Seventy-five Years of the Telephone: An Evolution in Technology

By W. H. MARTIN

SEVENTY-FIVE years ago—on March 10, 1876—the inventor spoke and his assistant heard the first sentence to be transmitted by telephone: "MR. WATSON, COME HERE; I WANT YOU." Three days earlier, *U.S. Patent No.* 174,465 had been granted to Alexander Graham Bell for his concept of means for making the conversion between the air vibrations of an uttered sound and their corresponding electrical undulations.

On this historic occasion, Bell talked into his liquid transmitter, and Thomas A. Watson listened to a tuned-reed receiver. In this receiver, shown at the right of Fig. 1, the free end of a steel armature was caused to vibrate by the undulatory currents through an electromagnet. Bell's famous patent showed such a structure with the free end of the reed attached to the middle of a stretched membrane, as at the left of Fig. 1. In Bell's liquid transmitter, in the middle of Fig. 1, a wire attached to a sound-vibrated diaphragm varied the length of its contact with some acidulated water, and thus produced a resistance changing in accordance with the impinging sound waves. This sound-controlled variable resistance in a battery circuit provided a means of associating amplification with the conversion of speech waves into their electrical counterparts. Thus, the first telephonic transmission of information demonstrated the two general principles of making the conversion between sound and electricity which have continued to be embodied universally—after much evolution through invention, research and development—in the transmitters and receivers of commercial telephony.

Today Bell would be called a scientist. He had been trained for work in the field of speech and hearing. He set himself the problem of transmitting and reproducing speech, which he approached analytically and experimentally. Where he thought more knowledge would help him in the solution, he tried to get it. Watson was the engineer of the team; he expressed Bell's ideas in forms for further experimentation and for use. The telephone business came into being out of such procedures and in a laboratory; that laboratory was the progenitor of the Bell Telephone Laboratories.

In this anniversary article, it has been deemed appropriate to portray the evolution of the methods and technology, and the scope of the activities in Bell Telephone Laboratories and its predecessors in the line of descent, which have been applied to the development of Bell's telephone instruments to bring them to their present state. This portrayal will show that Bell's

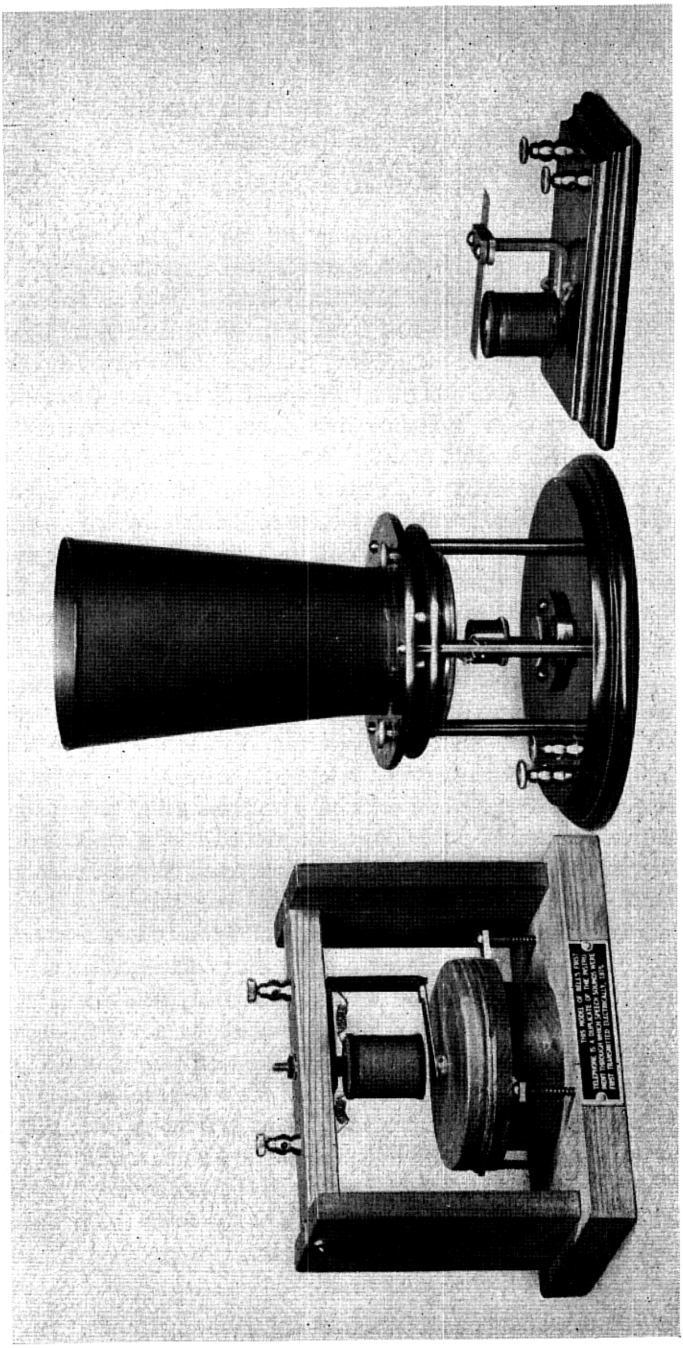

FIG. 1—The "gallows" type telephone shown in Bell's patent, at the left; the liquid transmitter used for the first transmission of speech, center; and the tuned-reed receiver also used in the first speech transmission, at the right.

vision of the telephone and his precepts and practices in following it have guided the scientists and engineers who have followed him and still live in the expansion of his activities in these Laboratories which bear his name.

Before moving into this evolution of devices, methods and technology, it should be recalled that Bell's vision covered not only the devices which he invented and which formed the basis of telephony, but extended also to the manner of providing a communication system extending throughout the land. While in England in 1878 Bell wrote:

> ". . . it is conceivable that cables of telephone wires could be laid underground, or suspended overhead, communicating by branch wires with private dwellings, country houses, shops, manufactories, etc., etc., uniting them through the main cable with a central office where the wires could be connected as desired, establishing direct communication between any two places in the city. Such a plan as this, though impracticable at the present moment, will, I firmly believe, be the outcome of the introduction of the telephone to the public. I believe, in the future, wires will unite the head offices of the Telephone Company in different cities, and a man in one part of the country may communicate by word of mouth with another in a distant place. . . . Believing, however, as I do, that such a scheme will be the ultimate result of the telephone to the public, I will impress upon you all the advisability of keeping this end in view, that all present arrangements of the telephone may be eventually realized in this grand system. . . ."[a]

In Bell's prophetic conception of the telephone system, it is evident that there was then in his mind a realization of the invention and development that would be required beyond his work on the telephone itself to make possible the kind of communication system which he envisioned. In "keeping this end in view," there has been a continuing activity over the years to make Bell's telephone perform better and better to meet the requirements of the "grand system." An important factor from this standpoint was embodied in Bell's liquid transmitter. It has been the continued development of the variable resistance transmitter that has made available at the talker's position a thousand-fold amplification of the small amount of energy in speech sounds. This has made it possible to use lower cost, smaller wires in the extensive network connecting private dwellings, shops, manufactories and central offices as contemplated by Bell.

For the "outside plant" and "central office" portions of Bell's 1878 con-

[a] This and other information about the early years of the telephone are taken from the well documented book "Beginnings of Telephony" by F. L. Rhodes. Item 1 in Bibliography at end of this article.

cept of the "grand system" for local and toll service, there has likewise been continuing invention, research and development over the years for their advancement in performance and application. While it would be necessary to include also these portions of the telephone system to show the extent of the influence on technology of Bell's vision, the activities covered here will be those in the "station" portion of the plant, and primarily those on the transmitter and receiver.

In looking back over the progressive development of the telephone, the four factors—invention, experiment, theory, and measurement—may be noted as tending to be dominant in turn for a period. It is perhaps unnecessary to state that the claimed dominance of any one of these factors in a period does not imply there were not important contributions from the others. It should be added that this succession of dominant factors is not confined to the development of the telephone but exemplifies the progress in adapting other contemporary devices to man's use. It is thought, however, that the development of the telephone has certain distinctions, possibly in degree of complexity and application, and of the effects of subjective performance.

After discussing these four factors with respect to the development of the telephone instruments, some brief indications will be given of the great effects of the work on the last two—theory and measurement—on the performance and design of these devices in the latter part of this seventy-five year period.

Invention

Following the transmission of the first sentence, Bell continued to experiment in his Boston laboratory and Watson to make models embodying the ideas coming out of this work. By May of 1876, Bell had devised the "iron box"[b] receiver with its permanent magnet and peripherally supported diaphragm of iron. In October 1876, these two ideas were incorporated in the first "box" telephone[c], and in May 1877 in the wood-encased hand telephone.[d] This 'box' telephone was used to introduce commercial telephony but was followed soon by the hand-held type.[e]

Bell's invention stimulated others to work and invent in this field. A series of variable resistance transmitters quickly followed Bell's liquid type. In 1878 Blake invented the platinum-carbon contact transmitter, Edison patented his compressed lamp-black carbon transmitter and Hunnings applied for a patent in England on a transmitter containing a pulverized form of carbon to secure a large number of microphonic contact points. Edison's

[b] Bibliography item 1, p. 30.
[c] Ibid., p. 176.
[d] Ibid., p. 43.
[e] Ibid., pp. 176, 177.

patent application on granules of carbonized hard coal was filed in 1886.[(f),2]

As early as 1878, the idea of mounting both the transmitter and the receiver on a common handle had been invented and such "handsets" were used by boy operators in the 'Gold and Stock' telephone exchange in New York City.[3]

In 1878, Watson patented his polarized two-gong ringer and designed the hand-cranked magneto for its actuation. The receiver-operated switch-hook was invented in 1877. Patent applications were filed in 1877 covering the association of an induction coil with the transmitter.

Thus, by the end of 1878, the general nature and principles of operation of most of the components of the present-day telephone set had been invented. One of them, the ringer, has come through the years in a form very similar to its original design. Other components, such as the carbon transmitter and the handset, have called for a large amount of research and development to make the application of the general principles satisfactory for the conditions of modern commercial telephony.

Other important inventions which affected the telephone set were the centralized battery for signaling in 1880 and the common battery for both talking and signaling purposes in the latter part of that decade. The bipolar hand receiver came into use in 1890 and the White solid-back carbon transmitter was invented in 1890. The rotary dial was first used by the Automatic Electric Company in 1896.

Figure 2 shows telephone equipment manufactured in 1882 by Charles Williams, Jr., in whose shop Bell had met Watson. This represents an early idea of combining in a unit-mounting the various pieces of apparatus for the use of the telephone. This unit—suitable for installation on the premises of a telephone subscriber—may be taken as typifying the first step toward the telephone station set as we know it. This 1882 telephone set included the Blake transmitter, single-pole hand receiver, ringer, magneto, switch-hook and induction coil. Incidentally, this arrangement of apparatus was later produced by the Western Electric Company which became the manufacturing organization of the Bell System in 1882.

Many changes have taken place in the elements and form of the station sets used in the Bell System since this 1882 set. Certain outstanding steps are illustrated in Fig. 3, showing a deskstand of 1919, the handset of 1927, the combined set of 1937, and the set on which production started in 1950. The 1919 set used a solid-back transmitter and a bipolar hand receiver which were the results of several stages of improvement of the types introduced in the 1890's. The 1927 handset required the invention of important changes in the granular carbon transmitter. The 1937 set introduced a new

(f) Ibid., Chap. V.
(2) Numbers refer to items in the Bibliography.

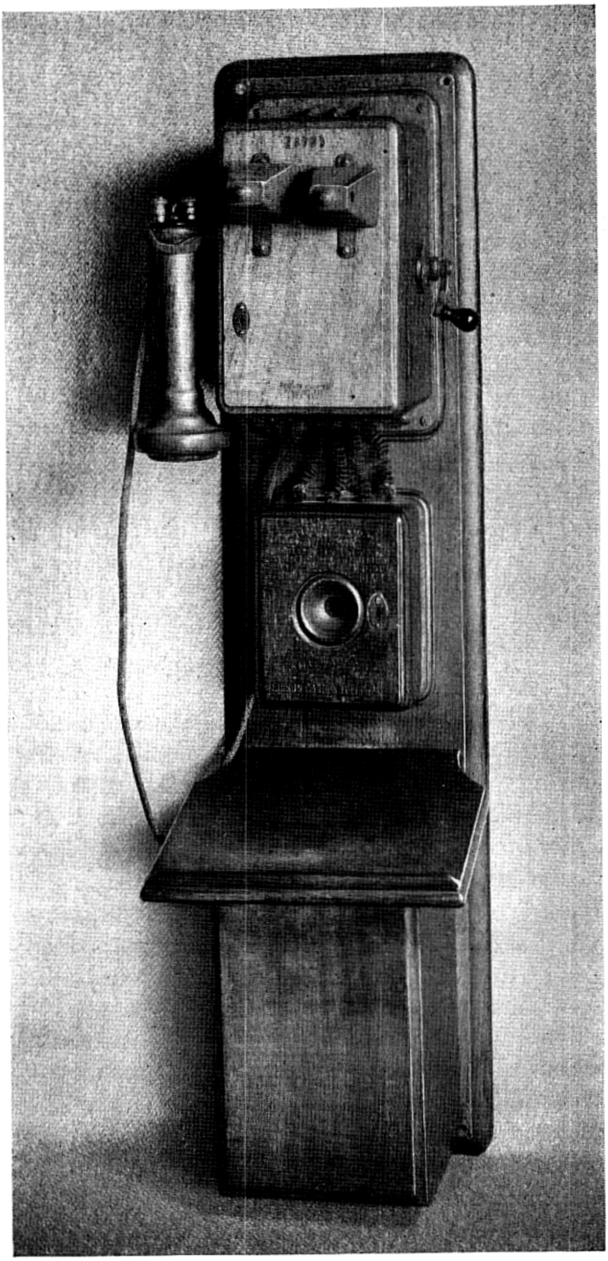

FIG. 2—Telephone equipment manufactured by Charles Williams, Jr. in 1882.

FIG. 3—The telephone deskstand of 1919, at top; the handset of 1927, left center; the combined set of 1937, right center; and the 500-type set of 1950, bottom.

principle of receiver operation and the 1950 set incorporated the invention of a radically new receiver structure.

Experiment

The solid-back granular-carbon transmitter and the bipolar hand receiver which were introduced in the last decade of the nineteenth century typify in their general structures the telephone instruments of the first quarter of the twentieth, in the Bell System and elsewhere. Throughout most of this period the progress made in telephone instruments may be characterized largely as improvements determined by experiments on modifications in details of form. Many important results were obtained in this field by this empirical or "cut and try" method, as was also the case with the other elements of the telephone set and with apparatus in many other fields in this period. That was generally the technology of the time. Progress by "cut and try," however, tends to be cumbersome, slow and unsystematic.

The vibrating diaphragms of both transmitter and receiver had their primary resonances in the transmitted range of voice frequencies. By listening to the speech sounds reproduced by various structures, judgments were made as to their relative merits on the sources of loudness, intelligibility and naturalness. By such qualitative tests, the primary resonances of these structures were moved to around one thousand cycles as being the most advantageous location in the audible frequency range.

Since the resonance of the vibratory elements of these instruments contributed so much to their overall conversion efficiencies, the changes in the design tended to enhance these resonance effects. Improvements came in efficiency, reliability and form, but the resonance effects remained peaked around one thousand cycles. Loudness of the sounds reproduced at the other end of the circuit was of great importance and it was early realized that the ear and mind of the listener can do an amazing job in associating distorted reproduced sounds with those spoken by the talker. So amplification by the granular carbon in the transmitter and the fostering of efficiency by resonances in both instruments were features of development in this period and played a large role in keeping down the cost of the circuits required for the expansion of telephony.

The undesirable effects of resonance were increasingly appreciated throughout this period of experiment, but no practicable means were discovered of reducing resonance without sacrificing unduly the loudness of the sounds reproduced in the ear of the listener. Since resonance had to be—and the importance of the loudness was so readily recognized—the efforts were directed to making the most of resonance.

An outstanding feature of this period in the progress of the telephone was the difficulty of measuring performance. The technical people then working in telephony strove to be quantitative. In their judgments of the relative talking performance of two instruments or circuits, percentage figures were used to show degree of difference. Later the length of trunk in one of the circuits was adjusted to get judged equality of performance and, at the beginning of the century, there was adopted the Standard Cable Reference System, with an adjustable network representing a 19-gauge cable pair in the trunk connecting commercial type common battery station sets.[4] By comparisons and substitutions, numbers of "miles of cable" were associated with relative performances on the basis of effect on the loudness of the reproduced sounds.

In 1912, a bulletin was issued for the use of the Bell System Operating Companies—largely the work of O. B. Blackwell—in which quantitative ratings in terms of the cable reference system were placed on the performances of various instruments and sets, and loops and trunks of different gauges of conductors.

Theory

Around the beginning of the 20th century, the "theory" factor began to increase significantly. Prior to that, the theoretical material applicable to telephony was very limited—such as that produced in Europe by Helmholtz, Hertz, Rayleigh, Poincare and Heaviside. Within a decade, there was produced a wealth of theoretical material dealing specifically with the problems of telephone transmission. This is exemplified outstandingly by the work of G. A. Campbell—his theory of loading,[5] from which he developed the theory of the electric wave filter,[6] theories of electrical networks as published in his article "Cisoidal Oscillations"[7] and his exposition of maximum output circuits[8] covering all ways of achieving, with one transformer and one balancing impedance, what has come to be called the "anti-sidetone" station circuit. While some of this work of Campbell's was not published until later, it was available to his colleagues.

The results of these theoretical studies of Campbell and those of his contemporaries of that time, notably Blackwell, were utilized to explore by computation the transmission of telephonic currents over lines and through the various circuits associated with these lines in central offices and at telephone stations.

Because of the complexity of many of these circuits and the need for exploring them for the range of frequencies involved in telephonic transmission, use developed of the equivalent network for computing the transmission effects of circuits consisting of pieces of open wire and cable, with the transformers, relays and networks associated with them at terminal or switching points. The application of these theories to the solution of telephone network problems was presented in books by K. S. Johnson[9] and T. E. Shea.[10]

While much of this theoretical material had very little effect at the time upon the development of telephone instruments, it provided a storehouse to be drawn upon later for that purpose by the brilliant concept of an analogy.

A further publication to be noted in that first decade of this century is another by Campbell on the use of syllables to measure the efficiency of telephone circuits in reproducing intelligible speech.[11]

MEASUREMENT

With this sketch of the roles of invention, experiment and theory, the stage is set for the great part to be played by measurement and what it fostered. The major theme of this part may be briefed as *the role of measurement in promoting and implementing the application of theory to design.*

In communication by telephone, the performance of the telephone system is inextricably combined with the performances of its users. This relationship is close for all the devices of the telephone set which directly involve the user, but is especially so for the instruments. This means that not only are physical measurements needed of instrument performance—input and output sounds and corresponding electrical counterparts—but also subjective measurements of performance involving the talkers and listeners—the generation and understanding by them of speech sounds and their reactions to the conditions of telephony.

Until the early part of the 20th century there was no means of measuring electrical currents or voltages of the magnitudes and frequencies involved in telephony. Progress in the field of acoustics also had been small because the means for quantitative measurement there were limited. For the design of telephone instruments there was little quantitative information as to the relations which should be maintained between the original sounds and the reproduced sounds to provide for their recognition. This situation tempers any criticism against the lack of great progress in the period which was necessarily limited to development by "cut and try" and crude qualitative judgments of performance.

Physical Measurements

The electronic vacuum tube—the epochal invention of Lee DeForest—was first welcomed into telephony as the long-sought means of stretching the toll lines across the country and thus making Bell's "grand system" cover the nation. Soon after this accomplishment, however, it was recognized that the vacuum tube had other important applications—as an amplifier for measuring the currents and voltages[12] of telephony and as an oscillator in generating currents of the frequencies in the voice range. For a short time prior to the availability of the vacuum tube, the Vreeland mercury-arc oscillator[13] was used as a source of currents for measurement with a thermocouple operating a galvanometer. Telephone circuits were measured by these cumbersome means but there were limitations to the range of frequencies and levels. This oscillator was used also with various forms of bridges for measuring the impedances of lines and apparatus.

The vacuum tube amplifier and oscillator quickly opened up the electrical measurement of telephone circuits at the levels of speech current and replaced the laborious computation of circuit performance. Also the amplifier made it possible to use the oscillographs of the time to make photographic records of speech currents and of single frequency currents of corresponding levels.[14, 15] These measurements and records revealed a lot about telephone transmission properties of lines and apparatus and put the design of transformers[16] and other circuit elements on a better basis.

In 1915 a proposal was made by Dr. H. D. Arnold, the carrying out of which had momentous effects. The proposal was that the vacuum tube amplifier be associated with as nearly perfect devices as could be developed to carry out the functions of transmitter and receiver and by these means to create a practically perfect telephone transmission system which would approach air transmission. With the large amplification available, it would be possible to utilize transmitters and receivers in which efficiency of conversion could be sacrificed to the extent necessary to approach freedom from distortion.

Arnold also had the conception that, with this nearly perfect transmission system, the effects of distortion on the intelligibility of reproduced sounds could be studied in a controlled manner—that is, distortion could be introduced into the electrical part of this transmission system by electrical networks and therefore be specifiable and reproducible.

In carrying out this proposal, Crandall and then Wente worked on the development of the required transmitters and receivers and from this work came the condenser transmitter[17, 18] and later the high quality moving coil receiver.[19]

From this activity then came some more important concepts and results. A transmitter of the condenser type which was stable and uniform in response over a wide range of frequencies was used with an amplifier operating into a meter to give a direct-reading indication of the magnitude of sounds even at quite low levels. With this there was developed[20, 21, 22] the theory of the thermophone as a means of setting up, in a specified closed chamber associated with the condenser microphone, an absolute level of sound, so that the combination of the condenser transmitter and amplifier could then be used to give an absolute measurement of the intensity of a sound field at a point. This made possible the absolute measurement of sound over the range of intensities and frequencies involved in speech and hearing. By associating a probe tube with the condenser transmitter, absolute measurements of sound intensity could be made in the ear canal.

This method of sound measurement led also to the closed-coupler artificial ear[23, 24] means of measuring the acoustic output of a telephone receiver under specified conditions approximating those of a typical human ear.

Another important measuring device derived from this work was the volume indicator[25, 26] whose rate of response to the fluctuations of speech sound energy was made to approximate the ear in this respect. This indicator when connected through a suitable amplifier to a telephone circuit could be used to measure the level of speech currents at that point. When a volume indicator was associated through an amplifier with a suitable pickup microphone it became a sound level meter for giving a measurement of the level of the complex tones of speech, music and noise.

Another device made practicable by the availability of the vacuum tube amplifier was the loudspeaker. This permitted suitable sound levels to be delivered by loudspeakers[25, 27, 28] which were progressively freed from distortion as the theory and technique of electroacoustic devices was advanced. The loudspeaker was employed in the artificial mouth[24] as a means of producing speech sounds of prescribed character and level for the testing of transmitters.

This combination of sound and electrical level meters, artificial mouth and ear, provided for the measurement of the physical performance of transmitters and receivers over the frequency range involved in telephony, for the levels at which they were operated and with both speech sounds and single frequency tones. The overall physical performance of these devices were thereby brought to quantitative determination.

With this situation the "standard cable system" was replaced as a reference system in the latter part of the twenties by what was termed the "Master Reference System for Telephone Transmission."[29] This system—an outgrowth of Arnold's "perfect" transmission system—with the thermophone means for absolute calibration of the transmitter and the closed coupler arrangement for absolute calibration of the receiver, provided a telephone reproducing system, the performance of which was specifiable in absolute physical terms. Means were furnished in this Master System for including distortion networks to make the idealized instruments of the reference system approximate the characteristics of the instruments used commerically; this distortion facilitated loudness balances with commercial instruments and circuits. This reference system became the reference for expressing loudness reproducing efficiency of commercial circuits and their components. It was adopted as a standard by the Bell System and by the C.C.I.F.†

† Comite Consultatif International Telephonique.

Subjective Measurements

We come now to the carrying out of Arnold's concept of using this reference system as a means of investigating the effects of distortion on the recognition of reproduced speech sounds. This was first started in the Laboratories under Crandall and then continued under Fletcher and his associates. This work involved the use of people as meters, with the problems of their calibration.

For such tests, lists of monosyllables were prepared which went far beyond the simple lists proposed by Campbell. A large amount of work was done in the determination of the basic sounds to be used, the most suitable form of syllables and the arrangement of syllables in groups to have balance with respect to their content of basic sounds.[30]

Starting with the earlier versions of the Master Reference System, the effects were measured by these articulation tests of changes in loudness, distortion and accompanying noise, on the understanding of the reproduced sounds and syllables. This study of distortion included resonance such as characterized commercial instruments and the variation of response with frequency as encountered in commercial circuits. Also, extensive articulation tests and analyses were devoted to the fundamental investigation of the effects of bandwidth as provided by electric wave filters of the Campbell type, and from these was derived a quantitative determination of the importance of the different parts of the transmitted band on the recognition of the reproduced sounds of speech. This work is described in Fletcher's book "Speech and Hearing"[31] and in many papers listed in the bibliography.[32, 33, 34, 35, 36, 37]

From this work there was developed also a procedure for computing the articulation of a telephone circuit from the physical characteristics of the circuit. With the availability of this computational method[38, 39] it has been practical to discontinue articulation testing itself except for special purposes.

Another factor which comes into telephony as an important effect in the use of the telephone is "sidetone." The speaker's voice reaching his own ear through the sidetone path of the telephone set reacts on his loudness of talking, this loudness being decreased unconsciously as the sidetone is increased. Also, in listening, sidetone introduces into the listening ear the room noise picked up by the transmitter. Both of these effects of sidetone were studied in the laboratory under controlled conditions, so that an appreciation was obtained of the magnitude of their effects.

There still remain the question as to applicability of the effects of volume, distortion, noise and sidetone as determined in the laboratory to commercial telephony with the conditions uncontrolled at the telephone stations and the users untrammeled in their habits and reactions. Information regarding this extension was obtained by observations on circuits covering a range in the various factors affecting transmission, and a count made of the number of repetitions which were requested per unit time by the users in carrying on normal telephone conversations. This repetition-rate method of measuring performance of telephone circuits bridged the gap between the laboratory and the plant, and established a relation between physical and subjective measurements in the laboratory and subjective results in service.[40, 41] In fact, the rating method derived from the repetition count observations was needed to prove that the effect of the reduced sidetone of the anti-sidetone circuit was sufficient to offset the additional circuit losses, complexity and cost of that circuit and so to justify its general use.

The development of the idealized transmission system and of the devices for measuring the electrical and acoustic inputs and outputs of telephone instruments, and the carrying out of the articulation and repetition rate measurements, together with the analyses of their results and deduction of relationships, required a large amount of activity for about fifteen years from the time of Arnold's concept, to cover the scope outlined here. Subsequent work has been directed to refining the devices and the results.

This work of physical and subjective measurement produced the knowledge of the performance characteristics which telephone transmitters and receivers should have and also the way to specify and analyze their performance—in other words, what to strive for in the development of new designs and how to determine the degree to which it has been attained.

Design Theory

The work which was done in developing the transmitters and receivers for the idealized transmission system promoted an evolution of the theory of the vibratory elements of such devices, including the effects of the associated air chambers. From this came large advances in the theoretical understanding of electro-acoustic converters, as exemplified by the book of Crandall "Theory of Vibrating Systems and Sound"[42] and publications by Wegel,[43] Wente[17, 44] and others.

One further concept was necessary to bring the design theory on instruments to its present level. As has been discussed earlier, the analysis of telephone circuits from the electrical standpoint made extensive application of the idea of the equivalent network. The new concept involved two steps: One was that the theory of electro-acoustic devices could be reduced to the simplicity of electrical network theory by using electrical analogs for the vibrating system. This was well brought out by R. L. Wegel in his paper of 1921[43]. The second step, promoted by H. C. Harrison,[45, 46] E. L. Norton and others, was that mechanical wave transmission systems could be designed as analogs of electric circuits.

This concept brought to bear on the development and design of electro-acoustic devices all the wealth of electrical transmission theory and measurement techniques, and especially the Campbell filter idea of designing a system to transmit efficiently a band of frequencies. With this analytical method, the means of controlling resonance could be explored quantitatively and systematically. Also thereby, means could be studied of compensating for limitations in the behavior of one part of the network by corrective measures elsewhere.

This electrical analog equivalent network concept not only facilitated the analysis of the overall performance of electro-acoustic devices but also made possible the study of the contribution of each element and of changes in each characteristic of each element to that performance. This could be done, mathematically or by measurement, on the simulating electrical network. Such studies promoted the understanding of the functioning of such devices and indicated what needed to be done to improve their performance. This method of analysis made it readily possible to determine the effect of modifications in the material properties and dimensions of the mechanical and magnetic parts, and of damping and dissipation in the acoustic elements. This pointed the way to meeting the response characteristics which were shown to be desirable by the subjective measurements on the intelligibility of reproduced sounds.

With this technique, advances can be made intelligently in the kinds of materials[47] used for the diaphragms of instruments and for the other magnetic parts of receivers; and the designer has been put in the position not solely of considering the materials that are offered to him by the metallurgist and other material engineers, but also of giving to them the specifications of desired properties. Incidentally, this specific tailoring of the characteristics and dimensions of the material to the performance requirements of the part in which it is used is an important factor in the miniaturization of apparatus and in minimizing in its design the old "factor of safety" (or "factor of ignorance" as it might be termed with present technology).

Design for Performance

With this evolution, the technology of telephone transmitters and receivers has made great progress since the beginning of the era of measurement. The situation will be indicated by considering the development and design of these instruments from several aspects and by noting certain salient accomplishments.

By "design for performance" is meant the process of determining the performance characteristics to be striven for, then developing systematically the means for meeting them and embodying these means in a suitable operating design. In selecting the performance objectives, due regard must of course be given to the likelihood of their achievement. In the era when experiment was the dominant factor in development, advancement in performance was largely expressed in terms of the modification which was tested.

The results of this era of measurement began to have their effect on the design of commercial telephone instruments about twenty-five years ago.

Though the idea of a handset goes back to the early days of telephony[3] it was not found out until the middle 1920's how to get, in the instruments of a handset, service performance comparable to that afforded by the then available instruments when supported and separated as they were in the wall set and deskstand set. There were two important limitations to achieving this result—one, the so-called "howling" resulting from the coupling between the diaphragm of the transmitter and the diaphragm of the receiver; and the other, the degradation of the performance of the granular carbon transmitter with position. The importance of the amplification provided by this granular carbon on the design of the telephone plant has been indicated and it was the magnitude of this amplification and the resonances in the instruments that caused the howling difficulty in the handset. With such instruments directly coupled mechanically, the howling problem was difficult to solve.[48]

In the early twenties, in the development of the handset which was made available in 1927, the coupling factor between the diaphragms of the two instruments was measured for a variety of proposed designs of handle; and the development and selection of the design was on the basis of a handle having resonance out of the range of the instruments used and of such material as to provide dissipation of energy in this mechanical transmission path.[49]

The other factor that made possible the solution of this problem was the development of a transmitter in which the vibratory system was essentially free from resonance and the positional effect of the carbon chamber was materially reduced. This transmitter—the first non-resonant transmitter[49] in commercial telephony—gave a decrease in the magnitude of the electrical output. It was demonstrated, however, by articulation and repetition-rate tests, that the reduction in loudness output was compensated for by the lower distortion of the reproduced sounds; and hence the combination of higher quality with decreased loudness gave a resultant intelligibility in service comparable to that obtained with the then available deskstand transmitter. The change in transmitter response is shown by a comparison of curves A and B of Fig. 4(a). The elimination of sharp resonances gives an additional improvement in transient response.

A comparison of curves A and B of Fig. 4(b) shows that the small receiver of the 1927 handset was made to give the same performance as the preceding

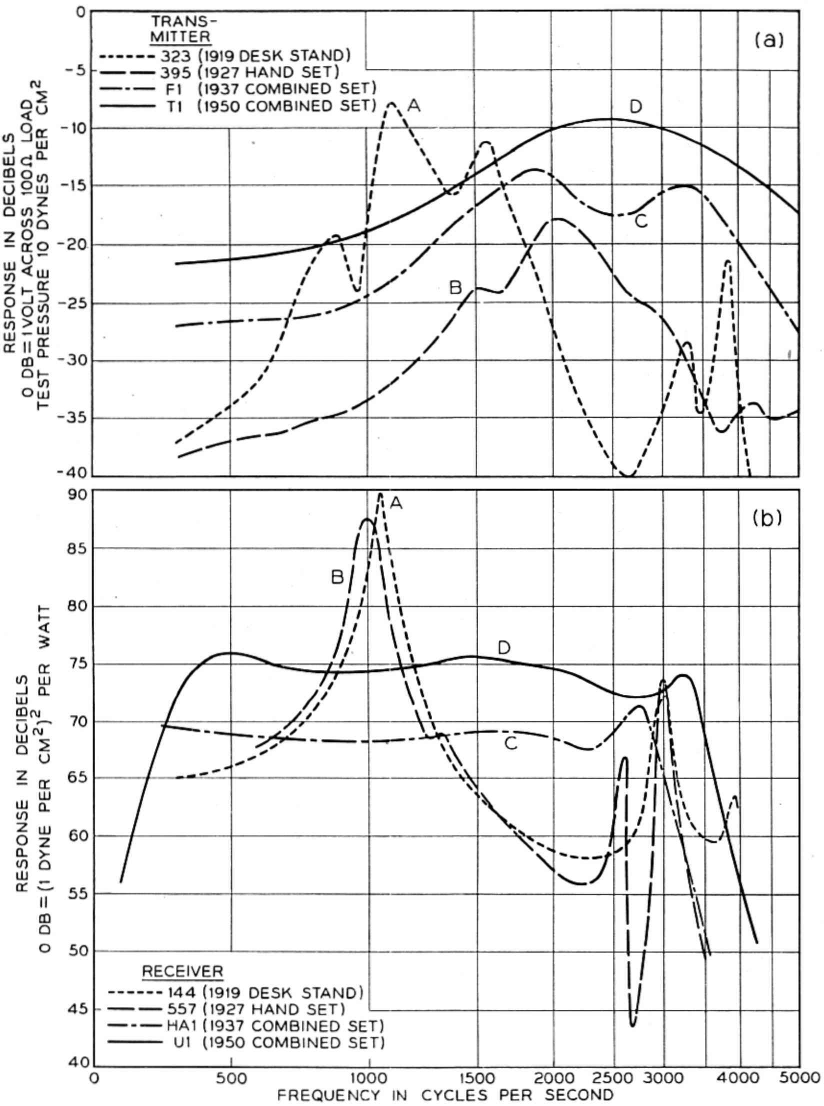

FIG. 4—(a) Artificial mouth response of the station set transmitter; (b) available power response of station set receiver.

larger hand-held receiver. This was the result of improved magnetic circuit and materials.

The handset of 1937[50, 51] included a new design of transmitter which was made available about 1934 for use in the earlier handset. In this transmitter the freedom from resonance was preserved and the effect of the improving analytical and quantitative approach is demonstrated by the much higher electrical output than that of the 1927 transmitter. This is shown by the comparison of Curves B and C of Fig. 4(a).

For the 1937 handset, the objective was set of making the receiver also free of resonance. The method of obtaining this result in terms of the equivalent electrical circuit is discussed in the W. C. Jones paper[50] of 1938, which shows also the electrical analog for the transmitter of this handset. A comparison of the receiver of the 1927 and 1937 handsets is given by Curves B and C of Fig. 4(b). It is seen that the diaphragm resonance is completely eliminated. The Jones paper indicates how the air spaces associated with the diaphragm and an acoustic resistance element are employed to control the motion of the diaphragm.

In the 1937 receiver, three special magnetic alloys are employed—permendur for the diaphragm, 45 percent permalloy for the pole pieces and remalloy for the magnets. In the manufacture of these receivers, each one is magnetized to its optimum value.[50]

In the instruments of the telephone set of 1950, the application of these design procedures has been carried still further. As brought out in a currently published paper,[52] the performance requirements for these instruments were set on the basis of what it was desired to have in the way of bandwidth, frequency characteristics, and efficiency. The instruments were then developed to attain these characteristics.

The response of the 1950 transmitter is shown by Curve D in Fig. 4(a). The shape of this response was deliberately planned to be as shown in order to approach the characteristic of the air transmission path. The gain over Curve C of the 1934 transmitter is obtained with a decreased size of diaphragm and unit.

Also in the 1950 transmitter, a further improvement has been made in the granular carbon to increase its stability with time. For many years, intensive studies[53, 54] have been made of the performance of granular carbon in the telephone transmitter to understand the contact action and to determine the causes of aging with use and time, and the means of alleviating these effects. From these and other studies of the structure of the chamber containing the carbon, have come remarkable results in improving the performance of this very critical mass of loose granules. It has been stated that the telephone system is built around a loose contact which is a thing that the electrical engineer hopes to avoid. The fact is that, today as a result of all this work which has been done on the use of granular carbon in the transmitter, little of value would be gained in the quality of reproduction in commercial telephony by the replacement of the current desgins of this simple low-cost means of making the conversion between acoustic and electrical energy, by a combination of a passive device with a vacuum tube form of amplification. Furthermore, the carbon transmitter has been made to behave well with respect to position, use and time.

The 1950 receiver, invented prior to World War II, involves a radically new structure—a receiver having a composite diaphragm with an outer annular portion of magnetic material and an inner circular part of domed impregnated fabric. This invention was stimulated by the analytical demonstration of the benefits of a diaphragm of low dynamic mass. A paper[55] published in the January 1951 issue of this *Journal* gives the theory of this receiver and describes the manner in which it was developed and designed to have the projected performance. That presentation shows the high level which the technology of the design of such devices has now reached.

From Curve D of Fig. 4(b), it is seen that this latest receiver is 5 db more efficient than the 1937 design and reproduces a wider frequency range. The dropping of the response at the lower end is intentional to avoid increasing the interference from power systems.[55]

By these extensive studies in theory, the development and application of physical and subjective measurements, and the advanced technology of design, the present generation of the descendants of Bell's transmitter and receiver approach in their performance the inherent limitations of the structures and materials, with the compromises that are chosen in the interests of quality and cost of production, and ruggedness and uniformity in use. As embodied in the 1950 set, the efficiencies of conversion of the transmitter and receiver are now so high that, on the shorter loops, losses are automatically introduced in order to avoid the delivery of sounds of too great loudness to the ear of the listener.

Design for Production

Since the war, production of the instruments of the 1937 type handset reached a rate of around five million a year apiece. This production has demonstrated that devices of such sensitivity and refinement in design can be made in large quantity with closely controlled quality and at low cost. The analytical quantitative approach to design in the case of these instruments has been an important factor in the adaptation of these designs to quantity production with present manufacturing techniques. Such production may call for changes from the designer's ideas as to the properties of the materials, their fabrication or the tolerances to be met. With the analytical quantitative approach to design, the effect of such changes can be readily evaluated, and proper judgments reached as to whether such compromises with the design are justified in the interests of control of product and lower costs. Such judgments can be made without the necessity of exploring the range of possibility by a series of models.

Furthermore, to carry out such kind of production, many of the measuring devices, such as the artificial mouth, artificial ear, with calibrated condenser transmitters and oscilloscopes, are carried to the factory assembly line to measure precisely each instrument as produced.

In the case of the instruments of the 1950 set, knowing that they were destined for large scale production by modern machines, tools, processes and assembly lines, the design for production was carried along with the design for performance. Thus the dictates of theory and laboratory performance were being continuously matched with those of fabrication and cost.

Design for Service

It has long been the practice in the Bell System to make trials in the operating plant of laboratory models or samples from the initial production of new designs. This has two major purposes—one to determine functioning under service conditions and the other to detect if there are weaknesses which may result in unexpected deterioration or failure. In addition, routine and special studies are made of service performance and troubles throughout the use of a device or system. As a result, information is continually being supplied to the designers to show the benefits of improvements and the needs for changes. This knowledge of service functioning and maintenance can thus be coordinated with the procedures which have been termed "design for performance" and "design for production." In the development of new designs or the modification of current ones, the Bell Telephone Laboratories designer is in a position to integrate concurrently the dictates not only of the laboratory and of the factory, but also those of service performance. This "design for service" can be carried out in the interest of getting the optimum ratio of service for the users, to the cost of employing the device in the plant, including not only the carrying charges on the initial price but also the cost of its operation and maintenance. Since the customers of the telephone system are paying for service and not buying equipment, the purpose of "design for service" is directed toward the goal of giving the most service for the money.

One result of this integration of plant experience into design has been a reduction in the last fifteen years of four to one in the service troubles with telephone instruments in the Bell System plant. These devices now approach the performance in this respect of many passive circuit elements.

Conclusion

In closing this scant presentation of the scope and results of the activities which have been carried on in Bell Telephone Laboratories primarily to improve the telephone devices invented by Alexander Graham Bell, mention should be made of the many important benefits which have been derived from this work in other fields. The condenser transmitter developed for the ideal telephone transmission system was the pickup microphone used in the introductory period of public address systems, radio broadcasting, electrical recording for phonograph reproduction and both disc and film recording for sound pictures. Subsequent other high quality microphones[56–60] in these fields and the succession of loudspeakers[61–63] of increasing quality of reproduction owe their development to the same techniques which were evolved to improve Bell's instruments. The same techniques of design were applied also to the light valve[64, 65] for film records, the electrical recorder[45, 66, 67] for disc records and to the many types of reproducers.[68] Thus this technology of telephone instruments has had widespread application in the mass use of sound reproduction in the phonograph, sound pictures and broadcasting.

Another application which would have been especially pleasing to Dr. Bell was that to the microphones and receivers of hearing aids[69–75] and to the measurement of hearing impairments[76–79]. Also of interest to him would have been the contributions which these measuring techniques have made to the work on the nature of speech and hearing.

In addition, these measurement tools and devices derived from them have provided solutions to many problems of architectural acoustics, and of noise and vibration reduction.

In World War II, this technology made it possible to determine quickly the desirable performance characteristics of microphones and receivers suitable for the high noise conditions of military applications such as in planes and tanks, and to develop the structures to provide this performance and meet the other military requirements. In the submarine field, this technology was applied to develop rapidly the instruments and methods for the measurement of underwater sound and to design and improve the various acoustic devices employed in that field.[80]

The analytical quantitative equivalent network method of design for performance, which has been applied in such a refined manner and so successfully to electro-acoustic devices, has been extended to mechanisms outside the acoustic field. Many of those who participated in pioneering this kind of design in acoustic devices are now engaged in the Laboratories on the development of improved mechanical devices. This method is a powerful tool but requires a type of training which is beyond that generally offered to mechanical designers; their studies might well be directed along the lines of the material in some of the articles cited here.

All this constitutes a wonderful illustration of the manner in which the results of research and fundamental development in a particular field and for a particular purpose can ramify into other fields, and have as by-products many other important applications. One indication of this ramification is the widespread use of the "db", the unit which was originally adopted for telephone transmission work.

While this evolution in technology, which has been outlined here, has been presented in its application to the telephone transmitter and receiver, it is in keeping generally with the progress of the technology of the times. To expand a previous statement, this application has claims to distinction in the degree to which it has been necessary to go in measuring subjective performance, and in the degree to which it has been possible to go in integrating the dictates of the laboratory, factory and field in making "design for service" approach its goal of maximum ratio of service to cost.

Although only a few have been named here, many have taken part in this evolution in technology. These many are collaborators in this anniversary article and in furthering Bell's vision of the "grand system."

Bibliography

1. Beginnings of Telephony, F. L. Rhodes, Harper & Bros., New York and London, 1929.
2. The Development of the Microphone, H. A. Frederick, *Bell Tel. Quarterly*, V. 10, July 1931, pp. 164–188.
3. Early Handsets, H. A. Frederick, *Bell Lab. Record*, V. 12, July 1934, pp. 322–326.
4. The Transmission Unit and Telephone Transmission Reference Systems, W. H. Martin, *A.I.E.E. Jl.*, V. 43, June 1924, pp. 504–507.
5. On Loaded Lines in Telephonic Transmission, G. A. Campbell, *Phil. Mag.* V. 5, March 1903, pp. 313–330.
6. Physical Theory of the Electric Wave Filter, G. A. Campbell, *Bell System Tech. Jour.*, Nov. 1922, V. 1 pp. 1–32.
7. Cisoidal Oscillations, G. A. Campbell, *A.I.E.E. Proc.*, V. 30, April 25, 1911, pp. 789–824.
8. Maximum Output Networks for Telephone Sub Station and Repeater Circuits, G. A. Campbell and R. M. Foster, *A.I.E.E. Trans.* V. 39, Part 1, Feb. 1920, pp. 231–290.
9. Transmission Circuits for Telephonic Communication, K. S. Johnson, third printing, Van Nostrand, N.Y., 1927.
10. Transmission Networks and Wave Filters, T. E. Shea, Van Nostrand, N. Y., 1929.
11. Telephonic Intelligibility, G. A. Campbell, *Philosophical Mag.*, 6th Series, V. 19, January 1910, pp. 152–159.
12. Historic Firsts—Vacuum Tube Voltmeter, *Bell Lab. Record*, V. 24, July 1946, pp. 270 and 274.
13. *Patents* 829,447 and 829,934 issued to F. K. Vreeland.
14. A Dynamical Study of the Vowel Sounds, I. B. Crandall, and C. F. Sacia, *Bell Sys. Tech. Jour.*, V. 3, April 1924, pp. 232 to 237.
15. The Sounds of Speech, I. B. Crandall, *Bell Sys. Tech. Jour.*, V. 4, October 1925, pp. 586 to 626.
16. Telephone Transformers, W. L. Casper, *A.I.E.E. Trans.*, V. 43, February 1924, pp. 443–456.
17. A Condenser Transmitter as a Uniformly Sensitive Instrument for the Absolute Measurement of Sound Intensity, E. C. Wente, *Phys. Rev.*, V. 10, pp. 39–63, July 1917.
18. Historic Firsts—The Condenser Microphone, *Bell Lab. Record*, V. 21, July 1943, p. 394.
19. Moving Coil Telephone Receivers and Microphones, E. C. Wente and A. L. Thuras, *Bell Sys. Tech. Jour.*, V. 10, October 1931, pp. 565–576.
20. The Thermophone as a Precision Source of Sound, H. D. Arnold and I. B. Crandall, *Phys. Rev.*, V. 10, July 1917, pp. 22–38.
21. The Thermophone, E. C. Wente, *Phys. Rev.*, V. 19, April 1922, pp. 333–345.

22. Historic Firsts—The Thermophone, *Bell Lab. Record*, V. 22, November 1943, p. 105.
23. Telephone Transmission Reference System, L. J. Sivian, *Elec. Comm.*, V. 3, October 1924, pp. 114–126.
24. A Voice and Ear for Telephone Measurements, Inglis, Gray and Jenkins, *Bell Sys. Tech. Jour.*, V. 11, April 1932, pp. 293–317.
25. Public Address Systems, I. W. Green and J. P. Maxfield, *A.I.E.E. Trans.*, V. 42, February 1923, pp. 64–75.
26. Speech Power and Its Measurement, L. J. Sivian, *Bell Sys. Tech. Jour.*, V. 8, October 1929, pp. 646–661.
27. New 548 Type Loud Speaking Telephone, *Bell. Lab. Record*, V. 6, December 1925, pp. 160–163.
28. A High Efficiency Receiver for a Horn Type Loudspeaker of Large Power Capacity, A. L. Thuras and E. C. Wente, *Bell Sys. Tech. Jour.*, January 1928, pp. 140–153, V. 7.
29. Master Reference System for Telephone Transmission, W. H. Martin and C. H. G. Gray, *Bell Sys. Tech. Jour.*, V. 8, July 1929, pp. 536–559.
30. Articulation Testing Methods by Fletcher and Steinberg, *Bell Sys. Tech. Jour.*, V. 8, October 1929, pp. 806–854.
31. Speech and Hearing, H. Fletcher, D. Van Nostrand, N. Y., 1929.
32. The Nature of Speech and Its Interpretation, H. Fletcher, *Bell. Sys Tech. Jour.*, July 1922, V. 1, pp. 129–144.
33. Physical Measurements of Audition and Their Bearing on the Theory of Hearing, H. Fletcher, *Bell Sys. Tech. Jour.*, V. 2, October 1923, pp. 145–180.
34. The Physical Properties of Speech, Music and Noise and Their Relation to Transmission Problems, H. Fletcher, *B.T.L. Reprint* B-94-1. (An address before N.Y. Tel. Soc. and N.Y. Elec. Soc., February 1924.)
35. The Dependence of the Loudness of a Complex Sound Upon the Energy in the Various Frequency Regions of the Sound, Fletcher and Steinberg, *Phys. Rev.*, V. 24, September 1924, pp. 306–317.
36. Effects of Distortion upon the Recognition of Speech Sounds, J. C. Steinberg, *Acoustical Soc. of America Jl.*, V. 1, October 1929, pp. 121–137.
37. Developments in the Application of Articulation Testing, T. G. Castner and C. W. Carter, Jr., *Bell Sys. Tech. Jour.*, V. 12, July 1933, pp. 347–370.
38. Factors Governing the Intelligibility of Speech Sounds, French and Steinberg, *Acoustical Soc. Am. Jl.*, V. 19, pp. 90–119, January 1947.
39. The Perception of Speech and Its Relation to Telephony, Fletcher and Galt, *J.A.S.A.*, V. 22, No. 2, March 1950, pp. 89–151.
40. Rating the Transmission Performance of Telephone Circuits, W. H. Martin, *Bell Sys. Tech. Jour.*, V. 10, January 1931, pp. 116–131.
41. A System of Effective Transmission Data for Rating Telephone Circuits, F. W. McKown and J. W. Emling, *Bell Sys. Tech. Jour.*, V. 12, July 1933, pp. 331–346.
42. Theory of Vibrating Systems and Sound, I. B. Crandall, D. Van Nostrand, N.Y., 1926.
43. Theory of Magneto-Mechanical Systems as Applied to Telephone Receivers and Similar Structures, R. L. Wegel, *A.I.E.E. Jl.*, V. 40, October 1921, pp. 791–802.
44. Acoustical Instruments, E. C. Wente, *Bell Sys. Tech. Jour.*, V. 14, July 1935, pp. 388–412.
45. Methods of High Quality Recording and Reproducing of Music and Speech Based on Telephone Research, J. P. Maxfield and H. C. Harrison, *Bell Sys. Tech. Jour.*, V. 5, July 1926, pp. 493–523.
46. Historic Firsts—The Orthophonic Phonograph, *Bell Lab. Record*, V. 24, August 1946, pp. 300–301.
47. Magnetic Materials in the Telephone System, V. E. Legg, *Bell Sys. Tech. Jour.*, V. 18, July 1939, pp. 438–464.
48. The Theory of the Operation of the Howling Telephone with Experimental Confirmation, H. Fletcher, *Bell Sys. Tech. Jour.*, V. 5, January 1926, pp. 27–49.
49. The Development of a Handset for Telephone Stations, A. H. Inglis and W. C. Jones, *Bell Sys. Tech. Jour.*, V. 11, April 1932, pp. 245–263.
50. Instruments for the New Telephone Sets, W. C. Jones, *Bell Sys. Tech. Jour.*, V. 17, July 1938, pp. 338–357.
51. Transmission Features of the New Telephone Sets, A. H. Inglis, *Bell Sys. Tech. Jour.*, V. 17, July 1938, pp. 358–380.
52. An Improved Telephone Set, A. H. Inglis and W. L. Tuffnell, *Bell Sys. Tech. Jour.*, V. 30, April 1951.

53. Microphonic Action in Telephone Transmitters, F. S. Goucher, *Bell Lab. Record*, V. 8, August 1930, pp. 566–569.
54. The Carbon Microphone: An Account of Some Researches Bearing on Its Action, F. S. Goucher, *Bell Sys. Tech. Jour.*, V. 13, April 1934, pp. 163–194.
55. The Ring Armature Telephone Receiver, E. E. Mott and R. C. Miner, *Bell Sys. Tech. Jour.*, V. 30, No. 1, January 1951, pp. 110–140.
56. A Moving Coil Microphone for High Quality Sound Reproduction, W. C. Jones and L. W. Giles, *Jl. of Soc. of Motion Pic. Engrs.*, V. 17, December 1931, pp. 977–993.
57. An Efficient Miniature Condenser Microphone System, H. C. Harrison and P. B. Flanders, *Bell Sys. Tech. Jour.*, V. 11, July 1932, pp. 451–461.
58. A Non-Directional Microphone, R. N. Marshall and F. F. Romanow, *Bell Sys. Tech. Jour.*, V. 15, July 1936, pp. 405–423.
59. A Tubular Directional Microphone, W. P. Mason and R. N. Marshall, *Jl. A.S. of A.*, V. 10, January 1939, pp. 206–215.
60. New Microphone Providing Uniform Directivity Over Extended Frequency Range, R. N. Marshall and W. R. Harry, *Jl. A. S. of A.*, V. 12, April 1941, pp. 481–498.
61. An Efficient Loudspeaker at the Higher Audible Frequencies, L. G. Bostwick, *Jl. A. S. of A.*, V. 2, October 1930, pp. 242–250.
62. Auditory Perspective—Loudspeakers and Microphones, E. C. Wente and A. L. Thuras, *Bell Sys. Tech. Jour.*, V. 13, April 1934, pp. 259–277.
63. Modern Theater Loudspeakers and Their Development, C. Flannagan, R. Wolf and W. C. Jones, *S.M.P.E. Jl.*, V. 28, pp. 246–263, March 1937.
64. *Patents* 1,638,555 and 1,656,255 issued to E. C. Wente.
65. The Principles of the Light Valve, Shea, Herriot and Goehner, *Soc. of Motion Picture Engineers Journal*, V. 18, pp. 697–731, June 1932.
66. Recent Developments in Hill and Dale Recorders, L. Vieth and C. F. Wiebusch, *S.M.P.E. Jl.*, V. 30, January 1938, pp. 96–104.
67. Lateral Feedback Disc Recorders, G. A. Yenzer, *Audio Engineer*, V. 33, September 1949, pp. 22–26, 44–45.
68. Universal Phonograph Reproducer, H. A. Henning, *Bell Lab. Record*, V. 19, October 1940, pp. 57–60.
69. Two Inventions Aid Hard of Hearing, *W.E.Co. News*, V. 14, November 1925, pp. 24–29.
70. Hearing Aids and Deafness, H. Fletcher, *Bell Lab. Record*, V. 5, October 1927, pp. 33–37.
71. Audiphones, W. L. Betts, *Bell Lab. Record*, V. 10, June 1932, pp. 362–366.
72. A Modernized Hearing Aid, R. Nordenswan, *Bell Lab. Record*, V. 15, January 1937, pp. 163–166.
73. The Orthotechnic Audiphone, W. L. Tuffnell, *Bell Lab. Record*, V. 18, September 1939, pp. 8–11.
74. Bone Conduction Receiver, M. S. Hawley, *Bell Lab. Record*, V. 18, September 1939, pp. 12–14.
75. Models 65–66 Hearing Aids, J. R. Power, *Bell Lab. Record*, V. 26, January 1948, pp. 30–33.
76. Audiometric Measurements and Their Uses, H. Fletcher, *Volta Rev.*, V. 26, January 1924, pp. 10–14.
77. 5A Audiometer, L. G. Hoyt, *Bell Lab. Record*, V. 5, January 1928, pp. 159–162.
78. The 6BP Audiometer, A. H. Miller, *Bell Lab. Record*, V. 23, December 1945, pp. 464–465.
79. Historic Firsts—The Audiometer, *Bell Lab. Record*, V. 24, February 1946, pp. 57–58.
80. Scientists Against Time, J. P. Baxter, 3rd. Little, Brown and Company, Boston 1946, pp. 175–176.