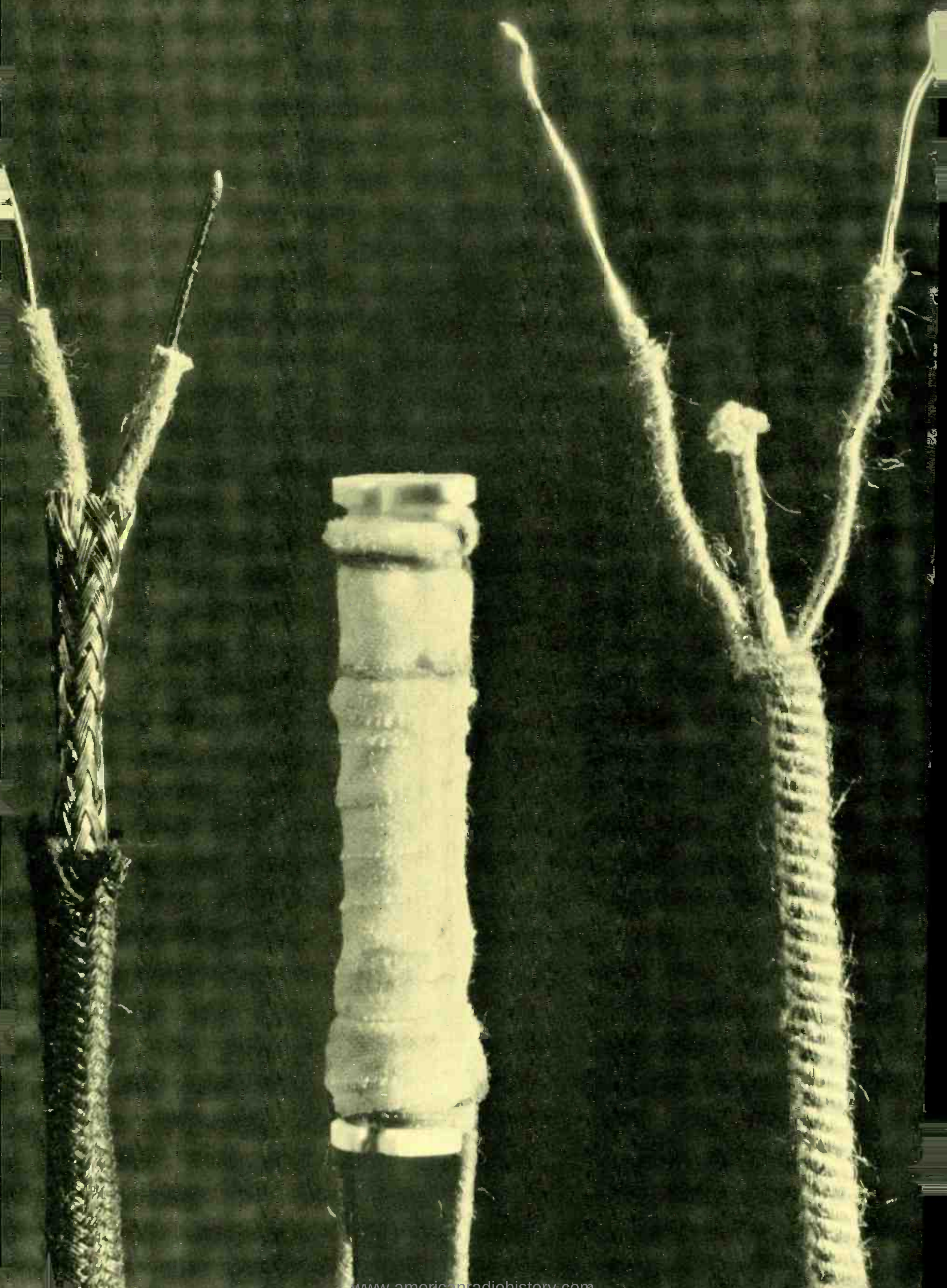
III

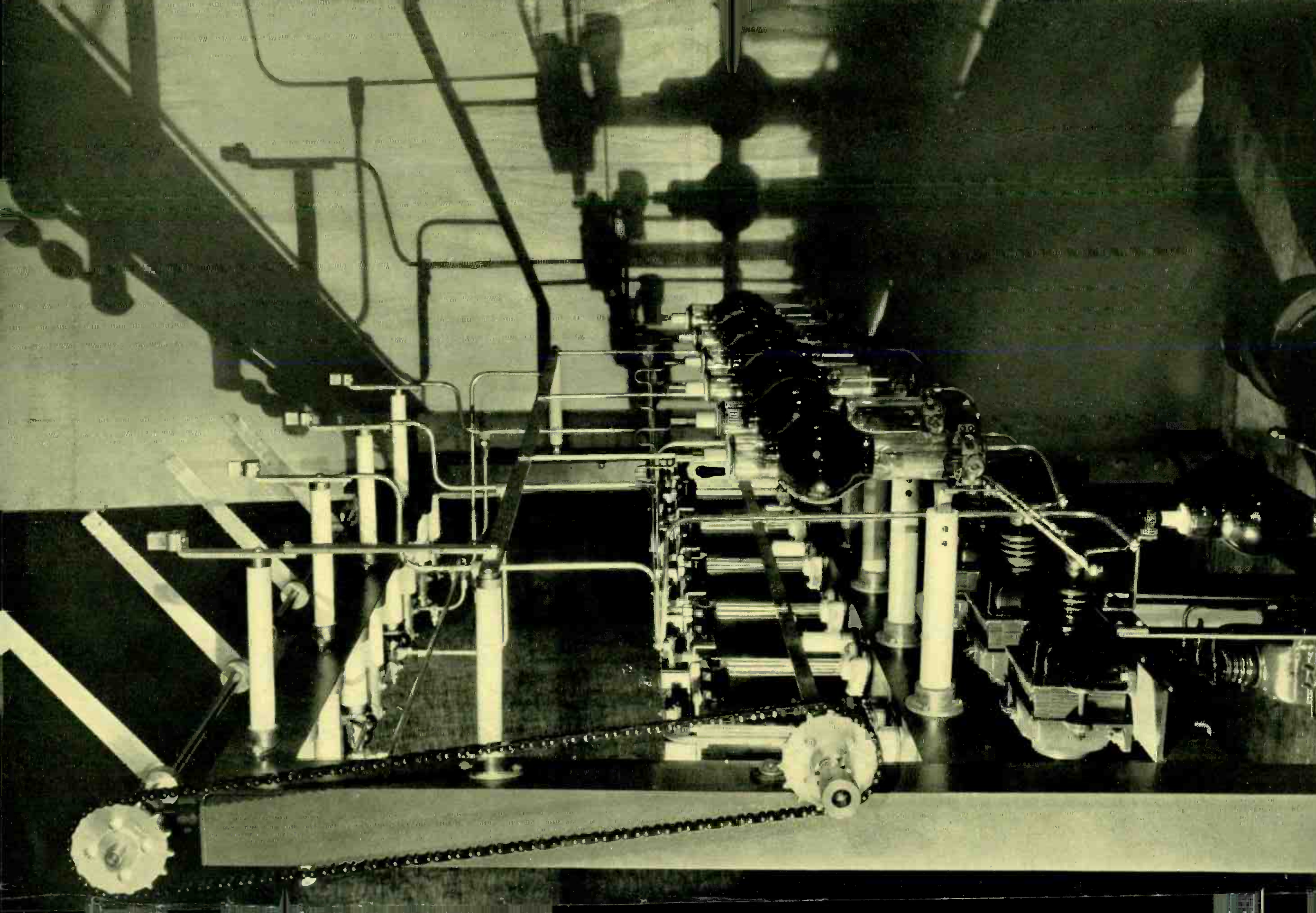
Battery of air-cooled rectifier tubes in a five-kilowatt amplifier; part of a modern broadcasting transmitter.

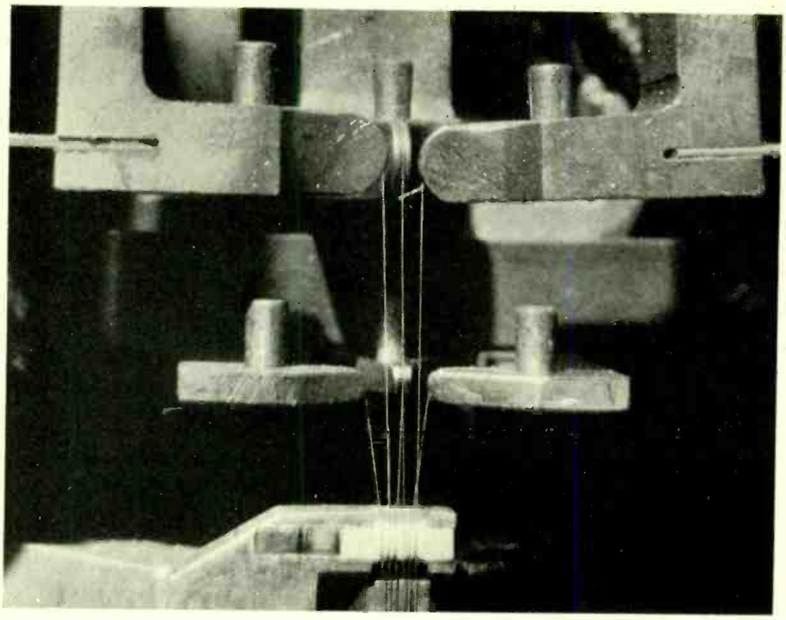
IV

Western Electric radio telephone equipment in the trawler Flow, *at sea off Boston.*









The Six-String Oscillograph

By A. M. CURTIS

Wire Transmission Research

WHEN the first model of the rapid record oscillograph* was designed in 1929, it appeared that an instrument capable of recording simultaneously three currents of any frequency in the commercial speech band extending to 3000 cycles per second would probably answer most needs, and that the higher frequencies would be studied by the cathode-ray oscillograph. But almost as soon as members of the Laboratories became accustomed to the convenience of the new instrument they began complaining that it was not good enough. One wanted to see what went on in the 4800-7600 cycle carrier band in his apparatus; why did the oscillograph have to stop at 3000 cycles? Another wanted to push a button on the front of a panel and see what happened on the oscillograph back of the row of racks, and he couldn't be on both sides at once. Still another wanted to watch a wave which was supposed to be continuous but sometimes wasn't, without using a mile of paper in the process.

First we tried shortening the string of the oscillograph galvanometer and pushed its frequency up to 6000 cycles, when we happened to have a good batch of wire. This required a lens of greater magnification in order to get the same deflection as before on the paper, which meant a thicker string image and less light where we needed more; and we could use only two strings where some customers wanted four or six.

Then we enlisted the help of mathematics. E. L. Norton designed a network which would equalize the 6000-

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*Record, *August*, 1930, *p.* 580.

cycle string up to 9000 cycles. The network served as long as we had the spool of wire which was used in the galvanometer in obtaining the characteristics to be equalized, but unfortunately the wire on the next spool was so soft that it couldn't be stretched to a frequency of 6000 cycles. A new equalizer had to be designed, based on a natural frequency of 4500, and improved design let us push the range to 10,000 cycles. Strings in an oscillograph used by a dozen different engineers break in a dozen mysterious ways, and soon that spool of wire was gone. The next wire was nice and strong, and could be pulled to 8000 cycles, but its resistance was twenty-five per cent higher than the first lot and wouldn't fit either equalizer.

After obtaining a dozen or so batches of wire, we found that we could never expect it to be the same twice in succession. Making duralumin wire 0.0008 inch in diameter is no snap, but we must have it, low in resistance, high in tensile strength, free from tight curls and uniform in all respects. Apparently the problem of improving the frequency range of the oscillograph reduced itself to finding out how to make fine duralumin wire. The metallurgists in the Chemical Laboratories could heat-treat duralumin and draw it down to 0.001 inch, but their draw bench ran at too high a speed for smaller sizes, and dust caused by the remodeling of Section H of the Laboratories building interfered with their work.

A draw bench was built by E. Lund at the Canal Street branch of the Laboratories, according to designs by A. E. Melhose, who then tried to find out how to tease the wire made by H. T. Reeve's group down to 0.0008 inch. We began to wonder what duralumin was: why one sample would draw quite easily, but be weak and low in resistance, and another sample from the same ingot would draw with great difficulty but turn out strong and high in resistance. In a series of experiments, J. W. Nalencz heat-treated and drew down to 0.002 inch several different alloys all called duralumin which were then drawn to the final size and tested in the oscillograph by A. E. Melhose. We finally found that one alloy, when heat-treated exactly thus and so, and drawn at a certain speed and no faster (deadly slowly as a matter of fact) would come out straight and strong and low in resistance all at the same time, if the dies were absolutely clean and the wire wasn't allowed to oxidize between passes at the small sizes.

At first it was rare for a piece a foot long to get through the die without breaking, and each break required that the end of the wire, already thinner than the finest needle point, be ground down

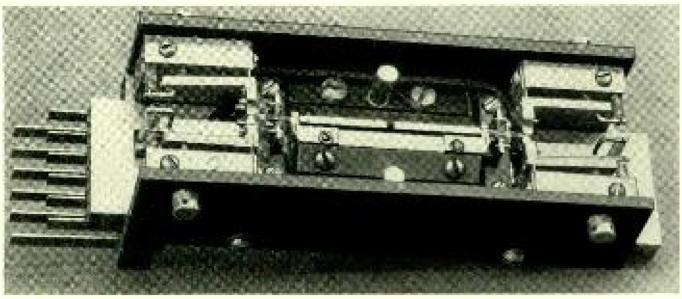

Fig. 1—In the galvanometer of the six-string oscillograph, the six strings pass across a small hole in the pole piece, through which light shines to form their images on the light-sensitive tape

to a long point and pushed through a hole, visible only with the aid of a microscope, in a diamond die. Later the technique was improved until the wire would often run a hundred feet without a break, and eventually two thousand feet of uniform wire were stored under an evacuated bell jar.

Careful inspection of the older samples showed spontaneous breakages of the wire on the spools, and the microscope showed localized corrosion, accompanied by the formation of minute white crystals. The corrosion of the purchased wire, wound on molded bakelite spools, was considerably worse than on the turned spools we had made ourselves. The trouble was evidently due to some chemical in the molding compound, and the remedy was to rewind all the wire on aluminum spools.

At first the demand for this wire was quite active, but it fell off as soon as all the oscillographs were supplied. The new wire, being two or three times as strong as the old, was much less likely to be broken.

Setting out to design equalizers, we had to learn wire-drawing, but now with a supply of uniform wire we could go ahead. The natural frequency of the first oscillograph galvanometers was 3200 cycles, all the old wire would permit. Experiments showed that it was not wise to attempt to equalize the string much beyond two and one-half times its natural frequency, since some peculiar effects occur in the neighborhood of the third multiple of the string's fundamental frequency, where the sensitivity varies with amplitude. The new wire would permit a natural frequency of 4500 cycles with a good margin of safety, and Messrs. Norton and Wood designed a new equalizer which gave a flat characteristic up to 10,000 cycles, to be used with the standard three-string galvanometer and optical system. The light, the developer and the maximum paper speed of the oscillograph are inadequate for the higher frequencies.

Fig. 2—A record being inspected, as the oscillograph takes it, by T. L. Tuffnell

The new equalizers relieved us of one source of complaints, the voice-frequency engineers. The power required for an oscillogram—about sixty milliamperes in eight ohms, or about thirty milliwatts—could be obtained from a reasonably simple amplifier. But it was another story with those who wanted to go all the way down to direct currents, in studying the contact chatter of some relays, for example. The best low impedance vacuum tube then available, the Western Electric 275A, could not give more than ten milliamperes direct-current output without troublesome distortion. An amplifier with six 275A tubes in the output stage, even if one were

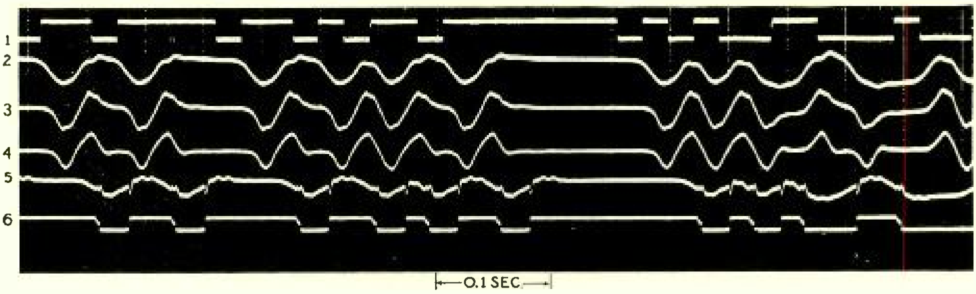

Fig. 3—This oscillogram of an experimental telegraph repeater system shows (1) *the sending voltage,* (2) *the current at the output of the first* 100*-mile line,* (3) *the current at the input of the second line,* (4) *the disturbance (amplified) which it creates there across a telephone circuit at the composite set,* (5) *the current in the winding of the receiving relay, and* (6) *the current in the receiving subscriber's loop*

available, would be rather awkward, since a quarter ampere of plate current must be supplied at about 200 volts from a battery which must be insulated from ground and thus cannot be a plant B-battery. Some alternative had to be found.

The equalizers work by taking a strong, complicated input current and attenuating the lower frequencies to make the deflection of the equalized oscillograph linear with frequency. An amplifier supplying the signal has to pass the currents of the lower frequencies which are later on discarded. A possible alternative to the use of the equalizer and linear amplifier is the use of two amplifiers in parallel: a linear one supplying the direct and low-frequency currents, and one for the higher frequencies whose output increases with frequency. Such an amplifier was built and worked as expected.

A simpler method of producing the same result was then developed by Ira E. Wood and Ira E. Cole, who designed an amplifier output circuit in which the oscillograph galvanometer was equalized by the usual resonant shunt up to its natural frequency, the amplifier being linear with frequency so far, but was equalized beyond this by the circuit which coupled the plates of the amplifier output stage to the string. That circuit* is like an autotransformer in several sections: for low frequencies it is a simple direct connection, but as the frequency increases, its effectiveness increases. It allowed us to reduce our hypothetical six-tube output stage to a real two-tube stage, and the design of a direct-coupled first stage of voltage amplification was comparatively simple. Our troubles will start when someone needs such a sensitivity for direct currents that two direct-coupled stages must be put ahead of the output stage.

Considerable work was done before the equalizing amplifier was considered safe for general use in the laboratory. A pair of thermal delay-relays prevents the oscillograph string from being connected to the amplifier while the filaments are heating, and a cage with a door switch prevents curiously inclined people from adjusting the interstage coupling circuits or tapping the grid connection of the first-stage tube while the string is in circuit. The probability of breaking the string is reduced by the proportioning of the output circuit.

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*For which a patent was issued to W. R. Bennett last spring.

A pair of these amplifiers with all their batteries mounts on a six-foot portable relay-rack and extends the range of the oscillograph to 10,000 cycles with voltage inputs into impedances of several values from 100,000 ohms to three megohms. The signal voltage required is from three-tenths volt to a hundred volts, depending on the dial settings; the amplifier is not intended for use as a voltmeter on circuits of very high impedance. The transformer input gives negligible phase and frequency distortion from 50 to 10,000 cycles and requires only two-tenths milliampere into twenty ohms for the usual oscillogram.

Neither the rapid record oscillograph nor the amplifier may safely be connected in circuits on the high side of an inductance through which current from a grounded battery is to be made and broken. The voltage to ground in such a case will often reach 1500 volts, causing a spark to pass from the string to the pole face, only four-thousandths inch away, and burning off the string. Most of the mysterious cases of string breakage are due to this simple trouble. For example, in studying the wave shape of the current in a relay attached to a plant battery, the string must be connected between relay and battery, not between relay and circuit. It is also unsafe to connect one string on the high side of a positive-grounded −130-volt telegraph battery, and another on the high side of a negative-grounded +130-volt B-battery. If the strings are deflected by the signal so that they touch or pass, they are quite likely to pull together and burn off. The safest practice is to arrange the circuit so as to keep all strings as close to ground potential as possible.

Making an oscillogram from a distance was readily made possible by replacing the hand lever which starts and stops the paper by a simple solenoid actuated through a relay and a push button. The latter may be replaced by an ordinary relay controlled from any distance. For about a year, for instance, things occurring in experimental apparatus in the transatlantic radio control room at 32 Sixth Avenue have been recorded on an oscillograph at the West Street building of the Laboratories, controlled from Sixth Avenue.

The new feature of the visual attachment designed for the rapid

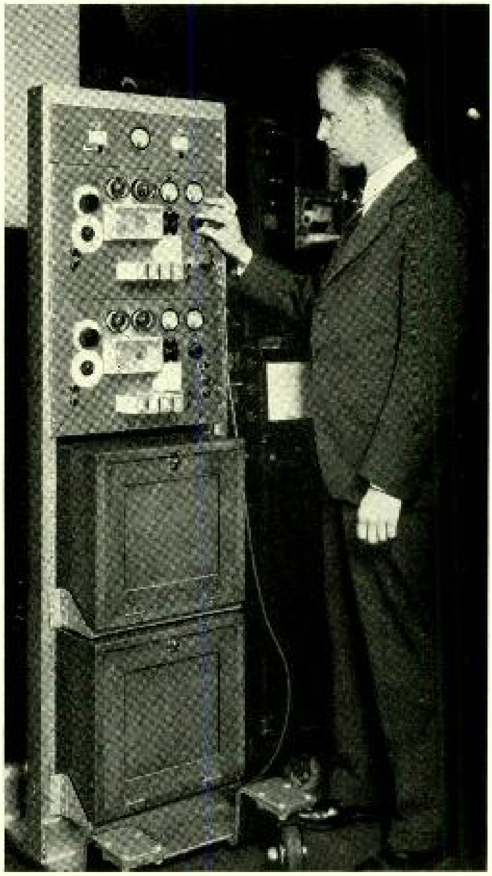

Fig. 4—The new amplifier for use with the rapid record oscillograph, being operated by A. E. Melhose

record oscillograph is that it uses only that part of the light beam which is wasted anyway. This permits an oscillogram to be recorded while it is being watched on the screen of the revolving mirror, and a change in a wave which occurs only occasionally may be watched for and caught on the paper when it does happen, if its duration is not less than a few tenths of a second.

We still had to take care of the telegraph engineers who complained that the sensitivity of the oscillograph was too low for studies of things such as the "Morse metallic" circuit unless an amplifier was used. As they were content with a record of the signal frequencies from zero to 1000 cycles, it was a simple matter to lengthen the string and reduce the tension.

A model with six strings would satisfy the demands of those interested in records of many things at once. It could be used in the "sound ranging" of artillery shells. It would also be helpful in locating oil pools underground by the method which uses the fact that oil and a "dome" of rock salt occur together. A charge of dynamite is set off in the ground at one side of the suspected area, and the arrival of the explosion wave through the ground is picked up by six microphones buried at various locations. A difference in the rate of travel of the wave along the six radii gives a clue to the location of the rock salt. In the Laboratories the six strings have proved very useful. In the study of a telegraph repeater, for instance, it is possible to record almost everything which happens at both terminals and the intermediate station.

"Signals and Speech in Electrical Communication"

It is a commonplace in industrial research that no invention, and especially no electrical contrivance, is ready for the public until it is "fool-proof," that is, until any fool can operate it and no fool can easily misuse it. Thus we have come to accept the dial phone, transatlantic telephony, and the radio as casually as we do sunshine, or the processes of digestion—except that they do not get out of order nearly so often.

There are those, however, who retain a curiosity as to how they work. This exposition is not easy, for it usually includes not only a large mass of fundamental science but also a record of prodigious research by thousands of highly trained scientists. The research bulletins of the Bell Telephone Laboratories alone fill many a long shelf. From this mountain of applied science John Mills has in this book selected sixteen rather crucial subjects for lucid discussion with the layman.

No one is better qualified for the task. His "Within the Atom" was one of the first books to open that field to the public and has been a model for twenty years. Now he manages to make simple such important but complex subjects as scrambled speech, multiple telephone circuits, the electric eye, television and the fascinating story of why both long-distance telephony and radio transmission have become as perfect as they are. It is all so neatly done that the book, like the inventions, is practically fool-proof.

From a book review by Gerald Wendt in The Herald Tribune (New York), November 18, 1934.

Galvanometry in Vacuo

By W. B. ELLWOOD
Special Research

BY its association with the science of hurling missiles, the word "ballistic" describes a certain type of galvanometer very graphically. When a charge of electricity is shot through such a galvanometer, the instrument measures the amount of that charge. Theoretically, indeed, the more nearly the charge is compressed into a single projectile-like packet, the more accurately the galvanometer will measure it.

Practically, of course, the charge flows through the galvanometer during a small but appreciable period of time. Its passage constitutes a pulse of current, and it is the task of the galvanometer to integrate or sum up the instantaneous current values of this pulse and indicate the result of this integration accurately in its deflection. The galvanometer accomplishes this best if its period of swing is so long that the charge has completely passed through it before it begins to move appreciably.

Such a galvanometer forms a convenient means for studying the magnetic properties of materials. A sample of a material is placed in a magnetic field and a suitable coil about the sample is connected to the galvanometer. When the field is suddenly removed or reversed, the magnetic flux which it had established in the material cuts through the coil, inducing a voltage in it which drives a charge of electricity through the galvanometer. The galvanometer reading is thus a measure of the flux which the field had established, and such readings can be used, together with the known values of the field strengths, as a basis for drawing the familiar curves relating field strengths to the fluxes they produce. Because of the low field strengths and fluxes frequently utilized in communication apparatus,

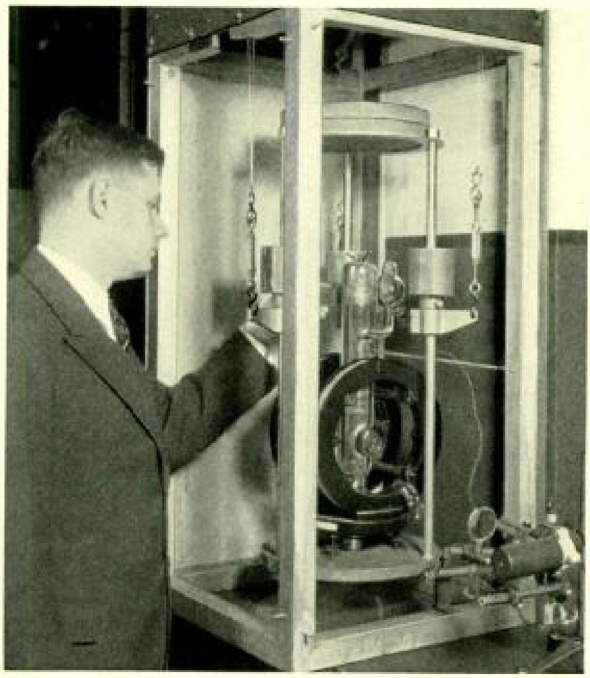

Fig. 1—In the new ballistic galvanometer, the moving element is a fine coil suspended in a highly evacuated glass tube

the investigation of magnetic materials in these Laboratories requires unusually sensitive and accurate measuring equipment.

Ballistic measurements can be made with suitably constructed galvanometers of either of two general types; that in which the charge passes through a fixed coil and the resulting magnetic field moves a permanent magnet, or that in which the charge passes through a movable coil and the induced field reacts with the field of a fixed magnet to move the coil. For measurements on magnetic materials at low flux densities, the moving-magnet type can be made amply sensitive, but it is inaccurate because it cannot readily be shielded from the effects of external fields and does not accurately integrate pulses of current of appreciable duration. Commercial moving-coil galvanometers, on the other hand, while better integrators, are still inadequate both in this respect and in sensitivity for extremely delicate measurements.

Fortunately there is a principle, stated by Maxwell, whereby the effective sensitivity of a ballistic galvanometer can be considerably increased; and the application of this, together with other principles tending to improve both the sensitivity and the accuracy of integration, are embodied in a new moving-coil galvanometer recently developed in these Laboratories. The principle is that, if the charge to be measured can be sent repeatedly through the galvanometer, timed in proper relation to the natural period of its swing, the amplitude of the swings will increase to a steady value which is proportional to

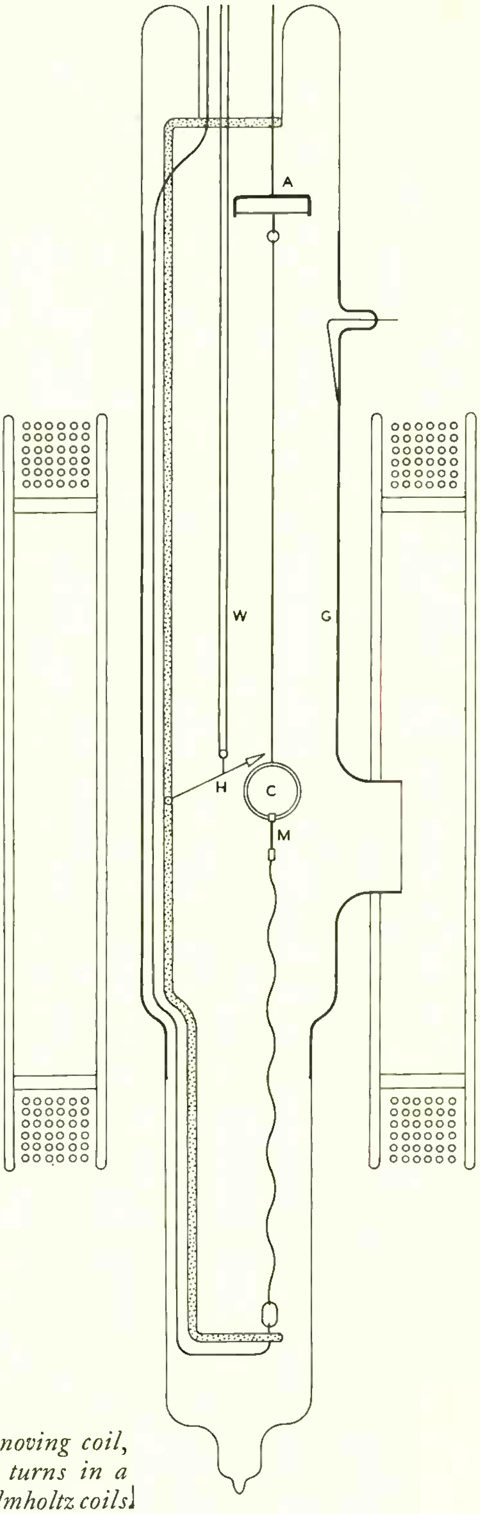

Fig. 2—In the new ballistic galvanometer a moving coil, carrying the pulse of current to be measured, turns in a magnetic field which is produced by a pair of Helmholtz coils

the charge and which is greater the smaller the damping. Air damping is eliminated by suspending the moving-coil in a vacuum, and elastic hysteresis in the suspension is minimized by the use of a flat tape so thin as to approach a bifilar suspension in its properties. By avoiding the use of metal in the neighborhood of the coil, eddy currents and hysteresis losses in the galvanometer are also minimized, and the accuracy is correspondingly improved.

The construction of the galvanometer is shown in simplified form in Figure 2. The moving-coil C, two centimeters in diameter, consists of thirty-six turns of enameled wire, held together by enamel. It can be clamped or released by the glass hooks H and the wire W, which expands when heated electrically, and can be set at any azimuth by the magnetically controllable armature A. The mirror M is a gold-plated glass strip, perpendicular to the coil and attached to it by an isolantite saddle. The upper suspension, attached to the coil by a bit of metal held in a similar saddle, is a flat strip of copper only three-thousandths millimeter thick and less than one-tenth millimeter wide, and a similar strip coiled into a spiral forms the lower suspension. Copper was chosen as the material presenting the best combination of low resistivity and low coefficient of internal friction.

All these parts are supported on a glass stem sealed into a glass tube which was baked, exhausted, and sealed at an extremely low pressure.* Since the baking temperature of the assembly is limited by the suspension fiber to 100 degrees Centigrade, the coil and tube were prebaked at 300 degrees. A transparent conducting film of gold G, connected at one terminal of the suspension and grounded, affords electrostatic shielding. A pair of large Helmholtz coils outside the tube provides the necessary field in which the coil turns. The strength of the field is about forty oersteds when the coils are connected to a 135-volt battery. The whole in-

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*About 10^{-5} mm. Hg. There is no advantage in evacuation unless it is carried to the point where the mean free path of the gas molecules is comparable to the diameter of the coil.

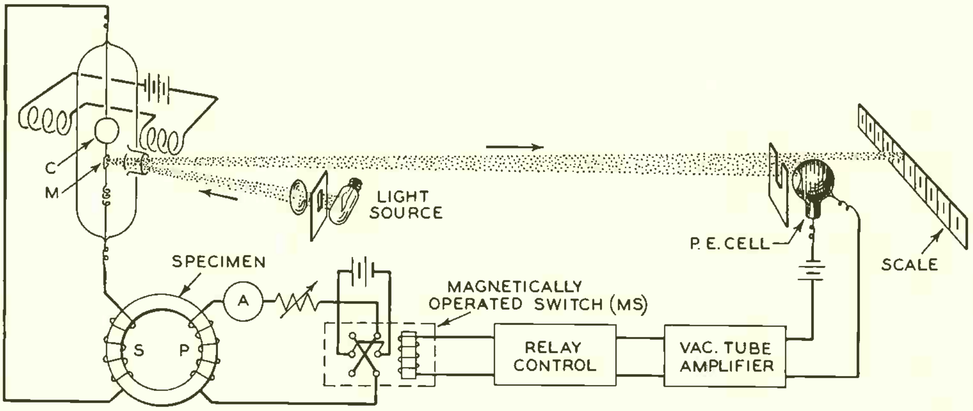

Fig. 3—Every time the galvanometer coil swings through its zero position, a beam of light acts through a photoelectric cell to reverse the current through the primary winding of the transformer under test, and thus passes another pulse of current through the galvanometer, in a direction tending to increase its swing

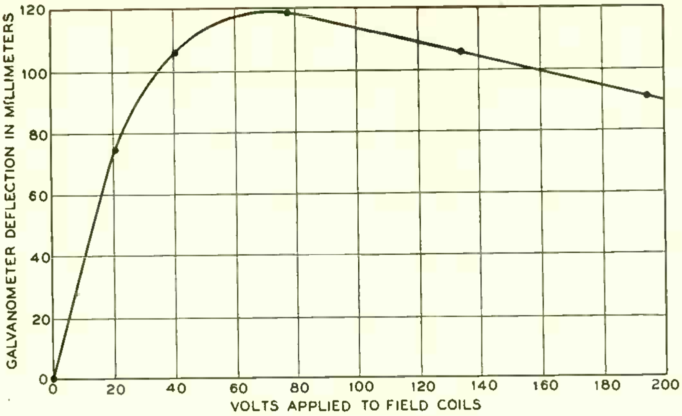

Fig. 4—There is a definite external field strength at which the deflection of the galvanometer will be a maximum

strument is mounted on a vibration-absorbing suspension.

Outside the tube a light source and a photoelectric cell are so placed, behind slits, that the mirror reflects a beam of light into the photoelectric cell when the galvanometer is undeflected, as shown in Figure 3. The magnetic material to be investigated is made up into a toroidal transformer, whose secondary winding is connected to the galvanometer and whose primary is connected to a battery through a reversing switch. When the switch is operated, the flux through the transformer core is reversed and a momentary voltage is induced in the secondary winding, deflecting the galvanometer. When the coil swings back through its zero position, the photoelectric cell receives a light impulse and acts through an amplifier and relays to throw the switch and reverse the flux again, passing another momentary current through the galvanometer in a direction tending to increase its swing. Once started, the instrument can be left to operate in this fashion until, *in about a half hour*, the deflection has so nearly reached its ultimate value that it can be satisfactorily taken as the measurement. The ultimate deflection is about thirty-three times the initial deflection. It is important for the accuracy of the final reading that the successive impulses be accurately timed to occur while the coil is passing through its zero position.

The deflection of such a galvanometer is limited by both electrical and mechanical factors. Of the latter the most important are the viscous drag of the air and of the coil suspension, which have been reduced by evacuation and by the use of a thin tape suspension. As for the electrical factor, it can be shown that there is a relation connecting the deflection of the coil with the number of turns of wire in it, the area enclosed by it,

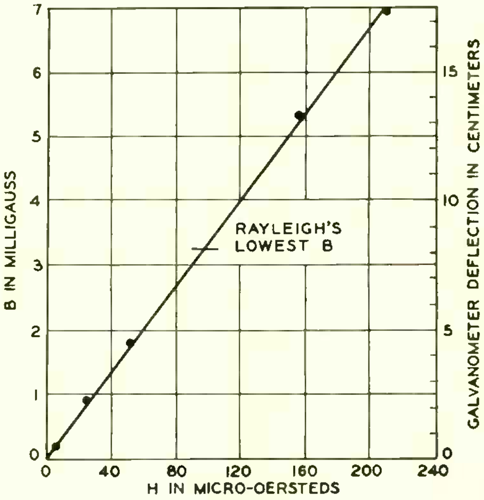

Fig. 5—With the new galvanometer it has been possible to measure the fluxes produced in iron-dust cores by very weak fields, carrying the investigation into flux ranges far lower than those of Rayleigh's classical researches

its resistance, the strength of the fixed field, and the sum of all other damping factors. After the galvanometer has been constructed, all these features are constant except the strength of the field produced by the Helmholtz coils, and there is a certain strength at which the deflection will be a maximum for all measurements, as shown in Figure 4.

The galvanometer is actually operated at a field strength somewhat higher than the optimum, in order to reduce the time constant of the galvanometer so that the swings will increase in amplitude sufficiently rapidly to permit readings within a reasonable time. The period of the swings remains sufficiently long to fulfill the classical requirement for accuracy of integration: that the charge to be measured should pass through the galvanometer before it moves appreciably. Within the half hour ordinarily consumed in a measurement, the galvanometer executes about a hundred swings and the deflection reaches about ninety-nine per cent of its ultimate value. Calibration shows the response of the galvanometer to be strictly linear: always proportional to the amount of the charge which has passed through it.

The qualities of the new galvanometer have made it almost indispensable in magnetic measurements where the available change in flux is small. The curve of field against flux for the toroidal iron-dust core of a loading coil, shown in Figure 5, is an example of its utility. The flux densities measured range from seven-thousandths gauss down to the extraordinarily small value of two ten-thousandths gauss. Accurate measurements at these extremely low flux densities are only made possible by the fact that the sensitivity of the new galvanometer is some 135 times that of the galvanometers previously used in these Laboratories.

Brazing the water-cooled anode of a vacuum tube

A Portable Public Address System

By A. F. PRICE

Special Products Development

PACKING the shouts of a giant in a suitcase is a feat which was placed within reach of all several years ago, when the 13A Public Address System was developed by these Laboratories and made available by the Western Electric Company. Certain auxiliary units have now been developed which add considerably to the flexibility of the system.

The system provides adequate amplification for medium-sized halls and small outdoor gatherings. Amplifier, loud speaker, control units, case and connections weigh altogether about seventy pounds. To make its convenience complete, the system is arranged for operation on the regular alternating current power supply of 115 volts at 60 cycles.

Some of the equipment used in the system has already been described in the RECORD. The three-stage amplifier, and the loud speaker of the dynamic cone type, permanently housed in the case, are the same, except for minor modifications, as those used in the portable sound picture system for sixteen-millimeter film.*

One of the available control units, the 10B for the input end, contains a network through which transmitter current for a lapel microphone† is obtained from the rectifier supplying plate voltage to the amplifier. The gain of the system can be adjusted by a potentiometer connected to the control unit by a thirty-foot cord.

When the speaker arrives at his meeting, he need only set the case in

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*RECORD, *August*, 1932, *p.* 417.

†RECORD, *January*, 1932, *p.* 170.

a convenient place, plug into an electric lighting line, clip the microphone on his lapel, step up on the platform and begin talking in his ordinary tone. The cord from the microphone gives him thirty feet of free movement, a great advantage when using stereopticon or other illustrations. By the volume control it is possible, when necessary, for an attendant seated as far as thirty feet from the loud speaker to adjust the amplification.

In order to use more than one lapel microphone, another control cabinet (the 718A) can be obtained which provides ready means for switching into the circuit any one of from two to five microphones. The cabinet is so designed that clicks due to connecting and disconnecting microphones are not transmitted through the system. Its use obviates the necessity of removing the microphones from speakers' lapels or altering the cord connections when a number of speakers use the system.

Another control unit (the 21A) is similar to the 10B except that it also provides switching facilities to permit the use of any one of three transmitters: one lapel microphone and two 600A stationary broadcast transmitters of the push-pull carbon-button type. This unit, in addition to making possible the use of stationary transmitters for public address, will be found valuable for auditions in broadcast studios and for remote pick-up of broadcast or other programs.

Amplifier, loud speaker, control units, case and connections weigh altogether about seventy pounds

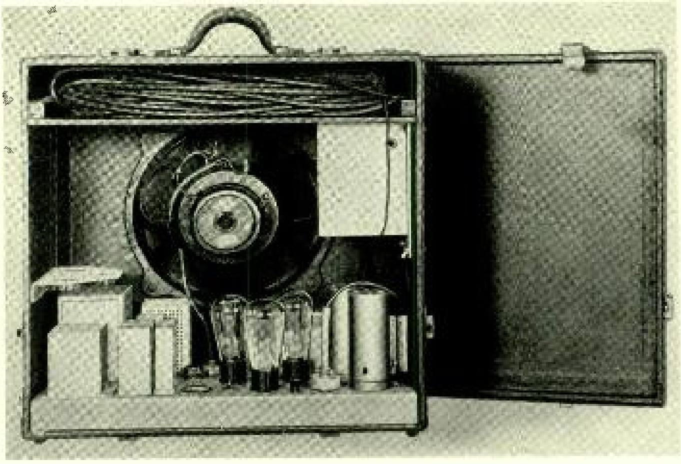

Fig. 1—Removing the rear cover of the carrying case reveals the compact arrangement of apparatus within it, including the shelf for the long cords at the top and the rack for spare tubes at the left

When using this equipment as a remote pick-up, another control unit (the 22A) for the output end is available for connecting the system to wire lines and so transmitting the program to a broadcast station or other point. This unit gives facilities for using the loud speaker in the case for monitoring purposes, and at the same time supplying a portion of the amplifier output to either of two lines. A volume indicator and a potentiometer permit adjustment of the energy level supplied to the lines. The amplification of the system as a whole can be adjusted as before at the input end. Like the input units, this output unit fits into the carrying case.

Testing a vacuum-tube circuit designed to transfer the load from the main ringing machine to a second machine in the event of low or high voltage at the ringing panel or upon failure of a brush in the ringing machine. Readings being taken by E. E. Helin of the Equipment Development section of the Systems Department

Contributors to This Issue

Harvey Fletcher received his undergraduate degree from Brigham Young University in 1907 and the Ph.D. degree from the University of Chicago in 1911. During his years of graduate study he was Instructor in Physics first at Brigham Young and then at Chicago, and on receiving the graduate degree became Professor of Physics at Brigham Young. In 1916 he came to these Laboratories, undertaking the investigations of speech and hearing which have made him one of the foremost authorities in this field. For many years he was, as Acoustical Research Director, in charge of groups occupied in studying the many aspects of sound, including the development of methods for aiding those who hear with difficulty. At the present time, as Physical Research Director, his supervision covers research work in acoustics, electronics, magnetism, and vibrating systems.

W. B. Ellwood received the A.B. degree from the University of Missouri in 1924 and came to New York to pursue further study at Columbia University. There he received the M.A. degree in 1926 and the Ph.D. degree in 1933. Meanwhile, in 1930, he joined the magnetics research group in these Laboratories, and engaged in studies of the magnetic properties of materials at very low field strengths. More recently he has been occupied with similar studies of magnetic properties at very high field strengths.

W. D. Voelker graduated from Cornell University with the degree of Electrical Engineer in 1929 and at once joined the Technical Staff of these Laboratories. Here with the Telephone Apparatus Development Department he first worked on the design of electrical measuring apparatus. At the present time he is engaged in the design of power transformers and retard coils.

A. M. Curtis left Heffley Institute in Brooklyn to ship as a wireless operator for the United Wireless Company. In 1910 he became chief operator, inspector, and installer for the radio systems of the Brazilian shipping company, Lloyd Bra-

Harvey Fletcher

W. B. Ellwood

W. D. Voelker

A. M. Curtis

C. C. Hipkins

A. F. Price

zileiro. Two years later he went up the Amazon River on an exploring expedition of the Brazilian Department of Agriculture, with the job of keeping in radio communication with the base. He joined the Western Electric Company the following year and in 1915 was in Paris for the Arlington-Paris radio-telephone tests. Two years later he joined the Signal Corps, becoming a Captain in charge of the inspection section of the Division of Research and Inspection in Paris. In 1919 he returned to these Laboratories to engage in the development of systems for telephone communication over submarine cable, in which the provision of suitable recording oscillographs has been of the greatest importance. He now heads a group devoted to the development of submarine cable apparatus.

After receiving his B.S. degree from Catholic University in 1925, C. C. Hipkins entered the Laboratories and for two years worked on the testing of cable, condenser and impregnated papers, coated fabrics and various insulating materials. Since 1927 he has been occupied with the investigation of organic finishing materials. He has contributed to the development of apparatus and methods of testing finishes, and to the design of finishes used on various telephone equipment.

After an early three-year connection with these Laboratories as a physical laboratory assistant, A. F. Price went to Brooklyn Polytechnic Institute, where he received the E.E. degree in 1917. For two years thereafter he was in France as a member of the research division of the U. S. Signal Corps, and on his return came to West Street, becoming one of the supervisors in a group through which passed the manufacturing specifications issued by the Laboratories. In 1925 he transferred to the special products group where he took charge first of field work on power-line carrier telephone equipment, and later of the mechanical design on such projects as picture transmission, transatlantic radio, and sound pictures. For the past five years he has had charge of a group devoted to the electrical design of public address, program distributing, and naval announcing systems.