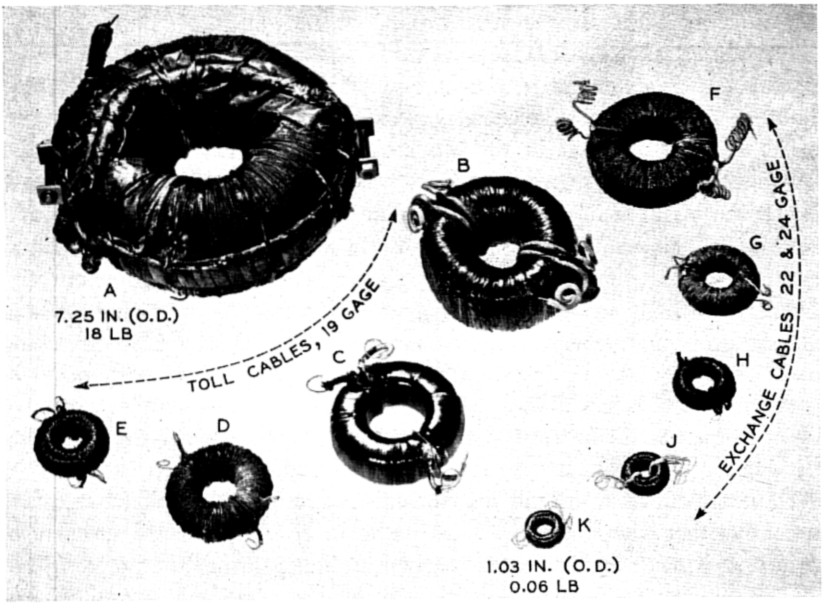

Headpiece.—A panorama of loading coils 1904–1948.

The Evolution of Inductive Loading for Bell System Telephone Facilities

By THOMAS SHAW

INTRODUCTION

THIS is the story of the contributions of inductive loading in the growth of the Bell Telephone System to its present great stature. In particular, it tells how these contributions have been made. We see in it the great economic value of organized research, of research scientists and design and development engineers, of manufacturing skill and care, and of the application of sound engineering principles to the design of the telephone plant.

The story told here is almost entirely concerned with series inductance coil loading, since other types of loading have had very little use in the Bell System. To make the story more complete, however, a brief account is included of Bell System developments and applications of continuous loading.

The main story starts soon after the turn of the century, following the development of the first standard loading coils and loading systems, and carries through to the end of 1949. In the beginning of this period emphasis was placed on urgently needed increases in the range of telephone transmission over open-wire lines and cables, and in the use of cheaper cables. In this connection it should be remembered that a really satisfactory type of telephone repeater did not become available for general use until 1915, about 15 years after the invention of loading.

The commercial limit in the economical use of loading to extend the transmission range of open-wire lines was reached in 1911, several years before the vacuum-tube repeater became available. Then, repeaters and loading had to be used as teammates to conquer the transcontinental distances. Subsequent improvements in repeaters, auxiliary equipment and circuits eventually made it advantageous to discontinue open-wire loading, and simultaneously opened an important new field for impedance-matching loading on the entrance and intermediate cables that unavoidably occur in open-wire lines. When different types of carrier systems became available for open-wire facilities, several new types of impedance-matching loading suitable for these carrier systems were developed.

The early efforts to extend the transmission range of long-distance cables in competition with open-wire lines, so as to obtain increased stability of service and lower facility costs, reached a climax during the period 1911–1915 in the use of composite, quadded, 10 ga. and 13 ga. cables, and of loading coils nearly as large as the open-wire loading coils. This trend slowed down shortly after vacuum-tube repeaters became commercially available. During the next fifteen years or so, intensive development work on improved repeaters, on equalizing and regulating networks, and on higher velocity, higher cut-off loading, made it feasible to use 19-gauge conductors and loading coils no larger than the initial standard cable coils for distances ranging up to about 1500 miles.

In the exchange area cable plant, coil loading has made it possible at a low cost to meet the needs imposed by geographical factors, with as yet very little competition by telephone repeaters. Large reductions in the costs of the trunk plant have resulted from the extensive utilization of 22- and 24-gauge cables, made feasible by the use of inexpensive loading. The substantially continuous transmission developments in exchange area services also made possible important improvements in the intelligibility of transmission by using higher cut-off loading to transmit wider speech-frequency bands.

The important loading apparatus developments in the period covered by the review have taken full advantage of the development at fairly even-spaced intervals of a series of successively better magnetic core-materials to improve the transmission service performance or reduce loading costs, sometimes combining these features. The loading coil cost-reductions which resulted from the large size-reductions made possible by the standardization of compressed permalloy-powder core loading coils during the late 1920's were especially important in influencing the growth of the long distance and exchange area cable plant, and in leading to important service improvements.

As described, step by step, in the present story, coil loading has been a very important factor in making possible the provision of satisfactory telephone service at reasonable rates which have encouraged a continually increasing use. Important elements in the public satisfaction to which loading has made fundamental contributions are: (1) high-quality transmission, and (2) high-speed service facilitated by the provision of relatively large groups of relatively low-cost facilities. In the extensive utilization of the long-distance service over repeatered, loaded, voice-frequency toll cable facilities, loading must of course share the credit for the improved transmission, plant cost-reduction, and speed of service with the telephone repeaters and associated equalizing and regulating networks, where involved.

All of the coil loading development work for Bell System needs, including the specific developments described in the present review, has been done by Bell System people without outside aid. Coil loading was independently invented by Dr. G. A. Campbell[1] of the headquarters staff of the American Bell Telephone Company, and by Professor M. I. Pupin[2] of Columbia University, at nearly the same time, in 1899. The patent interference proceedings made necessary by the conflicting claims of the Pupin and Campbell applications resulted in a priority award to Pupin during April 1904, on the basis of a few days' earlier disclosure. The prompt purchase of Pupin's rights in the invention before the interference action had gone far assured the Telephone Company complete freedom to develop the new loading art in the most advantageous ways.

The improvements worked out and applied over the years are principally due to groups of scientists and engineers working as teams on various phases of the transmission research, development, and engineering problems; on the magnetic materials research and development problems; on the apparatus-design and manufacturing problems; and on the field-construction and traffic problems. Nearly all aspects of telephone systems' development have been involved to a greater or less extent.

In the aggregate, a large number of individuals have made important contributions to the advancement of the loading art. The writer of this review is to be regarded as a spokesman for his co-workers. Since the assignment of a fair measure of personal credit to each individual who has been involved would be extremely difficult, it is not attempted in the present review.

PART I: THE BEGINNINGS OF COIL LOADING

GENERAL THEORY

For present purposes, a rigorous presentation of the mathematical theory of coil loading is unnecessary.(a) A simple description and a brief statement of theory is sufficient.

The primary purpose of coil loading is to improve the transmission of intelligence by substantially reducing the circuit attenuation, and by making the circuit attenuation approximately uniform throughout a predetermined frequency-band. These transmission benefits are obtained by serially inserting coils having uniform inductance values at regularly recurring intervals along the circuit, but are limited to a frequency-band below the loading cut-off frequency. This is an inverse function of the square root of the product of the coil inductance and of the mutual capacitance of the loading sections between successive coils, as determined by the coil spacing and unit-length capacitance of the circuit. Above the loading cut-off frequency, there is a substantial suppression of transmission.

For more than a decade prior to Campbell's and Pupin's 1899 researches, the theoretical possibility of improving transmission over telephone lines by artificially increasing their inductance had become known from the mathematical studies of Vaschy and Heaviside. Also there had been considerable speculation by them[4, 5], and by others, regarding the practicability of approximating the advantages of uniformly distributed inductance by inserting low-resistance inductance coils along the line. Rules for spacing the lumped inductances had not been worked out, however, nor had suitable coils been developed.

The requisite coil-spacing turned out to be such that there are several coils per wave length at the highest frequency which should be efficiently transmitted to obtain satisfactory intelligibility. Here, "several" means more than two, since at the theoretical cut-off frequency there are two coils per wave length. In terms of the nominal velocity of propagation of the "corresponding smooth line" (a hypothetical line having the same total inductance and capacitance) there are π coils per wave length at the cut-off frequency; expressed in "loads-per-second," this nominal velocity is exactly π times the cut-off frequency in cycles per second.

The attenuation improvement obtainable with loading corresponds somewhat to the increase in impedance that results from the increase in induct-

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(a) Readers interested in the rigorous mathematical theory are referred to Bibliography items (1) and (2). Campbell's treatment has been extensively used by communication engineers because of its comprehensive coverage of the frequency band concept in which the cut-off effects on propagation and impedance are emphasized. Also, his disclosures include explicitly the effects of conductor resistance and ratio of coil resistance to conductor resistance. His general formulas include the distributed inductance and leakage.

ance. This can be understood from the fact that in the (low-impedance) non-loaded circuit, the series dissipation losses which are proportional to the square of the line current are ordinarily very large relative to the dielectric dissipation (i.e. shunt) losses which are proportional to the square of the line potential. When the line impedance is increased a suitable amount by the loading, the decrease in series losses is much greater than the increase in shunt losses. In commercial practice, economic considerations generally prevent the use of high loading impedances which would result in the shunt losses becoming as great or greater than the series losses.

In situations where voice frequency attenuation improvement is the principal objective, the unit transmission loss can usually be reduced to the order of one-third to one-fourth of the non-loaded value. The loss reduction is less than this at low voice frequencies and more at high frequencies, resulting in a much more uniform transmission of the important frequencies that are required for intelligibility and naturalness. In certain situations which will be discussed later a lower ratio of attenuation reduction is accepted in order to obtain other, more important, transmission advantages.

Pioneering Developments

General

A full account of the pioneering research and development work would take much more space than is available in a review devoted primarily to the evolution of the loading art. The present account is therefore limited to a brief description of the first loading systems and apparatus standards that resulted from the pioneering work.(b)

Although the success of the 1899 laboratory investigations, and the Bell System's 1900 experimental installations on exchange cables and on open-wire lines, quickly built up a substantial demand for loading, the commercial applications had to be deferred pending the development of satisfactory types of loading coils. Then there followed a series of what should be considered as trial installations of different types of loading, tailored to the specific needs of particular projects. Analyses of the performance characteristics of these installations, supplemented by continuing experimental work in the laboratory and by engineering cost-studies, resulted in the establishment of a series of standard cable loading systems for general use late in 1904. The commercial development of satisfactory open-wire loading encountered many even more complicated problems than those involved in cable loading, and in consequence the standard loading for 104-mil lines did not evolve until 1905. This same type of loading be-

(b) A more complete description of these standards is given in Bibliography Reference (6). Reference (7) is also of interest. Reference (1) gives some details of Campbell's early work.

came standard for 165-mil lines in 1910, after a long period of additional development work to get better line-insulation.

All of this early loading development work was for non-quadded cables and for non-phantomed open-wire lines.

Loading Coils

The earliest speculative suggestions regarding coil loading recognized the critical need for obtaining a low ratio of coil resistance to circuit resistance, and by implication a low ratio of coil resistance to coil inductance. As was expected, this turned out to be a difficult design and manufacturing problem, especially with open-wire loading which was given development priority.

By April 1901, a very satisfactory coil-design had been worked out for open-wire loading by Mr. H. S. Warren, an associate of Dr. G. A. Campbell. It had a toroidal core, formed by winding a bundle of insulated mild-steel wires, 4 mils in diameter, on a suitably shaped spool, several miles of wire being used in each core. The manufacturing process of the outside supplier included cold drawing to obtain a magnetically hard wire having an initial permeability of about 65. The two line-windings, each confined to separate halves of the core winding-space, made use of insulated, stranded wire. The fine subdivision of the magnetic material and of the copper conductor was essential to the satisfactory control of eddy current losses.

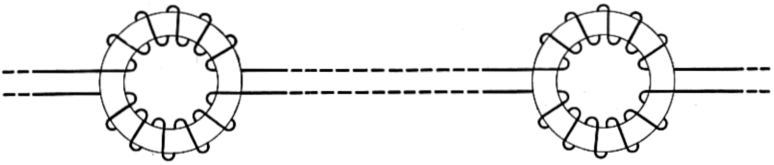

Fig. 1—Non-phantom type loading coils. Coil winding schematic and method of connection into circuit.

This coil, Code No. 501, was the first standard loading coil. It remained standard for about a decade, until a redesign became necessary to facilitate an extensive commercial exploitation of phantom working. Because of the very low-resistance design objective, it had to be a large coil. Some of its dimensional and electrical characteristics are included in Table I. In size, it was approximately 25% larger than the largest coil shown in the headpiece.

The cable loading coils listed in the table were standardized for general use during 1904, following occasional use of other types of coils having different inductances and in some instances using a different core material. These coils were generally similar in their basic design features to the open-wire loading coil, but for economic reasons were much smaller in size.(c)

(c) Core weight 3.5 lbs., 69000 turns iron wire; length 11 miles.

Also, their ratios of resistance to inductance were considerably higher. In size, these coils are typified by Coil B in the headpiece.

The 4-mil (No. 38 A.W.G.) wire used in these cable coil cores had a nominal initial permeability of 95, nearly 50% higher than that of the open-wire loading coil core-material. The differences in magnetic performance characteristics, including permeability, core losses, and certain other features subsequently discussed, resulted solely from differences in the annealing treatments during the wire-drawing process.

Additional important differences between the cable coils and the open-wire coil were: (1) the use of non-stranded conductors in the windings of the cable coils, and (2) the use of lower dielectric-strength insulation in the cable coils.

TABLE I
CHARACTERISTICS OF FIRST STANDARD LOADING COILS

Code No.	Nominal Inductance (henry)	Resistance (ohms)		Use	Over-all Dimensions (inches)	
		d.c.	1000 cycles		Diameter	Axial Height
501	0.265	2.5	5.9	Open-Wire Lines	9	4
506	0.250	6.4	22.3	Cables	4½	2¼
508	0.175	4.2	13.0	"	4½	2¼
507	0.135	3.2	9.1	"	4½	2¼

Loading Coil Cases

The open-wire loading coils were individually potted in cast-iron cases designed for mounting on pole fixtures. The coil terminals issued from the case in individual rubber-insulated leads.

The cable loading coils were assembled in multi-coil groups on wooden spindles, and potted in cast-iron cases, suitable for installation in cable manholes and on pole fixtures. Intercoil crosstalk was controlled: (1) by mounting adjacent coils so there would be approximately a minimum coupling between their (small) magnetic-leakage fields; (2) by using iron shielding-washers between adjacent coils; and (3) by placing the spindle groups of coils in individual compartments cast in the cases. The coil-terminal leads issued from the cases in a twisted-pair, lead-covered, stub cable.

Prior to potting, the coils were thoroughly dried out under vacuum, and were impregnated with moisture-proofing compound.

Loading Systems

As previously indicated, the standard practices for cable loading were established in advance of those for open-wire loading, notwithstanding an earlier commercial beginning.(d) Three different cable loading standards were adopted, to provide for a range of attenuation-reduction performance. Some data regarding these systems are given in Table II. The transmission data apply to the early types of cable having an average mutual capacitance of about 0.070 mf/mi.

The theoretical loading cut-off frequencies were approximately 2300 cycles (about 7000 loads per second). This initial standard was the result of extensive series of speech transmission tests to determine the minimum cut-off frequency that would be commercially satisfactory with respect to intelligibility. A materially higher cut-off would have increased the loading costs by requiring the loading coils to be more closely spaced.

TABLE II
FIRST STANDARD CABLE LOADING SYSTEMS
(USING COILS OF TABLE I)

Loading Designation	Coil Inductance (henry)	Coil Spacing (miles)	Nominal Impedance (ohms)	Nominal Velocity (mi/sec.)	Attenuation Loss (db/mile)		
					19 A.W.G.	16 A.W.G.	13 A.W.G.
Heavy	0.250	1.25	1800	8750	0.28	0.16	0.11
Medium	0.175	1.75	1300	12200	0.39	0.21	0.14
Light	0.135	2.5	900	17500	0.51	0.27	0.17
Non-Loaded Cable					1.05	0.74	0.59

Note: The figures given in the columns headed "nominal impedance" and "nominal velocity" apply for the nominal impedances and the nominal velocities of the hypothetical "corresponding smooth lines," having the same total inductance and total capacitance.

The first standard open-wire loading used No. 501 coils at about 8-mile spacing, giving an impedance of about 2100 ohms and a cut-off frequency close to the standard cut-off frequency for cable loading. Under dry-weather insulation conditions (5 megohm-miles or better) the attenuation losses in the 104-mil and 165-mil lines were about 0.031 and 0.014 db/mi, respectively. The corresponding losses without loading were 0.075 and 0.033 db/mi, respectively. The approximate 8-mile spacing fitted in with the open-wire transposition arrangements and gave a satisfactory attenuation-loss reduction. The earlier attempts to secure a much greater attenuation reduction had involved shorter spacings, ranging down to 2.5 miles, and were unsuccessful. At extended periods of low line-insulation caused by wet weather, these higher-impedance loading arrangements had poor transmission, sometimes worse than non-loaded lines. Excessive noise, crosstalk, and reflection losses also were unfavorable factors.

(d) N. Y.-Chicago, 165-mil open-wire line, November 1901; New York-Newark cable, August, 1902.

PREVIEW OF SUBSEQUENT DEVELOPMENTS

General Outline

For convenience in discussion and ease of understanding it has been found desirable to divide the remaining subject matter of this review into several parts, each covering a particular phase of the evolution of the loading art, as follows:

Part II—Loading for Long Distance Circuits.
III—Loading for Exchange Area Cables.
IV—Cable Loading Coil Cases.
V—Loading for Incidental Cables in Open-Wire Lines.
VI—Continuous Loading.
VII—Extent of Use and Economic Significance.
VIII—Summary and Conclusion.

Parts II, III, IV, V, and VII are wholly concerned with coil-loading.

In Parts II, III and V, specific coil loading systems and loading apparatus developments are separately considered under headings which indicate the development emphasis. In general, the individual developments are discussed in chronological sequence so as to tie closely together the interrelated systems and apparatus developments. The chronological procedure also applies in Parts IV and VI. The dates which are given and the cross references from section to section permit the reader to fit the important developments into a definite time pattern.

Although the review is primarily concerned with the evolution of loading, and its contributions to the growth of the Bell System, appropriate references are also included regarding other related advances in the telephone art which have influenced the design and performance of the loading systems and apparatus, and the extent of use.

Loading Systems

The changes in voice-frequency loading systems have been primarily for the purpose of improving the service performance, including the transmission of wider frequency-bands to improve intelligibility. The loading changes for repeatered circuits have catered to the various special problems that arose in consequence of the great increase in circuit lengths.

The loading systems for cable circuits transmitting radio broadcasting programs and those for voice-frequency and carrier-frequency impedance-matching in incidental cables that occur in open-wire lines also had their own individual requirements to meet the specific service needs.

Loading Coils

The loading coil developments substantially paralleled the loading systems developments in variety and scope. In many instances, new loading coils were developed to take advantage of the availability of (new) superior materials, improved design techniques, and fabrication methods, for cost reduction or service improvements. In other important instances, new types of loading coils were necessary to provide for new types of facilities; for example, (1) to permit the commercial exploitation of phantom working, (2) for a network of coarse-gauge, long-distance cables, (3) for facilities to transmit programs for radio broadcasting stations, and (4) for incidental cables in open-wire carrier systems.

TABLE III

LOADING COIL CORE-MATERIALS

Item No.	Type of Material	Effective[(a)] Volume Permeability	Approx. Period Commercial Mfg.	Principal Fields of Use	Bibliography References—Prior Publications
(1)	65-permeability, 4-mil, iron wire.	36	1901–1924 1911–1927	Open-Wire Lines Toll Cables	(6) & (8)
(2)	95-permeability, 4-mil, iron wire.	52	1904–1911 1904–1916	Early Toll Cables Exchange Cables	(6) & (8)
(3)	Annealed, compressed, powdered iron.	55	1916–1927 1916–1924	Exchange Cables Toll Cables	(6), (8) & (13)
(4)	Unannealed, compressed, powdered iron.	35	1918–1928 1924–1928	Toll Cables Exchange Cables	(6), (8) & (13)
(5)	Compressed, powdered permalloy.	75	1927–1937 1927–1938	Exchange Cables Toll Cables	(24)
(6)	Compressed, powdered molybdenum-permalloy.	125	1937– 1938–	Exchange Cables Toll Cables	(26)
(7)	Compressed, powdered molybdenum-permalloy.	60	1948–	15 kc Cable Program Transmission	(26)
(8)	Non-magnetic.	1	1920–	Carrier Loading Coils for Incidental Cables Open-Wire Lines	(8)

(a) Initial permeability.

Certain economic concepts have dominated the design work on the individual loading coils. In the introductory section of the review, the general need for having the loading coil resistance low relative to that of the circuit resistance was mentioned. In applying this design rule, the principle of cost-equilibrium(e) has been a basic criterion. It has resulted in the de-

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(e) This is a condition of cost-balance in which a small transmission improvement can be made by improving the coils at about the same cost as would be involved in improving the circuit in other ways—for example, by using a slightly larger size of conductor.

velopment of: (1) large-size, very low resistance coils for open-wire lines and for 10 ga. and 13 ga. long-distance toll cables, (2) smaller-size, higher-resistance coils for smaller-gauge toll cables, and (3) still smaller size of coils having still higher resistances for fine-wire exchange cables. Over the years, the progressive use of superior core-materials has made possible several successive, substantial size-reductions in the cable coils, with somewhat larger-ratio size-reductions in exchange area loading coils than in the toll cable coils, because of their less complex service-requirements and also in conformity with cost-equilibrium criteria. These progressive size-reductions are well illustrated in the headpiece.

Improved magnetic materials have been very important factors in the loading coil development work. The different magnetic materials which have been used in standard loading coils are listed in Table III with approximate dates, in terms of the beginning and end of manufacture, and other pertinent data.

PART II: LOADING FOR LONG-DISTANCE CIRCUITS

The early applications of standard open-wire loading made loaded 104-mil circuits about as good from the attenuation standpoint as non-loaded 165-mil circuits of equal length. When this loading was later applied to 165-mil circuits, the first New York-Denver loaded 165-mil line (1911) was approximately equivalent in transmission performance to the original non-loaded New York-Chicago 165-mil line (1892).

Large economies also resulted from the application of the first standard cable loading to suburban trunk cables and toll connecting trunks in exchange areas, and to interurban toll cables. Notable examples of the latter were the Boston-Worcester (1904), New York-Philadelphia (1906), and New York-New Haven (1906) cables. The toll cables used heavy loading. Considerable medium loading was used in long exchange cables.

(1) PHANTOM GROUP LOADING

This was the first major new loading development to follow the pioneering standardization work. Beginning late in 1907, it culminated in commercial applications on open-wire lines and on new quadded cables during 1910.(f)

Entirely new types of coils were developed for loading the phantom circuits. Each of its four line-windings comprised a tandem connection of an inner-section winding located on one core-quadrant and an outer-section winding located on the opposite core-quadrant, the two line windings associated with the same side circuit being distributed over the same pair

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(f) A much more comprehensive story of the phantom loading development and its relation to the development of quadded cable and to phantom working on open-wire lines is given in Bibliography items (8) and (9).

of opposite core-quadrants. The line windings were inserted in the four line wires of the phantom circuit and connected to have all of the mutual inductances aid the self inductances. In the individual side circuits the mutual inductances opposed the self inductances, and in consequence the coils contributed negligible leakage inductances to the circuits. The phantom coils were about twice as large in weight and volume as the associated side circuit coils, for cost-equilibrium reasons.

The side circuit coils were closely similar in size to the existing standard non-phantom coils. Each of their two line windings consisted of an inner-section winding on one half-core and an outer-section winding on the other half-core, and thus in effect were evenly distributed about the entire core. The close magnetic-coupling thus obtained resulted in a negligible leakage inductance to the phantom circuit in the parallel-opposing connections of line windings. The mutual inductances aided the self-inductances in the side circuits.

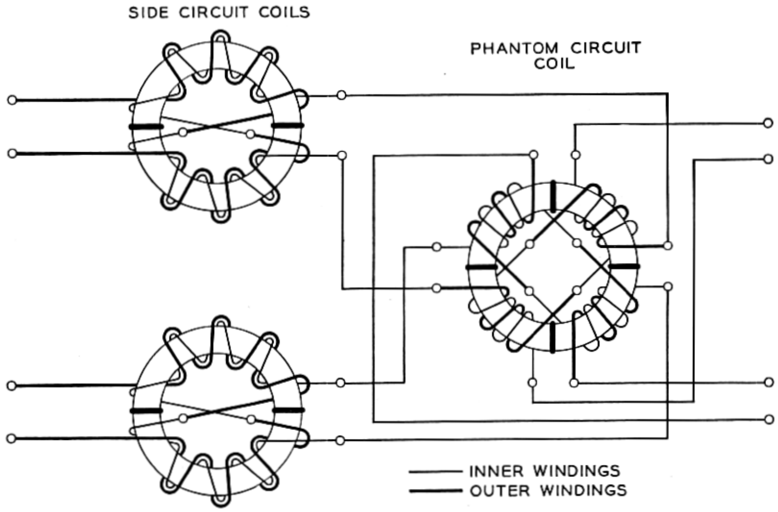

Fig. 2—Phantom group loading. Coil winding schematics and method of connection into circuit.

Figure 2 schematically illustrates the coil winding arrangements. The general design symmetry of the individual coils also included essential symmetry in the distribution of the direct admittances among the line windings and from the line windings to the core and the case. The initial designs so well satisfied the service needs that only a very few minor design refinements were subsequently required from the crosstalk standpoint. The real difficulties encountered in meeting the service crosstalk-requirements were in controlling or correcting the small accidental unbalances that were unavoidable in manufacture.

The transmission performance in loaded side circuits was about the same as that of loaded non-phantom circuits on similar-size conductors. A slight attenuation impairment resulted from the non-inductive resistance of the phantom coils.

The phantom coils were located at side circuit loading points and the phantom inductance was chosen to give a cut-off frequency of about 2300 cycles, the same as in the side circuits, and in non-phantomed circuits. In consequence, the nominal impedance of the loaded phantoms was approximately 60% of that of the associated side circuits. The attenuation was about 13% better than that of the associated side circuits of open-wire lines, and from 15 to 20% better in loaded cables, depending upon conductor size.

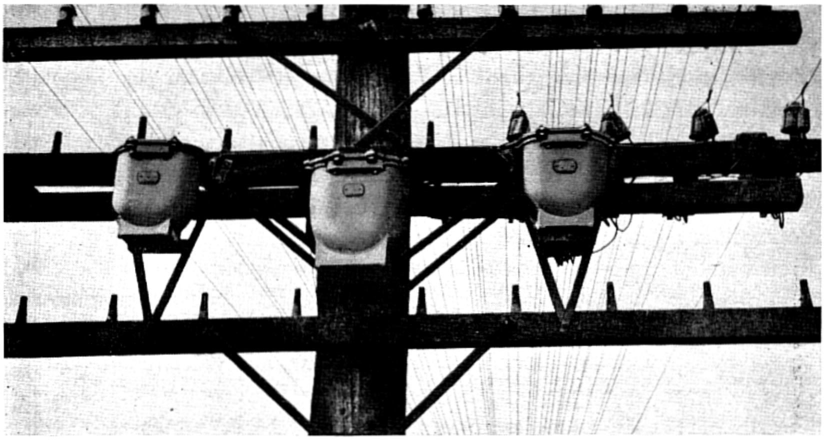

Fig. 3—An early installation of open-wire phantom group loading. Individually potted coils; phantom coil on pole; side-circuit coils on crossarms.

The great commercial importance of the phantom-group loading development is indicated by the fact that nearly two-thirds of all the voice-frequency loading coils installed on quadded toll and toll entrance cables are coils of side circuit type, and nearly one-third are phantom loading coils. Over the years during which phantom loading and quadded cable have been available, only a relatively small amount of non-phantom type loading has been used in voice-frequency toll cable facilities. Important facilities in this special category are the loaded cable program-transmission circuits subsequently described and the "order wire" maintenance circuits in coaxial cables. Also, during the 1940's, there was some occasional use of non-phantom type coils on non-quadded exchange type cables for short haul toll facilities, in place of phantom group loading on quadded toll cables.

(2) LOADED COARSE-GAUGE QUADDED TOLL CABLES

The need for extending the telephone transmission range in storm-proof toll cable, and the unavailability of telephone repeaters suitable for use on loaded circuits, led to a great activity in the development of composite coarse-gauge quadded cables and of entirely new loading coils for these cables, beginning during 1910. The first application (1911) was the new Philadelphia-Washington Section of the Boston-Washington underground cable system.(g)

The new coils for the 10 AWG sides and phantoms were generally similar in design to the open-wire loading coils, even in their use of stranded copper conductors, and were only about 20% smaller. The coils for the 13-gauge conductors were intermediate in size (approx. geometrical mean) between the coils for the 10-gauge conductors, and the coils previously developed for 19 and 16 ga. cables. The size and efficiency relations among these three series of coils were approximately in cost-equilibrium for the grades of cable involved.

In new underground sections of these coarse-gauge cables a new standard "medium-heavy" weight of loading was used, the coil spacing and inductance being midway between those for standard heavy and medium loading and having the same cut-off frequency. The new weight of loading was nearly as good in transmission performance as the heavy loading that was used in old parts of the Boston-Washington route and other routes where the loading vaults had been laid out for heavy loading, and was considerably less expensive. In the medium-heavy loaded 10-gauge circuits, the attenuation was 0.050 and 0.040 db/mi, respectively for the sides and phantoms; the corresponding values in the 13 ga. circuits were 0.069 and 0.085 db/mi, respectively. The 10 ga. loaded circuits were designed for service between Boston and New York, and between New York and Washington. On an emergency basis, the phantoms could be used for Boston-Washington service.

It is appropriate at this point to mention the substantial reduction in toll cable dielectric losses that was worked out in the period under discussion. The extensive use of loading for the first time on long 10 gauge and 13 gauge circuits greatly increased the importance of reducing the amount of moisture that unavoidably accumulated in the conductor insulation during

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(g) A more comprehensive account of this development and associated quadded cable developments is given in References (8) and (9).

the early stages of cable manufacture. This was done by refinements in the cable drying treatments.

(3) Changing Fields of Use for Iron-Wire Core Loading Coils

The new coarse-gauge cable loading coils, above referred to, marked the beginning of the use of 65-permeability iron-wire in place of 95-permeability wire in the cores of standard cable loading coils.

In every respect except permeability, the 65-permeability wire was superior to the higher permeability wire. The lower permeability was relatively disadvantageous as regards d-c resistance per unit inductance in coils of a given size. On the other hand, the core-loss resistance was substantially smaller, by virtue of the lower permeability and the superior hysteresis characteristics. In consequence, the total effective resistance of the 65-permeability core coils was lower at the upper speech-frequencies and nearly the same at the important middle frequencies, so that there was considerably less attenuation-frequency distortion.

Other even more important service advantages of the 65-permeability core toll cable loading coils resulted from their much greater magnetic stability. D-c signaling currents caused smaller temporary changes in inductance and effective resistance, in consequence of the superimposed d-c magnetization. Also, the residual effects of strong superimposed currents, manifested as permanent or semipermanent changes in inductance and effective resistance, were much smaller.

A specially valuable advantage of the 65-permeability wire core-material was in the substantially smaller amount of telephone transmission distortion caused by the operation of superposed composite telegraph systems.[10] The transient core-magnetization caused by the telegraph currents caused small transient changes in the inductances of the coils, and relatively very large transient changes in the effective resistances. The resulting non-linear distortion became known as "telegraph flutter." It varied as a function of telephone frequency and telegraph speed, the size of the core, the inductance of the windings, and the ratio of the amplitudes of the telephone and telegraph currents. It was accumulative in effect as the circuit lengths increased. Since simultaneous telephony and telegraphy was very general and was important from the revenue standpoint in the open-wire and cable long-distance facilities, the control of "telegraph flutter" became an increasingly important requirement in the development of new loading coils.

(The need for satisfactory control of "telegraph flutter" eventually led to the development of the improved cable telegraph systems which are described in Section 8 of this review.)

By 1912, the use of 95-permeability core-material in new toll cable coils had stopped. However, since exchange area circuits and suburban trunk cables were seldom used for composite telegraph working, the use of 95-permeability iron-wire continued standard until 1916, when compressed, powdered-iron, core coils became available.

(4) LOADED REPEATERED OPEN-WIRE LINES

The pioneering phases of the development of better lines and better loading coils for use on repeatered long-distance facilities had their first commercial application in the transcontinental open-wire circuits between New York and San Francisco, January 1915. The adaptation of the lines to the requirements of repeater operation was secondary in importance only to the development of satisfactory repeater elements, and of circuits for associating the repeater elements with the line. A comprehensive account of all phases of the very important transcontinental telephony-development project has been published in an article, "The Conquest of Distance by Wire Telephony."[9] Accordingly, the account in the present review is limited to the loading for the line. Comprehensive information regarding telephone repeaters is given in a 1919 paper by B. Gherardi and F. B. Jewett.[11]

Since the lines were used for two-way transmission, a high degree of impedance balance between the line and the repeater balancing-network circuit was necessary in order to obtain satisfactory repeater gains. This problem involved the construction of lines having a new order of regularity and stability in their impedance characteristics over the working frequency-band, to make feasible the design of simple types of balancing networks[12] for adequate simulation of the line impedances.

The requirements just stated involved a much greater degree of uniformity in the loading coil spacing than was necessary in non-repeatered circuits, and a corresponding reduction in the coil inductance deviations. This latter requirement meant that the new coils must have a much greater resistance to the magnetizing effects of superposed steady and transient line-currents, especially since exposure to lightning surges had to be accepted as a normal service experience.

The new requirement for high magnetic stability in the loading coils was met by using short air-gaps at diametrically opposite points in their toroidal-type 65-permeability iron-wire cores. This construction feature also resulted in a substantial reduction in (but not the elimination of) telephone transmission distortion caused by "telegraph flutter" phenomena, when composite telegraph circuits were superposed on the loaded circuits. The new side circuit and phantom circuit loading coils were coded 550 and 549, respectively. They were a little smaller than the coils which they superseded, and had somewhat higher resistances. The resulting attenuation impairments, however, were negligible in the repeatered circuits. The headpiece includes a 550 coil (the largest coil, designated A).

During the decade that followed the beginning of transcontinental telephony, a large enough quantity of Nos. 549 and 550 coils were installed to load approximately 300,000 circuit miles. In the beginning, the improved loading was concentrated on parts of a proposed backbone-network of repeatered 165-mil lines. Soon it became apparent from: (a) the continuing development work on telephone repeaters, repeater circuits and auxiliary apparatus and transmission networks, and from (b) field experiments supplemented by theoretical cost studies, that non-loaded 165-mil lines with additional repeaters would have much more satisfactory transmission characteristics than repeatered loaded lines, and would be less expensive. The principal transmission advantages were: (1) the practicability of securing materially lower net losses, in consequence of the effect of the higher velocity of transmission in reducing echo-current disturbances, (2) more uniform attenuation and impedance characteristics under varying weather condi-

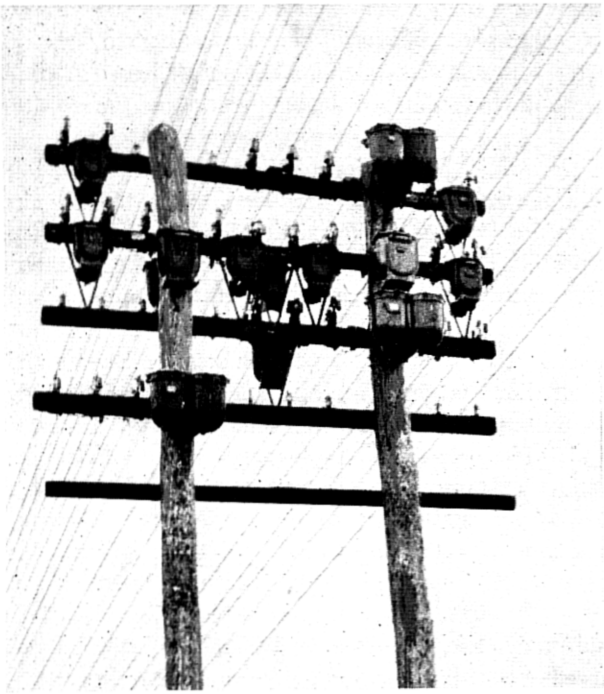

Fig. 4—Typical installation of high stability open-wire loading coils. Note the three phantom loading unit combinations in 3-coil cases supported on the poles; other individually potted side-circuit and phantom coils are supported on the crossarms.

tions, (3) reduced delay-distortion because of the more uniform velocity-frequency characteristics at the upper speech frequencies, (4) complete elimination of telegraph-flutter impairments, and (5) better quality of speech transmission by the effective transmission of a much wider frequency-band. In this latter connection, it is of interest that the transmission band which was effectively transmitted over the loaded, repeatered, transcontinental circuits ranged from about 350 to 1250 cycles, defining the band as that between the lowest and highest frequencies whose transmission was not more than 10 db higher than that of the 1000-cycle transmission. At the higher frequencies, the line losses and the loading coil losses piled up so as to effectively suppress transmission. The excess losses at the low voice-frequencies were due to the line terminal apparatus and the repeater auxiliary apparatus.

The rapidly growing appreciation of these advantages led initially to a curtailment in the installation of new loading on 165-mil circuits, and subsequently to the removal of the existing loading and the installation of additional repeaters.(h) By this time, the vacuum-tube repeater had been accepted in its own right as an independent instrumentality for improving transmission.

On 104-mil lines, the economic competition between loading and repeaters was much closer than that on 165-mil line, and for a period of several years the aggregate mileage of loaded 104-mil lines increased substantially while the mileage of loaded 165-mil lines decreased at an accelerating rate. In this connection the transmission disadvantages of loading on repeatered 104-mil lines were not so serious as those on repeatered 165-mil lines, partly because of the much shorter lengths involved and partly because of their more stable transmission performance under varying weather conditions.

During the early 1920's, the commercial exploitation of open-wire carrier telephone and carrier telegraph systems became an increasingly important factor in the removal of loading from open-wire lines.

About 1924, the practice of installing new loading on 104-mil lines was stopped in order to increase the plant flexibility for the more extensive use of repeaters and of carrier systems, and accordingly the production of new open-wire loading coils was discontinued. The removal of the existing loading, however, was not completed until about 1934.

(5) HIGH STABILITY TYPE COILS FOR COARSE-GAUGE TOLL CABLES

The use of improved telephone repeaters started on a small-scale basis on loaded coarse-gauge circuits along the Boston-Washington route even

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(h) The unloading of the original transcontinental circuits was completed early in 1920. The net loss was reduced from about 20 db to 11 db, and the width of the effective transmission band was doubled.

before the loaded, repeatered transcontinental open-wire circuits were ready for service. To permit more satisfactory repeater operation in the remaining loading complements of these cables, and in many more coarse-gauge toll cables which were installed during the next few years, a series of high-stability type of loading coils was standardized during 1916.(i) The coils in this series used air-gaps in their 65-permeability, iron-wire cores. Since the availability of satisfactory types of telephone repeaters had reduced the need for 10-gauge conductors, the new coils were "compromise" designs, suitable for either 10 ga. or 13 ga. conductors. Accordingly they were intermediate in size between the two different series of coarse-gauge cable coils that were developed in the 1911–1913 period.

These new loading coils remained standard for toll cable uses for only a few years. The practice of installing 10 ga. and 13 ga. toll cables substantially stopped before 1920, because theoretical studies of the possibilities of improving repeaters and loading systems were indicating that it should ultimately be possible to use repeatered, loaded 19-gauge or 16-gauge conductors for spanning the longest distances likely to be involved in the long-distance cable plant. The use of 4-wire repeatered facilities became a very important objective in the new development plans, making necessary an intensive development of transmission equalizing and regulating networks and practices.

(6) COMPRESSED POWDERED-IRON CORE LOADING COILS FOR REPEATERED AND NON-REPEATERED 19 AND 16-GAUGE TOLL CABLES

6.1 *Compressed Powdered-Iron Core-Material*

General

This was the first new loading coil core-material to be developed since the establishment of the first loading standards. Many other possibilities had been considered on a number of occasions, notably silicon steel in fine-wire form, but no core-material had been discovered that was superior to the 65-permeability iron-wire in its major performance characteristics.

The compressed powdered-iron development was the pioneering beginning of an entirely new and very important art in the design of high-stability, low-loss, magnetic core-materials. It was started by the Engineering Dept. of the Western Electric Co. as an independent project, alongside the basic research work on various phases of transcontinental telephony, and reached the first stage of commercial fruition during 1916. An important objective was to obtain much better magnetic stability than that of iron-wire cores, and at a lower cost than that of wire cores having series air-gaps. Also, from

(i) Additional information regarding this development is given in References (8) and (9).

the manufacturing standpoint it was desirable to have a better control of the magnetic properties of loading coil core material, and to be free from limitations on quantity such as were occasionally experienced in obtaining iron core wire from outside manufacturers. These particular difficulties were very serious during the First World War in consequence of the greatly increased demand for loading coils and the impossibility of securing an adequate supply of diamond dies for drawing the 4-mil core wire. (In normal times, all dies were imported from Europe.) Incidentally, the supply limitations on diamond dies made it necessary to permit the use of over-size core wire even though this resulted in an impairment in transmission performance due to the abnormal (eddy current) core losses. Fortunately, the compressed powdered-iron core material became commercially available in time to be of great value in helping the Western Electric Co. to increase the output of loading coils.[j]

The success achieved in this development subsequently led to the application of the compressed, insulated, magnetic-powder technology to magnetic alloys, for use in the cores of loading coils and of other types of coils used in various types of transmission networks, including electric wave filters. Initially worked out for voice frequency applications, the new technology expanded to become an important factor in the design economy of carrier and radio transmission systems. The low eddy current losses made possible in large part by the use of very small, insulated, magnetic particles, were inherently important elements in the high frequency applications. Following its development in the United States, the compressed, magnetic powder core, in one form or another, spread to Europe, and became important in world wide communications.

The prior art is of historical interest, in that experiments with finely divided magnetic particles had extended over a period of several decades. As an early example, Oliver Heaviside described in his "Electrical Papers" some work on magnet cores with magnetic powder embedded in wax. It is also of interest that during the Bell System pioneering efforts to obtain satisfactory loading coil cores, considerable experimental work was done (1901) on magnetic oxide cores involving high temperature heat treatments of loosely formed iron wire or iron tape core structures in an oxygen atmosphere. (U. S. Patents Nos. 705,935, and 705,936, July 29, 1902.)

[j] The total output, however, could not be increased sufficiently fast to meet the high 1917–1918 demand for loaded facilities. This resulted in a temporary practice of what came to be known as "omitted-coil loading" on a substantial mileage of toll cable facilities. In the initial installation of loading on these particular facilities, the coils were placed at alternate load points along the line;—for example, at 12,000 ft. spacing instead of the standard 6,000 ft. spacing. The resulting transmission impairments were accepted as being tolerable under war emergency conditions. As soon as practicable, however, the "omitted loads" were "filled in," so that shortly after the end of the war the coil spacing conformed to the established standard practices.

None of the early work by these and other investigators, however, had resulted in commercially usable iron powder cores. It was not until the Western Electric concept of pressures sufficient to deform the magnetic particles, and of an insulating medium of such character as to withstand these high pressures and provide an exceedingly thin insulating film between particles, was developed, that commercially usable results were obtained.

The Western Electric compressed powdered-iron development was carried out in two distinct steps, one after the other, using the same basic magnetic material. In the early work, consideration was given to the use of chemically produced iron powder. Then, mainly for cost reasons, the development efforts were concentrated upon the use of electrolytically deposited iron which was processed so that it could easily be ground into particle sizes of the required fineness. The iron particles were thoroughly mixed with suitable insulating material and then moulded into thin core rings of desired over-all dimensions under moulding pressures of about 100 tons per square inch. These core rings were stacked vertically and bound with insulating tape for use as loading coil cores.

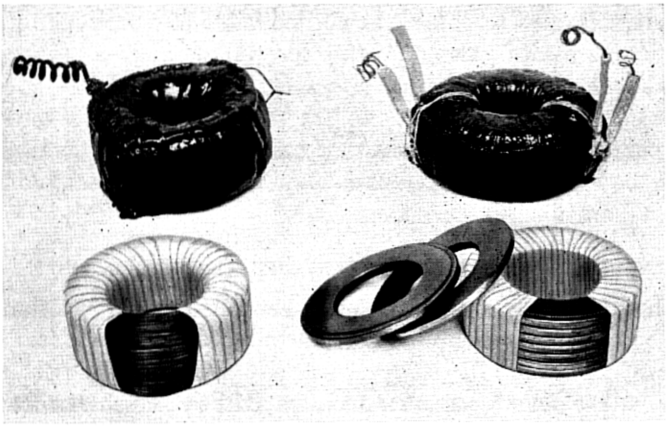

Fig. 5—Early cable loading coils and their cores. At left: Iron wire core coil; core has insulating-binding tape partly removed to show core construction. At right: Compressed iron powder core coil; 7-ring core has binding tape partly removed. Also 2 individual core rings.

In the first commercially usable product, the iron-powder was annealed prior to the insulating and ring-moulding operations. When a higher-grade loading coil core material became necessary for reasons subsequently discussed, the iron-powder annealing process was omitted and a larger amount of insulation was mixed with the magnetic material, which changes resulted in a substantial reduction of effective permeability. Other process differences were also involved. These two magnetically different, compressed loading coil core-materials were sometimes known as "soft-iron dust" and "hard-iron dust" or as "compressed annealed iron-powder" and "compressed unannealed iron-powder," respectively. In the Speed-Elmen classic paper[13] on "Magnetic Properties of Compressed Powdered Iron," these two materials are referred to as "Grade A" and "Grade B", respectively. A still lower permeability core material, known as "Grade C", was developed primarily for use in carrier frequency inductance coils. In this material, a larger amount of particle insulation than that in the "A" and "B" grades was used, and the average size of particle was smaller.

In commercial production the "Grade B" cores consisted of a mixture of 90% unannealed powder and 10% annealed powder, the latter component being included to obtain the desired value of permeability, and to increase the mechanical strength of the core rings.

The different magnetic characteristics of the "A" and "B" grades of compressed, powdered iron were basic factors in the evolution of the loading practices for the new loading coils that used them in their cores. A brief review of these practice differences follows, and includes some additional general data regarding the coils themselves.(k)

6.2 *Compressed, Annealed, Powdered-Iron Core Loading Coils*

Referring to Table III, it will be noted that cores using this new material had nearly the same effective volume-permeability as the cores of 95-permeability iron-wire. By using similar-size cores, and closely similar windings, it was found possible to obtain effective resistance-frequency characteristics close to those of the standard small-gauge cable loading coils using 95-permeability wire cores, as typified in the 508 coils of Table I, and corresponding grades of side circuit and phantom loading coils. Also the new potting developments were minimized.

An outstanding service advantage of the new "soft-iron dust" core loading coils was in their very high stability of residual inductance, by virtue of the self-demagnetizing action of the very large number of very small series air-gaps in the cores. After a temporary exposure to magnetization by abnormally large superimposed currents that might be caused by accidental grounds on superposed d-c signaling circuits or by induction from outside sources (lightning, power-line shorts or grounds), the coil inductance would return to within a few per cent of the initial value. On the other hand, after extreme exposure to strong magnetic shocks the residual inductance in the 95-permeability wire-core coils might be as much as 40% below the initial inductance, the high retentivity of the magnetic circuit being an important factor in this performance.

(k) Some additional detailed data regarding these two series of loading coils were published in Reference (8).

The new coils also were considerably better than the 95-permeability wire-core coils in the following important features:

(a) Their susceptibility to changes in inductance and effective resistance during service intervals involving the superposition of steady d-c signaling currents;

(b) Their susceptibility to the transient magnetizing effects of superposed composite-telegraph currents, i.e., "telegraph flutter".

The relative performance characteristics, above described, resulted in the "soft-iron dust" core coils superseding the standard 95-permeability wire-core coils in the fields of use in which these older standard coils had been used. As an important example, the original standard 508 coil, used principally for medium loading in exchange cables, was superseded in 1916 by the 574 coil, which remained standard for about a decade.

The telegraph-flutter characteristics, Item (b) above, prevented the new coils from being used generally in place of 65-permeability wire-core coils on toll cables quads having all four wires composited for grounded telegraph operation. However, for a few years there was a "compromise" practice of combining "soft-iron dust" side circuit loading coils with 65-permeability wire-core phantom loading coils in 19 and 16-gauge toll cable projects where the needs for superposed grounded-telegraph operation could be satisfied by compositing the phantoms, and the demands for repeatered facilities could be met by limiting repeater operation to the side circuits. In this special loading setup, the transmission distortion by "telegraph flutter" was controlled in the phantoms, and was completely avoided in the side circuits because the grounded telegraph currents, flowing in parallel through the side circuit coil windings, neutralized each other's effect in magnetizing the cores. With respect to regularity in circuit impedance-frequency characteristics in relation to repeater gains, the high residual-inductance stability of the soft-iron dust-core loading coils made them distinctly preferable to the 65-permeability wire-core coils in the repeatered side circuits.

During 1917–1918, when the subsequently described work on improved loading systems for long repeatered toll cables got well under way, theoretical studies of the use of soft-iron dust core loading coils on such facilities disclosed seriously objectionable non-linear transmission distortion that had not been bothersome on short circuits. This was due to the relatively large hysteresis losses in the loading coil cores, which cause the effective resistances of the coils and the circuit attenuation loss to increase appreciably in magnitude as a function of line current amplitude. The effects of these losses are much more serious in the repeatered circuits, because of the larger line currents, and because of the much greater circuit lengths. Since the hysteresis losses also vary in direct proportion to the telephone frequency, the resultant coil-resistance increments and attenuation increments are greater at the high-speech-frequencies than at low frequencies.

As none of the other energy losses in the core or winding vary with line current strength, it became convenient to consider the attenuation loss caused by hysteresis as an "excess" loss, when referred to the attenuation that would result if the hysteresis should be vanishingly small or zero. The theoretical studies above mentioned not only showed the "excess" attenuation in long loaded, repeatered, circuits to vary as a function of the magnitude of the input current and frequency, as above noted, but also showed it to vary as a function of the length of repeater section, the position of the repeaters in the line, the weight of loading, and the over-all circuit length. Since it is not possible to offset the effects of loading coil hysteresis by means of distortion corrective or equalizing networks at repeater stations or circuit terminals, the piling up of the "excess" losses along the line in very long loaded, repeatered, circuits could reach values that would be large relative to the desired over-all working equivalent, if the individual loading coils should have large hysteresis losses, as did the soft-iron dust-core loading coils.

Comparative theoretical studies of the excess loss due to hysteresis effects in 65-permeability core loading coils showed these coils to be greatly superior to the soft-iron dust-core coils in this feature. On the other hand, the wire-core coils were relatively unsatisfactory from the inductance-stability standpoint for use on long repeatered circuits.

6.3 *Compressed, Unannealed, Powdered-Iron Core Loading Coils*

It was very fortunate that the development work on the compressed, unannealed, powdered-iron core-material, previously mentioned, approached commercial fruition at about the time the unsuitability of the soft-iron dust-core loading coils for very long repeatered circuits became apparent.

As noted in Table III, the effective volume permeability of this improved core-material was closely that of the 65-permeability wire-cores. The new standard loading coils using this improved material had cores generally similar in dimensions to those of the older coils used on 19 and 16 ga. toll cables, and their over-all dimensions were sufficiently similar to avoid the need for developing new loading coil cases.

In general terms, the new coils combined the best qualities of the soft-iron dust-core loading coils with the best performance characteristics of the 65-permeability wire-core loading coils. Actually, they were much better than the soft iron-dust core coils with respect to stability of residual inductance, and susceptibility to magnetization by superposed steady currents. In these respects they were also substantially superior to the 65-permeability wire-core loading coils. However, they were not quite so good as the low permeability wire-core coils with respect to hysteresis losses and telegraph flutter transmission impairments. On the other hand, they were substantially as good in their effective resistance-frequency characteristics. The above summarized advantageous electrical and magnetic properties resulted during 1918 in the standardization of the new compressed, annealed, powdered-iron core loading coils for general toll cable use in place of the 65-permeability wire-core coils and soft-iron dust-core coils. The availability of the improved loading coils quickly stopped the previously mentioned temporary, compromise practice of using soft-iron dust side circuit loading coils in combination with 65-permeability wire-core phantom loading coils.

After the hard-iron dust-core loading coils became commercially available, the remaining development work on improved toll cable loading systems described in the following pages was in terms of these coils.

(7) NEW LOADING SYSTEMS FOR REPEATERED 19 AND 16 GA. TOLL CABLES

7.1 *General*

The basic problems of learning how to use telephone repeaters most advantageously on long cable circuits began to receive serious attention soon after the completion of the open-wire transcontinental telephony project, along with the repeater development work that ultimately resulted in the obsolescence of open-wire loading, as previously mentioned. During the decade or more of intensive, continuous development activity on the repeatered toll cable problem that followed, it was found highly advantageous to work loading and repeaters together as equal partners in a team, each making its contribution according to its own nature. The important contributions of loading were the substantial reductions of attenuation and of frequency distortion at a cost (for voice-frequency transmission) much lower than the cost of the additional repeaters and the distortion corrective-networks which would have been required on non-loaded cables. Incidentally, the use of loading substantially simplified the solution of the important equalization and regulation problems.

The attainment of the good working partnership between loading and repeaters involved the development of new loading systems having substantially improved transmission characteristics, and the development of improved repeaters and improvements in repeatered circuits, including equalizing networks and arrangements for controlling the cable transmission-performance changes that result from seasonal and daily changes in temperature. A classic report on these related developments is given in a paper[14] by A. B. Clark, entitled, "Telephone Transmission over Long Cable Circuits."(1) The present discussion is primarily concerned with the features of the improved loading that were essential to satisfactory transmission-performance in long repeatered cable circuits.

(1) Reference (15) is also of interest with respect to engineering aspects.

The compressed, unannealed, powdered iron-core loading coils previously described were found to be satisfactory with respect to inductance stability and other properties, including hysteresis effects for use in the improved loading systems. New smaller inductance values were necessary, however, for the coils used in the longest circuits. It was of course necessary to control the geographical spacing deviations, and the factory deviations in cable capacitance and in the loading coil inductances, so as to obtain a satisfactory degree of "regularity" in the impedance characteristics of the loaded circuits.

7.2 *Transmission Limitations of Existing Loading Systems*

(a) *General:* As the lengths of loaded cables progressively increased beyond those involved in the establishment of the first standard loading systems, certain transmission effects which were initially unnoticed or comparatively unimportant became very noticeable as objectionable transmission impairments. By increasing the electrical lengths of the circuits, the use of repeaters greatly aggravated these impairments and it became very desirable to correct them so far as feasible at their source. Complex problems thus arose in providing better quality of transmission over much greater distances.

The impairments referred to above were directly related to the band width of frequency transmitted by the line, which is determined by the cut-off frequency, and to the velocity of transmission. They are discussed briefly in the following paragraphs.

(b) *Attenuation-Frequency Distortion:* At frequencies above about 70% of the theoretical cut-off frequency, the attenuation increases with rising frequency at a continuously accelerating rate, in consequence of the accumulation of the effects of internal reflections at the individual loading points.

At lower frequencies where these so-called "lumpiness of loading" effects are not of dominating consequence, the attenuation increases with rising frequency are largely due to the energy losses in the loading coils. (Usually the eddy-current losses in the cores are the most important component loss, since they are proportional to the square of the frequency.) It thus happens that the attenuation losses may pile up in long loaded cables in such a way as to substantially suppress the transmission of the higher-frequency components of speech, even when the attenuation losses are tolerable at lower frequencies. In consequence, the width of the transmission band which is effectively transmitted over a long loaded cable becomes narrower and the quality of transmission progressively deteriorates as the circuit length increases, unless suitable auxiliary equalizing networks and additional repeaters are utilized. The large amount of attenuation-frequency distortion which occurred in the first transcontinental telephone circuits was previously commented upon.

The attenuation-frequency distortion in long loaded cables can be reduced by raising the theoretical cut-off frequency. As a secondary factor, the reduction of core losses in the loading coils is advantageous.

(c) *Velocity Distortion:* This became noticeable as peculiarly disturbing, transient distortion in the intervals when spoken syllables were building up or dying down, prior to, or after, their steady-state transmission. It is most disturbing at the upper speech-frequencies where the steady-stage velocity of wave propagation varies at an accelerating rate as the cut-off frequency is approached. It can be particularly disturbing in very long circuits where repeaters are used to reduce the over-all loss, and in extreme cases it could make the circuits unusable for commercial service. These transient distortion impairments may be reduced by raising the loading cut-off frequency, and by increasing the velocity of wave propagation. The loading design changes that were made in these features gave a satisfactory control of the velocity distortion in the longest loaded cables used commercially, without requiring the use of velocity-distortion corrective networks in the lines or at repeater stations.

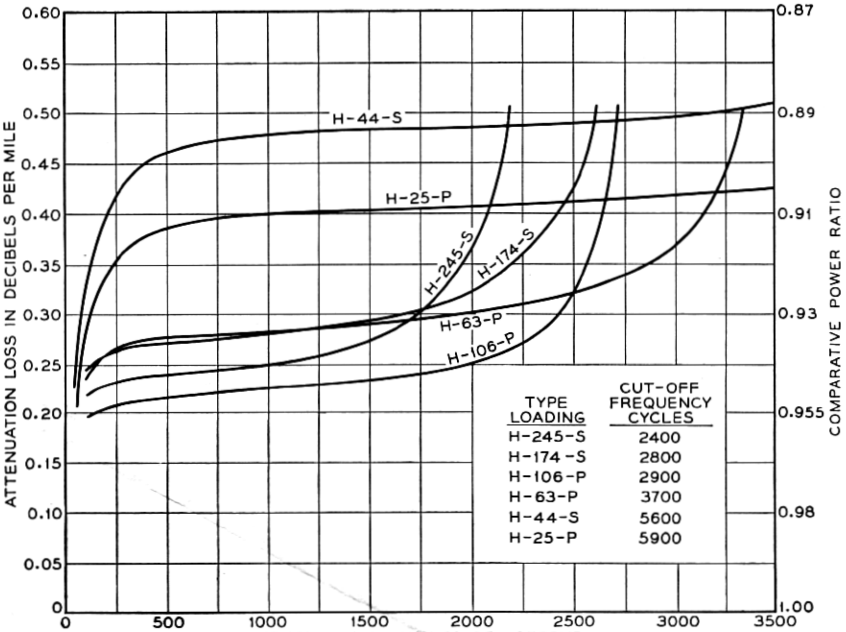

Fig. 6—Attenuation frequency characteristics toll cable loading.

(d) *Echoes:* Echo effects also were found to be potentially limiting factors in providing satisfactory transmission-performance over long loaded cable circuits. They are due to the transmission of reflected energy from points of impedance irregularity. They are troublesome factors whenever the time of transmission between the point of reflection and the disturbed subscriber is appreciable, especially when the use of repeaters prevents the attenuation of the reflected energy from being negligible in magnitude. Increasing the velocity of wave propagation is a sure procedure for reducing echo effects. Control of the impedance irregularities which cause them is also important, but cannot be carried to a sufficiently fine degree in long, low-velocity circuits. For the satisfactory control of echo effects in very long, four-wire type, high-velocity, (H44-25) loaded circuits, the use of auxiliary devices known as "echo suppressors" was found to be very advantageous.[16]

(e) *Basic Networks and Filters:* The previously mentioned basic networks[12] which simulate the impedances of the loaded circuits are vitally necessary features of the balancing lines that are used with the repeaters employed on two-way speech circuits. Relatively simple types of networks provide satisfactory impedance simulation up to a high fraction of the cut-off frequency, in loaded circuits having regular coil spacing and uniform coil inductances. At frequencies near the loading cut-off, however, it is not feasible to provide basic networks which satisfactorily simulate the impedances of the loaded circuits. Consequently, in order to avoid large repeater unbalances which would cause objectionable singing at these frequencies, it is necessary to associate with the repeaters low-pass type electric wave filters[17] which have cut-off frequencies appreciably lower than the loading cut-off frequencies. Usually this cut-off frequency differential is of the order of 10% or more of the loading cut-off. The reduction of transmitted band width caused by these filters aggravates the frequency attenuation distortion effects previously discussed. This use of filters with the repeaters thus became a contributory factor in the need for raising the loading cut-off frequency in long repeatered circuits.

By reducing the transmitted frequency band width, however, the filters used with the repeaters have favorable effects in reducing the high-frequency velocity distortion caused by the loading. The filters used with the repeaters on long H44-25 circuits, subsequently described, had cut-off frequencies substantially below the loading cut-off frequencies primarily for the purpose of controlling velocity distortion impairments.

7.3 *Improved Loading Systems*

(a) *General:* To sum up the foregoing, the theoretical analyses of the limitations of the standard toll cable loading pointed definitely towards an increase in cut-off frequency and in the velocity of wave propagation. Since the state of the art was such that theoretical studies[14, 18] alone could not determine the magnitudes of the changes that would be required, extensive investigations of experimental installations also became necessary. For cost reasons, it seemed desirable that the improved loading should be used at standard "heavy loading" spacing, i.e., 6000 ft. In consequence, the increase in cut-off was proportional to the increase in velocity. Also, there was a proportional reduction in the nominal impedance, accompanied by an increase in the unit-length attenuation.

TABLE IV

LOADING SYSTEMS—SMALL GAUGE REPEATERED TOLL CABLES

Item No.	Loading (a) System	Circuit	Coil (b) Code No.	Nominal Impedance (ohms)	Theoretical Cut-off Frequency (cycles)	Nominal Velocity (mi/sec.)	Attenuation Loss (c) (db/mile at 1000 Cycles)		Maximum (d) Geographical Length (miles)
							19 A.W.G.	16 A.W.G.	
(1)	H174-106	Side	584	1550	2800	10000	0.28	0.16	500
(2)	"	Phantom	583	950	2900	10000	0.22	0.13	500
(3)	H44-25	Side	590	800	5600	19000	0.48	0.25	2000
(4)	"	Phantom	589	450	5900	20000	0.40	0.21	2000
(5)	H174-63	Side	584	1550	2800	10000	0.28	0.16	500
(6)	"	Phantom	587	750	3700	13000	0.28	0.16	1500
(7)	H245-155	Side	582	1850	2400	8000	0.25	0.16	250
(8)	"	Phantom	581	1150	2400	8000	0.20	0.12	250

Notes: (a) Nominal coil spacing is 6000 feet in cable having a capacitance of 0.062 mf/mile in the side circuits and 0.100 mf/mile in the phantom circuits.

(b) The code numbers of the first standard compressed, unannealed, powdered-iron core coils used in the loading systems.

(c) These attenuation values apply at 55°F. Under extreme high or low temperature conditions, the actual attenuation may be approximately 12 per cent larger or smaller, due principally to changes in conductor resistance with temperature. In long repeatered cable circuits these variations of attenuation with temperature require special corrective treatment by means of automatic transmission regulators.

(d) These particular length-limitations were set by velocity-distortion effects. By using velocity-distortion corrective networks in the lines or at repeater stations, it would have been possible to extend the circuit lengths beyond the listed limits, provided also that adequate steps could be taken to control echo currents. Under actual service conditions, however, echo currents might limit the circuit lengths to considerably lower values than those listed above, depending upon the grade of balance of the lines and the permissible overall loss.

The transmission development work resulted in the standardization of two new phantom-group loading systems, designated H174-106 and H44-25(m) in Table IV. Several years later (1923), a new H63 phantom

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(m) The letter-number loading designations used in Table IV, and in the remainder of the text, were simplifications adopted for general use in 1923. The letter prefix symbolizes the geographical spacing in feet; the numbers correspond to the nominal inductances (in millihenrys) of the associated side circuit and phantom loading coils, in the sequence noted. The letter "H" designates "Heavy" loading spacing. In the early days this was about 1.25 miles; later it became 6000 ft.

loading was substituted for H106 phantom loading, to provide H174-63 phantom-group loading as a successor standard for H174-106 loading.

(b) *H174-106 Loading:* The development work on H174-106 loading preceded that on the H44-25 system. By using available standard "medium" loading coils at standard "heavy" spacing, the transmission velocity and the cut-off frequency were raised to values about 20% higher than those of the H245-155 loading which had been, by far, the most widely used loading on 19 and 16 gauge toll cables. The new combination of inductances and spacings became widely known in the early installations as "medium-heavy, high cut-off" loading. This designation called attention to the first change in standard loading cut-off frequency since the establishment of the initial loading standards in 1904.

When used in conjunction with improved repeaters, the H174-106 loading enabled satisfactory transmission to be obtained over circuits about twice the length of the longest H245-155 repeatered circuits which were satisfactory from the transmission standpoint. In the beginning, H174-106 loading was extensively used on 4-wire repeatered circuits. After the new transmission systems using H44-25 loading came into general use, H174-106 (and H174-63) loading was largely restricted to short haul two-wire circuits.

The 1917 trial installation tests showed H174-106 loading to be a substantial step forward in the struggle to extend the transmission range in repeatered 19 and 16-gauge toll cables, but far from a big enough step to satisfy the transmission requirements in very long cables such as the New York-Chicago cable project which had been accepted as a definite development objective. The continuing studies which considered other combinations of lower inductances and of standard and new spacings ended in the decision to standardize H44-25 toll cable loading.

(c) *H44-25 Loading:* Although these inductance values had been used for impedance matching loading on entrance cables, they had not previously been used on toll cables. The initial designation for the improved loading was "extra-light, very high cut-off " loading. The cut-off frequency and transmission velocity were about twice as high as those in H174-106 loading, and the nominal impedance was 50% lower.

H44-25 was necessary for the longest repeatered circuits. It was developed primarily for use on 19-gauge 4-wire circuits in which large repeater gains could be obtained by the repeaters in the one-way paths, to offset the relatively high bare-line attenuation. The first installation of H44-25 loading was made during 1919 on circuits in the New York-Philadelphia-Reading Cable. Trial service of a complete four-wire system, including new regulating and equalizing arrangements, and an echo suppressor, started during 1923. In October 1925, commercial service between New York and Chicago started over a H-44-25 four-wire repeatered system.

It had taken a long time to work out the necessary improvements in the repeaters and their associated distortion-corrective networks, and to learn how to use regulating repeaters to control satisfactorily the very large transmission changes that resulted from temperature variations in long circuits.

During the mid 1920's aerial cable came into use extensively along new cross-country routes where underground cable conduits would have been unduly expensive. Such cables, however, presented added difficulties and expense in transmission regulation since the temperature range variations are about three times as great as in underground cable. During 1930 the use of buried cables started. With respect to transmission regulation and service continuity, they compare well with cables in underground conduit and are less expensive, when the number of cables along the route is small. However, buried toll cable generally tends to be more expensive than aerial cable. At the end of 1949 the aggregate wire mileage in buried toll cables was nearly one-third of that in aerial toll cables.

A substantial amount of H44-25 loading was also used on 16-gauge 2-wire repeatered facilities, for circuit lengths intermediate between the transmission limits of H174-106 and H174-63 loading and lengths where echo-impairment difficulties made necessary the use of 19-gauge 4-wire facilities. In such two-wire circuits, very good line-balance was of course required at the intermediate repeaters. An important economic factor in this "medium" long-haul practice was the 50% lower loading cost per unit of facility length of the two-wire circuits. This intermediate-length usage of 16-gauge 2-wire circuits, however, tapered off in the long-distance plant of the A.T.&T.Co. during the late 1920's, so as to obtain the important plant flexibility and operating advantages that were inherent in the general use of 19-gauge 4-wire circuits for medium-haul and long-haul toll cable facilities.

Notwithstanding the 2:1 ratio in loading cut-off frequencies, the width of the frequency-band transmitted over long H44-25 circuits was not much wider than that transmitted over the much shorter H174-106 facilities. This was largely due to the filters which were used to suppress the upper half of the H44-25 transmission band, primarily for the purpose of reducing the very serious velocity-distortion transmission impairments that would have otherwise resulted in very long circuits. This suppression of the higher frequencies also eased the transmission equalization and regulation problems.

The attenuation-frequency distortion characteristics of the old and new toll cable loading are shown in Figs. 6 and 7.

Figure 6 (p. 175) shows the attenuation in db per mile. Figure 7 (p. 180) gives the bareline attenuation-frequency curves under specified circuit length and repeater conditions in which the total 1000-cycle attenuation is 10 db. The effect on frequency distortion of raising the loading cut-off frequency, and of using distortion corrective-networks, is clearly indicated.

(d) *H174-63 Loading:* Before concluding this summary of the basic development work on improved loading for long repeatered circuits, it is opportune to include some detailed information on the previously mentioned improvement of phantom loading for the so-called "medium-heavy" loading system, i.e., the combination of new H63 phantom loading with the existing H174 side circuit loading to constitute the H174-63 phantom-group loading system, data for which are included in Table IV. The practical importance of this development was in the substantial reduction it permitted in loading costs. It marked the beginning of commercial use (1923) of phantom loading coils having cores similar in size to those of the associated side circuit coils. The cost savings resulted directly from the coil size-reduction, and from the increased size of loading complements that could be placed in standard-size pots, and from the simplification of pot assembly and cabling arrangements. The choice of phantom coil inductance (63 mh) was such as to make the phantom circuit 1000 cycle attenuation the same as that on the associated side circuits, without increasing the side circuit attenuation above that in H174-106 loading. This reduction in the loading inductance substantially improved the phantom circuit's transmission performance-characteristics by virtue of the substantial increase in cut-off frequency and transmission velocity, and made the repeatered phantom circuits electrically suitable for much greater distances than their side circuits. This superiority was seldom utilized, however, because of the practical operating flexibility advantages inherent in the established practices of using the associated side circuits and phantoms interchangeably between the same operating or switching centers.

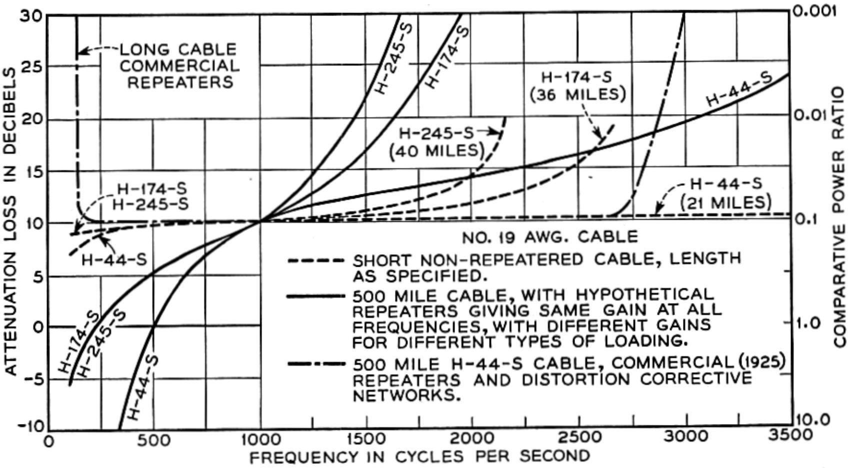

Fig. 7—Attenuation frequency characteristics of short and long loaded toll cable circuits having a net attenuation loss of 10 db at 1000 cycles per second.

In due course, the sizes of the other toll cable phantom loading coils were reduced to side circuit coil size, for cost-reduction reasons. The resultant economies were large relative to the value of the small attenuation impairments which resulted from this change.

(8) New Telegraph Systems for Loaded Cables

At several points in this review references have been made to the transient telephone transmission impairments which resulted from the operation of separate, superposed, grounded telegraph circuits over the individual line-wires of the loaded telephone circuits.(n) These "composite" telegraph systems had originally been developed for use on non-loaded open-wire lines and consequently required the utilization of telegraph currents of very large amplitude relative to the telephone currents.

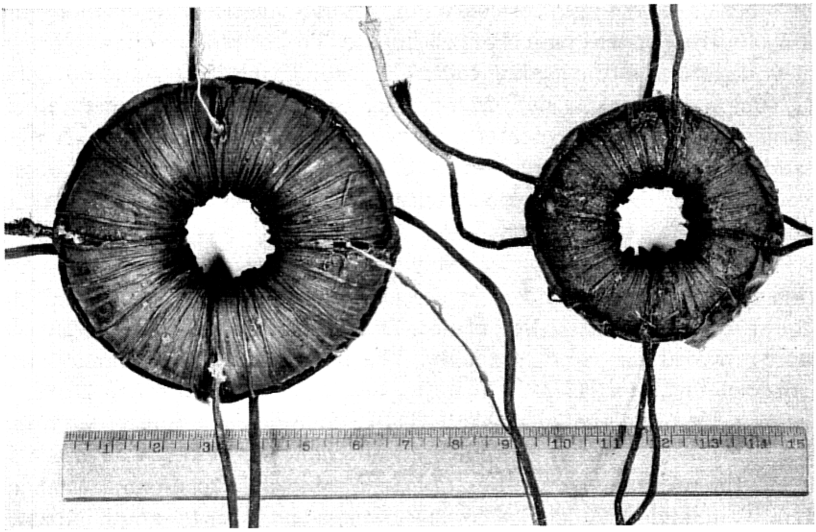

Fig. 8—Reduction of cable phantom coil size to that of associated side circuit coils. Large No. 581 Phantom Coil (106 m.h.) at left. Small No. 587 Phantom Coil (63 m.h.) at right. N.B. These phantom coils had compressed unannealed iron-powder cores.

The great extensions in the lengths of 19-gauge repeatered loaded cable that were to be expected from the use of the improved loading and repeaters, previously considered, put great emphasis upon a much better control of the telegraph-flutter interference, and led to the development of improved cable telegraph systems, along with the improved telephone transmission systems.

In one of these, known as the "Metallic Polar Duplex Telegraph System,"[19] the superposed telegraph current was of the same general order

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(n) Reference (10) gives a comprehensive discussion of telegraph-flutter phenomena.

of magnitude as the telephone current. This permitted a much greater reduction of the telegraph-flutter impairments than that which could have been obtained at a reasonable cost by using larger coils. A disadvantage of this system, however, was that it halved the number of superposed telegraph circuits per toll cable quad.

The other new telegraph system was a voice-frequency carrier system[20] which became commercially available during 1923 soon after the direct current metallic system just mentioned. This provided a total of 10 independent telegraph channels over the side circuits of special groups of H174-63 4-wire circuits used exclusively for telegraph service, and consequently there could be no telegraph-flutter reactions on telephone transmission. On the other hand, the need for controlling intermodulation effects among the associated carrier-telegraph channels imposed limits upon the allowable nonlinear distortion in the loading coils. The loading coils then standard (having compressed, unannealed, iron-powder cores) satisfactorily met the requirements, and with a greater margin than did the repeaters which were standard at that time. Interference considerations, however, prevented the general use of the metallic polar telegraph systems on loaded cable pairs used for carrier telegraphy.

The voice-frequency carrier-telegraph system soon became the most widely used telegraph system in the long distance toll cables. It did not require special facilities, but made effective use of the whole frequency-band provided for voice telephony. The initial number of channels was expanded to 12 on H174-63 facilities, and subsequently to a total of 24 channels by using the wider-band H44-25 facilities, previously described. The present-day system is limited to 18 channels, however, in order to permit the ready interconnection of loaded cable and broad-band telephone facilities in tandem. A detailed account of these and other telegraph improvements is given in a 1940 B.S.T.J. paper[21].

The strong-current, composite-grounded d-c telegraph system is very seldom used on modern toll cables. There is, however, a considerable use of the strong-current grounded d-c telegraph system on a simplex-phantom basis. Under this service condition, the telegraph current does not magnetize the loading coil cores and consequently there is no telegraph-flutter interference with telephone transmission. The metallic polar d-c telegraph system is usually limited to a few voice repeater-sections, because of the modern severe limits on telegraph-flutter impairments upon telephone transmission, and partly for economic reasons.

The improvements in telegraphy over loaded toll cables also included arrangements which were developed in 1922 for the purpose of reducing interference between d.c. telegraph circuits when superposed by the compositing method on wires of the same loaded cable quad.[22] This interference, known as telegraph crossfire, is mainly due to capacitance coupling between the cable conductors and in the central office equipment. In long circuits, the inductive coupling between the two line windings of each side circuit coil, and among the four line windings of each phantom loading coil, are important factors in the over-all crossfire between the telegraph circuits that are associated with the same cable quad.

(9) Compressed Permalloy-Powder Core Loading Coils

Since the transmission characteristics of the compressed, unannealed, powdered-iron core coils, which became available for general use in toll cables during 1918, were as satisfactory as was expected for the rapidly expanding repeatered toll-cable plant, greater emphasis was placed on cost reduction than on transmission improvement, in the continuing studies of new loading coil design-possibilities.

9.1 *Core-Material Development*

It was inevitable that permalloy[23] should be considered. This remarkable new nickel-iron alloy, invented by Mr. G. E. Elman of Western Electric research department, had important early applications in thin-tape form for continuous loading of deep-sea telegraph cables.

Some early studies and experiments indicated interesting possibilities of using it in thin sheets in non-toroidal type loading coil cores, but the prospects were much more intriguing if permalloy could be made available in compressed-powder toroidal cores. However, the initial experimental results with powdered-permalloy were disappointing. When the processes used in making compressed powdered-iron cores were employed, the permeability was unsatisfactorily low in consequence of the magnetic changes caused by the severe mechanical treatment involved in the embrittlement processes. The development moved forward rapidly after experiments with a physically sturdy type of ceramic-powder insulation for the permalloy particles proved that an annealing treatment after the core rings were pressed could erase the objectionable magnetic effects of the powderizing process and raise the permeability to desirable, high values. A complete account of this very important development is given in an A.I.E.E. paper[24] by W. J. Shackelton and I. G. Barber, "Compressed Powdered Permalloy, Manufacture and Magnetic Properties."

In the form developed for voice-frequency loading coil cores, the effective volume-permeability of the improved core-material was 75, more than twice that of the standard compressed, unannealed, powdered-iron core-material, and the intrinsic permalloy characteristic of very low hysteresis was retained. The combination of magnetic and electrical properties was such that large size-reductions could be made in the loading coils without degrading the important transmission-performance characteristics, relative to those of the standard powdered-iron core loading coils.

9.2 *Permalloy Core Loading Coils*

The coils standardized for toll cable loading were in volume and weight about one-third as large as the superseded types previously described. Coils C and B in the headpiece exemplify the coils under comparison. The direct-current resistances of the new coils were slightly lower than those of the superseded designs, their hysteresis losses were substantially lower, but their eddy-current losses were somewhat greater, because of the higher permeability. In consequence, their effective resistances were more favorable at the important low and middle speech-frequencies, than those of the compressed annealed iron powder core coils but not quite as good at the top frequencies.

The stability of residual inductance after magnetization by strong superposed currents was appreciably better than that of the superseded designs. The hysteresis advantages included a substantial reduction in non-linear distortion effects and about a 50% reduction in the transient distortion effects that are unavoidable in the operation of grounded telegraph over composited circuits. Their telegraph-flutter rating was considerably better than that of any of the prior standard cable loading coils, excepting only the large-size "high-stability" type of coarse-gauge cable coils, previously described. (Subdivision 5.)

With the standardization of the permalloy-core loading coils there started the practice of coding the combination of two side circuit coils and the associated phantom coil as a phantom-group "loading unit." The letter "P" was used in the code designations; a code number associated with the code letter recognized the different inductances of the different loading units, the complete codes being P1, P2, etc.

The coil size-reduction resulted in a 2 to 1 reduction in the potting-space requirements and permitted twice as many coils to be potted in standard-size cases, thus reducing potting costs. The cost savings in potted coils ranged from 30 to 40%. Additional savings resulted in the installation costs, including the space costs in the loading vaults in underground cable projects.

The development was very timely, in that the much cheaper coils became available during 1928 for use in the unprecedented expansion of H44-25 four-wire repeatered facilities that started that year and built up to a very high peak during 1930. In the period 1928–1931, over 4,000,000 permalloy-core toll cable loading coils were manufactured for Bell System uses. The lower costs of these coils encouraged the provision of larger circuit-groups in the long-distance cable plant which made possible substantial improvements in the speed of service. This, in combination with excellent transmission performance, greatly increased the demand for service, up to the beginning of the business depression in the early 1930's.

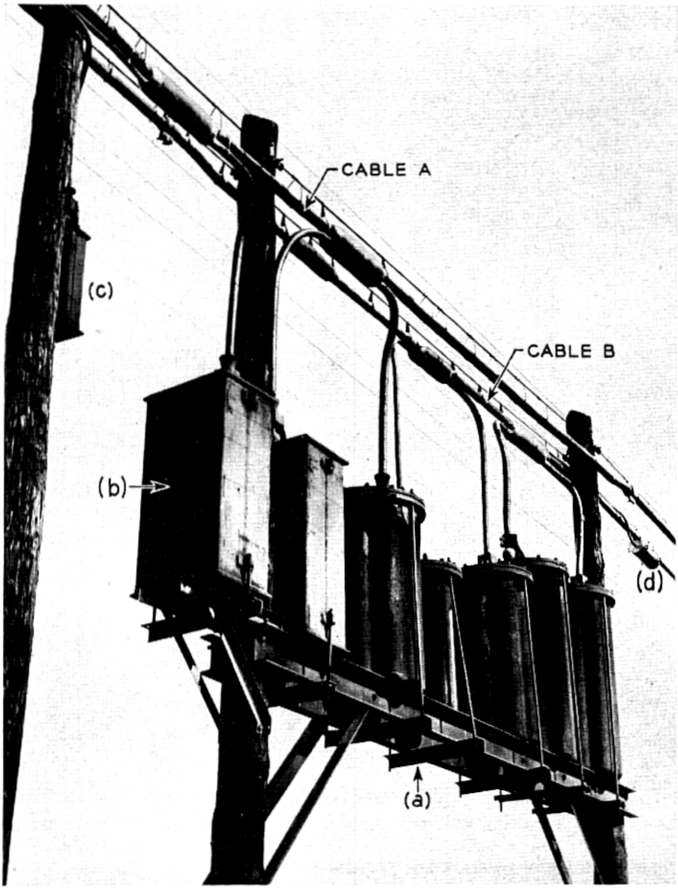

Fig. 9—Installed aerial toll cable loading. Four different methods of supporting the loading-coil cases are used in this installation, which provides loading for two cables: (a) On the platform of a 2-pole "H" fixture. (1 large welded steel case, and 5 large cast iron cases.) (b) A pole balcony supporting a large welded steel case. In this installation, it provides an extension of the "H" fixture. (c) A small welded steel case equipped with brackets, and fastened directly to pole. (d) Clamping a small lead-sleeve case to the main cable and its supporting strand. (This case contains program circuit loading coils.)

Around 1930, improved assembly-arrangements were worked out for the permalloy-core loading units. These involved the assembly of the individual loading units in individual unit-containers, and the code designations were changed. These used the letters "PB", and the same numbers as in the P-type units; the complete designations being P1B, P2B, etc.

The compressed powdered-permalloy core toll cable loading coils remained standard until 1938, when much cheaper and slightly better compressed, powdered molybdenum-permalloy core coils became available, as discussed in subdivision 11.

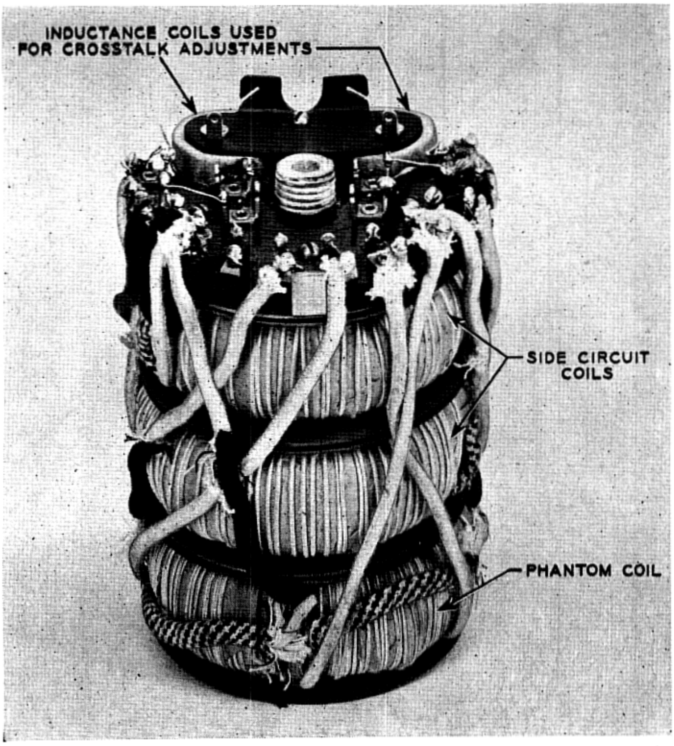

Fig. 10—P-B type loading unit potting assembly prior to placement in unit shielding container. Phantom coil is below the two side circuit coils. Midget inductance coils are used in phantom-to-side crosstalk adjustments.

(10) Improved Loading Standards for Two-Way Repeatered Toll Cables

During the late 1920's considerable attention was given to the improvement of transmission standards made possible by the use of the improved repeaters and the improved loading. This included reductions in the allowable net losses between terminals and improvements in crosstalk performance. Also, steps were taken to obtain better control of attenuation-frequency distortion, the important objective being to provide fairly uniform transmission in the frequency-band between 250 and 2750 cycles per second.[25]

The transmission requirements over the frequency-band just mentioned could be met without undue difficulty on the H44-25 four-wire and two-wire facilities, but were not feasible on the H174-63 facilities then being used mainly on a two-wire basis.

The work on the improved standards problem resulted in the development of the B88-50 and H88-50 toll cable loading systems, data for which are given in Table V.

In effect, this development established a new minimum cut-off standard of about 4,000 cycles per second for loading used on repeatered circuits. Also, as noted in the table, the transmission velocity was increased in H88-50 loading. B88-50 loading, using a coil spacing of 3,000 ft. (i.e., one-half of H-spacing), was originally intended for use in "long" repeater sections. The cheaper H88-50 loading was used on "short" repeater sections, and in consequence some facilities had tandem combinations of the two new types of loading. In the early applications H88-50 loading was used in repeater sections ranging up to about 45 miles in length and the more expensive B88-50 loading was used on longer sections. Later, improvements in the control of crosstalk and special procedures for reducing loading section capacitance-deviations made H88-50 loading suitable for longer repeater sections. During recent years, the voice frequency repeater points have usually been laid out to permit the use of H88-50 loading, and at present there is little use for new B88-50 loading.

TABLE V

H88-50 AND B88-50 LOADING

Loading System	Circuit	Nominal Impedance (ohms)	Theoretical Cut-off Frequency (cycles)	Nominal Velocity (mi/sec.)	Attenuation Loss (db/mile at 1000 Cycles)	
					19 A.W.G.	16 A.W.G.
H88-50	Side	1100	4000	14500	0.35	0.19
	Phantom	700	4200	15000	0.30	0.16
B88-50	Side	1550	5600	10000	0.25	0.16
	Phantom	950	5900	10500	0.23	0.14

New loading coils were developed for the new loading systems, and were coded in the "PB" loading unit series, previously mentioned. This apparatus development included substantial improvements in crosstalk performance obtained by new assembly-methods, and refinements in the crosstalk adjustments and test circuits. These new assembly-methods were applied to all standard toll cable and toll entrance cable loading units and provided flexibility for potting different types of loading units in the same case, and for identification of their terminal leads in the stub cables.

The new H88-50 and B88-50 loading became available for general use during 1932.

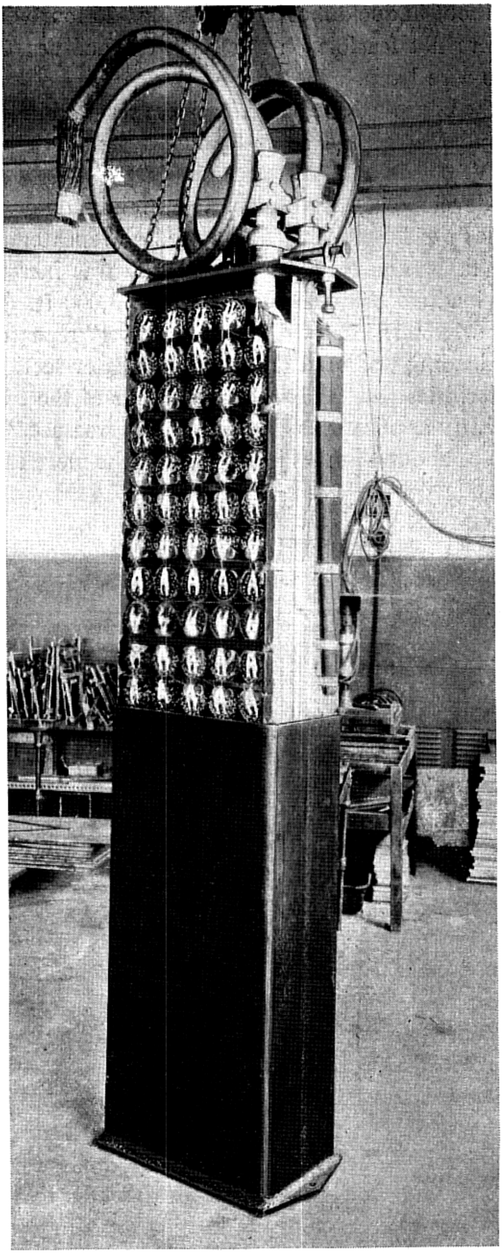

Fig. 11—Potting assembly—108 P-B type loading units in large welded steel case. Assembly ready for lowering into casing. Half of loading units are on far side of assembly frame, not visible in picture. The large number of loading coils makes necessary the use of 2 stub cables.

(11) COMPRESSED MOLYBDENUM-PERMALLOY POWDER CORE LOADING COILS

11.1 *The Improved Core-Material*

The continuing search for still better core-materials culminated during the middle 1930's in the development of the 125-permeability compressed molybdenum-permalloy material, described in an A.I.E.E. paper[26] by V. E. Legg and F. J. Given, "Compressed Powdered Molybdenum-Permalloy for High-Quality Inductance Coils." In its intrinsic magnetic and electrical properties as used in voice-frequency loading coils, the improved permalloy-material is nearly as much superior to the old standard 75-permeability permalloy as this latter material was to the 35-permeability compressed powdered-iron which it superseded as standard during the late 1920's.

The improved permalloy owed its superior characteristics mainly to the inclusion of molybdenum in the alloy, the principal constituents of which are approximately 2% molybdenum, 81% nickel, and 17% iron. The molybdenum component substantially raises the permeability and the specific resistance, and materially reduces hysteresis. The eddy-current losses are much lower than in the 75-permeability permalloy material, because the effect of the higher permeability in increasing these losses is more than offset by the effect of the higher intrinsic resistance in reducing them.

In developing the material, it was considered to be very important to go as far as possible in improving the intrinsically favorable hysteresis properties. This was accomplished without adverse effects on permeability and eddy-current losses and other important properties, by annealing the pressed core rings in hydrogen at a much higher temperature than that previously used with material under treatment while exposed to the atmosphere. Also an improved type of particle insulation was developed. All in all, a large number of unusually difficult processing problems had to be solved in the research and development stages. Also, some of the processes required considerable additional attention during the manufacturing preparations for quantity production.

In the voice-frequency loading applications, the successful efforts to reduce hysteresis to a minimum fitted in with the preliminary economic design studies, which indicated it would be desirable to take advantage of the superior intrinsic properties of the new magnetic material by using it in smaller cores, so as to reduce loading-apparatus costs as much as possible without appreciably degrading transmission performance. In this connection, it is noteworthy that with any given magnetic-material the hysteresis losses become greater as the core size is reduced, in consequence of the greater intensity of magnetization.

The 125-permeability molybdenum-permalloy core material under discussion was developed primarily for voice-frequency uses. At much higher frequencies, lower permeabilities are necessary to prevent the core losses from becoming too high. Accordingly, other grades of compressed molybdenum-permalloy powder having lower permeability values are available. These are obtained by diluting the molybdenum-permalloy powder with inert material before pressing. Also, smaller-size particles are used. A new grade not described in the Legg-Given paper,[26] previously referred to, which has an effective permeability of 60, was used in small carrier loading coils for the Army spiral-four field cable during the war,[27] and is now being used in the cores of cable loading coils for 15-kc program transmission circuits which are described in Subdivision 13.3.

11.2 *M-type Molybdenum-Permalloy Core Loading Units*

The initial standard, molybdenum-permalloy core, phantom loading units which were coded in the M-series became available for commercial use during 1938. The individual coils were about 60% smaller than the standard, 75-permeability, permalloy-core coils which they superseded for use in new plant. In the headpiece, these size-relations are typified by coils D and C, respectively.

By design, the new coils had about the same d-c resistance and hysteresis loss as the superseded designs. Their eddy-current losses were considerably lower than those of the 75-permeability permalloy designs, and in consequence the total effective resistance was lower at the upper frequencies, thereby improving the steady-state frequency-distortion characteristics of the circuits in which they were used. In plant-design engineering, the new coils were accepted as being equivalent to the older coils. The residual inductance stability was a little better, and the telegraph-flutter distortion characteristics were considerably better. The susceptibility to superposed d-c magnetization, however, was worse. This minor impairment was the only adverse effect of the substantial increase in permeability, and the substantial reduction in coil size.

The development was timely in that the new coils were available for use in meeting the accelerating demand for toll cable loading that started in 1939 and continued for several years. In the five-year period 1938–1942, a total of about 800,000 side and phantom toll cable loading coils were manufactured for Bell System use notwithstanding the large installation of Type K carrier systems on non-loaded and unloaded cables that occurred in this period, thereby reducing the demand for additional, repeatered, loaded cable voice-frequency facilities.

The economic advantage of the broad-band carrier system is largely due to the fact that the cost of the conductors and the repeaters and of the distortion corrective-networks and regulating devices which are used to shape and control the transmission medium is shared by all of the transmission paths. Very valuable transmission advantages result from the relatively very high velocity of transmission over the non-loaded conductors.(o)

One of the effects of the new carrier systems' competition was to more than reverse the relative amounts of loading for new installations of 4-wire and 2-wire circuits—somewhat less than $\frac{1}{3}$ the total being provided for 4-wire circuits, during the period under consideration. The substantial cost-reductions, resulting from the introduction of the 75-permeability permalloy coils, of course materially limited the additional savings that could be realized by further size-reduction. Notwithstanding this, and taking into account also the declining demand for toll cable loading, the development of the M-type loading units turned out to be a very profitable operation, in terms of the reduced costs of new plant.

11.3 *SM and MF-type Molybdenum-Permalloy Core Loading Units*

These war-emergency designs owed their existence to the necessity for conserving strategic materials, especially nickel. They use half as much molybdenum-permalloy as the M-type loading units. The use of a new type of insulation, Formex enamel,(p) on the conductors in place of a combination of cotton with an older type of enamel, greatly improved the winding space-factor and minimized the increase in d-c resistance that necessarily followed from the 50% reduction in coil size. In the frontispiece, Coil E is one of these new coils, Coil D being the superseded coil.

To minimize delays in introducing the war-emergency designs into commercial use, which began during 1942, they were (initially) assembled in the unit-containers and potted in the loading coil cases that had been designed for the M-type loading units. They were initially coded as the SM-type loading units.

Subsequently, to conserve steel, entirely new unit-assembly arrangements were made in new smaller-size unit containers and new smaller-size loading coil cases were developed to take full advantage of the loading coil size-reduction. The coils themselves were not changed but new code-designations were assigned in the "MF" series, in conformity with the long established practice of coding phantom loading units in their unit containers.

The d-c resistances of the SM and MF loading units are about 25% higher than those of the corresponding M-type loading units, and the hysteresis effects are about 40% greater, under similar operating conditions. The other core-losses are unchanged in magnitude because they do not vary as

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(o) Published information regarding the cable carrier systems is given in Bibliography References (28) and (29).

(p) This improved wire-insulation had already found valuable uses in new exchange area loading coils, as discussed in Section 22.

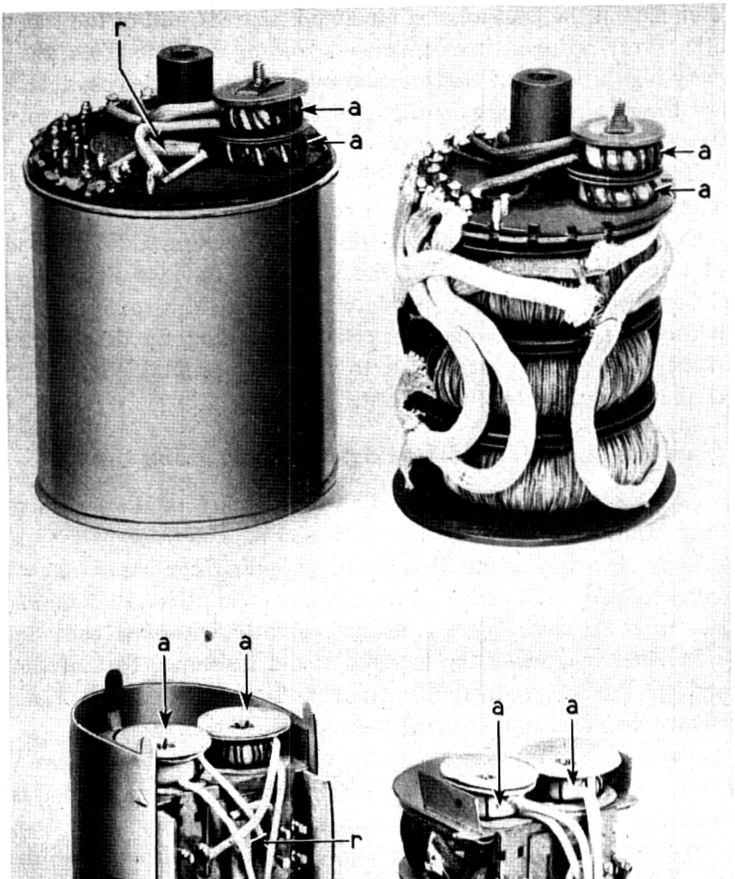

Fig. 12—M-type and MF type phantom loading units. Before and after placement in their unit shielding containers. M-type unit above the MF-type unit. "a" designates midget inductance coils (used in crosstalk adjustments); "r" designates midget resistors (used in crosstalk adjustments). The loading units shown outside the containers are not the same as those shown inside the containers.

a function of coil size. For the most important types of loading, the increases in attenuation that result from the higher coil resistances are in the range

1 to 3% at 1000 cycles on 19 ga. cables. At the top voice-frequencies, the attenuation increments are less than twice as large as the 1-kc increments. In 50-mile repeater sections, the resulting increases in the bare-line attenuation are of the order of 0.2 to 0.4 db at 1000 cycles depending on the type of loading and much of this increment-loss usually can be recovered by raising the repeater gains. The stability of residual inductance is as good as that in the M-type loading units.

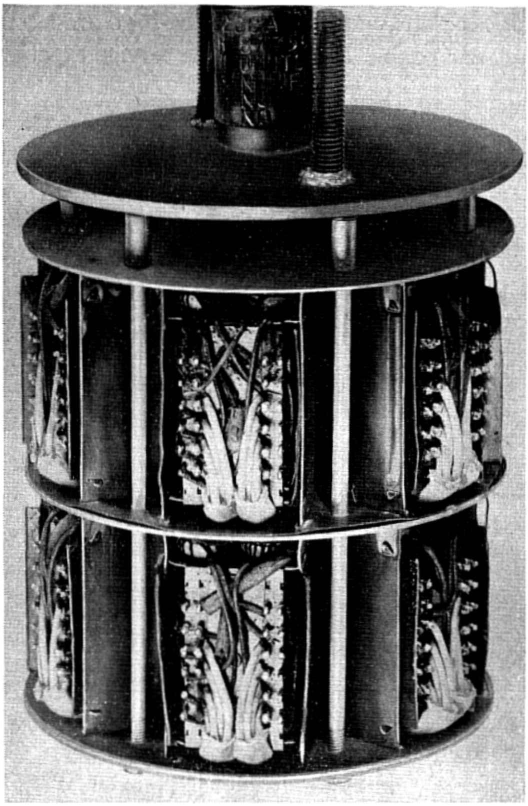

Fig. 13—Potting assembly methods—medium and large size complements of MF-type units. For placement in cylindrical, thin steel, casings.

The impaired hysteresis effects, above mentioned, are accompanied by increased non-linear distortion, including telegraph-flutter effects. Also the smaller coils are somewhat more susceptible to changes in inductance and effective resistance when the circuits in which they are used have steady currents superposed upon them during talking intervals.

Additional information regarding the smallest loading units is included in an A.I.E.E. paper[30] by S. G. Hale, A. L. Quinlan, and J. E. Ranges, "Recent Improvements in Loading Apparatus For Telephone Cables."

The various relative transmission-impairments, above mentioned, were accepted in advance as being tolerable from the service standpoint under war conditions, considering the types of circuits required and their probable relatively short lengths. At that time it was thought possible that better loading units, not necessarily as good as the M-type units, might be warranted in the post-war period. Meanwhile, the service experience with the small loading units has been reasonably satisfactory, largely because of the easing-up of performance requirements that is resulting from the restriction of toll cable loading to short-haul facilities. These seldom have more than two repeater sections, in consequence of the economic competition offered by present standard and proposed new, cheaper, carrier systems on non-loaded cable. Under these circumstances, the cost of developing better loading units which would probably increase the loading costs would be hard to prove in. Thus, the MF-type war-emergency loading units became post-war loading standards.

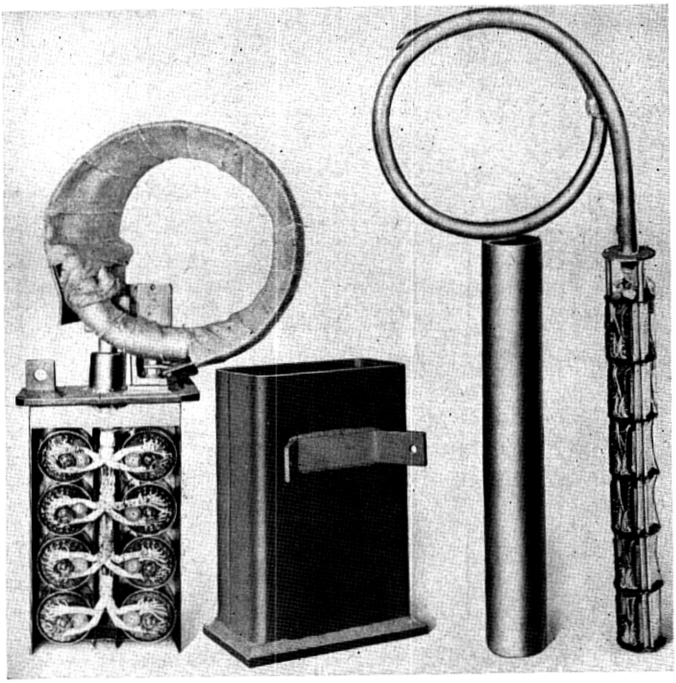

Fig. 14—Potting assembly methods—small complements of M-type and MF-type loading units. Note use of lead sleeve casing for MF type units, and relatively large welded-steel casing for M-type units.

It should not be inferred from the foregoing that the MF (and SM) loading units have unimportant significance in the economy of Bell System toll cable plant-design. For example, during the period 1942–1949, a total of about two million side and phantom coils were manufactured for assembly in these smallest, standard, phantom loading units. A large majority was installed subsequent to VJ-day, as part of the Bell System program of plant expansion to meet the greatly increased demand for long-distance telephone service, and to restore the speed of service to the pre-war standards.

TABLE VI

ELECTRICAL DATA—MOST IMPORTANT VOICE-FREQUENCY PHANTOM LOADING UNITS

Loading Unit Code Nos.	Nominal Inductances (1)—mh		Approx. Avg. Resistances(2) —Ohms			
			Side Circuits		Phantoms	
	Side	Phantoms	d-c	1 kc	d-c	1 kc
P1, P1B	172.4	63.6	10.7	13.6	5.3	6.2
M1	172.4	63.6	10.8	13.0	5.4	6.0
MF1, SM1	172.4	63.6	13.8	16.4	6.9	7.6
P2, P2B	43.5	25.1	3.8	4.4	1.9	2.2
M2	43.5	25.1	3.6	4.0	1.8	2.0
MF2, SM2	43.5	25.1	4.5	5.0	2.2	2.5
P4, P4B	30.9	17.8	2.7	3.0	1.3	1.5
M4	30.9	17.8	2.4	2.7	1.2	1.4
MF4, SM4	30.9	17.8	3.1	3.4	1.5	1.7
P11B	88.7	50.2	6.1	7.0	3.05	3.5
M11	88.7	50.2	6.3	7.2	3.1	3.6
MF11, SM11	88.7	50.2	7.9	9.1	4.0	4.6

Notes: (1) The listed inductance values are the mean specification inductance values (at 1800 cycles).
(2) The coil resistance values allow for 19-gauge stub cables of 7.5-ft. external length.

(12) COMPARATIVE ELECTRICAL DATA, VOICE-FREQUENCY PHANTOM-GROUP LOADING UNITS

Comparative electrical data regarding the commercially most important, former standard and present standard, voice-frequency phantom-group loading units are given in Table VI, above. Those coded in the "P" and "PB" series used compressed permalloy-powder cores; the M, SM, and MF-type units used compressed, molybdenum-permalloy powder cores. Prior to the standardization of the P and PB-type units, the side circuit and phantom circuit coils had their own individual code numbers. They were interconnected in loading unit formation during the case assembly and cabling procedures.

The loading units having the digit 4 in their code designations are "full-weight" units for H31-18 voice-frequency entrance cable described in Part V of this review. The loading units having the digit 2 in their designations are used in H44-25 four-wire repeatered circuits. The other loading units are used in two-wire repeatered circuits, and also in circuits not long enough to require repeaters.

(13) Improved Loading for (Long-Distance) Cable Program Transmission Circuits

13.1 *General*

In the early days of radio chain-broadcasting (during the early 1920's), the links which connected the broadcasting stations with the studios where the programs originated usually were open-wire voice-frequency telephone circuits modified to meet the special requirements of this new type of service. In some instances, toll cable circuits were used for links not more than a few hundred miles long.

Where available, side circuits of H44-25 facilities, previously described, were preferred for the cable program-transmission service because of their high cut-off frequency. By using suitable equalizing and regulating networks in conjunction with modified one-way amplifiers, a fairly satisfactory transmission-medium could be obtained, providing a frequency-band ranging from about 100 cycles up to about 4000 cycles. While these circuits were adequate for speech broadcasting they were not equally satisfactory for classical music programs by symphony orchestras.

As early as 1924, some preliminary studies were started on entirely new types of loaded cable facilities primarily for use in transmitting the highest grade of radio-broadcast program material. These studies showed 16 ga. cable pairs to be desirable for long program circuits. At the time, however, there was considerable question as to what the ultimate performance-requirements should be, and some doubt as to whether the commercial demand would be sufficiently large to warrant the high cost of developing and providing a suitable new type of facility.

During the following years, there was a large increase in the number of broadcasting stations and in the need for inter-connecting links. Also the toll cable network expansion had commenced to accelerate rapidly. Beginning about 1926, the new toll cables that were installed usually included a small complement of 16-gauge non-quadded pairs (generally 6) in anticipation of their ultimate use for improved program facilities, if the then expected demand should eventually materialize. Studies of improved loading, and of the very important equalization and temperature regulation problems were renewed. This work progressed sufficiently so that early in 1927 a trial installation of H22 loading was planned for program facilities in a new cable between New York and Philadelphia. This loading had a 40% higher cut-off frequency than the H44 loading previously mentioned, and a 30% lower nominal impedance. It was expected that the program frequency-band could be stretched to a 6000-cycle top. It used a new loading coil described later on.

13.2 *B22 Program Facilities*

While the preparation for the H22 trial installations was still under way, further experimental and theoretical studies showed it would be desirable to provide an equalized transmission-band from about 50 cycles to about 8000 cycles, so as to obtain a margin for probable future improvements in broadcasting services. Accordingly, a decision was reached in September 1927 to develop a new type of cable program facility that would be satisfactory for lengths of 2000 miles or more. A new type of loading, designated B22 (22 mh loading coils at 3000-ft. spacing), was authorized and a trial installation on cable circuits looped back and forth between New York and Pittsburgh was planned.

The development of the new loading was only a small part of the total development effort. The equalizing and temperature-regulation problems were much more difficult than those previously encountered in the development of long-distance telephone message facilities, partly because of the much wider transmission-band and partly because of the more severe limits necessarily imposed. Improved repeaters were required and crosstalk and noise problems demanded very serious attention. A comprehensive account of the development work and a detailed description of the B22 cable program-facility is given in an A.I.E.E. paper[31] by Messrs. A. B. Clark and C. W. Green. Accordingly, the remaining discussion herein is limited to the loading.

The theoretical cut-off frequency of B22 loading is a little over 11,000 cycles; its nominal impedance is closely equal to that of H44 loading, previously mentioned. The theoretical nominal velocity of wave propagation is about 20,000 miles per second. The use of phase equalization networks of 8 kc band width, however, slows down the actual velocity to about 13,000 mi/sec. The attenuation on 16 ga. pairs at average temperature is about 0.24 db/mi at 1000 cycles, and ranges from about .14 db/mi at 35 cycles to about .38 db/mi at 8000 cycles.

The new 22 mh non-phantom type loading coils used compressed, permalloy-powder cores similar in size to those of the toll cable side circuit and phantom loading coils previously described in general terms. Non-linear distortion in the line was satisfactorily low in consequence of the favorable hysteresis characteristics of the permalloy-core coils.

The satisfactory completion of the system's trial-installation tests in 1929 resulted in a large amount of B22 loading being installed during 1930 and 1931 on 16-gauge pairs in cables that had been installed in advance of the facility development work, as previously mentioned, and in new cables.

During 1936, compressed, molybdenum-permalloy powder-core program loading coils became available for use in place of the permalloy-core coils above described. The new coils were smaller than their predecessors, and were substantially as good or better in the lower half of the working frequency band. At the high frequencies they were better than the permalloy-core coils, because of the lower eddy-current losses previously mentioned. An important factor in the choice of coil size was to make the coil suitable for installation within the loading splice-sleeves so as to reduce potting and installation costs. This practice became quite general, especially at the "B" loading points intermediate between the "H" loading points where phantom loading units were installed on telephone message circuits in the same cable. In these "splice installations," the per-coil savings in potting and installation cost were large relative to the direct savings in loading coil costs resulting from size reduction. In order to realize these substantial combined savings as quickly as possible, the new program coils were given priority in the commercial exploitation of the molybdenum-permalloy core-material.

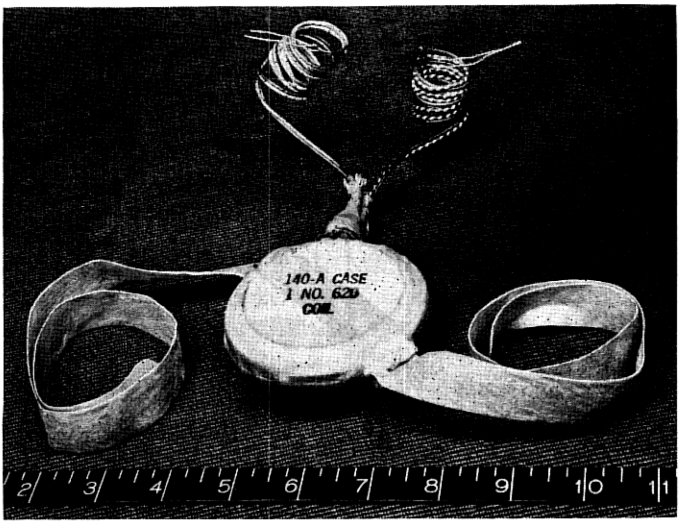

Fig. 15—Molybdenum-permalloy core program circuit loading coil potted for installation within cable splice sleeves. The canvas bag shown in the picture is used to prevent the metal shielding-container of the coil from damaging the insulation of nearby conductors in the cable splice. The fabric strips are used to tie the coil case to the cable core at the splice.

As an indication of the commercial importance of the program circuit loading above described, it is of interest to note that enough program coils were manufactured during the period 1928–1948 to provide loading for more than 100,000 pair-miles of B22 facilities. The demand for the new B22 loading is rapidly declining however, in consequence of the post-war development of program transmission facilities using combinations of channels in non-loaded cable carrier systems. From now on, it seems probable that new B22 loading will largely be limited to short extensions of existing loaded facilities, and to short links between cable carrier-system terminals and the points where broadcasting programs are picked up or delivered.

13.3 *15-kc Program Transmission Circuits*

The development of new loading for use on cable facilities transmitting FM broadcasting material was completed early in 1948. It provides a transmission band extending up to 15 kc and is suitable for use on circuits that connect FM broadcasting transmitters with their studios, in situations where its use will reduce costs as compared with the use of intermediate amplifiers.

Two weights of 15-kc loading are available, one having a nominal impedance equal to that of B22 loading (800 ohms), and a lighter-weight loading having a nominal impedance of about 480 ohms.

The 800-ohm loading generally uses 11 mh coils at spacings which give a theoretical cut-off frequency of about 23 kc, and a nominal velocity of about 20,000 miles per second. In 0.062 mf/mi cables the coil spacing is 1500 ft. and in "high-capacitance" exchange cables, it is 1100 ft., in order to obtain closely the same total loading section capacitance and similar values of nominal impedance and cut-off frequency. Since studio-transmitter circuits usually include tandem combinations of component cables which have appreciably different unit-length mutual capacitances, this loading plan minimizes reflection effects which would otherwise result from impedance differences at the junctions of the component cables.

800-ohm loading is sometimes provided on program pairs in coaxial cables by using 7.5 mh coils at 1000 ft. spacing. When the coaxial cables are installed in 1000 ft. lengths, this loading arrangement avoids the need for making the (expensive) extra cable splices that would be required if 1500 ft. spacing should be used. Although 50% more program loading coils are required, the small additional cost of the loading is negligible in relation to the savings in cable splicing costs. This 7.5 mh, 800-ohm loading has a nominal velocity of about 20,000 mi/sec, and a theoretical cut-off frequency of about 34 kc.

The 480-ohm loading uses 7.5 mh coils at spacings twice as long as those for the 800-ohm loading using 11 mh coils. The theoretical cut-off is a little over 19 kc and the nominal transmission velocity is about 36,000 miles per second.

The 800-ohm loading is superior in all transmission features to the 480-

ohm loading, especially at low frequencies. It is an acceptable substitute for B22 loading for transmission of AM broadcasting material, being appreciably better in the frequency range 4 to 8 kc, because of its much higher cut-off frequency, and it is substantially as good at low frequencies. Accordingly, to provide plant flexibility for possible future broadcasting service requirements, this 800-ohm 15-kc loading is being installed on short-haul program pairs in new toll cables in situations where the anticipated initial needs are for AM broadcast programs. When the loading is installed in the course of the cable installation, the slightly higher cost of the broader-band loading is negligible in comparison with the plant flexibility-advantage above cited.

The field of use for the 480-ohm 15-kc program loading is in short repeater sections where the transmission requirements permit its use, and where it is desirable to take advantage of its lower cost, relative to the 800-ohm loading. This cost advantage is maximum when the loading has to be applied to cables previously installed.

The loading coils for the new 15-kc program loading are of the same size as the molybdenum-permalloy core coils developed for B22 loading. Accordingly, when installation conditions are favorable, economies can be achieved by placing the coils within the loading splices. The new program loading coils use 60-permeability, compressed, molybdenum-permalloy powder cores. This relatively new grade of molybdenum-permalloy has much lower eddy-current losses than the 125-permeability grade used in voice-frequency loading coils (and in B22 program loading), and is very advantageous in the reduction of attenuation over the upper two-thirds of the 15-kc transmission-band. The 60-permeability cores also have superior non-linear distortion-characteristics.

(14) CONTROL OF CROSSTALK

The control of crosstalk between adjacent telephone circuits has been a very important problem from the beginning of the use of loading, especially in loaded cables, and has been most difficult in long loaded, repeatered, quadded toll cables.

14.1 *Cable Unbalances*

The effect of loading in increasing the circuit impedance raises the voltages which act upon the unavoidable cable capacitance-unbalances, and reduces the magnitudes of the line currents which act upon the series resistance (and inductance) unbalances. Consequently, with the introduction of loading, it became necessary to improve the design of the cables so as to materially reduce the capacitance unbalances. This was accomplished by using different lengths of twist in adjacent pairs and in adjacent layers, and by using different lengths of lay in adjacent layers.

The development of quadded cable and of phantom-group loading during the period 1908–1910 introduced especially difficult requirements in the control of crosstalk between the phantom circuits and their side circuits, and to a lesser degree between the associated side circuits. Notwithstanding further improvements in design and great care in manufacture, it became necessary during the installation of the quadded cables to resort to the use of special splicing procedures which reduced the total capacitance-unbalance per loading section to satisfactory values.

For nearly a decade it was the practice in the control of phantom-to-side and side-to-side crosstalk to make the capacitance-unbalance test-splices at seven approximately even-spaced intermediate splicing-points in each loading section. By about 1919, further improvements in design and in manufacturing processes made it feasible to reduce the number of test splices per loading section to 3. This practice is still general for quadded cables used principally for two-wire repeatered facilities. In the period of very rapid extension of the installation of long repeatered, loaded four-wire circuits (1929–1931), it was found feasible to limit the number of test splices per loading section to one, by using supplementary balancing-condensers to reduce the high residual capacitance-unbalances on two-wire circuits, and by using additional balancing-condensers at one end of each repeater section on four-wire circuits, when required to obtain satisfactory low over-all crosstalk. The one-way transmission in the individual, oppositely-bound, paths of the four-wire circuits was a basic factor in making feasible these field-adjustment simplifications, thereby reducing installation costs.

14.2 *Loading Coil Crosstalk*

Although the side circuit and phantom loading coils never had objectionable design unbalances, it has always been difficult in manufacture to realize the inherent symmetry of their design. The series inductance unbalances have been the most troublesome accidental unbalances. In the early days, reasonably satisfactory control of crosstalk between circuits in the same phantom-group was obtained by care in manufacture, and by adjusting the inductance unbalances to the nearest turn.

A general, substantial, tightening of the crosstalk limits became necessary when repeaters came into general use, because of the effect of the repeaters in amplifying the unwanted crosstalk along with the wanted conversation, and because of the great increases in circuit length that the repeaters made feasible. During a period in the early 1920's, when intensive development was under way to reduce the loading apparatus crosstalk, the over-all repeater-section crosstalk was controlled by poling the unbalances of the coils against the cable unbalances in the loading sections near the repeaters.

The new development work, above referred to, included greater refinements in the manufacturing processes, including greater accuracy in the subdivision of the core winding-space, more uniform winding-arrangements in layer formation by automatic winding-machines, and the use of external series-inductance adjustments by means of preselected, miniature, inductance coils, which resulted in much smaller residual unbalances than could be obtained by the nearest full-turn adjustments. More precise crosstalk measurement-circuits were developed, and the practice started of making the crosstalk adjustments and measurements in test circuits having, at the test frequency, impedance characteristics approximating those of the lines in which the coils under test are used. (Previously a relatively insensitive test-circuit having "compromise" impedance characteristics had been used for all types of side and phantom coils.) Also, the factory crosstalk adjustments were concentrated on minimizing near-end crosstalk in loading units intended for two-wire circuits, since in such circuits the far-end crosstalk is relatively unimportant. In loading apparatus intended for use on four-wire circuits, the crosstalk adjustments were made to minimize far-end crosstalk because the associated phantom-group circuits are always used in the same direction of transmission and the one-way repeaters associated with them block the propagation of near-end crosstalk. The external inductance adjustments, above referred to, were especially designed for the reduction of phantom-to-side crosstalk. Other adjustments and assembly processes controlled crosstalk between associated side circuits.

As a result of the various improvements above referred to, the average phantom-to-side crosstalk in the loading apparatus was reduced to about one-fourth of the earlier values. These reduced values were of the same order as the cable crosstalk in the individual loading sections after the completion of the capacitance-unbalance test-splicing.

In the late 1920's and early 1930's, when the need for improved transmission systems on two-wire repeatered circuits resulted in the development of the H88-50 and B88-50 facilities previously described, another development campaign was started to improve loading apparatus crosstalk-performance. This resulted in the reduction of the average loading coil crosstalk to values much smaller than those caused by the cable residual capacitance-unbalances after test splicing, so that the effective repeater-section crosstalk is not significantly larger than that which would result if it were possible to manufacture perfectly balanced loading coils. Important factors in this improved performance were the use of series, external, resistance adjustments in particular loading units where worth-while crosstalk reduction could be thus obtained, and the use of a new series of inductance elements having closer gradations in their inductance values to more closely approach the theoretical optimum adjustments. More compact assembly-arrangements of the phantom loading units in individual shielding containers also contributed to the more favorable crosstalk-performance, along with other process improvements. (Refer to Fig. 10, page 186.)

The improved crosstalk-performance above discussed, which was achieved in the development of the PB-type permalloy-core phantom loading units, previously described, was maintained in the commercial production of the smaller-size M-type molybdenum-permalloy core loading units which superseded the PB-type loading units, and in the present standard MF-type loading units. (Refer to Fig. 12, page 192.)

It seems improbable that additional improvements in loading unit crosstalk-performance will be needed in the future, in view of the trend during recent years of restricting voice-frequency phantom-group loading to short-haul facilities.

A more comprehensive account of the successful struggle to control cable crosstalk in loaded toll cables is given in a 1935 Bell Telephone Quarterly article[32] by Mr. M. A. Weaver. An A.I.E.E. paper,[8] previously referred to, includes considerable additional information on the crosstalk-reduction work on the loading coils, up to 1926.

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