The Evolution of Inductive Loading for Bell System Telephone Facilities

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PART VI: CONTINUOUS LOADING

General

CONTINUOUS loading, i.e., the addition of uniformly distributed inductance, was studied theoretically in the Bell System several years before theoretical work started on coil loading. This early work of John Stone Stone, then a member of the headquarters technical staff of the American Bell Telephone Company, resulted in the issue to him on March 2, 1897 of a *U.S. Patent* (575,275) describing a "bi-metallic" wire cable.

Later on, when the commercial development was authorized, cost considerations made it desirable to start with laboratory experiments on an "electrically equivalent" artificial line using small lumped inductances. In planning these experiments, it soon became apparent that only a small amount of distributed inductance could be obtained with the best magnetic material then available, namely, iron. Recognition of the important advantages inherent in the use of large amounts of inductance, and of the absence of limitations regarding the magnitude of inductance that could be provided in coil form, then shifted the development emphasis to the as yet unsolved problem of spacing inductance coils in relation to wavelength. This theoretical problem was quickly solved by G. A. Campbell, who was then in charge of the project, and accordingly the laboratory artificial line was designed to demonstrate the practicability of coil-loading (early in 1899). The Bell System development work on continuous loading was then suspended for some time.

During the next two decades, coil loading was found to be economically suited to all Bell System needs for inductive loading, even on short intermediate submarine cables required at shallow water crossings of rivers and bays. Shortly after the First World War, however, it became necessary to undertake the development of continuously loaded cable to meet an urgent demand for telephone communication with Cuba. Exploratory theoretical studies and laboratory investigations had been started shortly before the war, but were discontinued during the war. The exploratory work included consideration of the possible use of a new nickel-iron magnetic alloy which was then under development by the Research Department of the Western Electric Company, and which later on became widely known as permalloy.[23]

Key West-Havana Submarine Telephone Cable System

This project required three different submarine cables ranging in length from about 100 to 105 nautical miles, each being a great deal longer than any previously designed for telephone transmission, and a large fraction of the route was in deep water, reaching a maximum depth somewhat over 6000 ft. The difficulties to be expected in protecting loading coils from injury under the great hydrostatic pressure involved, and the complications that would be encountered during installation and in subsequent maintenance work, prevented coil loading from receiving consideration. Moreover, the great water pressure also eliminated consideration of paper insulated cable.

Since the cables were intended for use in telephone circuits connecting remote points in the United States with Havana and remote points in Cuba, the over-all system design requirements were very formidable. In addition to a two-way telephone circuit in each cable, provision also was made for three carrier telegraph circuits above the voice range, and for direct current grounded telegraphy below the voice. These complex requirements brought in difficult problems regarding telegraph flutter interference and other types of non-linear distortion.

The fundamental design studies resulted in a decision to install single core, continuously loaded, cables using gutta-percha insulation, and having a concentric system of copper tapes wrapped around the insulated conductor, for use as a return conductor. (These cables were the first to be installed with this feature.) Iron-wire type continuous loading was chosen largely because the desired project in-service dates did not allow sufficient time for the additional research and development work, and the additional manufacturing preparations, that would have been necessary in order to use permalloy tape loading. The manufacturing situation presented serious problems, because it was necessary to plan for manufacture abroad, since no American company had facilities for making deep-sea submarine cable. Moreover, iron-wire type continuous loading (as proposed by C. E. Krarup* of Denmark) was old in the European telephone art, having been used in several short submarine cables, and some underground cables.

In the Cuban Straits cables under discussion, the central copper conductor had a diameter of about 0.140 inch. About this was closely wrapped a single layer of 0.008 inch soft iron wire and three layers of gutta-percha type insulation having a total thickness of about 0.135 inch. A thin copper tape directly on this core furnished protection against damage by the teredo,

* *E.T.Z.*, April 17, 1902.

and was part of the system of copper tapes previously mentioned which served as a return conductor.

The effective permeability of the iron-wire loading material was about 115. The distributed inductance of about 4.35 millihenrys per nautical mile resulted in a low nominal impedance of about 115 ohms. The energy losses in the loading material were the principal factors in limiting the top of the working frequency band to about 4000 cycles. At 1000 cycles per second, the bare line equivalent was of the order of about 22 db (for the mean value of the longest and shortest cable). At 4000 cycles it was about 2.2 times as great.

Space limitations prevent a more complete description and discussion here. Comprehensive information regarding all features of the project is given in a 1922 *A. I. E. E.* Paper[42] prepared by Messrs. W. H. Martin, G. A. Anderegg and B. W. Kendall. Engineers of the A. T. &. T. Co. and W. E. Co. were responsible for the electrical design of the cables, method of operation, and arrangement of the repeaters and other terminal apparatus. The cables were manufactured late in 1920 and installed early in 1921 by The Telegraph Construction and Maintenance Co. Ltd. of London, for the Cuban-American Telephone and Telegraph Company. The latter organization is jointly owned by the A. T. &. T. Co. and the Cuban Telephone Co. (a subsidiary of the International T. &. T. Co.)

1930 Non-Loaded Cable: Since the 1921 cables were not suitable for carrier telephone operation (largely because of excessive losses and non-linear distortion at high frequencies), it became necessary during 1930 to install a fourth cable between Key West and Havana in order to meet the demand for additional facilities. Advantage was taken of advances in the communication art, notably an improved cable insulation (paragutta), improved repeaters and carrier telephone systems, to design a non-loaded cable system which would be suitable for carrier operation. The initial carrier set-up provided three carrier telephone circuits, using a type C4 system which had originally been developed for open-wire lines. Early in 1942, a seven-channel system was substituted. Comprehensive information regarding the 1930 cable and its use of the 3-channel carrier telephone system is given in a 1932 *A. I. E. E.* paper by Messrs. Affel, Gorton and Chesnut.[43]

High Speed Transoceanic Loaded Telegraph Cables

During the First World War when the need for increasing the message-carrying capacity of existing non-loaded transoceanic telegraph cables became urgent, the Bell System engineers who worked on this problem finally came to the conclusion that to obtain a great advance in the existing art it would be necessary to have much better cables.

In July 1919 the continuing interest in this problem crystallized in a Western Electric proposal to use permalloy continuous loading in new transoceanic telegraph cables. Since this remarkable new magnetic alloy[23] had been invented and developed by Western Electric engineers, they were already familiar with its extraordinary high permeability characteristics, and had confidence in their ability to use it in providing a high impedance loading which would make practicable a great increase in message-carrying capacity. Loading with iron-wire would not have any advantage in telegraph speed, because of its low permeability. Intensive research work quickly started on the permalloy loaded cable design and installation problems, and on the related terminal apparatus and operating problems. The success attained in these efforts resulted in disclosures to the Western Union Telegraph Company regarding the great increase in telegraph signaling speed that could be obtained with the proposed new permalloy loading. In due course the Telegraph Company made arrangements with the Telegraph Construction and Maintenance Company Ltd. of London for the manufacture and installation of a 120-mile trial length, using loading material supplied by the Western Electric Company and applied and treated under the direction of Western Electric engineers. In October 1923 this experimental length was laid in deep water near the south shore of Bermuda. The trial installation tests were so satisfactory that the Western Union company arranged for the manufacture and installation of a 2300-mile cable to connect New York with Horta in the Azores. As with the trial length, the loading material was supplied by the Western Electric Company, and it was applied and treated under Western Electric supervision.

The new cable was laid during September 1924. After refined adjustments in the terminal apparatus, a speed of over 1900 letters per minute was obtained. This speed is about four times the carrying capacity of an ordinary non-loaded cable of the same length. At this point a brief statement of general theory is indicated: The effect of the inductance is to oppose the setting up of a current and to maintain it once it has been established, thus preserving a definite wave front as the signal impulse travels over the cable. The individuality of the signal impulses is retained, and thus the much higher speed becomes possible.

The permalloy loading material was applied in tape form in a close helix around a stranded copper conductor. The tape was 0.006 inch thick and 0.125 inch wide. The alloy was composed of about 79% of nickel and 21% of iron and a small amount of manganese, suitably heat treated. It provided an inductance of about 54 millihenrys per mile, slightly over 12 times that obtained by the use of iron wire in the Cuba cables previously described. The permeability of the loading was about 2300, or about 20 times that of the iron wire used on the Cuba cables. An important feature of the cable not previously mentioned was a layer of viscous insulating material (under the regular gutta-percha insulation) which protected the strain-sensitive permalloy from the stresses caused by hydrostatic pressure in the great depths of the ocean.

Demand for other high-speed loaded submarine cables quickly followed the successful demonstration of the New York-Horta cable and several were installed during 1926, reaching a total of about 15,000 miles of high-speed cables. The new installations included the Horta-Emden cable manufactured and installed by the Norddeutsche-Seekabelwerke A.G. for the Deutsch Atlantische Telegraphengesellschaft, and the New York-Bay Roberts-Penzance cable manufactured and installed by the T. C. & M. Company for the Western Union Telegraph Company. These particular cables used an improved form of permalloy supplied by the Western Electric Company containing about 80% nickel, 17.5% iron, 2% chromium, and 0.5% manganese. This alloy had an initial permeability of about 3700 and provided a higher impedance loading than that used on the first high-speed cable. In consequence, the newer cables were capable of speeds of about 2500 letters per minute.

Other high-speed continuously loaded cables, installed in 1926 and subsequent years, used permalloy material manufactured under Western Electric Company patent license, in some instances under a special foreign trade name.

Comprehensive information regarding all features of the high-speed cable projects specifically mentioned above is given in two papers by O. E. Buckley, published in 1925[44] and 1928[45], respectively.

In passing, it should be observed that the permalloy loaded cables under discussion were not intended for, and were not suitable for telephone communication. For this purpose, a new family of magnetic alloys, the perminvars, was developed.[46] Their composition centered on 47% nickel, 25% cobalt, 20% iron, 7.5% molybdenum, and 0.5% manganese. When used as a thin loading tape, this alloy has electrical and magnetic properties especially suitable for telephone transmission, including very low hysteresis which is very advantageous in the control of all forms of non-linear distortion.

A Proposed Transatlantic Telephone Cable

During the late 1920's, there was worked out a design of a perminvar loaded cable suitable for voice frequency telephony between Newfoundland and Ireland (1800 nautical miles). It was of the single core type with a concentric return conductor. Four layers of very thin perminvar tape provided the loading, and the loaded conductor was insulated with paragutta. The suitability of the design for use in deep water was verified by temporarily dropping a 20-mile length on the sea floor in a deep water section of the Bay of Biscay.

The general business depression of the early 1930's resulted in a postponement of the cable project because of its great cost. Later on the project was postponed indefinitely because, in the face of improvements in transatlantic radio telephone communicaion, so expensive a cable to carry a single conversation could no longer be justified.

Additional information regarding this cable project is included in Dr. O. E. Buckley's 1942 paper, "The Future of Transoceanic Telephony," constituting the 33rd Kelvin Lecture before the Institution of Electrical Engineers.[47]

Continuous Loading for Paper Insulated Telephone Cables

Tape and Wire Loading: When permalloy and perminvar first became available, theoretical studies were undertaken to determine the prospects of economic competition with coil loading on ordinary paper insulated telephone cables. Special consideration was given to the use of the magnetic alloys in situations where coil loading is most expensive, namely, in submarine intermediate cables at river crossings, many of which involve high-frequency carrier telephone operation. None of these studies, however, gave sufficient promise to warrant commercial development work.

Electroplated Permalloy Loading: During the middle 1920's, the Bell Telephone Laboratories started research work on a radical new concept of continuous loading using electroplated permalloy, which gave some promise of being less expensive than magnetic alloy tape or wire loading. The process involved the electrolytic deposition simultaneously of suitable proportions of nickel and iron on the copper conductor, and the use of special heat treatments to obtain the desired characteristic (magnetic and electrical) properties of permalloy. In due course, methods were devised for separating the concentric magnetic layer from the conductor, and for breaking it up into longitudinally discontinuous pieces, so as to secure the most advantageous properties for telephone transmission service, and to provide mechanical flexibility in handling.

The experimental work was concentrated on small copper conductors, partly because of the more simple process problems, and partly because such combinations appeared to have the best prospects of competing with coil loading from the plant cost standpoint. (N.B.—The amount of permalloy loading material required to provide a specified inductance per unit length, and its cost, is a direct function of the conductor diameter.)

The requirements for and the possibilities of using electroplated loading in the exchange area services were given priority in the theoretical cost studies—largely because of their extensive use of small conductor cables. These studies indicated some attractive possibilities of using light-weight electroplated loading on fine wires (26 and 24-gauge) as substitutes for larger size wires without loading, provided satisfactory solutions could be worked out for the circuit balance and magnetic instability problems. The balance problem arises from the difficulty of securing sufficient uniformity among the loaded conductors used as wire and mate in the individual pairs. This is complicated by the sensitivity of the permalloy continuous loading to magnetization by steady and intermittent superposed signaling currents. On the larger-size exchange cable wires that are not now used extensively without coil loading, the comparative cost estimates were not attractive for the electroplated loading.

The inflexibility of continuous loading is an adverse general factor, since it is not feasible to decrease or increase the weight of the loading after manufacture, in order to accommodate changes in transmission requirements made desirable by changes in performance standards or alterations in circuit layouts. Also, there would be inflexibility in conforming to changing requirements in complement sizes of loaded circuits in areas where it is necessary to have loaded and non-loaded circuits within the same cable sheath.

Theoretically, one of the flexibility limitations of the continuous loading could be reduced by using coil loading in combination with it, in order to extend its transmission range. However, this would reduce the width of the transmission band below that obtainable with the coil loading on a circuit not having continuous loading—the decrease in effective cutoff being a complex function of the ratio of distributed inductance to coil inductance. Combinations of high cutoff, low impedance, coil loading with low inductance continuous loading could be designed to have satisfactory band width properties. For a given grade of transmission performance, however, such combinations appear to be inherently more expensive than coil loading or continuous loading by themselves.

The experimental work on electroplated continuous loading for exchange area cables was carried on somewhat intermittently during the 1930's. At no time did the prospects of securing satisfactory over-all transmission performance, at costs which would encourage competition with coil loading, appear to be sufficient to warrant an all-out sustained attack on the many difficult technical problems involved. Although the development project has not been permanently abandoned, it had to be discontinued in the late 1930's on account of the great pressure of more urgent work.

The use of electroplated loading as a substitute for coil loading on toll cables, or on incidental cables in open-wire lines, did not appear to be attractive when the cost estimates and the complex requirements on circuit balance, stability, non-linear distortion and flexibility were taken into account.

Summary

Enough has been told in the preceding pages to support the earlier statements regarding the low importance of continuous loading in the growth of the Bell System, relative to that of coil loading. Obviously, the success attained by the intensive development and in the very extensive use of economical types of coil loading is an important factor in this situation. That these extent-of-use relations are not due to a lack of interest in continuous loading is well demonstrated by the Bell System initiative in developing the permalloy continuous loading that made high-speed telegraphy practicable in long submarine telegraph cables, and by the other development work summarized in this review.

PART VII: EXTENT OF USE AND ECONOMIC SIGNIFICANCE

Introduction

Up to now, this account of coil loading has been in terms of individual developments and their significance with respect to the prior art and current developments in related fields, with occasional information regarding their importance and extent of use.

It is now appropriate to supply and analyze some general statistics regarding the total amount of loading which has been used, in a rough appraisal of the importance of coil loading in the growth of the Bell Telephone System. Some important qualifications of the statistics are commented upon in advance of the presentation of actual figures.

The statistics here given and discussed are for the most extensive and most important applications of coil loading, namely, for voice-frequency loading over cable circuits. They are grouped in two principal categories: (1) non-phantom type coils used on non-quadded exchange area cables, and to a relatively very small extent on toll cables, and (2) side circuit and associated phantom coils used on quadded long-distance and interurban toll cables, and to a relatively very small extent on entrance cables in open-wire lines and on long quadded exchange cables.

The figures used are based on production statistics up to the end of 1949. The important significance of the production figures is that they measure at the time of manufacture the current demands for additional loaded facilities required by the growth of the telephone system, and the up-to-then accumulated total demand. In general, the loading coils were manufactured to meet specific customers' orders; manufacture for merchandise stock in anticipation of future orders was seldom undertaken, except during periods of extraordinarily high, sustained, demand. On this basis practically all of the coils that were manufactured were installed in the telephone plant.

The production statistics of course include a considerable number of coils which were installed shortly after manufacture and which were taken out of service many years later to facilitate the use of improved transmission systems that required different types of coils, or to permit the use of carrier systems on the unloaded toll cable circuits. In general, complete potting complements were not taken out of service in preparation for carrier systems operation; i.e., a large fraction of the disconnected loading coils remain in the cases in which they were originally potted and installed, and the other coils in the same cases are still in service. It is important to remember that the displaced loading coils played an important part in the improvement and growth of telephone service in their own period of commercial use. The unavailability of statistics regarding displaced loading makes it impossible to supply accurate information regarding the total number of loading coils now being used for regular telephone service. It seems probable, however, that about 80% or more of all the toll cable coils that have been manufactured are in service, or installed in circuits which will be used as soon as traffic growth requires them. The corresponding percentage figure for exchange area coils is probably higher. The number of loading coils taken out of service because of incipient defects that were not detected in the factory inspection tests, or which became unserviceable in consequence of service injuries, or which have been junked because of obsolescence, is a very small fraction of the total number of coils that have been manufactured for Bell System use

General Production Statistics, Voice-Frequency Cable Loading

Total Production

The grand total production figure (up to the end of 1949) for all types of voice-frequency loading coils for Bell System use is of the order of 20.7 million. Approximately 54% of this total (about 11,270,000 coils) are non-phantom type coils, used almost entirely on exchange area non-quadded cables. Nearly 9,500,000 coils are side circuit or phantom loading coils used on quadded toll and toll entrance cables. Approximately three-quarters of the grand total have been manufactured during the last two decades.

The greatly varying rates in the growth of loading coil production are shown, (a) in terms of accumulated total production through 1949 in

Table XIX and (b) in annual totals during the period 1920–1949, plotted in Fig. 35.

Annual Production Totals

In general, the average and peak figures of annual production prior to 1920 were very small relative to those in the 1920–1949 period covered by the chart. For example, the maximum annual production of side circuit and phantom toll cable coils prior to 1925 was in the war year 1918,* and the maximum annual production of non-phantom exchange area cable coils prior to 1923 was in the war year 1917.† Thus, with occasional exceptions, the production data for the years prior to 1920 could not be accurately plotted on the chart without using a confusing scale.

TABLE XIX
ACCUMULATED TOTAL PRODUCTION(1)—VOICE FREQUENCY CABLE LOADING COILS (IN MILLIONS OF COILS)

At End of Year	Side Circuit(2) and Phantom Coils	Non-Phantom Coils	Total
1915	0.31	0.22	0.53
18	0.52	0.30	0.82
20	0.64	0.35	0.99
22	0.73	0.39	1.12
1924	0.95	0.53	1.48
26	1.49	0.79	2.28
28	2.69	1.32	4.01
30	5.59	2.06	7.65
1934	6.44	2.60	9.04
38	6.65	3.21	9.86
40	7.04	3.81	10.85
42	7.82	5.15	12.97
1944	8.14	5.48	13.62
46	8.49	6.69	15.18
48	9.33	9.76	19.09
49	9.46	11.27	20.72

Notes: (1) All production figures are approximate values.
(2) Commercial production of side and phantom coils did not start until 1910. Up to that time non-phantom coils were used for toll cable loading (and for exchange area cables).

In the beginning, the use of loading was small relative to its subsequent use because the Bell System cable plant was small. For nearly a decade the expanding toll cable plant used fewer coils than the exchange plant. From then on, in the two-decade period 1913–1932, toll cable loading dominated

* 117,000 coil peak in 1918; 187,000 coil total in 1925.
† 33,000 coil peak in 1917; 38,000 coil total in 1923.

in the extent of use, reaching its all-time peak in growth during 1930. The four-year period of most rapid expansion of toll cable loading coincided with: (a) the full scale introduction of four-wire repeatered loaded (H44-25) circuits for long haul long-distance facilities, (b) the introduction of permalloy-core loading coils which resulted in large loading economies, and (c) the planned use of relatively large circuit-groups in order to speed up the long-distance service.

The business depression of the early 1930's terminated the rapid expansion period in all types of loading. Several years later, when business conditions

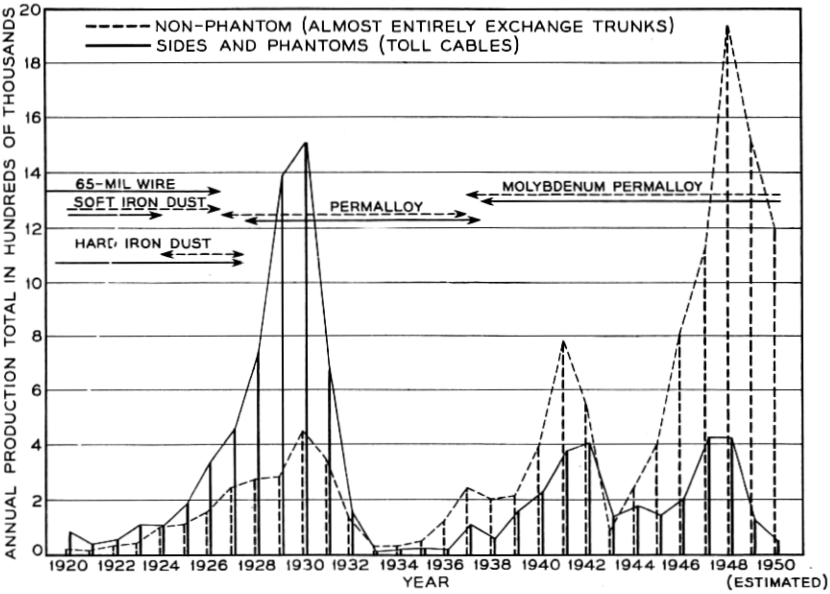

Fig. 35—Annual production totals of voice-frequency cable loading coils for Bell Telephone facilities.

improved sufficiently to require another large expansion in the toll cable facilities, the demand for new long-haul circuits was taken care of generally by the use of Type K carrier systems on non-loaded cable pairs and pairs from which loading was removed; and the use of new toll cable loading was largely restricted to short-haul repeatered and non-repeatered circuits. Thus it happened that, during the 1939–1942 period of rapid plant expansion, the production of exchange area loading coils substantially exceeded that for toll cable loading in the struggle to meet the demands for additional facilities required by the war effort.

The post-war drive to meet the greatly increased demands for long-distance telephone service, and the provision of a tremendous amount of new exchange plant to take care of more than eleven million new Bell System telephone stations, made it necessary to build up the production rates to higher values than those during the war period. An important factor in the new heavy demands was the desire to restore the speed of service to the pre-war standards.

The post-war demand for exchange area loading has been greatly in excess of that in any previous spurt in demand, reaching its peak value during 1948, and has been very large in relation to the toll cable loading requirements. The post-war rapid build-up of a backbone network of coaxial cables, together with the expanding use of carrier systems in existing and new cables of the conventional types, and the introduction of microwave radio relay systems have held down the demand for new toll cable loading to relatively small quantities for use on relatively short circuits.

Relative Costs, Toll and Exchange Loading

Production statistics by themselves do not indicate the relative economic importance of exchange area and toll cable loading. Except in the early years when coils of the same size were used for both types of loading, the toll cable loading coils have been considerably more expensive than the exchange area loading coils. During the periods of maximum production and use portrayed in Fig. 35, the average prices per potted toll cable loading coil have ranged up to about twice or three times as large as those per potted exchange area coil. Consequently, the total plant investment in toll cable loading is substantially greater than the total investment in exchange area loading, notwithstanding the somewhat greater total use of exchange area loading, as indicated by the production statistics. This is consistent with the fact that more expensive types of cable are used for the toll circuits and the service requirements are more difficult.

Analysis in Relation to Core Materials

There now follows a rough breakdown of total production in terms of core materials, in recognition of the importance of the cores in determining the coil performance characteristics and costs:

In general, the production percentage figures in Table XX do not discriminate between types of facilities (toll or exchange area). If separate percentage-of-total figures should be derived for toll facilities and for exchange area facilities, those for toll facilities would substantially exceed the tabulated figures for total iron-wire, iron-dust, and permalloy-powder core loading coils, especially in the case of the latter, and the percentage-of-total figure for exchange area molybdenum-permalloy core coils would greatly exceed that for toll cable loading.

In considering the two different permeability types of iron-wire and of iron-dust core-materials, it is important to note that in each case the lower permeability material had a much more extensive total use than the higher permeability material, and that it was used in the more important facilities.

It is of special interest from the plant-cost standpoint that nearly two-thirds of the compressed molybdenum-permalloy powder core coils (up to the end of 1949) are the reduced cost designs using Formex-insulated conductors in their windings, this being an important factor in coil-size reduction. The other molybdenum-permalloy core coils are larger-size coils using a combination of textile and old type of enamel conductor-insulation.

It is highly significant with respect to the economics of the Bell System plant growth that over one-third of all voice-frequency loading coils manufactured up to the end of 1949 are of the lowest-cost types ever standardized

TABLE XX

ESTIMATED DISTRIBUTION OF ACCUMULATED TOTAL LOADING COIL PRODUCTION UP TO END OF 1949 IN TERMS OF CORE MATERIALS

Core Material	Percentage of Total Loading Coil Production	Approx. Period (1) of Commercial Manufacture
Fine Iron-Wire	1.5	1901–1927
Compressed Powdered-Iron	10.5	1916–1928
Compressed Powdered-Permalloy	33.	1927–1938
Compressed Powdered Molybdenum-Permalloy	54.	1937–
Non-Magnetic (Carrier loading)	2.	1920–

Note (1): For more definite dates in relation to different types of facilities, and in relation to the two different permeability values of the iron-wire and iron-dust materials, reference should be made to Table III (page 158).

for general use. This total includes about 60% of the total production (through 1949) of all types of exchange area loading coils.

Loaded Circuit Mileage Estimates

To add some substance to the significance of the production statistics on voice-frequency loading, it is desirable to record some rough estimates regarding the aggregate length of the cable circuits which have been loaded.

For exchange area loading, a weighted average coil-spacing between the 6000 ft. and 3000 ft. values now standard can be assumed. Considering the time elements in the evolution of loading practices, as discussed in Part III of this review, it is reasonable to assume an average coil-spacing somewhat longer than the mean value of the two standard spacings, say about 5000 ft. On this assumption, the aggregate loaded cable-mileage which corresponds with an assumed production total of 11,200,000 coils is of the general order of 10,500,000 pair miles.

The 3000-ft. spacing has been used much less extensively on toll cable circuits than in the exchange plant, on which basis the weighted average coil-spacing for quadded toll cable loading is somewhat longer than the weighted average value for exchange area loading. Within the accuracy required for the present general estimates, 5500 ft. seems to be a reasonable estimate for the average coil spacing in quadded toll cable loading. On this basis, and assuming a production total of about 9,500,000 side circuit and phantom coils, the aggregate loaded toll cable circuit-mileage is of the order of 9,900,000 miles. Keeping in mind the substantially universal use of quadded cables and of phantom group loading for long-distance and inter-urban toll cables, the aggregate mileage of loaded toll cable quads is of the order of 3,300,000 miles. Because of the extensive installation of loaded H 44-25 four-wire repeatered circuits during the period 1925–1931, the *loaded "facility"* mileage-aggregate is considerably less than the *loaded "circuit"* mileage-figure above given. Meanwhile, much of the loaded H 44-25 4-wire circuit mileage has been converted for short haul two-wire circuit usage, and much has been unloaded to permit the operation of Type K carrier systems. The available data on these plant changes do not permit accurate estimates regarding the mileage of loaded four-wire and two-wire types of toll cable circuits now in commercial use. It is again appropriate, however, to call attention to the important part in the growth and improvement of the telephone service which the displaced loading coils played in their own period of commercial use.

Economic Significance

Since loading has been used only when it permitted the use of cheaper facilities than would otherwise have been feasible, the great economic value of loading in the growth of the Bell Telephone System is indicated by the circuit mileage-figures given above. Other factors, however, would have to receive consideration in a complete appraisal, namely, the contributions of loading to nation-wide customer satisfaction that have resulted from improved transmission performance and higher speed of service. In turn, these factors themselves have been greatly influenced by the unit plant-cost reductions made possible by the use of loading.

For example, if loading had not been available when new or additional facilities became desirable, it is highly questionable as to whether it would have been economically feasible to work to the high-grade transmission-performance standards that have been readily achieved at reasonable costs with the cheaper loaded facilities. Moreover, it is even more questionable whether it would have been economically feasible to provide as many facilities without loading as were actually installed on a loaded basis.

Because of the speculative uncertainties involved in making assumptions regarding relative transmission-performance and relative plant-size, with and without loading, and because of the practical difficulties involved in evaluating in monetary terms the differences in transmission performance and in speed of service, no complete appraisal of the economic value of coil loading has ever been attempted for the exchange area plant. These, and additional special complications subsequently discussed, have also prevented accurate appraisals of the economic value of toll cable loading.

Exchange Area Loading

During the first two decades or so of the use of exchange area loading, rough estimates of its economic significance were sometimes made by comparing the total costs of the loaded facilities with the much higher cost of the non-loaded cable plant which otherwise would have been required to meet the same trunk-loss limits at 800 or 1000 cycles. Depending on the period under study, the estimated aggregate plant-cost reduction figures ranged up to and beyond $100,000,000. These estimates included the plant-cost reductions that resulted from the use of less expensive pole lines for aerial cables, and less expensive conduit systems made possible by utilizing a smaller total number of cables, each having a larger number of pairs. If similar studies should be made now, the corresponding hypothetical plant-cost reduction figure would probably be many times as large as the figure previously mentioned. These figures ignore the superior over-all transmission in loaded trunk plant that results from the much more favorable distortion characteristics. Also they assume equal sizes of trunk plant, with and without loading. Because of these qualifications, and because of the magnitude of the cost-reduction estimates, it is difficult to define their real significance.

A better understanding may perhaps be obtained from consideration of the cable data given in Table XXI, following. This compares some of the most important types of cable on which loading has been used with the types which would probably have been required for transmission reasons, if loading had not been available.

The large savings which loading permitted in the use of cable copper and in the amount of lead sheath per cable pair, are indirectly indicated by the tabulated data. Moreover, with loading on finer-wire cables a given total number of facilities can be provided with a much smaller total number of cables, thus permitting the use of less expensive conduit systems. This factor is extremely important in some routes of congested sections of large metropolitan areas such as Manhattan and the loop section in Chicago, where there might well be a question as to the *physical practicability*, disregarding costs, of installing enough large-conductor, non-loaded cables to provide as many facilities as those made available in existing loaded small-conductor cables.

Toll Cable Loading: An accurate appraisal of the economic value of toll cable loading would have the specific complications mentioned above in the discussion of exchange area loading, and in addition certain intricate difficulties briefly discussed below.

In the aggregate, a very much larger amount of loading has been used on repeatered facilities than on non-repeatered voice-frequency circuits. The over-all plant-cost reduction and the transmission and speed of service

TABLE XXI

LOADED AND NON-LOADED EXCHANGE AREA CABLES
RELATIVE USE OF DIFFERENT TYPES

Degree of Use[a]	Loaded Exchange Area Cable			Alternative Types of Non-Loaded Cables		
	Conductor Size B & S ga.	Weight-Lbs.[1] Copper Pair-Mile	No. Pairs Full Size Cable	Conductor Size B & S ga.	Weight-Lbs.[1] Copper Pair-Mile	No. Pairs Full Size Cable
Very Extensive	22	21.0	909[2]	19 16	42.0 84.3	455[2] 152[3]
Very Extensive	24	13.2	1515[2]	22 19	21.0 42.0	909[2] 455[2]
Substantial	19	42.0	455[2]	16 13	84.3 168.8	152[3] 75[3]
Small	26	8.3	2121[2]	24 22	13.2 21.0	1515[2] 909[2]

Notes: (1) These weights include a small allowance for the effect of pair-twist and stranding, in increasing the conductor length, relative to the cable sheath-length.
(2) High-capacitance cables–(approx.) 0.082 (±) mf/mi.
(3) Low-capacitance cables–(approx.) 0.066 mf/mi.
(a) In the very extensive installations of exchange area loading during the 1928–1949 period, a very large fraction of the total use was on 22 and 24-gauge cables in nearly equal quantities.

improvements that have resulted from the use of loading in combination with voice-frequency repeaters must of course be jointly credited to the repeaters and the loading. Since as yet no rationally acceptable procedure for allocating the pro-ratio credits has evolved, very questionable arbitrary allocations would become necessary. Moreover, very debatable uncertainties would be involved in making assumptions regarding the types of facilities which would have been employed if loading and repeaters could not have been jointly used on small-gauge toll cable conductors.

In appraising the economic importance of toll cable loading it is therefore necessary to revert to general terms, namely, its great extent of use as indicated by the previously discussed production and circuit-mileage statistics.

In short-haul, non-repeatered, toll cable circuits, loaded 19 ga. conductors are generally used for service which would have required 16 or 13 gauge conductors without loading. The plant-cost savings in cable, copper, and lead are much greater per unit length than the average savings realized in the loaded exchange area cables. The aggregate mileage in this type of toll plant, however, is but a small fraction of that in the loaded exchange area plant.

Until the commercial exploitations of lower-cost carrier telephone systems started during the late 1930's, the loaded repeatered voice-frequency cable facilities satisfactorily met the quantitative and qualitative needs for the rapidly expanding long-distance telephone services along dense traffic routes where the use or the extension and expansion of the open-wire plant would have been unduly expensive, even on a carrier basis. In such backbone routes, and also along slow-growing tributary routes, and for short-haul toll facilities, the repeatered and non-repeatered loaded toll cables have provided more economical service than could have been obtained in an open-wire plant, and with increased dependability. Also, as previously indicated, larger circuit groups have been economically feasible, with valuable results as regards the speed of service.

In concluding this part of the review, it is noteworthy that the phantom-group loading almost universally used on voice-frequency repeatered and non-repeatered toll cable facilities is a major factor in the plant economies that have resulted from the commercial exploitation of the phantom working principle. These particular plant-cost savings constitute an important contribution to the aggregate economies achieved by toll cable loading.

PART VIII: SUMMARY AND CONCLUSION

General

The story of coil loading told in the present review is one of continuing evolution whereby its inherent capabilities have been substantially realized in its adaptation to the growing and changing needs of exchange area facilities and of interurban and long-distance communications by wires, throughout the Bell Telephone System. Also, full advantage has been taken of the opportunities offered by the development of better core-materials and new manufacturing techniques and tools to improve the loading apparatus and reduce its cost.

It was inevitable that by far the most important uses of coil loading would be for voice-frequency telephony over cable circuits. The very low ratio of distributed inductance to distributed capacitance, incidentally resulting in low impedances, and the relatively high conductor resistances of cable circuits, gave loading its greatest opportunities in exercising its natural functions of reducing the circuit attenuation and attenuation-frequency distortion. Clearly appreciated from the beginning, these possibilities have been advantageously realized to a very great extent, and they still have substantial economic importance for future voice-frequency applications in the continuing growth of the exchange area non-quadded cable plant, and short, quadded interurban toll cables.

Open-Wire Loading

The higher ratios of distributed inductance to distributed capacitance in the open-wire lines made the reduction of attenuation-frequency distortion a relatively minor objective in the use of loading, attenuation reduction being the primary objective. Incidentally, the relatively high impedances of the non-loaded lines that resulted from their higher ratios of inductance to capacitance limited the attenuation reduction obtainable by coil loading to smaller percentage values than those obtainable on cable circuits. However, full advantage of these important, though limited, possibilities was realized in the expanding open-wire plant during the decade that preceded the commercial introduction of vacuum-tube repeaters. The early uses of these repeaters on open-wire lines were on circuits having improved loading designed especially for use in conjunction with repeaters. In 1915, this combination of loading and repeaters made transcontinental telephony economically feasible, and for several years greatly increased the demand for loading. The importance of open-wire loading soon started to decline, however, as a result of improvements in the repeaters, their circuits, and auxiliary networks, which made it possible to secure considerably better voice-frequency transmission on long lines at a lower total cost by discarding loading and using more repeaters. The climactic event in this new trend was the beginning of the operation of the first transcontinental circuits on a non-loaded basis during 1920. During the middle and late 1920's the general removal of open-wire loading was expedited to increase the plant flexibility and facilitate the commercial exploitation of carrier telephone and telegraph systems over non-loaded lines.

Since, for transmission-cost reasons, it is not feasible to develop suitable loading for long lines over which carrier systems are operated, there is no reason to expect any new leases of life for open-wire coil loading. Notwithstanding its small extent of use relative to that for cable loading, and the relatively short period during which it was standard practice, open-wire loading was a necessary and a vitally important factor in the rapid expansion of long-distance telephony that began nearly five decades ago.

Toll Cable Loading

The pattern of the commercial evolution of loading practices for long-distance cable systems has been generally similar to that for open-wire loading, but with important quantitative and qualitative differences, and especially in the relative time-elements. These various differences have been mainly due to the previously mentioned inherent differences in the basic transmission properties of non-loaded cables and non-loaded open-wire lines.

Prior to the availability of vacuum-tube repeaters, loading was an essential factor in the establishment of a very important expanding network of storm-proof, intercity, toll cables; coarse-gauge conductors and expensive coils were used for distances ranging up to about 250 miles, 16 ga. conductors and less expensive coils being satisfactory for terminal business over short distances. Without using loading, these early toll cable systems would not have been economically feasible.

In the early uses of repeaters on toll cables the cable circuits also used loading. These combinations permitted improved transmission performance and important extensions in transmission range. In this general connection, it is of interest to note that it was not economical to use non-loaded conductors for toll cable transmission until cable carrier telephone systems became available about two decades after the commercial introduction of the vacuum-tube repeater. For voice-frequency transmission, the use of repeaters without loading would have been unduly expensive, due to the high costs of the additional repeaters and the much more expensive distortion-correcting networks and regulating networks that would have been required.

In the early part of the period that intervened between the introduction of vacuum-tube repeaters and of cable carrier systems, the substantially continuous development of improved loading, and of improved repeaters and auxiliary equalizing and regulating networks, provided improved facilities of several different types especially proportioned on a minimum cost basis to meet the transmission-service needs of different geographical distances.

High-velocity, four-wire, H 44-25 19 gauge circuits were very extensively used for long-haul facilities ranging up to about 2000 miles in length. It is of interest that the timely completion of the development of the first cable-carrier system stopped the contemporary efforts to make additional improvements in the H 44-25 voice-frequency loaded four-wire circuits so that they would be suitable for transcontinental distances. These improvements would have involved the use of velocity distortion corrective networks.

Nineteen gauge two-wire circuits having lower-velocity, higher-impedance, loading than that employed on the above mentioned four-wire circuits were very extensively used for short-haul repeatered and non-repeatered facilities.

A large curtailment in the demand for loading on new long cable circuits immediately followed the commercial exploitation of the Type K cable-carrier system, which started during the middle 1930's. The drastic nature of this impact was subsequently increased by the standardization of a still more economical (K2) cable carrier system,[48] and by the post-war extensive installation of coaxial cable systems. The very recent development of a relatively inexpensive short-haul carrier system (Type N), which uses two pairs in the same cable for its opposite-direction paths, promises an additional substantial reduction in the need for new loaded toll cable facilities, even for short distances. However, it seems probable that the demand for new loading may continue indefinitely on a low-level basis for more or less special short-haul situations where carrier telephony may be more expensive.

During the past two decades or so, loading cost-reduction has been carried so far that the prospects of further substantial cost-reductions are not now in sight. It seems improbable that any further design cost-reduction could be large enough to reverse the present general trend towards a large dependence upon carrier telephony for new short-haul toll cable facilities.

Exchange Area Loading

During the period covered by the present review, telephone transmission over exchange area cables has been entirely on a voice-frequency basis. Moreover, the use of vacuum-tube repeaters in conjunction with loading (or on non-loaded cables) has been statistically insignificant in comparison with the very extensive use of loading. In consequence, exchange area loading does not have to share with developments in repeaters and in carrier systems the great credit which it has earned with respect to the improvement of exchange area transmission performance and the reduction of plant cost.

The simple pattern in the evolution of exchange area loading practices, relative to those for toll cable loading, is of course basically due to the shortness of the circuits and the relatively uncomplicated service-requirements.

In certain important respects, the improvements achieved by the nearly continuous development work are generally similar in the two types of loading, notably: (1) the improvement in transmission quality obtained by increasing the transmission band-width, and (2) the successive facility-cost reductions resulting from the successive developments of lower-cost loading apparatus. These plant-cost reduction activities were carried out to a greater degree in the exchange area loading. It is especially noteworthy that the most important apparatus-cost reduction developments were completed in time for exploitation during periods of peak demand for new coils.

With respect to the effects of other developments in reducing the demand for exchange area loading, the introduction of improved subscriber sets during the 1930's warrants special mention. By permitting higher losses in the trunks, somewhat longer non-loaded trunks could be used.

Looking towards the future, the prospective use of a new low-cost repeater of an entirely new type (El telephone repeater) is expected to reduce the demand for the heavier weights of loading. Also, the new Type N short-haul cable carrier system, referred to on page 1240, may have some considerable use on relatively long non-loaded exchange trunks along heavy traffic routes. It is also of interest that a greatly improved telephone set (500-type) now in the final stages of development will probably reduce the need for loading on long subscriber loops.

Although it is not possible at present to make accurate quantitative estimates of the ultimate effects of the just mentioned new developments upon the future demand for new exchange area loading, there is no reason to believe they will be so drastic as the effects of carrier system developments upon the ultimate future demand for toll cable loading. It seems especially probable that the low-cost H-spaced loading will continue indefinitely to be an important factor in the economy of design of new exchange area cable plant to provide telephone service for a continually increasing number of subscribers.

Loading for Incidental Cables in Open-Wire Lines

The impedance-matching loading systems used on entrance and intermediate cables have made vital contributions to the excellence of the over-all performance of the open-wire transmission systems. These are of great importance relative to the amount and the cost of the loading actually used.

In consequence of the increasing utilization of open-wire carrier systems, the voice-frequency loading is much less important than it was two to three decades ago. However, an indefinitely continuing, though small, demand seems certain, because of the valuable transmission improvements which the loading makes available at low cost.

The demand for additional carrier loading is expected to continue in a somewhat rough proportion to the number of additional open-wire carrier systems that are installed. However, in consequence of the high cost of the loading for multi-channel systems (which is much higher than formerly in consequence of greatly increased labor and material costs), it seems probable that more and more consideration will be given (especially on "long" incidental cables) to the use of lower-cost transmission-improvement treatments, even though they are not so good as loading in certain respects.

Cable Program Circuit Loading

During the 1930's and early 1940's, there were extensive applications of loading on the cable sections of nation-wide chain networks used for transmitting AM broadcast program material. Now that high-grade program transmission circuits may be obtained by carrier methods on broadband cable carrier systems, the future demand for 8-kc loaded cable program circuits will be largely limited to special situations where the carrier program circuits are not economical.

It is expected also that there will be a moderate, continuing demand for the recently developed loading that provides a 15-kc band for the transmission of FM program broadcast material, principally on studio-transmitter circuits, and on end links in toll cable networks, where carrier program circuits may be uneconomical.

Continuous Loading

Over the years, a substantial amount of exploratory development work on continuous loading for ordinary types of paper-insulated cable has been done, but with negative results so far as commercial applications in the Bell System are concerned; it has not yet been found feasible to compete with coil loading in service performance and cost.

However, continuous loading has had a few applications in single core submarine cables, in deep water installations where coil loading is not feasible. The three 1921 cables between Key West and Havana are the only continuously loaded cables to become a part of the Bell System. They use iron wire as the loading material. Several years later, permalloy tape continuous loading developed by the Bell Telephone Laboratories made possible a great increase in the message-carrying capacity of transoceanic telegraph cables. During the middle 1920's, an aggregate of about 15,000 nautical miles of the new type, high speed, cable was installed for use by non-affiliated telegraph and cable companies.

Late in the 1920's, a perminvar type loaded cable suitable for voice-frequency telephony between Newfoundland and Ireland was developed by the Bell Telephone Laboratories. The business depression of the early 1930's intervened to cause a temporary postponement of the project; later on, an indefinite postponement resulted from improvements in transatlantic radio-telephony.

From the foregoing, it is clear that the importance of continuous loading has been low relative to that of coil loading in the growth of the Bell Telephone System.

Conclusion

During the half century that has intervened since its invention, coil loading has played a very important part in making nation-wide telephony possible and in helping to make possible the great growth in the business which has occurred. Although the application of coil loading to new circuits has now been greatly curtailed, due in large part to the development of carrier systems, coil loading still has an important field of application in exchange area telephone plant and for some rather special circuit applications.

The reader may take it for granted that the organization which has developed and used loading to the maximum degree of utility in the present telephone plant will be on the alert in the future to make full use of loading in situations wherever loaded circuits provide a more economical solution of the transmission service needs than the other available procedures. It is also reasonable to expect that new types of loading and new loading apparatus will be developed to the extent that may be economically warranted.

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