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FRANK B. JEWETT

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THE CONQUEST OF DISTANCE BY WIRE TELEPHONY

A Story of Transmission Development From the Early Days of Loading To the Wide Use of Thermionic Repeaters

By THOMAS SHAW

Editorial Foreword

SOME few months ago, in anticipation of the retirement of Dr. F. B. Jewett, an informal committee undertook to discover such action as the Journal might appropriately take to commemorate the event. The various possibilities finally narrowed down to one, a historical review appearing for various reasons to be the most suitable.

The period to be covered by the review was not difficult to fix. For sentimental reasons its beginning should naturally tally with Dr. Jewett's appearance upon the scene of telephone engineering, but as this followed close upon the invention of the loading coil, such a beginning had more than sentiment to recommend it.

The review is carried through the creation of the high vacuum tube to the demonstration by large scale practical application that this was the keystone of an art which would open up a new era in transmission of the voice. An examination of the record shows that the last twenty-five years of the art of telephone engineering have been adequately chronicled from year to year, almost from month to month, in the technical press. The immediately preceding period of approximately fifteen years covered by the review was badly in need of a historian in spite of the fact that in some respects the events of those years were as significant as any that have occurred subsequently.

Such considerations led to the decision to record these events while the story as it stood in the minds of certain of the chief participants was readily available. But while a committee may reach a decision, it is likely to prove a poor instrument of accomplishment. In consequence, the task of compiling the history has fallen upon the shoulders of a single individual, and we believe a very competent one. Mr. Shaw is to be congratulated in capturing to an unusual degree the spirit of the period which intervenes between the introduction of the loading coil and the completion of the first transcontinental line. He has compiled his history only after a painstaking review of the written record and many interviews with its surviving principal actors. Needless to say, he has been aided by the fact that he was, himself, a participant in much that he relates.

As in every effort of this sort, it has been necessary to set up rather definite boundaries in advance. The decision was reached deliberately to confine the present discussion to the broad phases of telephone transmission, with very little reference to the concomitant, and indeed related, developments and improvements such as occurred in the domains of substation apparatus, central office equipment, and operating methods.

Without striving for effect, and without forsaking a simple and easily comprehended engineering vernacular, Mr. Shaw makes the reader sense the momentous nature of the work in progress and the basic importance of the decisions under discussion. One sees in a new light, as he reads, the difficulties which were patiently but determinedly overcome in creating the first successful loaded phantom open-wire circuit; in reducing the crosstalk unbalance in early cables; in evaluating the relative merits of the multiple-twin and the spiral-four; and in obtaining the balancing networks needed to operate repeaters in tandem on a very long line. And, of course, there are other matters too numerous to mention here which are similarly dealt with. All in all, it is a recital whose simplicity is in sharp contrast to the intricate nature of much of the work it narrates.

And as one lays it down he feels a strongly renewed admiration for the executives who visioned, guided, counselled, and in the days of rough going had the courage to back their judgments, and more especially that of their engineers, to a magnificent extent.

We are now on the point of losing by retirement one of the best loved of these executives. Starting as a young recruit in 1904, through outstanding merit he was destined to rise so rapidly in responsibility as to become a very influential counsellor within a few years, and ever since has occupied a commanding position with respect to the Bell System's entire research and development program. No individual is more intimately associated with the scientific achievements of the System throughout the last forty years, in the minds both of the public at large and those within our organization. Under the circumstances, it is not easy to find an entirely adequate method of signalizing the respect and good-will we entertain toward him. But for a host of reasons—and for many more than the inherent modesty of the individual himself would allow to be pointed out—the following narrative is implicitly biographical. It must, therefore, bring back many cherished memories. Moreover, it stands as testimony to his excellent scientific judgment and courageous and sympathetic administration. It is an opportunity, therefore, which all welcome, especially the author and his intimate advisers, to dedicate this review to Dr. Frank Baldwin Jewett.*

* The text of this review is different in some degree from that published in monograph form on the date of Dr. Jewett's retirement.

Introduction

The universal telephone service now provided by the Bell System has become such a "taken-for-granted" factor in our every-day national business and social life that one may easily forget the existence of the many regional frontiers which greatly restricted the usefulness of the telephone as recently as three decades ago.

The technical developments which made economically practicable the complete elimination of these regional frontiers were worked out in this country during the first two decades of the century. In spite of their technical and social importance, there is still lacking a connected recital that sets forth the various coordinated efforts by which the difficulties inherent in the long distance transmission of the voice were gradually overcome. Substantial amplification would be required to do justice to the concurrent accomplishments of the engineers who worked on the related problems involving outside plant, equipment, traffic, apparatus, and manufacturing questions. Without the important contributions made by these engineers in the associated departments of the American Telephone and Telegraph Company and Western Electric Company, there could not have been complete success.

Mention should also here be made of the fact that during the period covered by the story, steady improvement of transmission was effected in subscribers' exchange services.

The story as it unfolds divides naturally into four parts. The first is concerned with the 1904–1907 period when the A. T. & T. Co. headquarters staff was located at Boston and includes a discussion of the then current state of the art as a general background for the subsequent developments. The second part has to do primarily with the important sequence of achievements of the 1907–1911 period in New York which step-by-step prepared the way for the development of transcontinental telephony. The third part is primarily concerned with the transcontinental project itself, including the planning of the project. The fourth and concluding part reviews the subsequent establishment of a Bell System backbone network of repeatered, non-loaded, 165 mil lines interconnecting the large cities, and includes the removal of loading from the transcontinental line.

CHAPTER I

1904 to 1907 at Boston

A Career Seeks the Man

IN the spring of 1903 Dr. George A. Campbell, then in charge of the work on "Loaded Lines and Theory of Telephone Transmission" in the Engineering Department of the American Telephone and Telegraph Company at Boston, visited Professor Harry E. Clifford of M.I.T. to inspect a 10,000 cycle generator that had just been acquired for some experimental work. While they were discussing the generator, a young instructor walked by. He was called back by Clifford and introduced to Campbell as Dr. Frank B. Jewett.

In the few minutes conversation that resulted, Campbell was much impressed with the charm of Jewett's personality and his alertness, high intelligence, and maturity. The thought flashed through his mind, "Here is the type of man we want in the Telephone Company." After Jewett had passed along, Campbell told Clifford his thoughts and impressions. The latter countered by remarking with evident satisfaction that Jewett was under contract to M.I.T. for the 1903–04 academic year.

The next year, however, Campbell renewed his efforts well in advance of the time for academic contract commitments and, in due time, Jewett visited the American Telephone and Telegraph Company engineering headquarters for an interview with Messrs. Hammond V. Hayes, Howard S. Warren, and G. A. Campbell. Warren, who was Campbell's immediate superior, was in charge of the so-called "Equipment Division," reporting to Hayes. At the time Warren had an authorization for a new man to work on protection problems, and he had become interested in Jewett as a prospect, in consequence of Campbell's recommendation. Hayes was one of the "Triumvirate" or Engineering Committee, that managed the Engineering Department in behalf of the Chief Engineer, Joseph P. Davis, then living in semi-retirement on account of illness.

The reactions of Hayes and Warren to Jewett's personality were similar to those earlier experienced by Campbell, and the interview resulted in a definite offer to Jewett and a tentative acceptance. This became final a few days later, after Jewett had convinced Hayes that he would be worth more than the amount previously suggested. The starting salary was $30.76 per week, or $1600 per year, which was big starting money. The standard starting rate then current for new college men without post-graduate work was $600 per year.

In his first few months with the Telephone Company Jewett worked on a wide variety of transmission problems, under Campbell's supervision, and handled considerable department correspondence. This was in accordance with the department's policy for an educational period prior to concentration on a specific line of work.

His first important 1904 assignment was a study of the Jacques' patent 767818 which had been offered for purchase. This patent had to do with a variety of schemes for improving transmission on long telephone lines. Jewett made an adverse report on the basis of theoretical studies and experiments which convinced him that the appearance of improvement was greater than the substance. His analysis was so fair and clear that it brought forth a note of commendation from some of the principal executives[1] of the organization, without known precedent for engineers just beginning their telephone careers, and must have been very heartening to its recipient.

1905 Happenings

A reorganization of the Engineering Department effective on January 1, 1905, resulted in Mr. Hammond V. Hayes becoming the chief engineer. The January 1905 organization chart on page 399 is the first official chart on which Dr. Jewett's name is listed. It is of incidental interest to note that he is the only individual mentioned by name who has remained in Bell System service up to 1944. There were a total of 195 employees in the Engineering Department, including a small, substantially autonomous, "operating" division under G. M. Yorke, whose headquarters were in New York City. This division was in fact the Engineering Department of the Long Distance Lines Department.

Early in 1905, Jewett made a good start on the protection job which had been in prospect when he was engaged. In his report[2] to Warren on the work done in 1905 Campbell listed the protection work as being one of three major activities, the other two being problems resulting from disturbances by alternating current railways, and the inspection of commercial transmission conditions. An intriguing feature of one of the protection development projects was the use of low inductance choke coils in series with the line at points adjacent to the protector blocks, in order to reduce protector

[1] Specifically Mr. Frederick P. Fish who was President of the American Telephone and Telegraph Co., and was also widely known as a successful patent attorney. Also from Mr. Thomas D. Lockwood who was in charge of the Telephone Company's Patent Department, and Mr. Hayes, himself.

[2] Some abstracts from Campbell's report to Warren, including the text of Jewett's 1905 report on the protection work, are given in Appendix I.

maintenance by curbing the severity of the lightning surges. Although the initial experiments were quite encouraging, the more extensive service trials proved insufficient advantage to warrant standardization.

Early in 1905 Jewett also started to build up a splendid record as a personnel recruiting agent for the headquarters staff.[3]

Jewett's 1905 engineering work, however, was not wholly taken up by protection problems or personnel recruiting. He also handled a large correspondence with the field engineers on current transmission engineering problems, including loading and phantom working, and made a number of special transmission and patent studies. This experience substantially broadened his training in the engineering work, and provided a helpful background for the assumption of new responsibilities on January 1, 1906, when he succeeded Dr. Campbell as head of the Electrical Department, reporting directly to Warren. For some time Campbell had been anxious to concentrate on theoretical research problems and he welcomed the availability of Jewett as a replacement. That Jewett was ready for department supervision responsibilities after less than 16 months' service with the Telephone Company proved the capabilities of the man and verified the initial appraisals of his potentialities made by Messrs. Hayes, Warren, and Campbell.

Now that the story has Jewett well started on his telephone career, it is appropriate to review the state of the art, and briefly consider organization responsibilities. Also the laboratory facilities and methods of transmission testing are briefly described.

State of the Art

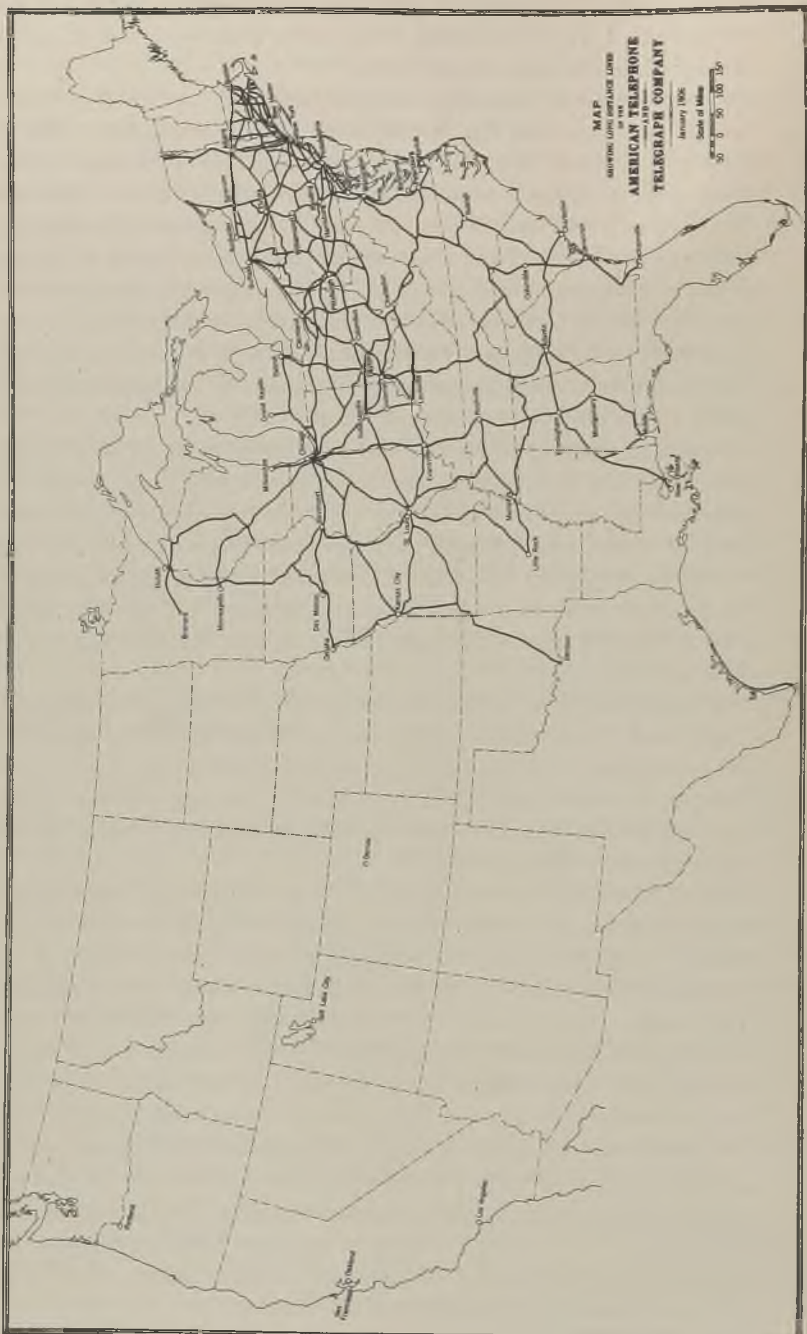
Regarding the general status of telephony at the beginning of 1906 we can take it from Frederick L. Rhodes' account in the "BEGINNINGS OF TELEPHONY" (published 1929) that the art had been very well begun and that the Bell System plant had been placed on a sound engineering basis. Much remained to be done, however, in all branches of the art, and in some of the fields which assumed great importance in later years the surface had hardly been scratched.

A few high spots of the 1906 status are briefly mentioned below to give some indication of what had been done and in some instances what remained to be done.

1. The telephone wire plant was substantially on a metallic circuit basis (excepting some rural subscriber lines).

[3] His early selectees included F. J. Chesterman now Vice-President of the Bell Telephone Company of Penna.; O. B. Blackwell now Vice-President of the Bell Telephone Laboratories; H. S. Osborne, now Chief Engineer of the American Telephone and Telegraph Co.; John Mills, Director of Publication, and W. H. Martin, now Director of Station of Apparatus Development, Bell Telephone Laboratories.

2. Paper-insulated, twisted-pair cable construction dominated the exchange plant, with about 80% of the cable underground. 22-gauge cable was coming into extensive use.
3. The preparation of comprehensive conduit plans for the larger cities had started soon after the development of paper-insulated cables in the early nineties. By 1906, this work had been broadened to include definite forecasts of the future requirements of those cities, and the resulting development plans showed not only the most economical size and distribution of the conduits and cables, for a period extending about 15 years into the future, but also the proper number, locations, and sizes of the central offices. This work, in later years termed "Commercial Surveys and Fundamental Plans," enabled the operating companies to keep abreast of the continually advancing business needs with a minimum of reconstruction.
4. Common battery switchboards had been installed in all of the large cities replacing the magneto boards, and were being installed in the smaller cities and towns. The use of the new switchboards made local batteries and magneto generators no longer necessary at the individual subscriber stations, and resulted in great improvements in the speed and quality of the telephone service. Switchboard lamps used as line and supervisory signals were also factors in the improved service.
5. High-grade telephone instruments were in universal use, including the "solid back" transmitter which was much superior to its predecessors with respect to power and freedom from carbon packing.
6. Message rate service had been introduced in the larger cities, supplementing flat rate service, and was still an important factor in the rapid rate of station growth.
7. An accompanying map shows the A. T. & T. Co. long distance lines at the beginning of 1906. The long distance circuits were almost entirely in open-wire construction, little cable being used except to provide entrance facilities to city toll offices, and at river crossings. The loading standardized in 1904 for 104 mil open-wire pairs made such circuits approximately equivalent in transmission to non-loaded 165 mil pairs, their range being of the order of 1000 miles. Study of the problems involved in loading 165 mil circuits had begun.
8. The leased-wire telegraph business had expanded to become an important source of revenue and was becoming a basic factor in the expansion of the long distance telephone plant. The telegraph circuits that were leased as private lines were usually obtained by compositing the telephone circuits, and thus the same wires were used simultaneously for telephone and telegraph.


MAP
AMERICAN TELEPHONE
AND
TELEGRAPH COMPANY
January 1906
Scale of Miles
50 0 50 100 150

9. Phantom working for non-loaded open-wire lines had gotten a good start in the 1904–05 period, in consequence of the standardization of the first satisfactory phantom repeating coil (37-A). The complete commercial exploitation of the phantom circuit, however, awaited the development of usable quadded cable and of phantom group loading.
10. Several different standard loading systems had been made available for different fields of service on telephone cables, and improved types of cable suitable for use with loading had been developed. In the initial standard loading, the theoretical cut-off frequency was about 2300 cycles. The principal early uses of loaded cable were for circuits between metropolitan city and suburban offices, long entrance cables, and long switching trunks. These installations had yielded large economies by permitting the abandonment of plans for installing sizable networks of these types of circuits in coarse-gauge low capacitance cable, which had been formulated just prior to the invention of loading. A good beginning had been made in the use and in the planning of loading for intercity toll cables, the longest in use being the Boston-Worcester (44 mi.) 1904 cable. Plans for the New York-Philadelphia (90 mi.) and the New York-New Haven (80 mi.) loaded cables had been started in 1905.
11. Substantially continuous efforts to develop a telephone repeater had started inside and outside the Bell System soon after the invention of the telephone. These efforts usually involved receiver-transmitter combinations, and the designation "telephone relay" was quite common. It was not until 1904, however, that there became available a commercially usable result, namely the Shreeve receiver-transmitter type mechanical repeater. This device was being used only on non-loaded open-wire lines, with not more than one repeater in the circuit. Improvements which increased its field of use were worked out later in connection with the transcontinental line developments.
12. In the reference period, competition by the independent telephone companies was very strong and on the increase, as indicated by the following statistics regarding approximate numbers of stations:

Item	*At the end of 1905*	*At the end of 1907*
Bell Connecting Companies	246,000	826,000
Non-Connecting Companies	1,596,000	2,280,000
Independent Co. Totals	1,842,000	3,106,000
Bell System Stations	2,240,000	3,035,000

During the latter part of 1909, the Bell stations began again to outnumber the independent stations. As another manifestation of the competitive situation, it is of interest to note that in the middle of 1905 a majority of the cities having more than 10,000 stations (total) had both independent and Bell exchanges.

Organization

In the period under consideration, 1906 and thereabouts, the Engineering Department in Boston was broadly responsible for Bell System engineering, development, and research work, and also had important responsibilities in inspection work. The organization units which handled the different types of work are indicated in appended organization charts.

The Department established engineering standards for plant design, prepared central office specifications, and advised the associated companies (then termed licensee companies) on current plant and traffic problems. By means of circulars, bulletins, and specifications, and in routine correspondence, it advised the field how to use new developments.

In conference committees and correspondence, it outlined the service requirements for telephone cable and the bulk of the telephone apparatus manufactured by the Western Electric Company—items on which the development work was done by Western Electric Company engineers, at New York or Chicago. In its own laboratories at Boston, it carried on considerable research work and also development work on many special items such as telephone instruments, loading coils, phantom repeating coils, and telephone repeaters.

Transmission

Within the Boston engineering department, most but not all of the transmission engineering work and all of the transmission development work was done by the group of nine engineers which became Jewett's responsibility on January 1, 1906. However, "cost studies" for plant extension projects, and exchange area loop and trunk studies, were then made by the Construction Division headed by F. L. Rhodes. Jewett's group also worked on electrical protection and inductive interference problems.

The laboratories were in a ground floor annex on Oliver Street. The principal "accessories" for transmission testing and impedance measurements included several single-frequency inductor-type generators ranging in frequency from about 200 to 5000 cycles, two "sound-proof" test rooms, two shielded-bridges for a-c measurements, fixed and variable inductance standards, capacitance standards, and several boxes of sectionalized artificial lines, one of them designed to "simulate" a long 104 mil open-wire line, while the others provided several adjustable lengths of standard 19-gauge reference cable. Facilities also were available for connection to outside lines in the plant of the American Company and the New England Company for experimental purposes.

Basically, the transmission tests were talking tests, usually with both ends of the circuit accessible at the test point, i.e., loop tests. The transmission equivalents of lines, and apparatus losses, were determined in terms of miles of reference cable. In tests to determine apparatus losses in lines, the losses were sometimes estimated on a percentage basis, when it was inconvenient to use the reference cable. Transmission quality judgments involving frequency distortion effects were usually expressed with a variety of non-standard adjectives, ranging from "sharp" to "boomy" or "drummy" and including others with a more salty personal flavor.

The non-availability of portable "high frequency" tone generators prevented the making of single frequency measurements in the field. However, in the period under discussion, considerable progress had been made in laboratory measurements of low amplitude alternating currents by means of thermocouples.

1906 and 1907 at Boston

During 1906, much effort of Jewett's group was devoted to field investigation and analytical studies of conditions affecting long distance telephone service, in consequence of transmission complaints by important users of the service. Much of the poor transmission was found to be due to defective apparatus and to departures from standard maintenance and operating practices. This transmission inspection work later became so extensive as to require the organization of a separate group of engineers. By progressive evolution, such investigations and corrective measures eventually led to the thorough organization of transmission maintenance work as we know it, now such an important factor in making the actual transmission performance of commercial telephone circuits closely approximate their theoretical design performance.

In 1906 a substantially increased fraction of the department effort was concentrated upon various phases of electrical interference work. This was made necessary by the increasing use of alternating current traction on interurban trolley lines, and the projected single-phase electrification of some important railroad systems, notably the N. Y., N. H., and H. R. R. This particular project continued to require a lot of attention for over a decade, initially in the electrification to Stamford and later in the extension to New Haven.

Engineering and apparatus problems arising from the rapid growth of loading, and the need to realize its maximum benefits took a great deal of time. Thus, loaded underground toll cables between New York and Philadelphia, and between New York and New Haven, were completed during 1906.

Further development work on phantom transposition systems and improvements in the balance of phantom repeating coils added to the advantages of phantom working on non-loaded open-wire lines.

To indicate the range and variety of the work done by Jewett's group, a copy of his report to Mr. Warren for the year 1906 is given in Appendix II.

1907 Reorganization

Early 1907 saw a serious reaction following the business boom which reached its climax in 1906. Difficulty had been experienced by the American Company in disposing of a large issue of bonds and "the financial sky was filled with the scudding clouds that foretold the impending storm. A period of retrenchment and doubt had begun." This situation resulted in the retirement of Mr. Fish as president and the election of Theodore N. Vail on May 1, and was followed by a quick drastic reorganization of the telephone organization under Vail's careful planning.

To carry out his broad plans on engineering, development, and research, Vail selected as the new Chief Engineer for the American Company John J. Carty, who at the time was Chief Engineer of the New York Telephone Company. Carty's reorganization activities during the summer of 1907 resulted in a consolidation of the development laboratories of the Bell System in the Engineering Department of the Western Electric Company at New York. This new organization included a substantial portion of the Chicago group of development engineers, and several members of the American Company's Boston group. The amalgamated organization expanded almost from its inception, and nearly two decades later became the Bell Telephone Laboratories, Inc.

The 1907 reorganization also resulted in the Western Electric Company's taking over all of the inspection activities that previously had been carried on by units of the American Company's Engineering Department. The Engineering Department itself was drastically reduced in size and in September 1907 moved to New York along with executive departments. Charts dated June 1907 and December 26, 1907, pages 400 and 401 respectively, show the organization set-up prior to and after the reorganization.

The late spring threats of drastic reorganization had been quite disturbing to the Boston engineers, especially to those who had only recently started their telephone careers. Several of them, including Jewett, began to wonder whether they might not have made a mistake in joining the Telephone Company. A number of attractive college teaching offers which reached Jewett at about that time inclined him towards a resumption of his academic career broken in 1904, but the temptation was thrust aside after he had made a special visit to New York to interview the new Chief Engineer relative to the prospects for future advancement in the Telephone Company.

CHAPTER II

The 1907–1911 Period in New York

IMPORTANT early developments of this period led to the successful loading of open-wire phantom lines and their side circuits; the commercial application of loading to 165 mil open-wire circuits; and the development of duplex (quadded) cable and of phantom group loading for such cables. Jewett's prestige rose high in consequence of his personal efforts and his supervision of these developments, and was further enhanced by the basic roles these developments played in the New York-Denver line, and the Boston-Washington cable projects, which are also described in this chapter. The Denver line proved to be, as was intended, a major preparatory step in the westward march to achieve transcontinental telephony, and then universal telephony within the United States.

The important but more or less routine engineering work that was necessary to maintain continuous progress in the telephone transmission art went forward along with the specific developments in long distance telephony that are described in detail herein. Mention should also be made on the continuing fundamental work on the reduction of noise and crosstalk. Especially in the long distance services, this was a vital necessity as the lines became longer and longer. The rapid extension of the use of loading and of phantom working over lines and cables, followed by the introduction and the wide use of telephone repeaters, substantially increased the complexity of the noise and crosstalk problems, and greatly magnified the importance of the work. The steady improvement of transposition systems was an important part of the effort on the open-wire lines.

1907 Happenings

Following the move of the reorganized Headquarters Staff Engineering Department to New York, and partly in consequence of conditions that had led to the recent reorganization, but mainly because of the critical general business panic which exploded in Wall St. in October 1907, engineering and development activities of the Telephone Company operated at a relatively low voltage for a considerable period. Fortunately, the steps that Vail had taken to improve the financial status of the Company had been effective, and the storm was weathered without important changes in the rate of station growth, and without substantial distress of any kind. While plant expansion was slowed down, the stringency did not prevent the start of important new development projects, or the continuation of important work which had been started at Boston.

The first new major project was that of developing phantom group loading for open-wire lines. The theoretical work on this problem started early in October 1907, and the design requirements for the new types of loading apparatus were put up to the Western Electric Company in December 1907. The general objective was to make possible the exploitation of the economies inherent in a full application of phantom working in the expensive open-wire plant. Other developments, mentioned later, were also essential to the full achievement of this objective. The important fact to remember in this general connection is that for a period of several years prior to the development of phantom group loading it was feasible to load 104 mil circuits, and to phantom non-loaded 104 mil circuits, but it was not possible to combine the advantages of phantom working and loading. Two new types of loading coils were necessary, one which became known as the side circuit loading coil for use on the phantomed pairs, and the other for use on the superposed phantom itself. The original standard open-wire loading coils were not suitable for use on side circuits because of the transmission impairments and the unbalances that they would have introduced into the associated phantom circuits. The critical problem in the new loading apparatus was to obtain satisfactorily low crosstalk among the associated side and phantom circuits. The results of this development work are described in a subsequent section.

Among the important old projects that were continued and pushed in the months that followed the move from Boston were (1) studies and experiments to enable loading to be used with satisfactory results on 165 mil open-wire circuits, and (2) problems involved in the use of telephone repeaters on loaded lines.

The problem of loading the 165 mil circuits was primarily one of improving and stabilizing the insulation of the circuits, so that during wet weather and the subsequent drying-out periods the transmission impairments caused by leakage losses would not materially offset the transmission loss reduction obtainable with the added inductance. In the early commercial attempts to load 165 mil circuits (beginning with the New York-Chicago line, 1901) the loading eventually proved to have much too high an impedance in relation to the wet weather line insulation, and it was removed late in 1905 because under unfavorable weather conditions the transmission equivalent became (temporarily) worse than that of a non-loaded 165 mil line. The solution of the loading and insulation problems for the 165 mil lines required a great deal more experimental work than had been involved in the successful application of loading to the 104 mil pairs, primarily because of the much greater sensitivity of the heavier conductors to leakage effects. The opening of the New York-Denver Line in 1911 proved, however, that the essential problems had been solved. A subsequent discussion includes a brief statement of the high spots of this and other developments that were essential to its success.

The early work on the problems involved in the use of repeaters on loaded lines was not so successful as that on the other concurrent major projects, a topic that we shall return to in connection with the planning of the transcontinental telephony project.

1908 Happenings

During 1908, Jewett's department initiated several additional important developments, including duplex (quadded) cable and low loss repeating coils for toll lines.

Over a long period, prior to 1908, many sporadic and unsuccessful experiments had been made, here and abroad, to obtain quadded cable suitable for phantom working. By the middle of 1908, however, very encouraging results had been obtained in the Bell System development work on open-wire phantom loading. Forecasts of the substantially universal use of loaded, phantomed, lines brought into sharp focus the need for loaded quadded entrance cables in the future open-wire toll plant. Also, if a satisfactory type of quadded cable could be developed and loaded, very large economies could be anticipated in long distance telephone cable systems that as yet were in the dream stage. These incentives were tremendous relative to those that governed the previous unsuccessful experiments referred to, and in fact compelled the success that was achieved in due course by the concentrated engineering efforts of the American Company and Western Electric Company, beginning in 1908. The first question to be decided by experiment and study was concerned with the type of construction that would offer the best chance of ultimate success. The leading competitors were the spiral-four type quad, and the multiple-twin quad, consisting of twisted pairs, twisted about one another. The twisted-pair quad eventually won out partly because of crosstalk considerations, but a not-negligible factor in the decision was the fact that if the new cable should not turn out to be completely satisfactory for phantom working, the side circuits of the twisted-pair would have characteristics more closely similar to those of non-quadded twisted-pair cable than would the side circuits of spiral-four quads. This was a powerful plant flexibility and homogeneity argument.

The cable development became commercially fruitful in 1910, and is described in a subsequent section of this story.

The 1908 repeating coil project mentioned in an earlier paragraph included high-efficiency phantom-deriving repeating coils especially for use on

165 mil open-wire pairs, and a high-efficiency non-phantom type repeating coil for Type B composite ringers. The existing standard 37A phantom-deriving repeating coil had been developed for use on lines operated on a 16-cycle ring-down basis, and had very good "ring-through" characteristics. In consequence of this feature, the speech transmission loss was quite substantial, being of the order of 1.5 db per coil at each end of a phantomed circuit. Two such coils, at opposite ends of a phantomed non-loaded 165 mil circuit, were equivalent to an extension of the length of the line by about 100 miles. This was too much of a transmission and economic penalty to be acceptable on expensive 165 mil circuits. By sacrificing the 16-cycle ring-through properties, it turned out to be a relatively simple job to reduce the transmission loss in the new coils to values below 20% of the loss in the 37A coil. In circuits equipped with the new coils, the signaling was accomplished by "composite" ringing (135-cycles).

Headquarters Staff Engineers Visit the Pacific Coast

There occurred late in 1908 and early in 1909 a Pacific Coast visit of several headquarters staff engineers which had an important place in the sequence of events that preceded the American Company's decision to provide transcontinental telephone service. Jewett participated in this expedition, and was joined later by Messrs. Carty, Gherardi, and others. The initial purpose of Jewett's trip was to advise the Pacific Tel. & Tel. engineers how to improve transmission conditions in certain parts of their territory, notably in the Oakland area, and on trunks to San Francisco, and also in the Los Angeles-Pasadena area. Aggressive competition by local independent companies was a factor in these problems. Improvements were also needed in the Pacific Company's long distance toll plant. An extensive use of loading was indicated. There were also a number of pressing inductive interference problems.

Before Jewett had finished his work on these various problems, Messrs. Carty and Gherardi reached San Francisco to consider with the Pacific Company executives some revisions in their 1909 budget, covering extensive plant additions that had become desirable. (Here again the competitive situation was a factor.) It was inevitable that Carty should become more deeply concerned with the telephonic isolation of the Pacific Coast when he was there and unable to talk to his staff in New York, than when he was in his own office in the east. This isolation was very real and oppressive; not only was there a large geographic gap in the wire plants of the Associated Companies, between the Pacific Coast area and the middle west, but also the limit then current on telephone transmission over the best available type of circuit was considerably less than one-half of the minimum transcontinental distance. Under the circumstances, it was natural that during his Pacific Coast trip Carty should spend considerable time with his New York assistants, and with the Pacific Company engineers, in surveying the principal problems involved, and the prospects for transcontinental telephony in terms of the development work then under way and of potential future researches, particularly on telephone repeaters. Apparently, the prospects were encouraging.

Carty was stimulated in this study by pressure from President Vail, who happened to visit San Francisco while Carty, Gherardi, and Jewett were there. It appears that Vail was under some pressure from Pacific Coast business men who were then very busy planning the Panama-Pacific Exposition (originally scheduled for 1914 but later postponed to 1915), and who wanted him to promise that San Francisco would be put in regular telephonic communication with the eastern cities when the Fair opened. Being a good business man himself, Vail was sympathetic to these appeals. Realizing that engineering difficulties would be involved, he consulted Carty, who as usual, was unwilling to commit himself without a careful survey of the prospects and possibilities. Presently, Carty made a favorable report, and Vail told the Fair management that the telephone company would attempt to provide the desired transcontinental telephony. It thus happened that before he returned to New York Carty added the transcontinental line to his list of "must" objectives.

The Engineering Situation in April 1909

A major reorganization of the engineering department became effective on March 13, 1909, soon after Carty's return from the Pacific Coast. As shown in the chart on page 402 the reorganized department had two major divisions respectively reporting to B. Gherardi as Engineer of Plant and K. W. Waterson as Engineer of Traffic. Jewett reported to Gherardi. A third division of the department handled engineering work on legal cases.

In a memorandum of April 8, 1909 addressed to Vice-President Thayer, his immediate superior, Carty discussed the planning of the new organization and asked for additional personnel to enable him to carry on the new duties and responsibilities in associate company relations which had been assigned to his department, and to undertake certain important new engineering and development work, without neglecting the important work then under way. This memorandum includes such a beautifully clear and significant exposition of the engineering situation that substantial extracts are included in Appendix III. Carty's discussion of the principal projects in which Jewett's department was or would be involved are included in full under the headings: Phantom Circuits and Duplex Cables; Further Development of Pupin Invention; The Problem of the Telephone Repeater. From this discussion, it is clear that Carty expected that it would be possible to accomplish speech between New York and Denver over loaded 165 mil open-wire circuits, but that this would be the geographical limit for loaded 165 mil circuits without also using repeaters which were not yet practicable on the loaded lines.

In building up the justification for the development of a "more powerful" telephone repeater, Carty wrote in part: "There is nothing in the nature of the case to discourage us in this line of work, and the art seems to have so many possibilities and the results to be obtained . . . are so far-reaching that the work . . . should be pushed vigorously. If we successfully load the Denver line and thereby accomplish speech between New York and Denver, the development of a successful repeater would enable us to accomplish speech between San Francisco and New York.[4] The achievement of this result would mean universal telephony throughout the United States and its importance is so apparent that no argument is needed to demonstrate it." At this point it is appropriate and permissible to note that New York-Denver transmission was commercially accomplished in 1911, and that just prior to this achievement a vigorous and successful attack was launched on the new repeater problems. Meanwhile, the experimental work continued on the general problem of applying the Shreeve mechanical repeater to loaded lines.

The "more powerful" telephone repeater which Carty had in mind was a hypothetical inertialess repeater of an entirely new type. In the previously mentioned Pacific Coast analyses of the problems that must be solved to achieve transcontinental telephony, Jewett had convinced Carty that there was a good chance of obtaining a new and satisfactory type of repeater if research workers trained in the modern electronic physics could be hired and put to work on the problem. In Chapter III of this story, Jewett's personal contribution to the planning of this research program is considered at greater length.

Other 1909 Happenings

In general, the year 1909 was marked by accelerating, favorable, progress in the major transmission development and engineering projects previously mentioned. The principal discordant notes in the otherwise harmonious and tuneful concerto were caused by expanding difficulties in learning how to use telephone repeaters effectively on loaded lines.

A 1909 event that was responsible for starting one of the most important engineering projects in the 1910–1915 period occurred on March 4, at the time of the inauguration of President Taft. By wrecking all of the open-wire lines out of Washington, an unusually severe blizzard telephonically and telegraphically isolated the capital from the rest of the country for a

[4] By reference to the quotations in Appendix III the reader will see that Carty's engineering group also clearly visualized that the repeater would be the open sesame to successful *radio* telephony.

period of several hours. This event dramatized the need for storm-proof communications to the capitol, and led to a decision by President Vail that a complete underground telephone cable system should be established along the Atlantic seaboard, between Boston and Washington. Vigorous development activity on the new types of cable and loading coils that would be required got underway early in 1910. A full discussion of this development is given later on under the heading "Boston–Washington Loaded Duplex Cable Project."

By the spring of 1909, the development work on quadded cable had reached a stage which made it desirable to start the development of new types of cable loading coils suitable for use on phantom and side circuits. This work benefited from the earlier work on the open-wire phantom loading. Since it then appeared that there would be little use for duplex cable on a non-loaded basis, the work on the cable loading coils was coordinated with the further work on the new type of cable, leading to a joint trial in 1910 on the Boston-Neponset project described later.

1910 Achievements

Progress during 1910 was especially important and interesting. It included the first (Bell System) loaded submarine cable installation, which is of special historical interest even though it was not directly related to the major transmission projects previously discussed. During 1910, the initial objectives of these major projects were realized in full measure, and before the end of the year the gains in the new engineering knowledge were being consolidated for very important new engineering projects, notably the New York-Denver line and the Boston-Washington underground cable. All of these various projects are separately discussed below.

Chesapeake Bay Loaded Submarine Cable

This was the first Bell System submarine cable to be provided with submarine loading. It was an intermediate cable, crossing upper Chesapeake Bay, in an open-wire line providing service from Baltimore to the Eastern Shore points, greatly shortening the route. It was a 17-pair, 13-gauge, paper-insulated cable and had two underwater loads. The engineering and installation of many loaded submarine cables that were subsequently installed in shallow water crossings of river or bay include practices that originated in the 1910 Chesapeake Bay project.

Open-Wire Phantom Loading

Returning to the story of the major transmission developments in which Jewett's department took a leading part, attention will first be given to open-wire phantom loading. This was proved feasible in a commercial trial on an open-wire phantom group of 104 mil conductors, between Newtown Square and Brushton (test stations near Philadelphia and Pittsburgh, respectively) installed during August 1910.

By design, the side circuit transmission characteristics were substantially identical with those of the loaded non-phantomed circuits then in extensive use. A slight impairment resulted from the increase in circuit resistance caused by the inserted phantom loading coils. These coils were installed at the same points as the side circuit loading coils, at systematic intervals of about eight miles, a distance set by the need to coordinate the coil spacing with the line transposition systems. The phantom loading coil inductance (0.163 henry) was chosen to provide a theoretical cut-off frequency close to that of the side circuit (approx. 2400 cycles). This resulted in a phantom circuit impedance approximately 60 per cent of that of the side circuits, and an attenuation nearly 20 per cent lower than that of the side circuits. This advantage resulted in the phantom being preferred for long-haul service. The increase in transmission efficiency obtained by loading the phantom (about 2.5 to 1) was practically as large as that obtained in the side circuits.

Since this was a pioneering project, it is understandable that the crosstalk results were not all that could be desired. There was some real satisfaction, however, in the fact that the crosstalk was not too close to the borderline of being intolerable. The crosstalk was due to unbalances in the line and in the loading coils. In commercial service, unbalances in the phantom-deriving repeating coils and in the composite telegraph sets were also factors in the crosstalk performance. In the course of time, in consequence of improvements in the phantom transposition systems and experience in the manufacture of the line and terminal apparatus, substantial improvements in the service crosstalk characteristics were secured.

The loaded phantom circuit was much more susceptible to noise induction than the side circuits, and increased the need for good line maintenance.

At this point, a few remarks regarding the conservative policy followed in this phantom loading development are appropriate. So far as the loading apparatus development work itself was concerned, a trial installation could have been made much earlier than the summer of 1910. The early laboratory work on the proposed initial loading coil designs showed several minor changes to be desirable from the crosstalk standpoint. After these were made, the designs appeared to be free from inherent dissymmetry that might cause crosstalk. The question as to whether the coils would have satisfactory balance when manufactured on a quantity production basis, however, could only be determined by undertaking manufacture of a sizable lot. When the question of making a trial installation was first considered informally with the Long Lines plant people, no suitable types of additional new facilities were in prospect, in consequence of the somewhat slow recovery of general business activity following the 1907 panic. Prior to starting production of the new types of coils, models were turned over to the Long Lines telegraph experts for tests to determine whether objectionable impairment in the superposed telegraph service would result in consequence of the increased magnetic coupling between the telegraph circuits, contributed by the loading coils. The favorable report on this feature was tinged with an informal suggestion of regret that the wide application of phantoms in the long distance plant would reduce the aggregate number of wires that would be available for the leased wire telegraph services.

In arranging for potting the loading coils used in the trial installation, the decision was made to encase the coils individually so that in the event of unsatisfactory results the phantom loading could be removed without disturbing the side circuit loading. The phantom coil was considerably larger than the side circuit coil, and a new case had to be developed for it. The practice of separate potting of the individual coils continued for several years, mainly for flexibility and maintenance reasons. Not long after the trial installation, the manufacture of the non-phantom type open-wire loading coils was discontinued in favor of the new side circuit type. Gradually, the bulk of the existing non-phantomed loaded circuits in the open-wire plant was made suitable for phantom working. The displaced non-phantom type loading coils were returned to the factory for "conversion" into side circuit type coils, by partial rewinding of the original cores.

Loading of 165 Mil Open-Wire Circuits

The development efforts to improve the wet weather insulation of 165 mil wires sufficiently to make loading commercially practicable culminated in an experimental installation of loading on a New York-Chicago circuit during 1909 and early 1910.

The initial steps in this trial were (a) to change the transposition arrangements from the single-pin type to the drop-bracket type in order to avoid tying to the same insulator the two wires being transposed, and (b) to install bridle wire insulators at all bridling points, including the loading coil and lightning arrester leads. Comparative wet weather tests of the single-pin and the drop-bracket transposition arrangements made previously had indicated the new method to be about 20 per cent better, and tests with the bridle wire insulators had indicated their use would substantially eliminate low insulation at bridling points.

The bridle wire insulator was the final result of a long period of development. It provided sheltered dry spots on the rubber-insulated braided leads of loading coils and lightning arresters, and on bridle wires to test stations and cable terminals. The need for these dry spots had become apparent from analyses of line tests which showed that after the braid on the wire had weathered and had begun to disintegrate, a considerable period of time elapsed after rain ceased before the line insulation returned to its usual dry weather excellence. The insulated wires passed through the insulator and at the point of exit the conductors were soldered to a metal insert moulded into the insulator. The bridle wires themselves supported the insulators at a point close to the connections to the line wires. It is of interest to note, in passing, that a patent was granted to Jewett on some design features of this insulator.

Returning to the discussion of the New York-Chicago loaded line experiment, it was found that the insulation improvements described above were insufficient to provide satisfactory transmission performance during periods of continuous bad weather. During fair weather periods, however, the transmission was as good as had been expected. The experiment thus proved beyond question the need for a new type of line insulator having substantially better insulating properties than those of the standard toll line insulators, which were made of glass and had a single petticoat.

Renewed studies of this particular question led to the rush development of a moulded double-petticoat porcelain insulator. The possibilities of porcelain insulators had been under consideration for several years, notwithstanding adverse cost factors. The accumulated test data on porcelain insulators generally similar in design to the standard glass insulators indicated that after a long period of exposure on roof racks the wet weather insulation was about twice as good as that with the glass insulators. Moreover, theoretical studies indicated that a properly designed double-petticoat porcelain insulator should be about twice as good as the single-petticoat porcelain insulator. The possibility that the opacity of the porcelain might unduly encourage insects to build their nests under the petticoats and thereby impair the wet weather insulating properties, however, could not be allowed for quantitatively in the preliminary estimates of the potential over-all improvement, due to the limited and conflicting evidence on this question.

Consideration of all of the factors involved, including favorable price estimates, led to a decision in October 1909 to substitute the new double-petticoat porcelain insulator on the experimental loaded line. An accumulation of manufacturing difficulties delayed the completion of the installation, so that the transmission observations and over-all line insulation tests did not get under way until the spring of 1910.

After a suitable test period it was found that although the wet weather line insulation was not so high as had been expected it was sufficiently good to warrant the general commercial use of loading on 165 mil circuits. Accordingly, the improved insulation features of the experimental loaded line, including the new porcelain insulator, were recommended[5] for this use.

The loading arrangements standardized for the 165 mil circuits were similar to those which for several years had been standard for 104 mil circuits, viz., 0.265 henry coils installed at intervals of about 8 miles. With line insulation of 5 megohm-miles or better, the transmission range of the loaded 165 mil circuits was about 2.3 times as great as that of non-loaded 165 mil circuits.

Loaded Duplex Cable:

The pioneering development work on duplex cable and on new types of loading coils for the cable phantom and side circuits culminated in a commercial installation between Boston and Neponset, which became ready for service early in September 1910.

By the fall of 1909, the experimental work and analysis of test data on experimental lengths of cable having multiple-twin quads and spiral-four quads respectively, and on the required new types of loading coils, had progressed sufficiently to make it desirable to undertake trial manufacture, preferably for a project that would meet a need for new facilities. In November 1909, it was decided that the Boston-Neponset cable project would be a suitable objective. About 5.8 miles of 37-quad 13-gauge cable was required, extending south from Boston, partly for use as an entrance cable for the American Company's Central and Shore (loaded open-wire) lines, and partly as a suburban trunk cable for the New England Company. The entrance facilities were to be provided with phantom group loading, in anticipation of extensive phantom working on the open-wire lines. Since phantom working was not needed or desired on the suburban trunks, the loading for the New England Company was limited to the quadded pairs, using side circuit type coils. This particular plan was more valuable from the standpoint of development experience and gave greater plant flexibility

[5] Before the end of 1911, an appreciable degradation was noticed in the wet weather line insulation of the initial installations. This appeared to be due to several causes which could not be separately appraised, including (1) an unexpected retention of deposits on the glazed surface, i.e. the insulator was not self-cleaning; (2) the nesting of insects underneath the petticoats; and (3) trouble with a large number of defective insulators. In general, the impaired insulation was not large enough to warrant the removal of the porcelain insulators, except those that were physically defective, nor was the "bug trouble" sufficiently serious to warrant the establishment of routine cleaning operations. Meanwhile, the prices of the porcelain insulator increased drastically in consequence of the continued manufacturing difficulties, which also greatly limited the supply of acceptable insulators. About the middle of 1912 it was decided to start using double-petticoat glass insulators on new installations of loaded 165 mil lines, in place of porcelain insulators. These glass insulators had become available in consequence of development work undertaken late in 1910 for the Western Union Telegraph Co. (at that time closely affiliated with the Bell System). The new glass insulators were much less expensive than the porcelain insulators and their insulating properties were nearly as good. Subsequent experience showed them to be fairly satisfactory for use on loaded 165 mil circuits.

than if non-quadded pairs and non-phantom type loading coils should have been used.

Cable Details: The multiple-twin quad was chosen in preference to the spiral-four quad on the basis of practical features involved in manufacture and installation and the resulting arrangement, in case phantom working should not prove successful. That is to say the twisted-pair side circuits would better serve the customer's plant flexibility needs than would the side circuits of spiral-four quads. Also the early experiments had indicated a high probability of superior balance among the very important within-quad couplings.

Additional factors that resulted in the subsequent standardization of multiple-twin quads were:

1. Their phantom capacitance is about 60 per cent higher than that of the side circuits, whereas in spiral-four quads the phantom capacitance is upward of three times as high as that of the side circuits. Consequently, when the phantom and sides are loaded for equal cut-off frequency and at the same spacing, the resulting impedances are such that the attenuation of the multiple-twin phantoms is considerably lower than that of their associated side circuits, whereas the attenuation of the spiral-four phantoms is inherently much higher than that of their side circuits. Since the phantom loading for the open-wire lines had provided phantom circuits which were preferable to their own (loaded) side circuits, due to their lower attenuation, it also seemed desirable that the loaded cable phantom should be better than the loaded side circuits.
2. The ratio of phantom circuit to side circuit capacitance in multiple-twin quads is close to that in the open-wire lines. In consequence, the loaded entrance cable impedances are better related to the open-wire impedances than would be practicable with simple loading on spiral-four quads. These comparisons again assume the phantom and side circuits to be loaded at the same spacing, with coil inductances giving equal cut-off frequencies.

In the design of the multiple-twin quad cable, the "staggered-twist" principle which had been found necessary from the crosstalk standpoint for use in loaded non-quadded pair cables was applied to the individual circuits of a quad. The lengths of twist were different for the two side circuits and a still different length of twist was used in the phantom. Adjacent quads had different combinations of pair and quad twists, and adjacent layers were stranded in opposite directions.

Notwithstanding these basic design precautions a great many manufacturing difficulties were encountered in preventing the phantom-to-side capacitance unbalances from being very much too large. In the first lengths of commercial cable made up, the unbalances were worse than those in the 1908 experimental lengths. From then on, engineers from the Engineering Departments of the Western Electric Company and the American Company cooperated closely with the factory engineers throughout the entire manufacturing period in working out important fundamental improvements. One of the greatest difficulties was in obtaining sufficiently symmetrical twisting of the individual pairs, prior to forming the quads. Machine limitations and the need for conductors of identical size and ductility, insulated with exactly the same thickness of paper, were factors in this problem. Other difficulties too many and too involved for present discussion were also encountered.

At the beginning of manufacture it was appreciated that it would probably be impossible with known techniques to obtain quadded cable that would be completely satisfactory from the crosstalk standpoint, especially phantom-to-side crosstalk, without resorting to capacitance unbalance adjustments during installation of the cable. Some preliminary consideration was given to the use of balancing condensers. Further studies of possible methods of field balancing led to the development of a technique for measuring the capacitance unbalances in adjacent lengths of cable and selectively splicing the conductors of the quads of one length to those of another length in such a manner that the like-type unbalances would tend to annul one another. Suitable field test sets were developed for determining the magnitudes of the cable capacitance unbalances and their relative phase relations. The planned splices made in accordance with the proposed technique became known as capacitance unbalance test splices.

In splicing the Boston-Neponset cable, a total of 7 capacitance unbalance test splices were made in each full loading section at intermediate points approximately $\frac{1}{8}$ of a full loading section apart. The first set of test splices was made at the $\frac{1}{8}$, $\frac{3}{8}$, $\frac{5}{8}$, and $\frac{7}{8}$ section points. Then "semi-final" tests were made at the $\frac{1}{4}$ and $\frac{3}{4}$ points. The test splice made at mid-section was most important because it was the final test splice. Splices required at points between the test splices were made on a random basis. The test splices were made primarily for the reduction of phantom-to-side unbalance. When individual quads had objectionably high side-to-side unbalances, reductions in the residual unbalances could usually be obtained by planned splicing to other quads having high side-to-side unbalances.

The test splicing procedure was very effective in reducing the pile-up of objectionable unbalances. In general, the maximum residual unbalances per loading section were kept below a predetermined tolerable value. The average residual phantom-to-side capacitance unbalance per full loading section turned out to be of the same order as the average unbalance in the individual (approx.) 500-foot lengths when they left the factory. Statistical considerations indicate that if the cable should have been spliced on a random basis, without regard to capacitance unbalance in individual lengths, the r.m.s. average residual unbalance per loading section would have been about four times as great as that actually obtained.

On the whole, crosstalk results, including the effects of the loading coil unbalances, were considered fairly satisfactory for an initial pioneering effort, but not good enough as a standard of excellence to work to in subsequent projects which were to be of an entirely different order of magnitude and importance in the scheme of nation-wide telephony.

Since the cost of the capacitance unbalance test splicing was small relative to the total cost, the general technique used on the Boston-Neponset cable was subsequently standardized for general use in installing quadded cable. Eventually, substantial reductions in the amount of the test splicing resulted from improvements in cable manufacture.

Loading Details: Except for its phantom working feature, the side circuit loading for the Boston-Neponset cable was similar to the old standard medium-weight loading, originally developed for non-quadded cable. 175 mh coils were installed at intervals averaging about 8520 feet. A total of 72 side circuits were loaded, using two cases, each containing 36 coils at each load point. Eighteen phantom circuits were loaded with 106 mh coils at an average spacing of about 8450 feet. The differences in average spacing resulted from manhole space limitations which led to the phantom coils being installed systematically at manholes next in line to the associated side circuit loading points, at distances ranging from 214 to 490 feet. This layout would have simplified the removal of the phantom loading, if the phantom-to-side crosstalk should have been large enough to make phantom working impracticable. The phantom loading just described conformed to the established cut-off frequency standard for cable loading (approx. 2300 cycles) and gave an attenuation loss reduction of the same order as that provided by the side circuit loading. The absolute attenuation in the loaded phantom was approximately 20% below that in the associated side circuits. The nominal impedances of the cable phantom and side circuit loading were about 800 and 1300 ohms, respectively.

The new types of loading coils used on the Boston-Neponset cable were generally similar in basic design features to the side circuit coils and phantom coils used in the open-wide trial installation of phantom loading, but were much smaller in dimensions. Mainly because of size differences, the unbalances in the cable coils were much smaller than those in the open-wire coils.

Exploitation of the New Developments

The pioneering developments just described were so basically important in extending the limits of long distance telephony, and reducing the cost of long distance facilities, that a substantial amount of engineering information regarding them was made available to the field in conferences, and in routine correspondence on current engineering projects, in advance of the completion of the development work. A coordinated quantitative statement was given in General Engineering Circular No. 107, "Aerial Loading and Duplex Cable," which was issued on August 19, 1910, in advance of the completion of the trial installations of open-wire phantom loading and loaded duplex cable, so as to assure that the new developments would be fully taken into account in preparing the 1911 Provisional Estimates and in planning the 1911 construction program.

In the open-wire plant, the new loading and phantoming developments had extensive application even before the end of 1910. The following pertinent quotation is from a paper, "Long Distance Telephony in America," read by John J. Carty at the second international conference of European Telephone & Telegraph Administrations, Paris, Sept. 1910.[6]

> "*Aerial Loading:* At the present time there are about 52,000 miles of loaded No. 12 NBSG Circuit in the United States and about 1000 miles of No. 8 BWG loaded circuit. There are at present under construction, or intended for completion by January 1, 1911, about 17,000 miles of No. 12 NBSG loaded circuit, and about 13,000 miles of No. 8 BWG loaded circuit. Of this latter, about 3800 miles, namely four circuits from New York to Chicago will be arranged for phantom working, . . ."

The Carty paper also was prepared in advance of the completion of the development work. In general it could be considered a European edition of G.E.C. 107, but it went beyond the latter in mentioning some high spots of certain spectacular new engineering projects, namely the New York-Denver line and Boston-Washington underground cable.

In the cable plant, also, there was accelerating activity in the installation of loaded duplex entrance cables, beginning in the latter part of 1910. This was especially desirable in connection with open-wire phantom lines that were used also for composite telegraph service, due to complications otherwise involved in carrying the telegraph circuits through the entrance cables. The use of loaded quadded cable for toll cable facilities also started quickly and expanded rapidly, the Boston-Washington project being the outstanding initial commitment.

From what has been said in the preceding paragraphs, however, it must not be inferred that the development ended with the completion of the initial commercial installations. As time went on, the service requirements became increasingly severe, especially as regards crosstalk, and there has been substantial continuous activity ever since in the laboratory, factory, and field in the reduction of crosstalk unbalances in quadded cable, lines,

[6] The Carty paper also was published in the March 1911 issue of "Telephone Engineer" (Chicago).

and phantom loading apparatus, and in other apparatus associated with phantom circuits and their side circuits.

The New York-Denver Line

This project was especially significant in utilizing the recent radical advances in the telephone transmission art to achieve a specific long distance objective which constituted a recognized necessary preparatory step in a broad fundamental plan for transcontinental telephony.

This line made use of the phantom circuit of loaded 165 mil open-wire phantom groups installed between New York and Chicago (via Buffalo) and between Omaha and Denver, during 1910. The intermediate Omaha-Denver portion of the circuit initially consisted of a 165 mil non-phantom pair loaded with the new side circuit type coils. Some time later, a second 165 mil pair on the line was moved to pins adjacent to the first mentioned pair so that these two pairs could be phantomed and the phantom loaded. From then on, the New York-Denver circuit was a continuous phantom circuit. The new high-efficiency type of phantom-deriving repeating coil was used throughout this installation.

The construction work on the initial layout of the line was completed in December 1910, and the first through talk was made on December 29, 1910. (These are the reasons for describing this project as a 1910 development.) Commercial service, however, did not start until May 8, 1911. The intervening time was utilized in clearing up noise and crosstalk trouble which the time schedule and the lack of complete engineering information had made it impossible for the engineers to predetermine and take care of in advance. The initial transmission tests showed the side circuits to be satisfactory with respect to transmission and noise. The phantom, however, was very noisy and the phantom-to-side crosstalk was quite heavy. The line crosstalk difficulties were found to be mainly due to transposition irregularities, including omitted transpositions. For noise reduction, considerable retransposition work was necessary in regions where inductive interference prevailed and some rerouting in entrance cable portions involving the use of selected pairs in existing non-quadded cables.

When the line was opened for public use, the transmission performance was as good as had been expected when the project was planned. Crosstalk and noise were well within tolerable limits. The theoretical equivalent was about 28.5 db (appreciably better than the equivalent of the older non-loaded 165 mil circuits between New York and Chicago). According to the standards for long distance transmission that were worked to in the period under discussion, the transmission was considered to be satisfactory between terminal stations in New York and Denver, but the margin of transmission was not great enough to provide really satisfactory service when long switching trunks were involved at the two ends. Consequently, as soon as the subsequent developments in telephone repeaters would permit, experimental repeaters were put into use on the New York-Denver connections.

The Denver line was not a through or terminal circuit, ready for use on call. It was built up when needed, with switches at Morrell Park (Chicago) and Omaha. When it became necessary to use side circuit portions as substitutes for the phantom circuit portions, the over-all transmission was several db worse than when the phantoms were used. This was partly a result of the higher attenuation of the side circuits, and partly because one of the side circuits was arranged for telephone connections and leased wire telegraph at several intermediate points between Omaha and Denver.

There was a heavy use of grounded d-c telegraph service on the composited line wires. At times, serious impairment to the telephone transmission was caused by non-linear distortion resulting from transient magnetization of the loading coil cores by the superposed telegraph currents. This effect became known as "Morse flutter" and later on as "telegraph flutter." It had previously been noticed on shorter loaded lines, but as the composited loaded lines became longer and longer, the flutter interference became more and more serious. Subsequent developments, first used on the transcontinental line, resulted in a considerable reduction of telegraph flutter per unit length of line, but there always was an appreciable amount on long loaded lines when they were used for composite telegraph circuits.

Boston-Washington Loaded Duplex Cable Project

As previously indicated, a main purpose of this project as planned in 1909–1910 was to provide storm-proof communications between the principal eastern cities. This project is historically significant as being the first long-distance cable system to use quadded cable and phantom group loading. It was also the longest telephone cable system ever designed for use without repeaters. Fortunately, a satisfactory type of telephone repeater became available for commercial use before the project was completed, and its value was thereby greatly enhanced.

General: The over-all length, Boston to Washington, was about 455 miles, with New York close to the half-way point. Underground conduit already existed for about half of the total distance—Boston to Providence, and New Haven to New York to Philadelphia to Wilmington. Heavy-loaded, non-quadded, 16, or 14, or 13-gauge cables were already in commercial use in different parts of the route but, in general, since they had been designed for shorter distances, they were not sufficiently efficient to be used in tandem connections with new cable as portions of Boston-New York or New York-Washington all-cable facilities without also using telephone repeaters. The magnitude of the over-all project was so great that the construction work and the manufacturing effort had to be undertaken in several steps, spread over a period of years.

The first step was to lay a new underground conduit between Wilmington and Washington via Baltimore, and install a composite coarse-gauge loaded cable between Philadelphia and Washington, thus closing the gap between New York and Washington. It was an economically fortunate coincidence that when it became necessary to engineer the cable and the loading, a good start had been made on the development of duplex cable and of cable phantom group loading. The status of these developments, however, was such that it was very far from a certainty that long-distance loaded duplex cable facilities could be made satisfactory from the crosstalk standpoint. On the other hand, the economic stakes were very great; if the crosstalk could be kept within tolerable limits, the complement of coarse-gauge circuits would be nearly 50% larger than if a coarse-gauge non-quadded cable should be used, and the transmission equivalents obtainable in the loaded phantoms would be appreciably lower than those on loaded non-quadded pairs using the same size conductors. The increment cost in getting the extra complement of higher grade circuits consisted principally of the cost of the phantom loading coils and the cable capacitance unbalance adjustments. This was judged to be small in proportion to the potential value of the circuits. The decision to proceed with the development of the duplex cable and phantom group loading was made in the spring of 1910, while the quadded cable for the Boston-Neponset project was under production, and prior to the start of production of the new phantom loading apparatus.

A fundamental transmission objective was to obtain facilities which upon completion of the project would meet talking standards desirable for Boston-New York and New York-Washington connections, with a few circuits suitable for emergency use between Boston and Washington in case the open-wire lines should go down. These requirements called for 10-gauge conductors. Also, there were requirements for all-cable circuits connecting intermediate points, which called for 13-gauge or 16-gauge conductors. Since the cable route intersected the existing open-wire routes at many points, patches could be made for the protection of the long distance service normally handled in open-wire.

Philadelphia-Washington Section: The requirements above summarized resulted in the design of a cable having 7 quads of 10 B&S gauge conductors, 18 quads of 13-gauge conductors, 6 non-quadded 13-gauge pairs in the interstices of the layer of 10-gauge quads, and 18 non-quadded 16-gauge pairs in the interstices of the 13-gauge quads. All quads were of the multiple-twin type. The loading cost study resulted in a decision to use a new weight of loading, medium-heavy, with coils installed at intervals of about 1.4 miles, intermediate between that of the spacings for standard heavy and medium loading. The coil inductances were chosen to provide a cut-off frequency of about 2300 cycles, which was standard for cable loading for nearly two decades. Heavy loading was also considered, but its efficiency would not have been enough better to justify the extra cost and the extra manufacturing and installation efforts in working to difficult rush schedules.

Since the loading coils were designed to be in approximate cost-equilibrium with the cable conductors, those used on the 10-gauge quads were nearly as large as the standard open-wire loading coils, and much larger than those used on 13-gauge quads, which in turn were appreciably larger than those used on the 16-gauge pairs. Also, for cost-equilibrium reasons, the phantom loading coils were larger than their associated side circuit coils and were potted with them, with the cross-connections between them made inside the cases at the point where the connections to the stub cables were made.

The manufacture of the Philadelphia-Washington section of the cable and the loading coils was completed during 1911, and commercial service started on March 22, 1912. A great many manufacturing difficulties were encountered in preventing the cable and coil unbalances from reaching unacceptable magnitudes, including some difficulties not previously experienced in the Boston-Neponset project which were in part due to the larger sizes of conductors.

As the associated phantom and side coils were potted in the same case it was possible to obtain some crosstalk advantages by poling the unbalances in one type of coil against those in the other type. In order to maintain schedules, it was sometimes necessary to accept loading apparatus and cable lengths having objectionably high unbalances. In such instances, special arrangements were made for installing these items at points remote from the principal toll centers so that the resulting crosstalk would be substantially attenuated before reaching the telephone subscribers.

In installing the cable, capacitance unbalance test splices were made at 7 points in each loading section, following the procedure used on the Boston-Neponset cable, but working to more severe limits on residual unbalances. In the over-all tests made prior to commercial service, the crosstalk was found to be within permissible limits, but was in excess of values considered satisfactory. In consequence, renewed and successful efforts were made to obtain better crosstalk performance in the next section of the project, that between Hartford and New Haven.

The transmission tests on the Philadelphia-Washington cable showed the attenuation to be about 13% better than had been estimated on the coarse-gauge circuits. This was in part due to conservatism in estimating, but mainly due to special manufacturing efforts to dry out the cable so as to reduce the dielectric losses. Also, the loading coils were somewhat bette than expected. In a report to Gherardi, Jewett wrote:

> "These tests indicate a most successful and gratifying outcome for a piece o work which has taxed our energies almost to the limit and which it must be ad mitted was an extremely large experiment at the time the original decision to lay cable was made. The results obtained seem to me conclusive proof, if such proo is still needed, of our ability to forecast transmission results without recourse t laboratory demonstration . . ."

It is of interest to note that the attenuation in the 10-gauge cable circuit was approximately $\frac{1}{3}$ lower than that of non-loaded 104 mil open-wire cir cuits, and only 50% higher than that of loaded 104 mil and non-loaded 16 mil open-wire. The attenuation in the 13-gauge circuits was approximatel 70% higher than that in the 10-gauge circuits.

Considerable telegraph flutter was noticed in the long cable circuits whe they were used simultaneously for telephony and telegraphy. This led t the restriction of the magnitudes of the superposed telegraph currents an to the development of more sensitive telegraph relays. Several years later (1916), the development of more stable types of loading coils proved to b beneficial in the reduction of telegraph flutter in the new facilities on whic they were used.

Remainder of Project: Work started on the manufacture of cable and coils for the New Haven-Providence section of the Boston-Washingto project before the Philadelphia-Washington section was completely installed The section between Hartford and New Haven was placed in service Feb ruary 13, 1913. Some manufacturing difficulties temporarily stoppe cable production, with the result that the Hartford-Providence section di not get into service until October 1913. This installation closed the las gap in the underground cable system between Boston and Washington, an led to the following statement by President Vail in the report to stockhold ers for the year 1913:

> "During the year 1913 we have made such further advances in the art of loadin and balancing underground circuits, and have so greatly improved the interme diate apparatus, that it is now possible to talk satisfactorily by underground wire from Boston to Washington, in part through types of cable formerly suitable fo short haul distances only. These short haul cables make up 47 per cent of th total cable in the line."

The "intermediate apparatus" referred to were telephone repeaters tha had been made available for a few long haul circuits, as mentioned later i the transcontinental repeater development story. In another paragrap of the report, Vail remarked:

"By using the underground in connection with the overhead, the Seaboard cities from Washington to Boston could be no longer isolated by storms destroying the overhead wires."

The storm-proof communications objective having been achieved, the remaining sections of the coarse-gauge quadded cable project were installed in accordance with the need for additional circuits in particular sections of the Boston-Washington route. These additional coarse-gauge cables became available for service in the following sequence: Boston-Providence, November 1914; New York-New Haven, April 1917; and New York-Philadelphia, 1918. The listed dates apply to the initial loading complements, which usually included all of the 10-gauge quads and half of the 13-gauge quads.

Several of the shorter sections made use of a new cable layup having 3 quads of 10-gauge conductors, 30 quads of 13-gauge conductors, and 18 pairs of 16-gauge conductors. This change in layup was a significant result of the new repeater developments then current, which greatly reduced the need for 10-gauge circuits. By dropping out 4 quads of 10-gauge conductors and the 6 interstice 13-gauge pairs (a total of 18 circuits), it was possible to provide 12 additional quads of 13-gauge conductors, giving a net gain of 18 circuits.

CHAPTER III

The Transcontinental Telephony Project

A. PLANNING THE PROJECT

FROM what was said regarding the 1908–09 Pacific Coast trip and Carty's analysis of the engineering situation early in 1909, and the accounts of the subsequent development work, there should be no occasion for surprise in the statement that the extension of the westward limit of commercial telephony to Denver in 1911 set in motion a planned series of new development and research projects for the specific purpose of achieving transcontinental telephony. It should not be inferred, however, that early in 1909 a complete, detailed, plan had been worked out and approved, and was ready to be carried out on a rush basis upon receipt of the go-ahead signal from the chief executive. Otherwise, it would not have been necessary to engage in the new studies and the planning work during the period November 1910–April 1911 which preceded the beginning of the necessary new fundamental researches on the telephone repeater and line problems.

Mr. Carty's memorandum of April 9, 1909 to Mr. Thayer, previously mentioned, outlined a broad plan, one part of which involved learning how to load 165 mil open-wire circuits, but knowing in advance that that step would not get beyond Denver. The other part, of greater basic importance but much more complicated and less predictable, involved the repeater research problems. These parts were carried out in orderly sequence.

The short story of the transcontinental line given in the Alfred Bigelow Paine biography of Mr. Vail, "In One Man's Life" (1921), indicates that business policy and financial questions were factors in timing the go-ahead signal to Carty. This account, however, blithely ignores the engineer's technical problems in developing the necessary new instrumentalities, and the inherent uncertainties. Emphasis was placed on costs. Some of the directors conceded it would be a good thing to do, but believed the venture would not pay. Vail finally decided, "Oh, well, if it is a good thing let's do it, anyhow". He was looking forward to a fulfillment of the company's objective of universal service which had been clearly pictured in the original incorporation papers of the American Company in 1885.

It should be emphasized here that the transcontinental project planning by the engineers did not wait until the Denver line had been placed in commercial service, since long before then they were confident of its success.

By November 1910 the development situation in relation to transcontinental telephony had begun to crystallize, and during the following months definite plans were made.

Preliminary Transmission Study

In this planning work, it was logical that the possibilities of reaching the Pacific Coast on loaded lines without repeaters should again be considered. A transmission-cost study made by Jewett and his associates (F.B.J. Memo of December 6, 1910 to Gherardi) demonstrated that it would be economically unsound to attempt New York-San Francisco transmission without developing an entirely new type of telephone repeater, then considered to be a development possibility.

On a non-repeater basis, to provide a satisfactory grade of transmission according to standards of that day, it would have been necessary to use a phantom circuit on #5 BWG wire (220 mil diameter, 774 lbs. per wire mile) having entirely new types of insulators and loaded with new types of ultra-high-efficiency coils, all the way from coast to coast. On the other hand, with a suitable type of repeater used in conjunction with loading, it should be possible to use the existing 165 mil wires between New York and Denver in conjunction with new 165 mil wires from Denver to the Coast. Jewett believed that the cost of the repeater solution would be very small relative to the cost differences between the two types of lines. The concluding paragraphs of the December 6, 1910 memorandum are quite revealing:

> "As a result of this preliminary study, I am more than ever impressed with the very great need for producing a satisfactory repeater for operation on loaded lines if we are to establish a truly universal service on the North American continent on a paying basis as well as one of true economy.
>
> "From a preliminary study of the situation, I feel very confident that if this repeater matter is tackled in the proper manner by suitably equipped men working with full coordination and under proper direction the desired results can be obtained at a relatively small cost. I feel, however, that to achieve this result it will be necessary to employ skilled physicists who are familiar with the recent advances in molecular physics and who are capable of appreciating such further advances as are continually being made, also that the work must be carefully supervised by some one having a full understanding of the requirements."

Review of Repeater Situation

This project transmission study occurred at a time when the repeater problems were being carefully reviewed and analyzed, looking backwards, and forward.

Looking backwards, it will be recalled that mention has been made on several occasions in this story of the efforts which were being made to learn how to use the mechanical telephone repeater on loaded circuits. Little has been said, however, regarding the results of this work, which was carried out entirely on loaded cables, because there was no progress in commercial utility to report. Nevertheless progress had been made, but of a somewhat negative character.

Much had been learned regarding the inherent limitations of the repeater element itself.

The loaded circuits of that era which were sufficiently regular for good transmission without repeaters were being found not to be sufficiently regular when used with repeaters. Moreover, similar types of loaded circuits in the same cable were found to have large differences in their impedance characteristics.

In all of the experiments the 21-type repeater circuit was used. In this circuit, the line sections between which the repeater works must be closely equal in impedance, in order to avoid transmission distortion by interaction of the input and output currents, which may be very disastrous to intelligibility, especially when attempts are made to operate two or more repeaters in tandem in the same circuit.

It thus happened that the limitations of the mechanical repeater element, the repeater circuit, and the lines, combined to accentuate each other's effect in piling up the practical difficulties.

A Plan Evolves

The November-December 1910 analyses of what had been done and what remained to be accomplished resulted in an engineering decision to renew the attack on the repeater problems on an "all-out" basis, according to a plan which would be designated as a "four-prong" offensive in the military language of today. The following statement of this fundamental plan is quoted from the Work Order No. 7655, "General Repeater Study," prepared by Jewett, and which was officially approved by Carty on April 1, 1911.

"*Nature of Work*

"A general study to determine the proper characteristics for the best telephone repeater, its circuit, and the general terminal and line conditions that must be fulfilled to make this repeater available for both loaded and non-loaded lines. This study will include—

"(1) A complete study of the characteristics of the existing receiver-transmitter (Shreeve) type of repeater with a view to determining whether the action of this repeater cannot be improved upon and whether modifications in the repeater element, its circuit or in the line conditions will make it suitable for general use on loaded lines.

"(2) A study of other possible repeater ideas, particularly in the domain of molecular physics. Certain characteristics of discharge of electricity through gases and vapors seem to offer considerable possibility of obtaining a telephone amplifier that will be suitable for use on loaded or non-loaded lines and which will give the desired amplification without a great deal of distortion.

"(3) A mathematical and laboratory study of two-way repeater circuits with a view to determining the best form of repeater circuit to be used in combination with any desired repeater element and any kind of loaded line.

"(4) A mathematical and experimental investigation of loaded line characteristics in the existing plant, and a determination of what changes, if any, must be made in the construction and installation of loading coils and cables in order to make loaded lines suitable for the application of telephone repeaters."

The executive decision to make the "all-out" attack on the repeater problems as an economically necessary step to transcontinental telephony was largely influenced by Jewett's advice and his confidence in the possibilities offered by the recent advances in electron physics. The decision proved to be very timely. By starting in time, and by continuous, vigorous, activity in the allied research, development, engineering, manufacturing, and construction problems, it was possible to have the Transcontinental Line ready for commercial service when the Pacific-Panama Exposition opened at San Francisco early in 1915. The advantages to all concerned in having the Transcontinental Line ready prior to the Fair are obvious.

Responsibilities for the Work Under the Plan

Returning to the discussion of the plan, the specific program for group and individual responsibilities in doing the work conformed to proposals made by Jewett in his memorandum to Gherardi, "Repeater on Loaded Lines," dated December 22, 1910, from which the following paragraphs are taken:

"As a result of my study of the matter it seems to me that as the results from all four investigations must ultimately mesh with an existing, or to-be-built, telephone plant, the general supervision of the problem, the formulation of the specific problems and the general coordination of the work can probably best be done by someone in this Engineering Department rather than by someone at the Western Electric Company.

"With regard to the probable best assignment of the specific divisions, it seems to me that the investigation of the present carbon-button type of repeater is clearly a problem for the Western Electric Company under the general supervision noted above. Also, it seems clear that as the investigation of new repeater principles will undoubtedly involve a large amount of laboratory work, this also is a matter for Western Electric investigation. As regards the other two, namely, the study of repeater circuits and the investigation of loaded line characteristics, I believe that best results will be obtained by having as much of the detailed work as possible done here. Primarily, the investigation of repeater circuits is a matter for theoretical and mathematical consideration, and secondarily, a matter for experimentation. In the making of this investigation it will be necessary to utilize all of the results obtained from the work on repeater element and line characteristics.

"My reason for thinking that the phase of the investigation which concerns the characteristics of loaded lines should be handled directly by us is that much work of this kind will have to be done by us in connection with our phantoming, phantom loading, duplex cable design, coil design, and superimposed telegraph work and unnecessary duplication can undoubtedly be accomplished by combining the two problems.

"The various phases of the problem are so interlocked that the utmost co-operation, between ourselves and the Western Electric Company, and between the various men engaged on the problem is absolutely essential to the accomplishment of successful results, and as under the present organization this Engineering Department is responsible for the specification of what shall or shall not go into the operating plant, I believe, as noted above, that the immediate supervision of the problem as a whole had best be located here. What I have in mind is that this problem should be handled in much the same way as the problem of phantom loading the duplex cables was handled. In this case part of the detailed work has been done by us and part by Western Electric Company, and while the general supervision has been with us there had been the utmost cooperation between all concerned, whether here or at the Western Electric Company.

"With proper handling and with proper men engaged on the various phases of the problem, I feel very confident that fruitful results should be obtained within a reasonable time."

It was most logical that the responsibility for the general direction of all this work should be assigned to Jewett in the beginning, and that he should continue to hold this broad responsibility when he was transferred to the Western Electric Company on April 1, 1912 to become an Assistant Chief Engineer, reporting to C. E. Scribner, the Chief Engineer.

Organizing of Personnel to Do the Work

The new work order was officially sent to the Western Electric Company on May 27, 1911, to cover that part of the work which had been delegated to the recently organized Research Branch of the Western's Engineering Department, under the direction of E. H. Colpitts, its first Research Engineer. Other Western engineering units joined in the development work later on.

Early in 1911, Jewett's own department acquired new personnel primarily to work on the "loaded lines characteristics" phase of the fundamental repeater study and on repeater circuit questions. These were R. S. Hoyt, transferred from the Special Development Laboratory of the Western Electric Company, and John Mills, fresh from a teaching job at Colorado College. At one time or other, practically all other members of Jewett's rapidly expanding department worked on the transcontinental line problems. As a research consultant, Dr. G. A. Campbell made important theoretical contributions. The American Company organization set-up as of December 1, 1911, after the 1911 crop of engineering graduates had been assimilated, is given on page 403.

The great organizational achievement was, of course, the creation of the Research Branch of the Western's Engineering Department, early in 1911. Jewett had important responsibilities in this planning, working in conjunction with Messrs. Carty and Gherardi of the American Company and Messrs. Scribner and Colpitts of the Western Electric Company. Jewett was also active in recruiting personnel. His most fruitful contribution to this phase of effort was the engagement of Dr. Harold D. Arnold, who eventually succeeded Colpitts as the Research Engineer, and who might have risen to positions of even greater responsibility but for his untimely death in 1933. The hiring of Dr. Arnold was the result of personal negotiations with Professor Robert A. Millikan of Chicago University, an old friend and former associate when Jewett was studying for his doctor's degree, and who had become widely recognized as a leading American expert in the whole realm of electronic physics. In a 1931 radio address by Millikan, Jewett's statement to him regarding the requirements for a satisfactory telephone repeater was quoted as follows:

> " . . . Such a device, in order to follow all of the minute modulations of the human voice must obviously be practically inertialess, and I don't see that we are likely to get such an inertialess moving part except by utilizing somehow these electron streams which you have been playing with here in your research work in physics for the past ten years. . . ."

Millikan was requested to recommend a man whose familiarity with the electronic technique and whose character would qualify him as being competent to attack the Telephone Company's research problems on repeaters. In due course Millikan recommended Arnold, who was then working in the Ryerson laboratory for his doctor's degree, and Jewett sponsored him. He reported for work with the new Research Branch of the Western Electric Company early in January 1911, knowing what was expected of him. Arnold's outstanding personal contributions to the project, as discussed later, fully justified Millikan's confidence and Jewett's expectations.

The first Western Electric organization chart to show the new Research Branch is that dated January 1, 1912, page 404. The chart on page 405 shows the complete engineering personnel of the departments for which Jewett became responsible on April 1, 1912, as Assistant Chief Engineer. Another chart dated July 1, 1912, page 406, shows Jewett's departments in relation to the complete Engineering Department of the Western Electric Company.

B. ACHIEVING TRANSCONTINENTAL TELEPHONY

This section of the story summarizes the significant research and development efforts that solved the basic problems of transcontinental telephony, culminating in the first talk over the New York-San Francisco line by Mr. Vail on July 29, 1914 and in the official opening of the line for commercial service on January 25, 1915. Many amusing stories are told of the efforts of the engineers to do their final testing on the line without transmitting any of their voices from coast to coast, the injunction having gone forth that under no circumstances was anything to happen that would detract from Vail's first talk.

In general, the present story does not discuss the personal contributions of individual engineers and physicists which were essential to the complete success of the project. Some information on these matters is available in an article, "The Line and The Laboratory," written by John Mills, and published in the January 1940 issue of the Bell Telephone Quarterly, along with other articles commemorating a quarter century of transcontinental service.

In the beginning, the Western Electric Research department and the Transmission Engineering department of the American Company were most actively engaged in the project. In the course of time, these departments were expanded to handle the increasing amount of work and other associated departments in these organizations became involved in the cooperative efforts. The engineers of the Long Lines department, and of the Pacific and Mountain States companies also, did their own very important jobs, and last but not least, so did the manufacturing organization of the Western Electric Company.

The Improved Mechanical Repeater

The 1911 analyses of the then available form of Shreeve repeater, receiver-transmitter mechanical type, indicated the principal defect to be a very marked natural period about midway in the telephone talking range, in which range the amplification was very much greater than at low and high voice frequencies. This caused distortion and tendency to sing well within the audible range. Other serious defects were a variable amplification with different magnitudes of input energy, the amplification with low levels being markedly less than with high level input, non-linear distortion, and a tendency for periodically variable amplification from instant to instant. Inertia of the moving parts was a congenital handicap that could not be completely overcome. The diaphragm of its receiver portion had to vibrate at any and all speech frequencies, and simultaneously drive at the same vibration rates the movable electrode of the carbon-button transmitter.

The analysis just summarized resulted in design modifications which materially improved the performance characteristics. Specifically, these modifications improved the magnetic circuit, reduced the movable mass, and raised the natural period of the vibratory system to the upper part of the voice range, approximately 2200 cycles. The sensitiveness of the repeater, which was greatest at its natural frequency, was reduced by means of a resonant shunt-type electrical filter of about the same critical frequency. This arrangement provided more uniform frequency-amplification characteristics and better quality. The modified repeater, however, was still not entirely satisfactory with respect to the variation of amplification with respect to input levels.

The 1912 improvements produced an amplifier element that was good enough for experimental use at Philadelphia in September 1912 on a loaded New York-Baltimore circuit in the New York-Washington cable, using the 22-repeater circuit subsequently described. Somewhat later there was an experimental installation on the New York-Denver loaded open-wire circuit, using the 22-type repeater arrangements with three repeaters in tandem. Further development work on refinements and auxiliary devices made the mechanical repeater fairly satisfactory from the quality, volume, and life standpoints, and several commercial installations were made during 1913 and 1914, including a number of points along the Boston-Washington cable, initially at Philadelphia, to improve and protect the service along this route.

The improved repeaters, code 3A, were used for a few days in the initial 3-repeater service (at Pittsburgh, Omaha, and Salt Lake City) on the transcontinental line in January 1915, as alternatives for vacuum tube repeaters installed at the same points. The New York-San Francisco service with the mechanical repeaters was fairly satisfactory, but not as good as that with the vacuum-tube repeaters, which were retained in service.

The inferior characteristics of the improved mechanical repeater, relative to the vacuum tube repeater, led to restrictions in its general use. The principal disadvantages of the mechanical repeater were those previously commented upon. These were such as to become more and more serious with increasing lengths of circuits, involving increasing numbers of repeaters in tandem. Moreover, even under most favorable operating conditions, the maximum repeater gain was well below that obtainable with the vacuum tube device. The inertia of its moving parts restricted its frequency range application to voice-frequency telephony. Within a few years after the opening of the transcontinental line no more installations were made, and vacuum tube repeaters were substituted in old installations. That is to say, the vacuum tube repeater soon became the standard.

New Types of Repeater Elements

(*a*) *The Mercury Arc Repeater*

The early theoretical survey of the possibilities of developing essentially inertialess telephone repeaters focussed attention on gaseous discharge devices as having great promise, and Arnold's initial research efforts were concentrated in this field, using a mercury arc. The suggestion to use the mercury arc as an amplifier was old, having been advanced in this country by Peter Cooper Hewitt, the inventor of the mercury vapor lamp, but it had never proved to be feasible in a practical way, because of its variable amplification, inefficiency, noise, and distortion. Arnold contributed new features based in part on novel phenomena discovered in his experimental work. These substantially reduced or eliminated the defects above listed. Patents were issued to him in due course, and rights were also obtained under the Hewitt patents.

The basic element of the Arnold amplifier was a stream of ionized molecules of mercury vapor flowing vertically from the positive electrode at the upper end of an evacuated tube to the negative electrode, a pool of mercury at the lower end, the energy for maintaining the arc being furnished by a direct current power source which included in its circuit a stabilizing choke coil and a regulating rheostat. Within the tube there were two auxiliary side electrodes (cathodes) symmetrically disposed with respect to the axis of the tube and closely spaced thereto. There also was a starting electrode located within an associated condensing chamber. The ionized mercury vapor stream was vibrated transversely between the two auxiliary side cathodes, by virtue of the electromagnetic action of the input telephone current flowing through coils which were mounted on the pole pieces of an external electromagnet and so disposed that the axis of the magnetic field was perpendicular to the axis of the ionic stream. The output circuit included a transformer which had a split primary winding, with its two main terminals connected to the two side cathodes respectively, and its mid-point connected to the negative terminal of the d-c power source previously mentioned. When there was no input telephone current in the receiver coils the arc stream flowed steadily, and no current was induced in the secondary windings of the output transformer because the equal currents from the two side cathodes flowed in opposite directions in the two halves of the primary winding and inductively annulled each other's effect on the core. On the other hand, when a telephone current flowed through the magnet coils, the arc stream was magnetically deflected first to one side cathode and then to the other, depending upon the magnetic polarity. This caused changes in the magnitudes of the currents flowing in the individual halves of the primary winding of the output transformer; as the current in one half-winding increased that in the other half-winding necessarily decreased, and vice versa. The resultant induced current in the secondary winding of the output coil had similar frequency components to the incoming telephone current and much greater energy, which was supplied by the current from the external battery, or other power source.

The theoretical principles of the device were studied to provide a background for straightening out initial design kinks, and to provide suitable auxiliary apparatus for associating the amplifier with the telephone circuit. Considerable difficulty was encountered in securing a sufficiently long life of the mercury tube to permit experimental use. The first field experiments occurred late in December 1912 at Philadelphia, on loaded circuits in the New York-Washington cable. During the next two years a number of other experimental installations were made. Sentimentally significant experiments were made on the transcontinental line in the late spring of 1915, using three and sometimes four repeaters in tandem. In some respects the over-all transmission performance was good, but it was not so generally satisfactory as with the vacuum tube repeaters. Considerable difficulty was encountered in starting and maintaining the mercury-arc amplifiers.

By the end of 1913, it was becoming apparent that the high vacuum tube amplifier was destined to become the leading type. As a matter of fact, the development work on the mercury arc device began to slow down late in 1912, soon after the work started on the improved audion, as subsequently discussed. The mercury arc repeater was never used in commercial service. The experimental installations were dismantled during 1915, and the development case was officially closed in October 1916.

The success that was quickly achieved in the development of a satisfactory high vacuum tube repeater, as described in the following pages, leaves unanswered the question as to whether the mercury arc repeater could have been developed to become a thoroughly satisfactory voice-frequency amplifier. Its more complicated structure, its need for more complicated and more expensive auxiliary devices for associating it with working telephone circuits, and the greater difficulties in operation and maintenance were serious handicaps. Also, it was more limited with respect to repeater gains, and with respect to working-frequency band. The device as developed was used only as a voice-frequency amplifier.

(*b*) *The High Vacuum Tube Amplifier*

Arnold's research and development work on thermionic amplifiers started in November 1912 soon after a laboratory demonstration on October 30 and 31 by Lee deForest of the amplifying properties of his Audion tube, which for several years had been extensively used as a detector for wireless telegraph signals. The Audion as submitted was a much simpler device than the mechanical and mercury arc amplifiers. It consisted of an evacuated glass tube containing three elements: (1) a filament which emits electrons when heated by an external "A" battery, (2) a metal-plate electrode which attracts and collects these electrons when maintained at a suitable positive potential by an external "B" battery, and (3) a grid electrode placed close to the filament in the path of electron flow to the plate electrode and used so as to exercise a very sensitive control of the electron stream. This third element was deForest's pioneering contribution to the art. In using the Audion as a telephone amplifier, the grid and filament terminals serve as the input terminals and the plate and filament terminals as the output terminals. Under proper operating conditions, variations in input voltage applied to the grid circuit so affect the flow of electrons as to produce amplified voltages in the plate or output circuit. Using energy drawn from the plate battery, an increase in energy is delivered to the output line. In deForest's recent use of the Audion as a radio receiving amplifier the grid circuit included a series condenser; this was also included in the arrangement offered as a telephone amplifier.

The laboratory demonstration had been arranged with Mr. Carty by John Stone Stone, a mutual friend and an independent research worker who had acquired a theoretical knowledge of telephone transmission problems when he was a member of the Boston headquarters staff of the telephone company during the nineties. Colpitts and Richards participated in the complete demonstration and Jewett in the final stages. This demonstration of the Audion was entirely qualitative in scope, under simple but adequate circuit conditions. With very low input levels, the speech currents were greatly amplified without perceptible impairment in intelligibility. However, when the speech input approached the levels that would be encountered in any commercial use of repeaters, the amplification was greatly reduced and very noticeable distortion and noise resulted. Under these conditions, a blue haze was prone to appear in the tube and it disappeared when the input level was reduced. As the plate potential was progressively raised, a permanent condition of blue haze developed and the device ceased to amplify.

On the following day, November 1, the Audion was called to Arnold's attention. He promptly repeated and extended the experiments, using deForest's tubes and auxiliary apparatus which had been loaned for that purpose. Arnold's broad training in electron physics enabled him without study or delay to explain the blue haze phenomena and to prescribe a remedy. The keynote of the explanation was that the blue haze was due to ionization of gas present in the device and the remedy was to secure a much higher vacuum. The medium vacuum in the Audion test samples was a normal result of the best evacuation processes then used by incandescent lamp manufacturers. Better results could be secured by laboratory processes known to research physicists and still better results could be expected from a new type of molecular pump then recently described in technical literature. Arnold's preliminary analysis also indicated that a better type of filament, providing a more profuse emission of electrons and a much longer life, could be used in place of deForest's tantalum filament. All in all, Arnold painted an exceedingly intriguing picture regarding the practically certain prospects of developing a really good telephone amplifier from the deForest Audion. There was, of course, considerable chagrin that these prospects had not been recognized much earlier in the Telephone Company's research work on repeaters, but no time was wasted in attempts to develop alibis. Arrangements were made for Arnold to spend most of his time on the vacuum tube job and several assistants were provided. From then on, the work on the mercury arc amplifier element slowed down. To get full freedom in the development and use of the improved audion, patent rights were purchased from deForest and later on, as commercial use approached, it became desirable to obtain patent rights from other outside inventors, American and foreign, who had been working on electronic repeaters.

Arnold was the first worker in the electronic field to determine the physical laws of operation of the 3-element high vacuum tube, this being his initial personal contribution to the development. In the concurrent and subsequent experimental work it was found that the grid condenser of the deForest circuit was a basic factor, along with the previously mentioned blue haze, in the paralysis of the Audion as an amplifier, when large input currents of the magnitudes involved in wire telephony were employed. Under these conditions it was found that the grid condenser acted as an electron trap which, by piling up a negative charge on the grid, would cut off the plate current and block the tube, even if the vacuum should be high enough to prevent blue haze phenomena. Consequently, the condenser was eliminated from the grid circuit. For some time, a grid leak was substituted (a very high resistance, grid to plate). This was subsequently replaced by a battery inserted in the grid circuit to maintain the grid at a positive potential relative to the filament; this held the grid impedance to a definite value and improved stability. Early in 1914, Arnold began using a negative "C" battery in the grid circuit and thereby increased the sensitivity and the stability. This led to the potentiometer input method of controlling gain. Still later, it was learned that Lowenstein had anticipated Arnold in the use of the negative C battery, and patent rights were obtained.

In carrying out the development of the vacuum tube repeater by "methods of pure science which were brought to its study in the spirit of research," many workers were involved and a host of problems had to be solved. A new manufacturing art had to be created in the research laboratory. Optimum conditions and means for connecting the vacuum tube elements into the repeater circuit had to be worked out. From the beginning, these involved the 22-type repeater circuit, discussed later on.

The work on the vacuum tube repeater during 1912 and 1913 was summarized in the 1913 report on Work Order 7655 as follows:

> " . . . The result has been the ability to construct an Audion amplifier to give distortionless amplification between desired limits of current input; to give outputs of energy far above any value that is normally met in telephony; to act as a potential or as a current transformer with the ability when connected two or more in series of giving current amplifications of as large amounts as 50 times or more; to present to the circuits between which it works practically constant impedance. The present form of the Audion gives practically perfect repetition and amplification of currents delivered to it."

It is of interest that on February 18, 1913 a laboratory demonstration of the promising possibilities of the audion-type repeater was made for President Vail and other executives on a 900-mile non-loaded artificial 104 mil open-wire line. This was a one-way test having several repeaters in tandem, and the tubes did not have a high vacuum, due to limitations of the then available apparatus in the laboratory. The first use of the high vacuum tube amplifier on commercial circuits was on October 18, 1913 when a 22-repeater installed at Philadelphia was placed in service on a New York-Baltimore loaded cable circuit.

Further developments resulted in improved amplifiers becoming available in the transcontinental line when Mr. Vail first talked over it in July 1914, and when commercial service started the following January. The important over-all service characteristics of the line, including the part played by the repeaters, are considered in a subsequent section of this story under the heading, "The First Transcontinental Circuits."

Repeater Circuits

The development work on repeater circuits for the transcontinental project had for its basic theoretical background a classical mathematical analysis of the relations between line impedance irregularities and repeater gains in two-way repeater circuits, reported by Dr. G. A. Campbell in May 1912. The study included the currently used two-way, one-repeater circuit (21-circuit), and the two-way, two-repeater circuit (22-circuit), which had not been commercially used, although it had been invented by W. L. Richards in 1895, long before the availability of a commercially usable repeater element. In a preliminary report dated March 7, 1912,[7] Campbell had recommended the 22-circuit on the basis of its greater stability and unrestricted flexibility, as subsequently discussed. The March 7 memorandum also discussed the four-wire repeater circuit which later became very

[7] A complete copy of this memorandum is given in the last item listed in the attached Bibliography.

important commercially in the application of repeaters to long loaded, small-gauge, toll cables.

The maximum repeater gain which could be obtained in two-way circuits without sustained singing that would block transmission, or near-singing that would degrade intelligibility, was expressed by Campbell as a function of the differences of the impedances of the circuits involved.

In the 21-circuit, the single repeater element amplifies transmission in both directions, and its usable gain is a function of the differences of the impedances of the circuits between which it works.

In the 22-circuit where the two repeater elements each function as one-way repeaters, the usable gain is a function of the differences of the impedances of the line East and the artificial line required to balance it, and of the differences of the impedances of the line West and its own balancing artificial line. In the general case, involving lines with irregular impedance-frequency characteristics, twice the power amplification feasible with the 21-circuit would be allowable if the lines should be connected through a 22-circuit, assuming the use of balancing lines having "average" impedances as described later. Statistically, the average balance obtainable between any one line of a given type and the "average" balancing line here assumed in the 22-circuit is 3 db better than the average balance obtainable between any single line and others of its type as involved in the use of the 21-circuit. In the limiting theoretical case, which may be approached but not attained in practice, if one of the lines using a 22-repeater should be perfectly balanced by its associated artificial line, singing could not occur at that repeater irrespective of the degree of the unbalance between the impedance of the other line and its associated artificial line.

The foregoing discussion is adequately summarized in the statement that when high repeater gains are required the lines using the 22-repeater do not need to be so uniform in their impedance frequency characteristics as would be necessary with 21-repeaters. This was very important in the transcontinental telephone project because of the serious practical difficulties involved in the reduction of line impedance irregularities to very small values, as discussed later.

Furthermore, the 22-circuit has an overwhelming superiority in stability over the 21-circuit, under conditions that require the use of repeaters in tandem. This follows from its characteristic property of transmitting the amplified energy in one direction only—the desired direction away from the source—whereas each 21-repeater transmits in both directions and one half of its amplified energy starts backwards towards the source, thereby setting up among the successive repeaters objectionable circulating currents which impose severe restrictions on the repeater gains.

The 22-circuit also has important practical service flexibility advantages in that the lines between which it works may be of radically different types, provided each line has associated with it an artificial balancing line having closely similar impedance-frequency characteristics. This flexibility feature also permits the 22-repeater to be used as a terminal repeater. Since in such service the terminal impedances (switching trunks and loops) vary over a wide range, operating flexibility requires the use of a compromise impedance balancing network instead of one that simulates the line. In consequence, the terminal repeater gains are restricted to values much smaller than those obtainable with intermediate repeaters.

In considering Campbell's proposal to use the 22-circuit instead of the 21-circuit, it initially appeared that the artificial balancing lines for use with loaded circuits would have to be complicated multi-section loaded lines which themselves would tend to possess appreciable irregularities in their own impedance-frequency characteristics. Since the technical difficulties involved were critical handicaps, and because of adverse cost factors, the question arose as to whether a simpler form of balancing network could be devised. The study of this problem resulted in the development of a simple 3-element 2-terminal network, to balance a regularly loaded line terminated at about 0.2 fractional section. To provide flexibility in use, a simple procedure was devised for building out this "basic network" to match the actual line termination when different from approximately 0.2 section termination. For example, if the loaded line should be terminated at mid-coil, i.e., with a half-weight loading coil, the basic network would be built out to full-section using a shunt condenser of proper capacitance and then a series inductance equivalent to the half-coil would be inserted in tandem. An alternative procedure would be to build out the line at the repeater station.

The simple basic network above mentioned consists of a fixed resistance equal to the nominal impedance of the loaded line, in series with an inductance shunted by a capacitance, these elements being proportioned to shape properly the reactance component of the impedance-frequency characteristic. The special virtue of the line termination chosen for the basic network design is that at 0.2-section termination the resistance component of the characteristic impedance of a regularly loaded line is approximately constant over the most important part of the working-frequency band.

It was this possibility of constructing a simple balancing network instead of a complicated loaded artificial line which made practicable the use of the 22-repeater circuit.

The simple type of basic network above mentioned was first used in 22-repeater circuit trials on loaded circuits in the Boston-Washington cable. Different proportioning of the elements was of course required for the later uses with loaded open-wire lines. Later on, when the 22-repeater circuit was used on non-loaded lines, new types of simple basic networks were devised to simulate the impedance of the non-loaded lines. It is also appropriate at this point to mention the fact that when commercial service started with 22-repeater circuits, the balancing networks of the repeaters included not only the basic networks, and building-out devices when required, but also apparatus for balancing line terminal apparatus which otherwise would have contributed objectionable impedance irregularities to the line. Such auxiliary apparatus usually included a repeating coil to balance the line repeating coil, and a simple 4-terminal network to balance the composite telegraph sets, when involved.

An additional very important new feature provided in 1912 for the 22-repeater circuits was the use of a low-pass electrical wave filter in the branches of the circuit where each repeater element functions as a one-way amplifier. As their cut-off frequency was about 300 cycles below that of the loading cut-off, these filters suppressed the unwanted and unneeded frequencies near and above the loading cut-off, thereby making these frequencies negligible factors in repeater singing phenomena. This was of special importance because the simple basic balancing networks above described did not simulate loaded line impedance at these frequencies, and had added importance where vacuum tube repeaters were involved in consequence of their tendency to amplify the same amount at all frequencies.

Subsequently, low-frequency filters were included in the 22-circuit to suppress unwanted frequencies below approximately 250 cycles, in which band are occasionally present currents resulting from the operation of superposed telegraph circuits, and noise current produced by induction from power circuits. Line irregularities are not important factors in the repeater balance problem at these frequencies when proper types of basic networks are used.

The line experiments made with the improved mechanical repeater and the mercury arc and vacuum tube repeaters and the commercial installations previously mentioned used the 22-type repeater circuit. Different types of auxiliary apparatus (input and output transformers, etc.) were of course required to obtain optimum results with the different types of repeater elements. When the experiments involving tandem 22-repeaters showed objectionable impedance irregularities to be caused by the impedances presented by the repeaters to the line, improvements in the repeaters were made to reduce these effects.

In due course, the 22-repeater became the standard two-way repeater. The use of the 21-repeater was restricted to special situations not requiring more than one repeater of relatively low gain and located near the middle of the circuit.

Improving the Line

When the development work for the transcontinental project started it was realized on the basis of the earlier work that impedance irregularities in the existing types of loaded circuits were large enough to set objectionable limitations upon the gains obtainable with two-way telephone repeaters. The recent availability of the Vreeland mercury arc, variable frequency, oscillator had made it possible to get a considerable number of impedance-frequency curves at close frequency intervals, but as yet the specific irregularities in the impedance curves had not been correlated with their individual causes. This prior work had been concentrated on loaded cables.

For a considerable time the new line studies were concentrated on loaded open-wire lines. Since the spacing irregularities were known to be as great or greater than in the cables, and since other sources of irregularity such as intermediate and entrance cables were also present, it was expected that the open-wire impedance-frequency curves would be even more irregular than the cable curves. And such was found to be the case, but in a much greater degree than anticipated.

Inductance Irregularities: The discussion will initially be directed to the inductance irregularities, since they proved to be the principal problem. In the course of the line measurements it happened that one set of impedance curves had a very unusual systematic sequence of ups and downs with rising frequency. This was especially intriguing since the usual curves had non-systematic bumpy characteristics. The cause was found to be an omitted load at a particular load point. This incident resulted in the development of a formula for estimating the position of an impedance irregularity in terms of the frequency spacing of resulting bumps in the impedance-frequency curve and the velocity of transmission.

A comprehensive series of impedance measurements were then started on a long loaded artificial cable at the laboratory, since it was much more simple to measure than to compute. Also, the magnitudes and circuit position of individual and multiple irregularities could easily be controlled. Very valuable data were collected in this manner.

When the loaded open-wire measurements were resumed, it was noticed that the changes in the impedance-frequency irregularity patterns of particular lines changed substantially from time to time. These changes were found to be due to large inductance changes, up or down, in individual loading coils, and the cause was eventually found to be the magnetizing or demagnetizing action of strong transient line currents induced by lightning discharges. In lines exposed to lightning, sooner or later the inductance of all exposed coils would drop well below the factory value. A coil thus partially magnetized by one shock would sooner or later be partly demagnetized by a subsequent shock and these experiences would be repeated again and again in different degrees. Moreover, there were no systematic relations among the effects on coils at different points in the same circuit, or on coils in different circuits at the same loading points. These effects usually occurred without mechanical injury to the coil windings, or to the associated lightning arresters with which each coil was protected against breakdown, and it was this fact that had delayed recognition of lightning as being the probable cause. Confirmation of this deduction was obtained when tests made on lines unexposed to lightning showed that the coil inductances were close to their factory adjustment values.

Laboratory tests showed the magnetizing effects of lightning surges to be of the same order as the residual magnetizing effects of superposed direct currents, ranging up to several amperes in amplitude. The high magnetic retentivity of the continuous wire-type toroidal cores of the loading coils was a basic factor in these phenomena.

The necessity for accepting exposure to lightning surges as a normal service experience for open-wire loading coils forced consideration of the practicability of providing new designs having much greater magnetic stability. Experimental work was started on (non-magnetizable) solenoidal type air-core coils having finely sectionalized windings, and on toroidal wire-core coils having series air-gaps in their magnetic circuit to decrease its retentivity.

Fortunately the statistical study which was made to determine the limits that should be placed upon individual line irregularities in order to avoid undesirable restrictions on the repeater gains showed that it would not be necessary to use perfectly stable coils, i.e., the air-core coils. The concurrent work on the wire-core coils with air-gaps had indicated that by properly proportioning the air-gaps the inductance changes that should be expected from magnetization by lightning surges could probably be kept to tolerably low values. A single air-gap would have been sufficient to provide the required stability, but crosstalk considerations and other factors made it desirable to have two air-gaps symmetrically located at diametral points in the toroidal cores. The resultant designs were better in all important respects than the air-core coils and were inferior only with respect to magnetic stability, which difference as above noted was tolerable. To assist in the control of the inductance deviations in the lines, the new loading coils were manufactured to $\pm 1\%$ precision inductance limits. On the older standard designs, $\pm 6\%$ manufacturing deviations had been allowed. The new coils had somewhat lower nominal inductance values than the old coils, so that their average service inductance values after partial magnetization by lightning surges would be about the same.

The size advantage of the wire-core coils with air-gaps made it possible to pot the three loading coils for an open-wire phantom group, connected as a phantom loading unit, in a 3-compartment case. This was the beginning of the use of "phantom loading units" in open-wire loading. To provide installation flexibility, cases were also developed for individual side and phantom loading coils. The over-all dimensions for all cases were small enough to avoid limitations on the number of circuits that could be loaded at the same loading points along any line. Double-pole H-fixtures, however, were required on routes having a large number of wires.

These air-gap type loading coils and their cases remained standard for open-wire loading until subsequent developments in the art, notably improvements in the repeater and the use of open-wire carrier systems, resulted in the gradual abandonment of open-wire loading.

Following the transcontinental project, wire-core coils with air-gaps were also developed for use on coarse-gauge duplex cables of the Boston-Washington type. It is also of interest to note that while the work on the transcontinental project was still under way a very good start was made on the development of the compressed magnetic powder core-type loading coil for small-gauge cables. The high stability characteristics of this general type of coil became an important factor in the wide use of telephone repeaters in the long distance cable plant.

Spacing Irregularities: Taking up the consideration of the impedance irregularities caused by loading spacing irregularities, the need for a substantial improvement was duly proved, and precision limits of ± 2 per cent in the spacing were established for lines to be used with high-gain repeaters, starting with the transcontinental project. In general, the required precision in new lines could be secured by proper engineering care, including more uniform transposition layouts, since coordination with the coil spacing was necessary. In applying the new high stability coils along old routes, as was necessary on the transcontinental line sections east of Denver, relocation of many of the loading points was found to be desirable. In these loading rearrangements and sometimes also on new lines, it was occasionally found to be desirable to tolerate the use of geographically underlength loading sections and build out their total capacitance to the theoretically desirable values by using shunt condensers. Mica condensers having suitable dielectric strength were used for this purpose, protected by loading coil type lightning arresters. In lines used for phantom working, a network of six condensers was used to provide the optimum building-out capacitance for the side circuits and their associated phantom. Subsequently, building-out condensers and stub cables also found use in the repeatered loaded cable plant for correction of objectionable spacing deficiencies.

Incidental Cables: In improving the open-wire lines for repeater operation, substantial development and engineering effort was also devoted to the reduction of impedance irregularities caused by incidental cables. Especially on the transcontinental line, such cables were avoided when practicable, and those that could not be avoided were made as short as practicable. In some instances long incidental cables were avoided by locating the repeaters in a test station at the city outskirts—Brushton (Pittsburgh) and Morrell Park (Chicago), for example.

Several types of treatment were applied to incidental cables that could not be avoided. Short cables having capacitances materially less than that of an open-wire loading section were taken into account in the layout of the open-wire loading. This method was also applied to bridle wire at test stations.

Long cables were provided with a new type of impedance-matching loading. The coil inductances and spacings were such that the loaded cable would have about the same nominal impedance and the same cut-off frequency as the loaded open-wire circuits, these being the requirements for minimizing the junction reflection effects. This was the first use of impedance-matching loading on incidental cables in loaded lines. Previously, it had been the general practice on entrance cables to use some standard weight of toll cable or exchange cable loading, for example on the Boston-Neponset cable described earlier in this story. These former loading practices reduced the cable attenuation and the junction reflection loss, both being desirable objectives, but resulted in junction impedance irregularities large enough to be objectionable on repeatered circuits. In due time, it was found desirable also to use an extra light-weight impedance-matching loading for incidental cables in non-loaded open-wire lines, when used in conjunction with telephone repeaters. Later on, this need became especially important in lines used for carrier telephone systems, and suitable types of high cut-off, impedance-matching, carrier loading, were developed.

Line Insulation: Because of the high impedance of the loaded line and its great length, it was particularly important to keep the leakage losses as low as possible. An interesting problem in this connection was the effect of the salt on the line in the vicinity of Great Salt Lake in Utah. The Mountain States Company equipped itself to take care of the situation by using steam from the boiler of an old Stanley steam automobile to clean the insulators, when necessary.

The First Transcontinental Circuits

The construction of an entirely new phantom group between Denver and San Francisco began during the summer of 1913 via Rawlings, Salt Lake City, Winnemucca, Sacramento, and Oakland. An interesting account of the construction problems is given in an article, "The Circuits Go Up," by H. H. Nance and R. M. Oram, which is one of a series of articles commemorating a quarter century of transcontinental service, published in the

January 1940 issue of the Bell Telephone Quarterly. The ceremonies that occurred at the time the line was opened for public service and the subsequent series of demonstrations of transcontinental service are also described in that article.

The new line had all of the latest improvements to provide regularity in the loading. These ideas were also applied to the lines east of Denver, making use of the new high-stability loading coils, and including respacing of the loading points where desirable. Also, a great many changes in transpositions were necessary. In addition to the open-wire phantom group between New York and Chicago, there was one between Boston and Chicago via Buffalo, and a New York-Buffalo phantom group for use as part of an alternate route to Chicago. Philadelphia, Baltimore, and Washington were also connected to this network by additional phantom groups or by non-phantomed pairs to Pittsburgh.

As previously mentioned, the first coast-to-coast conversation occurred on July 29, 1914 when President Vail spoke the first words to cross the continent. The engineering tests that preceded this ceremony had been made on long isolated sections of the circuit. In the period that preceded the opening of the New York-San Francisco circuits for public service on January 25, 1915, a great deal of work was done to make the lines suitable for commercial service and to train personnel in the operation and maintenance of the lines, including the repeaters. In some sections, noise troubles[8] had to be cleared by special transpositions. Crosstalk conditions required considerable attention. Some of the last minute improvements in the repeaters and other apparatus were utilized.

The New York-San Francisco circuits as first used commercially had some temporary or experimental features, especially as regards the repeaters. For several weeks, the transcontinental circuits used three intermediate repeaters located at Brushton (Pittsburgh), Omaha, and Salt Lake City. Then additional repeaters were used at Morrell Park (Chicago), Denver, and Winnemucca. Later on, permanent repeaters were substituted for the experimental repeaters. This change from three to six intermediate repeaters was made primarily to obtain greater flexibility in operation and to provide long-haul service, including leased telegraph service to some inter-

[8] This reference to noise reduction work on the transcontinental line makes it appropriate to mention at this point the very important fundamental investigation of inductive interference between electric power and communication circuits which was made in the period 1913–1917 by the "Joint Committee on Inductive Interference" appointed by the Railroad Commission of the State of California in 1912. The field engineering staff which planned and conducted the technical studies and prepared reports thereon included engineers from the transmission division of the American Telephone and Telegraph Company Engineering Department. Mr. H. S. Warren made important contributions in the planning and conduct of the investigation, and was elected to an honorary membership of the committee. The conclusion and principal reports of the work have been published and widely used (refer bibliography).

mediate points. In this connection, it should be remembered that the transcontinental circuits were not through circuits, ready upon call, but were built up by switches at two or three intermediate points as required.

It is of interest to note that the change from three repeaters to six repeaters did not significantly affect the overall transmission performance. The gains in the individual repeaters had to be reduced in order to avoid objectionable interaction effects.

The transmission performance and circuit data given below apply to the New York-San Francisco circuits, having six vacuum tube repeaters in tandem:

Over-all Length	3359 miles
Transmission Losses	
Bare Line	53 db
Apparatus	7 db
Over-all, Line and Apparatus	60 db
Total Repeater Gain	40 db
Net Equivalent	20 db
Over-all Transmission Time	0.067 second

The net equivalent above given is a dry weather value. Under bad weather conditions the line loss approximately doubled. Adjustment of the repeaters, made manually, was required to keep the overall equivalent within reasonable bounds.

The transmission band that was effectively transmitted ranged from about 350 to 1250 cycles, defining the transmission band as that between the lowest and highest frequencies whose transmission was not more than 10 db higher than that of the transmission of 1000 cycles. At frequencies between 400 and 1000 cycles, the over-all loss was appreciably less than at 1000 cycles. At frequencies above 1250 cycles, approximately 50% of the theoretical loading cut-off frequency, the line losses including the loading coil losses piled up so as to effectively suppress transmission. The excess transmission losses at the low voice frequencies were due to losses in the line terminal apparatus (repeating coils, composite sets) and in the repeater auxiliary apparatus. Although the 900-cycle frequency band effectively transmitted by the transcontinental circuits was only about $\frac{1}{3}$ as wide as that required by the present standards for long distance transmission, it was acceptable to the early users of the service, and did not noticeably handicap the public interest in the large number of country-wide demonstrations that were made in the "Hello, Frisco!" era.

In the concluding section of his report to the American Company stockholders for the year 1914, President Vail appraised the significance of the transcontinental line and related developments as follows:

> "It is a long step from a hardly intelligible telephonic conversation between two rooms, to a perfectly easy, low-voiced conversation between the extremes

of our land, East, West, North, South. Remarkable as this is, the progress made during the epoch of which this was the culminating point has been still more remarkable, but so quietly has it all been accomplished that it has been hardly appreciable. During the past ten years more has been done to increase the utility and availability of the telephone service, more has been done to increase its reliability, and greater obstacles have been overcome, than during its whole preceding existence.

"What has been accomplished perhaps never will be surpassed, the present contains the germs of the future development. Commercial practicability will be more controlling in the future than technical practicability."

CHAPTER IV

The Establishment of a Transcontinental Network of Repeatered 165 Mil Lines

This concluding part of the transmission development story is mainly concerned with the establishment of a country-wide network of 165 mil lines interconnecting all important cities, following the completion of the New York-San Francisco line. The American Company engineering department took the initiative in this work, and the Western Electric research and development groups handled their parts of the work under Jewett in accordance with their usual organization responsibilities. During the early part of this period, December 1916, Jewett became the chief engineer of the Western Electric Company. Early in 1921, he became Vice-President of the Western Electric Company in charge of the telephone department, having over-all responsibility for engineering and manufacture.

Planning a Backbone Network

Immediately after the opening of the New York-San Francisco line, the making of plans to exploit the new developments and the new engineering knowledge got well under way. On March 1, 1915, Carty approved the American Company Work Order 8230, "Network of No. 8 Gauge Circuits Equipped With Telephone Repeaters Connecting All Important Cities of the United States." The work was to consist of:

(A) Determination of the best routes, and the sequence of installation.
(B) Determination of changes in loading and transpositions to fit these lines for repeater use.
(C) Choice of repeater equipment and circuit arrangements.
(D) Determination of the best operating methods.

When this project was authorized it was expected that loaded 165 mil open-wire circuits would be universally used in the backbone network. This part of the plan, however, was soon modified in consequence of transmission studies which showed even more attractive possibilities in the use of non-loaded 165 mil lines having additional repeaters to make up for the increased line losses. The expected advantages of this proposed change were:

(a) Elimination of the telegraph flutter impairments that were quite troublesome on the long loaded circuits.
(b) More uniform attenuation and impedance characteristics under varying weather conditions.

(c) Better quality of speech transmission obtainable by the effective transmission of a much wider frequency band.

(d) A reduction in costs.

Additional advantages of non-loaded lines for voice-frequency telephony became apparent from subsequent studies and experiments:[9]

(1) The practicability of securing materially lower net losses, in consequence of the effect of the higher velocity of transmission in reducing disturbances caused by echo currents.

(2) A reduction of delay distortion, resulting from the fact that the velocity of transmission of the upper speech frequencies in the non-loaded line is approximately constant with frequency, whereas in the loaded line the velocity decreases substantially with rising frequency, especially near the cut-off.

In September 1915, quantitative line tests were made to verify the theoretical expectations per items (b) and (c), above. The tests involved a comparison of the transmission over a non-loaded New York-Denver circuit, via Pittsburgh and St. Louis using six intermediate repeaters, with that over the New York-Denver section of the loaded transcontinental line using three intermediate repeaters. The non-loaded circuit had a somewhat lower net loss and noticeably better quality, and, of course, a complete freedom from transmission distortion by telegraph flutter. As a result of these tests, plans for using loaded lines in certain parts of the proposed backbone network were quickly modified to call for non-loaded lines and additional repeaters. In some instances where the lines were already loaded with old types of coils that were susceptible to magnetization by lightning surges, the change in plans avoided the expense of installing new high-stability type loading.

Change in Engineering Attitude Towards Loading

This decision to use non-loaded 165 mil lines instead of loaded 165 mil lines for parts of the continental backbone network was of great significance in that it marked the beginning of a new engineering attitude with respect to the fields of use for loading and for repeaters. Up to that time, loading had been accepted as the dependable and indispensable method of improving transmission in long distance circuits and extending their range, and repeaters had been regarded primarily as auxiliary devices for stretching the transmission benefits obtainable with loading. It will be recalled that, prior to the transcontinental development project, the type of repeater

[9] The non-loaded lines also had important possibilities in the application of carrier telephone systems, the commercial development of which got well started during the 1915–1920 period under consideration in Chapter IV.

which was available could not be used as an adjunct to loading, and even on non-loaded lines its use was greatly restricted.

From 1916 on, the vacuum tube repeater was recognized in its own right and potentialities as an independent instrumentality for improving transmission. For nearly a decade, repeaters and loading were competitors in the open-wire plant, sometimes used together as a team. Beginning in 1916, loading was removed from many 165 mil lines on which it was planned to use repeaters, and this practice continued at an accelerating rate during the early twenties to facilitate the exploitation of open-wire carrier telephone systems. GEC-812, issued June 1918, definitely discouraged the provision of loading on new 165 mil circuits. On 104 mil circuits, however, the competition between loading and repeaters was much closer. Partly due to production limitations on repeaters, the mileage of loaded 104 mil circuits increased rapidly during the war period, and reached a peak about 1923. Not long afterwards, the practice of loading 104 mil circuits stopped and the removal of existing loading accelerated, so as to provide maximum plant flexibility for the use of repeaters and open-wire carrier telephone and carrier telegraph systems.[10] On all types of non-loaded lines used in conjunction with repeaters, however, loading continued to have an important function in the transmission treatment of the unavoidable incidental cables.

In the long distance cable field, repeaters and loading were continuously developed over a period of more than two decades to work together as equal partners in a team, each making its own optimum contribution on a basis that provided the desired over-all transmission performance at about the minimum total cost.

Development Work

Returning to the evolution of the continental backbone line network in terms of repeatered non-loaded 165 mil lines, it was fully appreciated at the beginning that because of the increase in the number of repeaters and the changes in the line, improved types of repeaters and auxiliary apparatus would be required. The principal need was an improvement in the gain-frequency characteristic. This involved among other matters a reduction of the frequency distortion characteristics of the auxiliary apparatus. It was also found desirable to stabilize the repeater gain and to improve the impedance of the repeater presented to the line so that it would more closely match the line impedance.

During 1917 and 1918, analyses of extended tests on repeatered lines and cables laid the foundation for computation techniques that enabled the over-all transmission performance of repeatered circuits to be predicted with

[10] It was not until 1934, however, that the use of open-wire loading ceased completely.

close accuracy. The principal factors were found to be the velocity of transmission, the number and spacing of repeaters, the line attenuation, and the reflections at significant points of irregularity; i.e., at the line terminals, and at the repeaters. These studies and line tests clearly demonstrated the importance of the transmission velocity in echo current phenomena, and the limitations on transmission performance imposed by the echo currents.

To achieve transcontinental transmission on non-loaded 165 mil lines became an objective in the repeater development work. Although this development was started in good time, the pressure of war work interfered so that not much progress occurred until late in 1918, when arrangements were made for a trial of the improved repeaters on a non-loaded circuit between New York and Chicago. The success of this tryout in 1919 led to arrangements being made for unloading the transcontinental circuits west of Chicago. At the new repeater points west of Chicago entirely new repeaters were installed; those used at other points and in the new non-loaded Chicago-New York circuits were modified to have equivalent transmission features, including 3000-cycle filters, which became a characteristic feature of the 22-repeaters for non-loaded lines. Different sections of the transcontinental line became available on a non-loaded basis at intervals during the spring of 1920.

The Un-Loaded Transcontinental Line

The through circuits had a total of twelve intermediate repeaters. The net loss was about 11 db, or 9 db below that of the loaded line, and the effective transmission band was twice as wide. The expected improvements in stability under varying weather conditions were realized in full. The better repeater balances that were obtainable with the inherently more uniform non-loaded lines were factors in the greatly reduced net loss. The factor of fundamental importance, however, was the approximately 3.5 to 1 increase in the velocity of transmission, which shortened the time interval between the direct transmission and echoes from points of impedance irregularity and thereby reduced the disturbing effects of the echoes. When the unloaded transcontinental circuits were demonstrated to a conference of Bell System presidents held at Yama Farm, N. Y., on May 25, 1920, the "sense of nearness" made possible by the high transmission speed was especially commented upon as a component of the improved transmission quality.

Following the unloading of the transcontinental line, other 165 mil circuits on important routes were unloaded, and soon there was a complete backbone of non-loaded 165 mil circuits operated with the improved repeaters.

CONCLUSION

The end of the present story is at hand.

It has shown the principal high spots of a most fruitful period in the development of long distance telephony, either when the specific accomplishments are taken into account in their own right or when they are considered as foundations for the subsequent developments which first made universal telephone service on the North American continent economically practicable, and then by radio links the inclusion of this network within a world-wide international network.

The prediction in the Carty memorandum of 1909 that a successful telephone repeater would also unravel the problems of radio telephony was amply fulfilled six years later.

The advent of the high vacuum tube repeater closed the era under review and has of course proved to be an outstanding legacy for the succeeding years. The initial aim during its commercial development was to overcome distance, then to improve the transmission standards. In time, these efforts made excellent transmission performance substantially independent of distance.[11]

As these objectives were approached and realized, the general development emphasis turned in various ways towards the reduction of the costs of the long distance facilities and the provision of much larger circuit groups; by the application of carrier telephone systems to open-wire lines, incidentally requiring the removal of the remaining voice-frequency loading; by the extensive use of repeatered, loaded, cables along routes where large groups of circuits were required, and where stability of service had become very important; and in recent years, by the application of wide-band carrier telephone systems to open-wire and to non-loaded cable, and to coaxial conductor systems. In these developments, the repeater played its own basic part in offsetting attenuation; and other new developments, in particular the electric wave filters, distortion corrective networks, and regulating devices played their parts in shaping and controlling the transmission medium. These various developments were basic to the improved speed of service and the reduced rates, which, along with the high quality transmission standards, have stimulated an ever increasing demand for long distance telephone service.

Some important aspects of these developments which followed the first transcontinental line, and other associated developments, are described in Jewett's article, "Transcontinental Panorama," published in the January

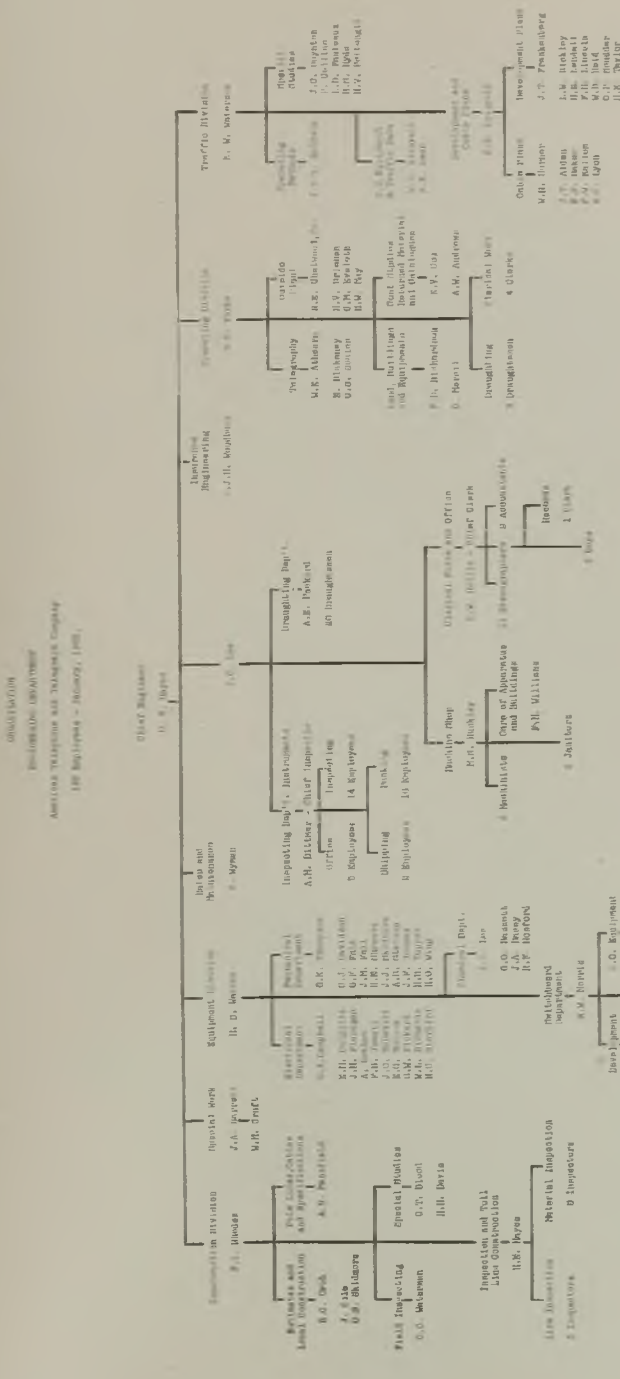
[11] The following pertinent quotation is from the 1922 company report to the stockholders: "In faithful reproduction of speech at a distance so that the person listening will understand with ease, so that the speech transmitted will be of proper volume and quality without distortion, our engineers and scientists have achieved what seemed to be the impossible. On the through lines, distance has been eliminated."

1940 issue of the Bell Telephone Quarterly to commemorate a quarter century of transcontinental telephone service. Its subtitle is revealing: "From the Solution of the Specific Problems of Transcontinental Telephony Have come Changes and Advances in the Art Which Have Affected Every Aspect of the Service." The author of that story is the individual who had the responsibility of leadership for the success of the transcontinental telephony project.

It is a project which has continued to grow mightily until the original phantom group has become some five hundred circuits distributed over five cross-country routes four of which are open-wire lines, and the fifth and latest an underground cable, with what might be called reverberative effects that have worked as leaven in every phase of telephony.

And finally, as the closing paragraph, I quote the conclusion of Jewett's own article, because it so well typifies the spirit of the man himself and also expresses in a minimum of words what has unquestionably been his most important contribution, viz., an organization of research scientists and development engineers and designers working harmoniously as a composite mind upon a single problem of vast technical ramifications as well as infinite details.

"It has been my good fortune to have had a part in a great adventure, some of whose principal features I have attempted to sketch out for you. I would be less than honest, and far less than generous, however, if I allowed any of you to depart with a false impression of my personal contribution. The achievements embody the contributions of many men, my associates (some of whom I do not even know), working through the years as a team of which I have been a member."

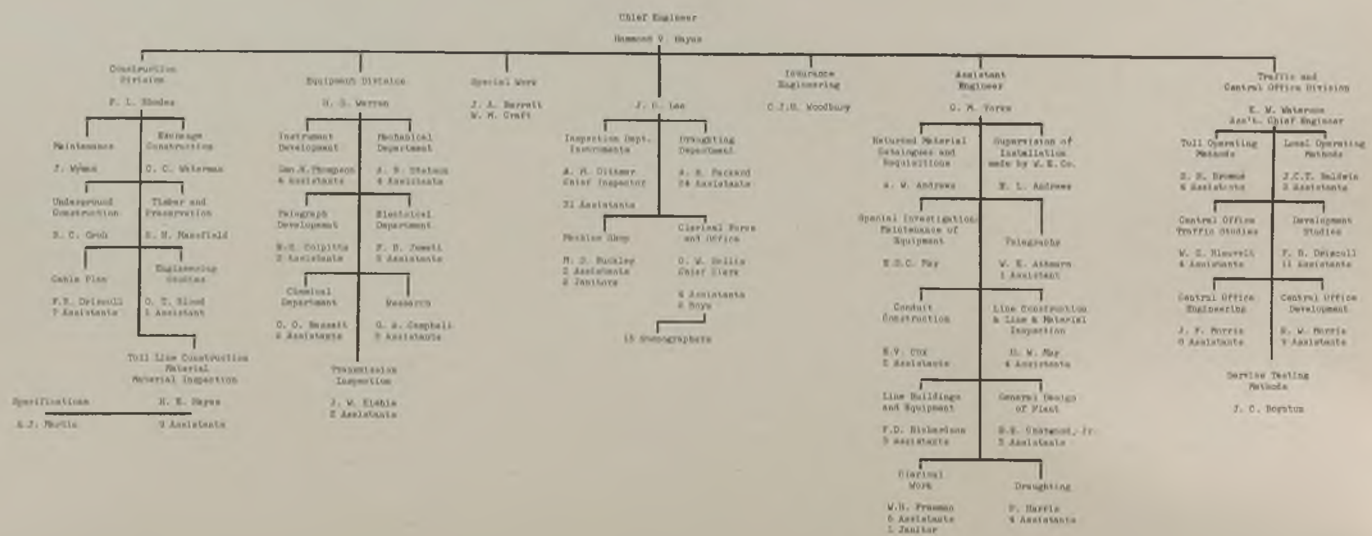

Special Work
Equipment
Inspecting Dep't. Instruments
Office
Inspecting
5 Employees
14 Employees
Shipping
8 Employees
Draughting Dep't.
60 Draughtsmen
Machine Shop
Machinists
Care of Apparatus and Buildings
3 Janitors
Chief Clerk
Records
1 Clerk
Field Inspecting
Special Studies
Inspection and Toll Line Construction
Material Inspection
9 Inspectors
Switchboard Department
Development
Telegraphy
Outside Plant
Draughting
Clerical Work
4 Clerks
Traffic Division
Development Plans

ORGANIZATION

ENGINEERING DEPARTMENT

American Telephone and Telegraph Company

236 Employees - June, 1909



ORGANIZATION

ENGINEERING DEPARTMENT

AMERICAN TELEPHONE AND TELEGRAPH CO.

DECEMBER 26, 1907.

Chief Engineer

J. J. Carty.

Outside Plant
F.L.Rhodes

Special Work
O.H.Arnold

Power Interference
J.A.Barrett
W.H.Craft

Electrical
H.S.Warren

Equipment and Buildings
B.Gherardi

Traffic & Clerical
K.W.Waterson
Asst. Chief Engineer

General Problems
G.T.Blood
W.H.Horner
E.H.Scudder

Construction
C.C.Waterman
J.T.Alden

Line Materials
A.N.Mansfield
W.A.Taylor

Transmission & Protection
F.B.Jewett
R.F.Hosford
W.M.Gould
T.Shaw
O.B.Blackwell

Apparatus
G.K.Thompson
C.J.Davidson
E.W.Niles

Research
G.A.Campbell

Telegraphy
J.M.Fell

Development
R.W.Morris
A.H.Moraweck
H.B.Van Etten
J.F.Toomey
K.W.Endres

Standardiz'g Equipt. & Buildings
J.F.Morris
W.L.Vatter
P.Woollcott
H.M.Davis

Semi-Mechanical Swbd.
W.G.Blauvelt
E.C.Molina
R.E.Wolfe

Strowger Switchboard
L.S.Keith
W.T.Ayer

Toll Traffic
S.H.Browne
J.W.Kiehle
E.S.Baker
H.P.Charlesworth
H.E.Darling
E.B.Nye
E.W.Kimball
W.A.Spencer

Local Traffic
F.B.Driscoll
W.Christensen
A.E.Swan
H.S.Hyde
F.W.Galway
H.L.Fitch

Service
J.C.Boynton

Fundamental Plans
O.F.Scudder
H.E.Taylor
W.G.Holt
L.W.Bickley
W.C.Hyatt
W.S.Warland

Clerical

Chief Clerk
R.S.Sutliffe

File Clerks
A.Graham
K.L.Kunze

Stenographers
E.M.Roberts
S.E.Ruddock
W.Scarffe
F.A.Davenport
V.A.Herwig
G.E.Miles
G.E.Murphy
B.M.Johnson

Boys
F.H.Geisecke
C.H.McMahon
G.Goshen
G.Moore

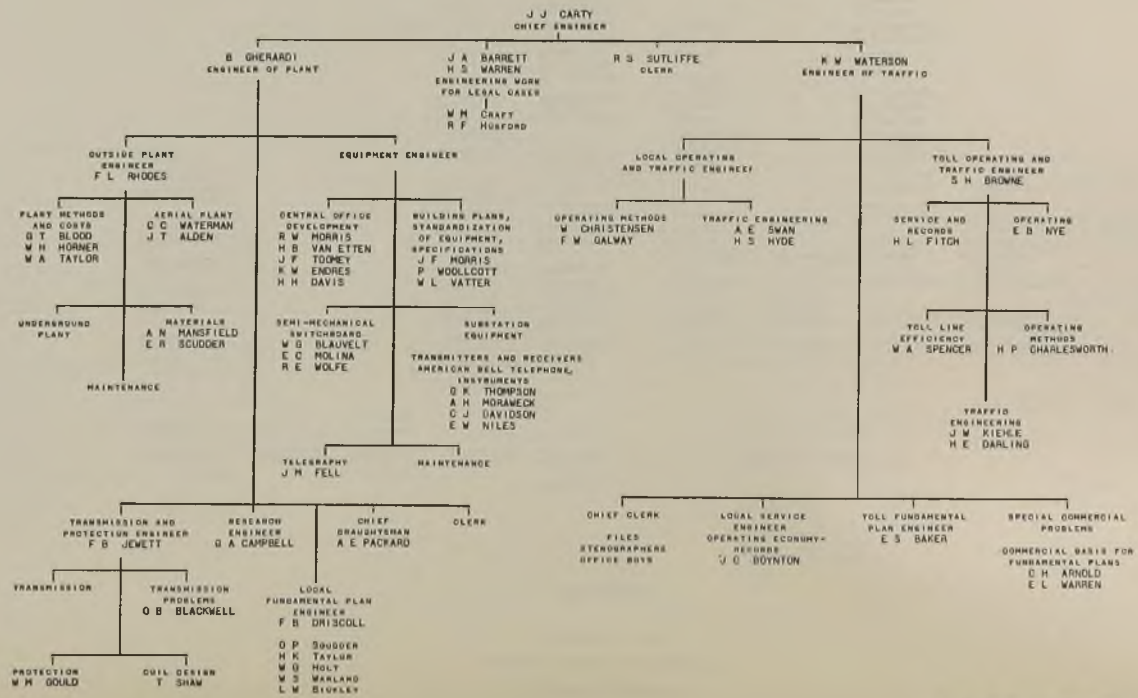
Draughting

Ch.Draughtsman
A.E.Packard

W.H.Copithorne
E.Packard
W.Davidson
C.A.Hederson
H.L.Crane
G.S.Skidmore
G.C.Webber
A.J.Hederson

	Dec.26,1907	July 1,1907
Engineers	60	101
Clerical	15	21
Draughtsmen	9	25
Instruments		32
Shop		10
Line Testers		8
	84	197

ORGANIZATION
ENGINEERING DEPARTMENT
AMERICAN TELEPHONE AND TELEGRAPH COMPANY
MARCH 13, 1909



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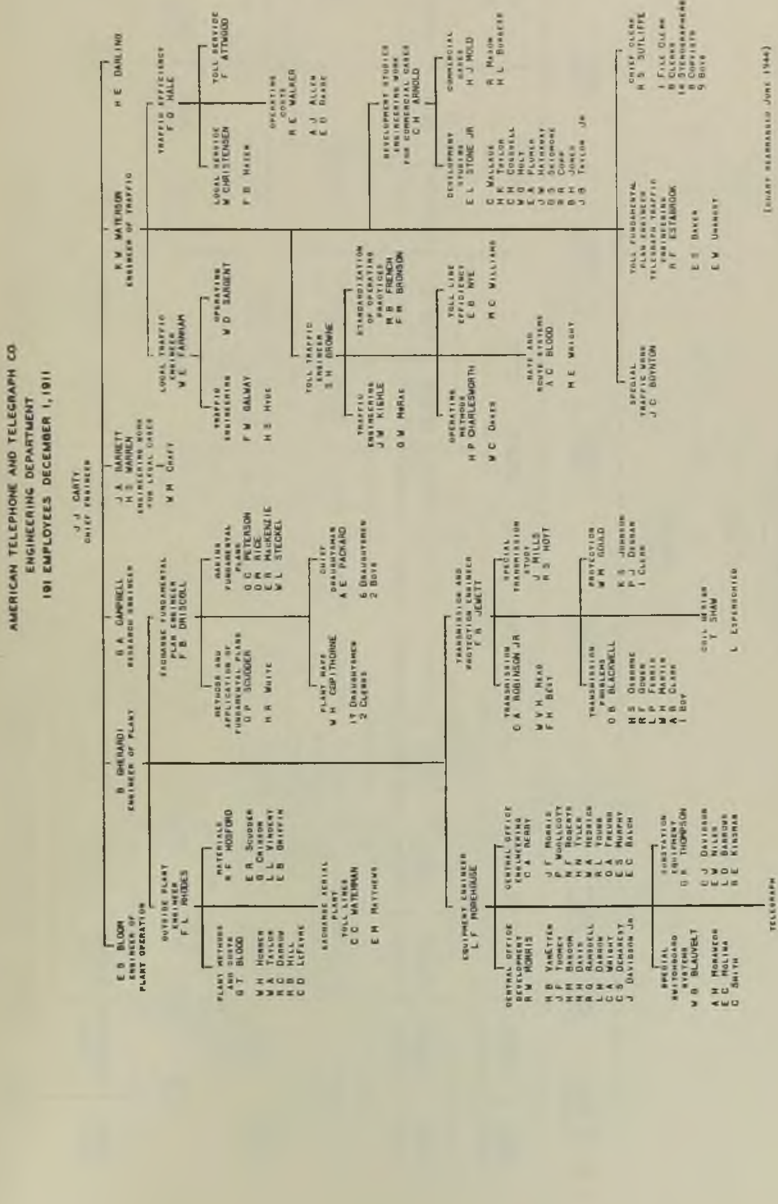
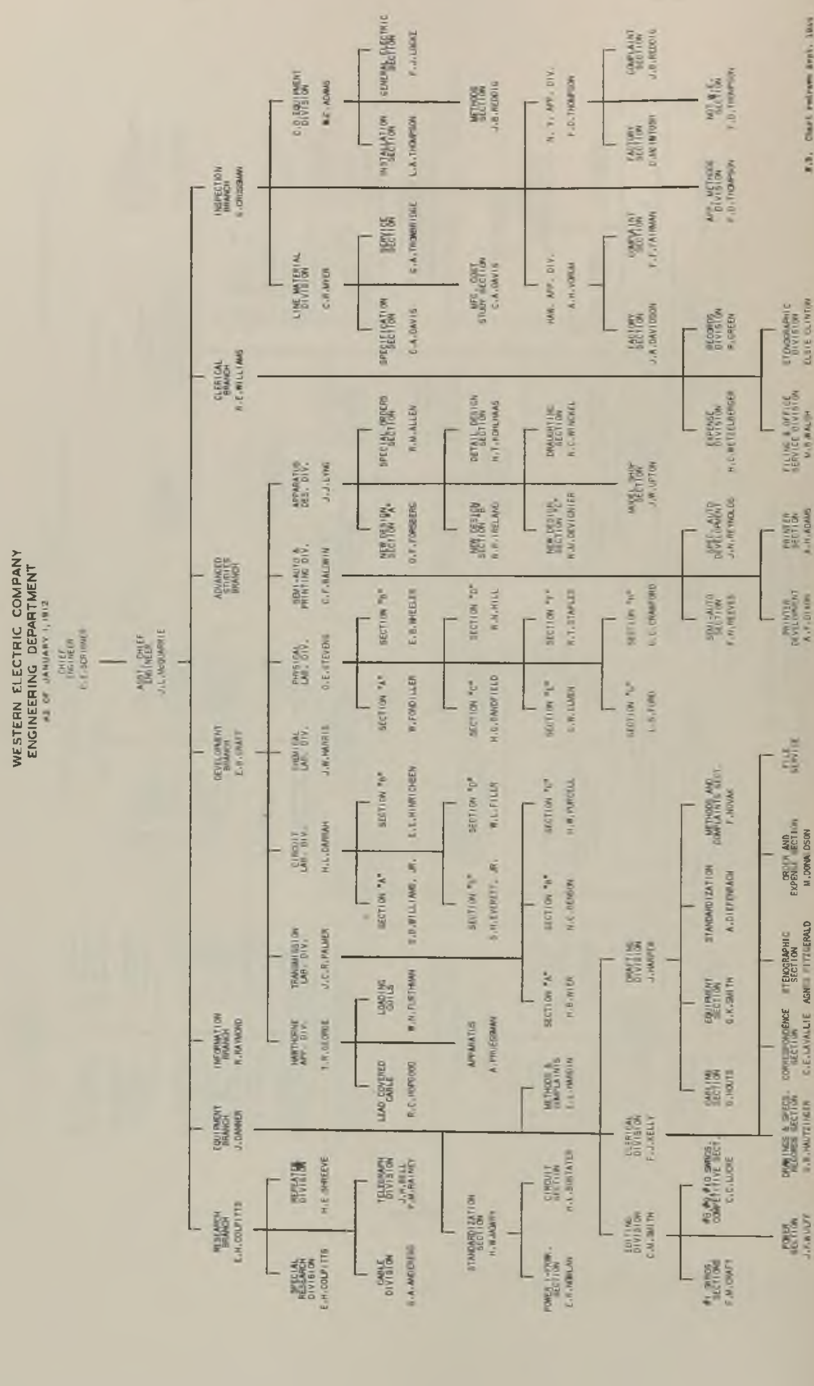

AMERICAN TELEPHONE AND TELEGRAPH CO
ENGINEERING DEPARTMENT
191 EMPLOYEES DECEMBER 1, 1911
J J CARTY
CHIEF ENGINEER
E B BLOOM
ENGINEER OF PLANT OPERATION
B GHERARDI
ENGINEER OF PLANT
G A CAMPBELL
RESEARCH ENGINEER
J A BARRETT
H S WARREN
ENGINEERING WORK FOR LEGAL CASES
W H CRAFT
K W WATERSON
ENGINEER OF TRAFFIC
H E DARLING
OUTSIDE PLANT ENGINEER
F L RHODES
PLANT METHODS AND COSTS
G T BLOOD
MATERIALS
H F HOSFORD
EXCHANGE AERIAL PLANT TOLL LINES
C C WATERMAN
E M MATTHEWS
EXCHANGE FUNDAMENTAL PLAN ENGINEER
F B DRISCOLL
METHODS AND APPLICATION OF FUNDAMENTAL PLANS
G P SCUDDER
H R WHITE
MAKING FUNDAMENTAL PLANS
O C PETERSON
D R RICE
E R MACKENZIE
W L STECKEL
PLANT MAPS
W H COPITHORNE
17 DRAUGHTSMEN
2 CLERKS
CHIEF DRAUGHTSMAN
A E PACKARD
6 DRAUGHTSMEN
2 BOYS
LOCAL TRAFFIC ENGINEER
W E FARNHAM
TRAFFIC ENGINEERING
F W GALWAY
OPERATING
W D SARGENT
TRAFFIC EFFICIENCY
F O HALE
LOCAL SERVICE
W CHRISTENSEN
TOLL SERVICE
F ATTWOOD
OPERATING COSTS
R E WALKER
TOLL TRAFFIC ENGINEER
S H BROWNE
TRAFFIC ENGINEERING
J W KIEHLE
STANDARDIZATION OF OPERATING PRACTICES
M B FRENCH
F M BRONSON
DEVELOPMENT STUDIES ENGINEERING WORK FOR COMMERCIAL CASES
C H ARNOLD
OPERATING METHODS
H P CHARLESWORTH
TOLL LINE EFFICIENCY
E B NYE
DEVELOPMENT STUDIES
E L STONE JR
COMMERCIAL CASES
H J MOLD
RATE AND ROUTE SYSTEMS
A C BLOOD
EQUIPMENT ENGINEER
L F MOREHOUSE
CENTRAL OFFICE DEVELOPMENT
R W MORRIS
CENTRAL OFFICE ENGINEERING
C A BERRY
SPECIAL SWITCHBOARD SYSTEMS
W B BLAUVELT
SUBSTATION EQUIPMENT
G R THOMPSON
TELEGRAPH EQUIPMENT
J M FELL
TRANSMISSION AND PROTECTION ENGINEER
F B JEWETT
TRANSMISSION
O A ROBINSON JR
SPECIAL TRANSMISSION STUDY
J MILLS
R S HOYT
TRANSMISSION PROBLEMS
O B BLACKWELL
PROTECTION
W H GOULD
COIL WINDER
T SHAW
SPECIAL TRAFFIC WORK
J C BOYNTON
TOLL FUNDAMENTAL PLAN ENGINEER TELEGRAPH TRAFFIC ENGINEERING
R F ESTABROOK
CHIEF CLERK
R S SUTLIFFE
(CHART REARRANGED JUNE 1944)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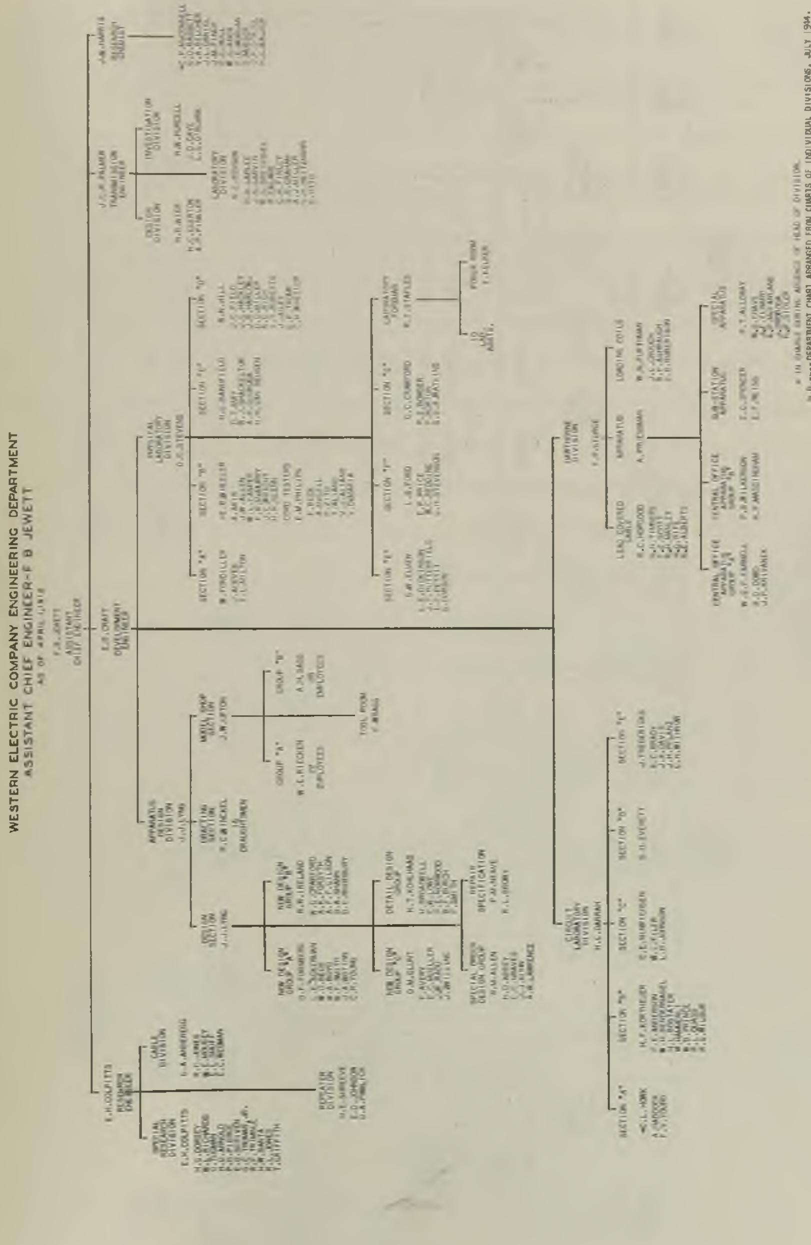
ENGINEERING DEPARTMENT
AS OF JANUARY 1, 1912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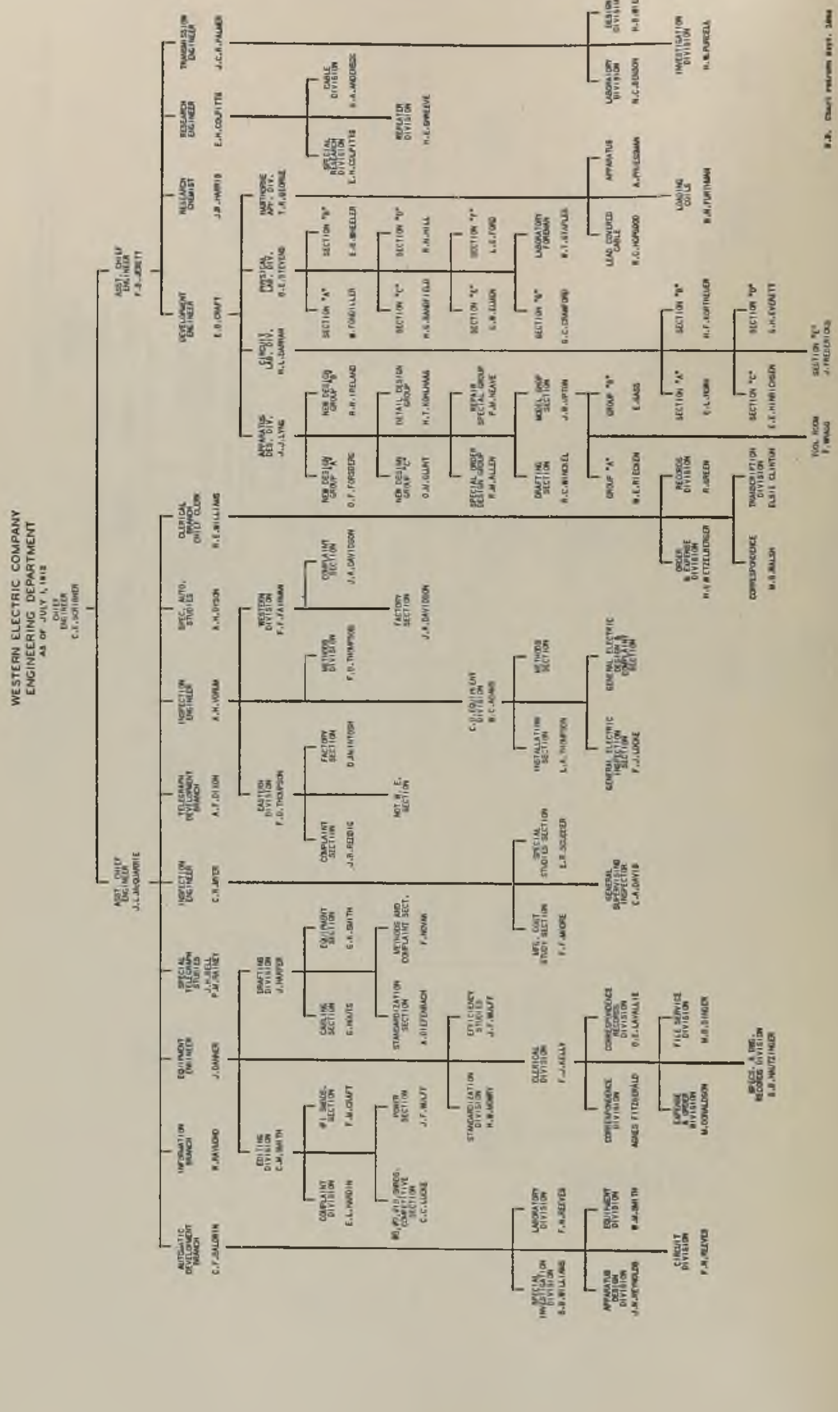
ASSISTANT CHIEF ENGINEER—F B JEWETT


WESTERN ELECTRIC COMPANY
ENGINEERING DEPARTMENT
AS OF JULY 1, 1912
CHIEF ENGINEER
C.E.SCRIBNER

Bibliography

In addition to the references in the text, the following will be of interest. In some instances, the articles are partly or largely concerned with developments during the period covered by the story, although the publishing dates are years later. In other instances involving late publication, the articles are of special interest in correlating the early developments with those subsequent to the period covered by the present story.

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B. Gherardi, "Some Recent Advances in the Transmission Efficiency of Long Distance Circuits," (Published Notes of a Talk before the Telephone Society of New York), April 18, 1911.

F. B. Jewett, "Long Distance Telephony in America," Pamphlet, Paper presented to International Congress of Applied Electricity, Turin, Sept., 1911.

"Inductive Interference Between Electric Power and Communication Circuits," Selected Technical Reports With Preliminary and Final Reports of the Joint Committee on Inductive Interference. Published by the Railroad Commission of the State of California, San Francisco, Calif., April 1, 1919.

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G. A. Campbell, "Physical Theory of the Electric Wave Filter," *Bell System Technical Journal*, Nov., 1922.

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R. S. Hoyt, "Impedance of Loaded Lines and Design of Simulating and Compensating Networks," *B.S.T.J.*, July, 1924.

George Crisson, "Irregularities in Loaded Telephone Circuits," *B.S.T.J.*, Oct., 1925.

T. Shaw and W. Fondiller, "Development and Application of Loading for Telephone Circuits," *B.S.T.J.*, April, 1926.

A. B. Clark, "Some Recent Developments in Long Distance Cables in the United States of America," *B.S.T.J.*, July, 1930.

F. B. Jewett, "Carty—The Engineer and the Man," *Bell Lab. Record*, Sept., 1930.

Wm. R. Ballard, "The High Vacuum Tube Comes Before the Supreme Court," *Bell Lab. Record*, July, 1931.

M. A. Weaver, "The Long Struggle Against Cable Crosstalk," *Bell Telephone Quarterly*, Jan., 1935.

F. B. Jewett, "Dr. George A. Campbell," *B.S.T.J.*, Oct., 1935.

"The Collected Papers of George A. Campbell," A.T.&T. Co., 1937: Introduction, by E. H. Colpitts; "Three Early Memoranda on Loading," Page 10; "Repeater Circuits," page 533.

APPENDIX I

Extracts from Annual Report* of the Electrical Department for the Year 1905

The problems upon which the main work of the year has been spent have been protection, disturbance from alternating current railways and the inspection of commercial transmission conditions. These together with the correspondence have consumed about one-half of the time of the department if the routine work such as the inspection of loading coils is excluded from consideration.

The attempt has been made this year to make the ledger numbers a more correct and more detailed record of the work of the department than has been the case in the past. There may be some question as to whether this is worth while, but I have thought it desirable to carry the plan through the entire year and in accordance with this plan I quote below the list of orders with the amount of time which has been charged to each. This will take the place of any special list of the problems which have come up during the year, and it will assist in showing how nearly eleven years work has been divided among these problems. The list gives the date when the ledger number was opened, the ledger number, the title of the number and the number of days charged to the ledger number during the year. In order to indicate somewhat the character of the work on each subject, the time charged has been divided into two classes. One including the work which has been on the whole independent and original and may be referred to as development, (D), and the other the work which has been more of the nature of assistance, (A). All figures are brought up to December 20th, 1905.

* * * * * * * * *

Protection

Jan. 27, '05	3787	Protection of Substation Sets.	79D.	41A.
Mar. 2, '05	3860	High Frequency Tests on #7 Fuse.	3D.	3A.
Mar. 16, '05	3896	Rating of Fuses.	2D.	3A.
Apr. 17, '05	3928	High Tension Protection.	132D.	3A.
Apr. 17, '05	3930	Protection Against Lightning.	9D.	0A.
Mar. 31, '05	3952	Examination of and Specifications for Protector #73-A.	2D.	0A.

The work on protection has been in charge of Mr. Jewett, who has had a large amount of correspondence to attend to in this connection, in addi-

* Letter, G. A. Campbell to H. S. Warren, 12/30/1905.

tion to the work indicated by the ledger numbers listed above. He reports as follows:

During the year a large number of experiments have been conducted with a view to ascertaining the amount of protection to terminal apparatus and the immunity from fire hazard afforded by the present standard protectors. These experiments have shown that, aside from one exception in the case of substation protectors, the present protective apparatus properly installed is capable of furnishing adequate protection to the central office and substation equipment for crosses of any potential.

With regard to the fire hazard incident to the operation of the protectors, the results obtained from the experiments showed that an appreciable danger from fire existed when the voltage of the circuit crossed with the telephone lead exceeded a certain value. In comparison with the high potentials now generally employed by light and power companies, this critical voltage was very low.

To decrease the hazard of a fire resulting from the operation of the protectors and to secure a substation protector on which the maintenance from lightning would be a minimum, an entirely new system of protection was developed and its elements subjected to these tests included numerous operating trials at the General Electric Company's Works at Lynn, and also two sets of tests at the power house of the New Milford (Connecticut) Power Company. In these latter tests the protective elements were subjected to a potential of 33,000 volts under such varying conditions as would be met with in practice.

In connection with the development of the system of complete protection and in conformity with the results obtained from the tests, the following pieces of apparatus have been designed:

(1) Substation Protector—providing for open-space cutouts and impedance coils—to be used at substations the lines of which are subject to severe static disturbances.

(2) Outside Fuse—to be used at substations on lines which are exposed to high tension circuits.

(3) Protector Mounting—to be used in cable boxes where open-space cutouts are required.

(4) Cable Terminal—provided for open-space cutouts and impedance coils—for use at cable terminals where the entering lines are subject to severe static disturbances.

(5) Metal Block Arrestor—an open-space cutout for use in connection with 1, 3 and 4.

These pieces of apparatus have been tested under laboratory conditions and are now being manufactured by the Western Electric Company. A large number are to be installed by some of the licensee companies and their operation and maintenance carefully watched during the coming summer. It is hoped that the data obtained in this way will afford sufficient information to enable us to so modify our present protective practice as to afford adequate protection in all cases, with a reasonable amount of maintenance on the protectors.

* * * * * * * * *

APPENDIX II

Memorandum from Dr. Jewett to Mr. Warren:

December 22, 1906.

I have enumerated below under a number of different more or less general headings the most important things upon which we have been engaged during the past year. Subjects marked with an asterisk (*) are those upon which work is still being done although in most cases one or more reports have been filed on certain phases of the investigation.

Cables.

*1. Work in connection with Conference Case #23-A on the development of cable for loading.
*2. A design of a switchboard cable for #2 Private Branch Exchanges.
3. A study of wool insulated cable for switchboard use.

Coils.

*1. A general study of iron for retardation and repeating coil cores.
2. The development of coils for use in a new form of Private Branch Exchange circuit.
3. Thorough investigation of the efficiency of repeating coil T-602 (25-K) for use as a terminal transformer on loaded lines.
4. The development of a method for manufacturing balanced phantom repeating coils.
*5. The development of a shellac insulation for loading coil core wires.
*6. The development of a submarine loading coil.
*7. The re-designing of an aerial loading coil.
*8. The development of extra light loading coils.
9. The development of a compensating coil for use on telephone lines exposed to alternating current railway induction.

Condensers.

1. A study of the alternating current capacity and conductance of #21 type condensers.

DISTURBANCES (Noise and Electrolysis).

1. A test at Derry, Pennsylvania, on the Scott compensator for reducing disturbances on telephone lines exposed to alternating current railway induction.
2. Test at East Pittsburg, Pennsylvania, of the Scott compensator for reducing disturbances on telephone lines exposed to alternating railway induction.
3. An investigation of the induction caused by alternating current railways along the lines of the Indiana and Cincinnati Traction Company.
4. A study of the Providence, Warren and Bristol trunks and preparation of the proper treatment of these lines to reduce excessive noise troubles.

*5. A study of the induction and electrolysis troubles likely to result from the alternating current electrification of the New York, New Haven and Hartford Railroad.

*6. A study of alternating current electrolysis.

*7. A study of battery crosstalk under varying conditions.

INSULATION.

1. A study of enamel wire insulation in connection with various forms of apparatus.
2. A study of enamel insulated wire submarine cables.

*3. A study of the insulation afforded by different types of aerial wire insulators under different weather conditions.

LOADING.

*1. The development of equipment for new loading coil testing room at the Western Electric Company's factory in New York.

2. A study of the loading of the Boston, Salem and Beverly low capacity cable.
3. A study of extra light loading for terminal and trunk cables.
4. A study of the loaded cables used for inter-office trunks in Kansas City.

*5. A general study of load coil efficiencies.

6. A study for a loaded cable between Albany and Schenectady.
7. A study for a loaded cable between Jordan City and Salt Lake City.
8. A study of loading for inter-office trunk cables in Chicago.
9. A study for loaded toll cables in Kansas City.
10. A study for loaded toll and trunk cables between Brockton, Taunton and Middleboro.

11. A study for the loading of open wire circuits for the New England Telephone and Telegraph Company.
12. A study for the loading of open wire circuits for the Southern Bell Telephone Company.

MEASURING APPARATUS.

1. The design of a new artificial cable using Ward Leonard enamel re-resistances.
2. The development of a method for determining transmission equivalents by means of an alternating current dynamometer measurement.
3. The development of a design of a universal receiver shunt for use in determining line equivalents.
4. The design and construction of a capacity unbalance testing set for the Central District and Printing Telegraph Company.
5. The development and construction of a testing set for use in transmission investigations.

PROTECTION.

1. The completion of a design on the experimental system of high potential protection for substations and the preparation of a circular letter on the same.
2. The development and construction of a high potential protected cable terminal.
3. An investigation of the Birsfield central office protector.

REPEATERS.

1. A study of the distortion introduced by the presence of telephone repeaters in an open wire circuit.
2. A study of the efficiency of telephone repeaters when used in tandem on long haul circuits.
3. The design of an induction telephone repeater.

SWITCHBOARDS.

*1. A study looking to the development of fire-proof switchboard resistances.

*2. A study for the development of an efficient type of Private Branch Exchange circuit.

TELEGRAPH.

1. A study of phantoplex interference and a development of remedies for the same.
2. An investigation of the Field quadruplex telegraph.

3. Work and tests connected with the development of the Bleakeney-Chetwood balance for use on telegraph lines subjected to heavy alternating current induction.
4. Tests of Mr. Athearn's circuit for use on lines subjected to alternating current railway induction.

TRANSPOSITIONS.

1. The development of a transposition system for short spur and loop lines.
2. The development of a transposition system for short toll lines.
3. The development of a phantom system of transpositions for the aerial line between Philadelphia and Atlantic City.
4. The preparation of a complete set of phantom transposition drawings and the preparation of a circular letter on phantom transpositions.

TRANSMISSION.

*1. Transmission study of the Boston and Maine circuits.
2. A study of the bridging effects of various types of ringers.
3. Transmission tests on the Boston and Wellesley loaded cable.
4. Transmission tests on the Boston-Hingham loaded cable.
5. Transmission investigation of the Boston-Chicago repeater circuits.
6. Transmission tests on the Grant-Brushton loaded cable.
7. A transmission investigation of the 48-volt exchange at Bryn Mawr, Pennsylvania.
8. A study of the conditions affecting long distance service from Buffalo, Rochester and Louisville.
9. A study of the conditions affecting long distance service between the Union Pacific Railroad Company's private branch exchange in New York and the Illinois Trust and Savings Bank's private branch exchange in Chicago.
*10. The commencement of a general study of the conditions affecting long distance transmission.
11. The determination of the transmission losses in various types of cord circuits.
12. The determination of the transmission losses in various types of outside distributing wire and switchboard cable.

MISCELLANEOUS.

1. A study of the effect of multipling call wires and terminal offices.
*2. A study of multiplex telephone (Weintraub system).
3. A study of the Cooper-Hewitt rectifier for use in charging storage batteries.

4. A study of dielectric cables.
5. The construction of a new capacity balance room for the laboratory at 15 Oliver Street.
*6. An investigation of the properties of low hysteresis iron.
7. A study of the costs involved in various types of construction for the New York, New Haven and Hartford Railroad electrification.

In addition to the above work which has been more or less in the nature of experimental and theoretical studies a large amount of time has had to be devoted to general correspondence since the number of outgoing letters during the past year is practically 50% larger than the number of outgoing letters in 1905. For the period from January 1st to December 20th, 1905, the number of outgoing letters was 768, while for the same period in 1906 the number of outgoing letters was 1120.

(Signed) F. B. JEWETT.

APPENDIX III

A. T. & T. Co. Engineering Situation, April 1909

In a memorandum dated April 8, 1909 to Vice-President Thayer, to whom he reported, Mr. J. J. Carty then Chief Engineer of the American Telephone & Telegraph Company gave an appraisal of the engineering situation as it appeared to him.

The following partial copy of Carty's memorandum includes in full his discussion of the transmission items on which Dr. Jewett and his department worked. The discussion of Outside Plant, Equipment, Traffic, and Operating items is not included. Other parts of the memorandum are also omitted from the attachment as not being important pertinent background material for a story primarily concerned with Dr. Jewett's career. Rows of asterisks indicate deleted material. (T.S.)

April 8, 1909.

MEMORANDUM for Mr. Thayer,
Vice President.

I have considered the best way to strengthen our forces so as to properly carry out the work which will necessarily devolve upon this department in consequence of the comprehensive and definite relations now being established with the associate companies. The work in connection with the new relations will of itself be of very great and far-reaching importance and will entail upon part of the department a great deal of labor. While all of the various things constituting this new work have been duly considered with you and while they are beyond question clearly within our functions, it is necessary that we should plan for these new duties on such a scale that we will not be obliged to neglect the very important classes of work which we are already engaged upon.

Before speaking of the work we now have in hand or which, under the arrangement heretofore existing pertained to this department, I will briefly outline the nature of the new duties as far as they have yet been developed. First, the department is being reorganized so as to have three principal divisions reporting to the Chief Engineer:

1. A department relating to legal, protection, and railroad and power and electric light interference matters. Work under these headings has for a year or more been going on, but under the new scheme a more effective contact with the associate companies will be possible and required.

* * * *

2. A department under the Plant Engineer, establishing standards of plant construction and maintenance, issuing them to the various Plant Superintendents as fast as such officials are created. These things include not only the most economical and efficient methods of construction, but also the most economical and efficient methods of maintenance.

* * * *

3. A department under the Traffic Engineer, establishing standard methods of operating, standard traffic engineering methods, standard traffic records and reports.

* * * *

While it will be seen that that portion of the work above outlined which is new is of great magnitude and importance, the department must be strengthened in order that, in taking care of the new duties, the existing work will not suffer. In judging then of the necessity for the proposed increase in the strength of the department, it will be helpful if we consider a few of the items of work upon which we are already engaged, or which, even under the old scheme of organization, we should undertake. After so doing, I think it will be seen that when we compare the increased payroll with the increased results which will be obtained, the additional sum of money to be expended is a moderate one.

Some of the work already in hand or which would be undertaken in due course is described below and an estimate of the savings which would be accomplished by its successful performance is given.

* * * *

PHANTOM CIRCUITS AND DUPLEX CABLES:

At the present time phantom circuits can be established only upon overhead lines and even there, where their value has been so abundantly demonstrated, they are restricted to overhead lines which are not loaded. Inasmuch as a great and increasing number of overhead lines must pass through cables at some point or points, the necessity for a satisfactory method of carrying phantom circuits through cables has assumed great importance. Inasmuch as the loading of overhead lines has already reached large proportions and as, in view of our recent work, this importance will rapidly increase, we must, unless some method is devised of loading phantom circuits, sacrifice the advantage either of loaded circuits or of phantom circuits. Neither of these alternatives should be tolerated. We believe and we confidentially predict that if we can place the organization of this department upon a proper basis, we will develop new types of cable for carrying phantom circuits and will devise and standardize methods for loading phantom circuits, both in cables and overhead. Aside from the relation which the phantom or duplex cable has to overhead phantom circuits, it is important of itself, even where these overhead circuits are not to be considered. This is because we are entering the period of long distance underground cables and the savings which may be made in these cables themselves, growing out of working them duplex, reach into very large figures. As soon as the department is strengthened so as to respond to the extension of its duties now projected, a special study will be made of physics and economics of long underground cables, say between Boston and New York and New York and Washington. We will also make a similar study with respect to the possibilities of universal long distance service throughout the United States. While we can already see as an outcome of these proposed studies matters of very great importance and promise, and while we can also see that in these directions great use will be made of loaded phantom circuits and of phantom circuits in cables, we have thought it best in the present memorandum not to count upon any savings which might lie in these directions, but have restricted ourselves to those savings which would follow in the natural course of events, even if our larger ideas were not realized. Thus, counting upon the new toll cable construction which will be done from year to year, we figure that the use of a successful duplex cable would reduce our construction costs for this class of work at the rate of about $180,000 a year.

We are confident that if we are provided with the necessary ways and means, we can devise a method whereby we can phantom loaded circuits. By such an achievement the circuit capacity of the existing plant of the American Telephone and Telegraph Company and the associate companies could be increased to an extent which would be attainable under the present state of the art only by an additional plant investment of $2,500,000, on which the annual charges would be $250,000. Assuming that we have thus increased the carrying capacity of the plant, additional circuits, by means of loaded phantom circuits and duplex cables, could be obtained at a much cheaper rate, which we estimate, with the amount of construction running along about as at present, would represent a saving in construction costs of $500,000 each year, on which the annual charges would be $50,000.

As has already been stated, a large use of phantom circuits has already been accomplished where unloaded lines and open wires are used. Even in those cases the phantom circuit work has not attained anything like a full measure of success. Take just the territory of one associate company, it was expected that by the use of phantom circuits, a saving in plant investment of $1,000,000 would be made. It was found upon investigation by this department that owing to faulty location with respect to electric power wires, nearly half of these circuits were too noisy to be operative, so that only part of this saving was realized. We believe it is possible to remove the cause of this failure in such cases. This would require special and detail studies conducted by the plant department of each associate company, such as were recently made by this department in the territory of the Pacific Telephone and Telegraph Company. The savings which could be made in this way throughout the country cannot be estimated, as we have no proper system of reports from, or relations with the plant departments of these various companies, and because in many of these companies such a thing as a plant department does not exist. It is clear that an enormous saving can be made in this way, but it could be accomplished only through improvement in organization all along the line and not by laboratory work or the mere issuing of standards.

Further Development of Pupin Invention:

Although most extraordinary savings have already been obtained from the use of the Pupin invention for loaded circuits, resulting in the case of the New York and the New York & New Jersey Companies in a reduced cost of construction of more than $7,000,000, we have not yet exhausted the possibilities of this class of circuits. Up to the present time it has not been practicable to load circuits as large as the No. 8 wires composing the New York-Chicago circuit. I was greatly impressed during my trip to the Pacific Coast with the great advantage which would accrue to the company operating there if loaded No. 8 circuits were practicable. Troublesome opposition companies exist in the southern and the northern part of the territory, and a vigorous opposition is opening in San Francisco, the heart of the territory. Long toll lines are being projected and some of them are being built by the independent companies. If loaded No. 8's were available, a first-class talk could be given between the most widely separated of the important places, say between Seattle and Los Angeles, a distance of about 1500 miles. Over this distance, loaded No. 8's would give excellent transmission and for a distance of 2000 miles or a little more, practicable talk could be given over them. Loaded No. 8's would tie this scattered territory together, would greatly redound to the prestige of the Pacific Company and would place the opposition concerns at a very great disadvantage. Even if no use were made elsewhere of such circuits, their importance in this territory would be so great, looked at from every point of view, that the cost of the work which we propose to do upon this subject becomes an utterly insignificant factor. But it is not only in the territory of the Pacific Coast that these loaded No. 8's would be of importance. We already have wires extending as far west as Denver and with the best data which we have before us now, we are warranted in the strong expectation that by loading No. 8's we could give a talk from New York to Denver which would at least be useful for advertising purposes, if indeed it would not have substantial direct commercial value. But leaving out this long talk to Denver, we have before us the problem of improving service to Chicago to about the same extent as the Boston-New York service has been improved. Over loaded No. 8's between New York and Chicago we should be able to give as good a talk as is now obtained between New York and Pittsburgh on unloaded No. 8's. This would be a very great uplift and would have a most satisfactory effect not only upon the long distance service between New York and Chicago, but upon service conditions in those two cities. What is true about New York and Chicago is also true between New York, Minneapolis, Omaha, St. Louis, Kansas City, New Orleans, Atlanta on the west and south, and Montreal and distant New England points on the north and east. Even Pittsburgh and Buffalo, while having relatively good transmission, would have the conditions improved to a sensational extent.

We have good reason to promise you that we will be able to accomplish these results in a reasonable time after the department is strengthened so that in the handling of the more comprehensive work now being undertaken, we will not be obliged to neglect matters such as these.

One motive which makes powerfully for the full development of the capabilities of the Pupin invention should be stated. Its importance is so great that it is worthy of your most careful consideration. It is this: the Pupin patent has already run eight years of its life. Nine years remain. The sooner we perfect the loading of No. 8 lines and possibly lines of even larger gauge, the longer will be the period during which we will have a monopoly of circuits constructed in this manner. If we accomplish this result within two years (I hope we will do it in one), we would have seven years during which we would be sure to exert a dominating influence in the long distance field and during which, by means of this influence and the incalculable prestige which we would thereby obtain, we could make successful headway against competing companies and entrench ourselves against the time when the Pupin patent will have expired.

THE PROBLEM OF THE TELEPHONE REPEATER:

At the present time we have in service in the long distance lines a number of telephone repeaters. When these instruments are working in the manner intended, they accomplish a substantial improvement in extending the range of telephone transmission. When working satisfactorily, and interposed at the half-way point in the New York-Chicago line, they cause an improvement in the transmission on that line by making it talk as well as though it were 300 miles shorter. They are not uniform in their action, but the chances of our making them so are so good that a strong effort in this direction is justified. This lack of uniformity of action is not the only difficulty with these repeaters. For reasons which need not be discussed here, they are not operative upon loaded lines. This constitutes a serious defect in the repeater situation, not only with respect to loaded overhead lines, but also with respect to loaded underground lines. Naturally it is difficult to forecast the saving in our future construction which would be accomplished by the use of a repeater having uniform action, but otherwise no more efficient than the present one. Some idea of this saving, however, may be obtained from results of a study which we have made with respect to plant which we have already constructed. This study shows that if such a repeater were available when the present loaded circuits were constructed, the first cost of these circuits would have been reduced by \$7,000,000. The annual charges on this figure are \$700,000. This, it should be borne in mind, does not count upon a repeater having greater power than the present one, nor does it count upon the saving which has been accomplished by the use of the repeater in non-loaded circuits. So important do we regard this repeater matter that we are satisfied that we should attempt to develop one having much greater power. There is nothing in the nature of the case to discourage us in this line of work and the art seems to have so many possibilities and the results to be obtained from a more powerful repeater are so far-reaching that work upon this line should be pushed vigorously. If we successfully load the Denver line and thereby accomplish speech between New York and Denver, the development of a successful repeater would enable us to accomplish speech between San Francisco and New York. The achievement of this result would mean universal telephony throughout the United States and its importance is so apparent that no argument is needed to demonstrate it.

I do not think it can be said that we are looking too far ahead in talking of a New York to San Francisco circuit, for our Operating Department is already studying the subject of connecting the telegraph system of the Pacific Telephone and Telegraph Company with our own, with a view of making a very important leased telegraph line contract. The officials of the American Telephone and Telegraph Company and the Pacific Telephone Company are actually at this time in consultation about this matter.

In addition to this, I have been advised unofficially that a most important customer of ours, a large brokerage firm of Boston, Messrs. Hornblower and Weeks, who pay to us and our associate companies as much as $65,000 a year for telephone and telegraph service, have written us asking whether within the next two years we will be able to furnish to them in addition to the extensive telegraph service which they now have, extending from New York to Boston, Chicago and Duluth and many other places, a much more extended telegraph service. The new places which they wish to reach are Butte, Montana; Portland, Oregon; Seattle, Washington; Tacoma, Washington; San Francisco, California; Los Angeles, California; and Kansas City, Missouri. While this proposed contract and this inquiry relate to telegraph circuits, it should be borne in mind that our telegraph service is almost uniformly conducted over telephone lines, over which speech is being transmitted at the same time telegraph messages are sent, so that the construction of lines to these most distant points for telegraph purposes would be rendered more economical if they could be also used for transmitting speech.

It looks to us now as though the possibilities of loaded No. 8's for transmitting speech would be exhausted when we reach Denver and that to extend our service beyond, we must have the repeater. As it now appears, we think we may soon know how to accomplish speech without the aid of the repeater as far as Denver, and having done this, all that can stand in the way of a New York-San Francisco talk and of a talk to all parts of the United States is the application of the improved repeater to loaded circuits.

One additional argument making for vigorous work upon the development of a more powerful repeater I call to your particular attention. At the present time scientists in Germany, France and Italy and a number of able experimenters in America are at work upon the problem of wireless telephony. While this branch of the art seems at present to be rather remote in its prospects of success, a most powerful impetus would be given to it if a suitable telephone repeater were available. Whoever can supply and control the necessary telephone repeater will exert a dominating influence in the art of wireless telephony when it is developed. The lack of such a repeater for the art of wireless telephony and the number of able people at work upon that art create a situation which may result in some of these outsiders developing a telephone repeater before we have obtained one ourselves, unless we adopt vigorous measures from now on. A successful telephone repeater, therefore, would not only react most favorably upon our service where wires are used, but might put us in a position of control with respect to the art of wireless telephony should it turn out to be a factor of importance.

*   *   *   *

(Signed) J. J. CARTY,
Chief Engineer.

Some Aspects of Powder Metallurgy

By EARLE E. SCHUMACHER and ALEXANDER G. SOUDEN

Introduction

THIS correlated review is an attempt to present some of the more common aspects of the powder metallurgy process in order to acquaint telephone engineers with an increasingly important production method, and to provide an outline of topic references that could otherwise be obtained only from many different sources.

Basically, the art of powder metallurgy deals with the preparation of metal powders and their utilization. This is a general description, however, and covers not only the metallurgical field, but also the paint and pigment and other more strictly chemical industries. As a more pertinent definition, the following has been suggested: "Powder metallurgy is the art of producing metal powders and shaped objects from individual, mixed, or alloyed metal powders, with or without the inclusion of non-metallic constituents, by pressing or forming objects which are simultaneously or subsequently heated to produce a coalesced, sintered, alloyed, brazed, or welded mass, characterized by the absence of fusion, or the fusion of a minor component only"[1].

In the past few years, powder metallurgy has received considerable attention, not only in technical publications, but also in the newspapers and popular periodicals, the general implication of the latter being that a completely new and revolutionary field of metallurgical endeavor has been uncovered. Actually, however, instead of something new, we are dealing with an art that had its inception at the time man first started using metals; numerous examples exist today of the early attempts to produce solid articles from metal powders. It is not surprising that early investigators and workers dealt with powders rather than massive structures of metals. With the exception of a few low melting metals such as tin and lead, most of the metals available melted at temperatures above those which could be attained at the time with crude furnace equipment. It was possible, however, to prepare powders of many metals by rather simple means without extensive furnace equipment, and a number of such powders were produced. Iron, for example, was reduced from its ores and worked to solid form at least 5,000 years ago, long before furnaces were devised which could even approach the melting point of the metal. The resulting reduced product was not, of course, massive iron, but was a sponge powder material which could be compacted, heated, sintered, and forged in much the same manner that metal powders are treated today. An outstanding example of the massive pieces produced by such methods is the $6\frac{1}{2}$ ton Delhi pillar made about 1,600 years ago[2].

History of Development

The ancient Egyptians and probably other early civilizations discovered how to make powders of gold, silver, copper, bronze, iron, lead, and to a limited extent, tin, antimony, and platinum[3], but it was necessity rather than desire which led these early workers to produce their massive metal tools, ornaments, and weapons by powder methods. It is interesting to note that as furnaces were devised to obtain higher temperatures, the list of metals prepared from powders decreased. The lower melting metals, of course, were the first to be prepared by melting and casting methods, and as higher temperatures were attained, only the more highly refractory metals remained on the powder preparation list.

Although iron had been known in prehistoric days, it remained a scarce, precious metal for several thousand years, and did not come into general use until introduced by the Hittites around 1300 B.C. The Hittites presumably mined iron ore in the iron region along the Black Sea in Asia Minor and worked the material to metal form[4]. By 100 B.C., the use of iron had spread westward to include many of the countries bordering the Aegean and the Mediterranean. The primitive methods of iron working probably consisted in heating the iron ore in a charcoal fire fanned by an air blast from a bellows until reduction of the oxide was attained. The spongy mass was then pressed, heated, and forged to the desired shape.

That this was the general practice followed in many countries in the production of metal objects has been observed from articles unearthed from earlier civilizations. Somewhat similar methods of working other metals have been observed, and where difficulty was experienced in obtaining sintering, other metal powders were added that were lower melting themselves, or that formed lower melting alloys which wet and welded together the particles of metal being worked to form a lump that could be shaped. The Incas in South America used such a method in fabricating many small articles of platinum[5]. The grains of native platinum were mixed with some gold and silver, and, by means of a blow-pipe, were fritted together by the lower melting alloy of gold and silver. The resulting mass could then be forged to the desired shape.

During the eighteenth century there was a fair amount of activity in the production of metal powders, and in studies of the fabrication of metal parts from the powders. Platinum was introduced into England in 1741 and attempts were made to produce the metal in compact usable form[3].

Various expedients were used, and one which utilized a unique principle is worthy of note.

It was observed about the middle of the century that platinum would fuse at relatively low temperatures in the presence of arsenic[3], and that, on prolonged heating, the arsenic could be volatilized out of the fused lump to leave behind a sponge of metallic platinum. This sponge could then be heated and forged to solid form. Similar results were obtained using mercury* or sulphur in place of arsenic; and the success of the forging methods led other investigators to study the welding of grains of native platinum or platinum scraps without the use of added elements to lower the fusion point.

Such was the situation in the early part of the nineteenth century when Wollaston[7] developed his method for the preparation of platinum ware. Numerous other investigators[3,6,8] had produced articles of platinum by treatment of finely divided platinum or sponge, but by careful refinements in the process with control of particle size, purity, compacting pressure and sintering treatment, Wollaston obtained a superior product. Precautions were taken to use only the more finely divided platinum particles, and to press the powder carefully in a mold while wet. This pressing of wet powder is claimed to have been one of the main contributions made by Wollaston since a much lower compacting pressure was allowable, and the particles were not work hardened. The resulting cake was then slowly dried to remove volatile matter and adsorbed gases before sintering at 800°–1000° C. The material was forged while still hot, and gave the first really pure, blister-free platinum sheet. That the process developed by Wollaston was sound is shown by the fact that the platinum produced by powder metallurgy at present in England is made by essentially the same procedure[21]. The careful studies made by Wollaston in fabricating platinum ware of high purity thus led to the basic principles utilized in successfully producing massive metal parts from metal powder.

During the nineteenth century, many metals were produced in powder form, but there seems to have been no correlated effort to convert the powders into coherent form. This may have been due to the development of better melting furnace equipment that allowed ordinary melting and casting techniques to be employed for most metals and alloys. On the other hand, there remained some of the more refractory metals such as tungsten, tanta-

* As an example of how new methods introduced can often be traced back to earlier sources, the use of mercury to form an amalgam which could then be heated to leave a powder sponge material, has been attributed to the monk Theophilus in the 11th century[6]. In this case, the amalgam process was used with gold, and the end product sought was gold powder which could be used as a pigment in inks for illuminating manuscripts. There was no attempt, however, to carry the process further to make solid metal parts as was the case with platinum as cited above.

lum, molybdenum, osmium, and iridium which could have been treated in much the same manner as in Wollaston's process for platinum.

There were, however, instances where real effort was made to develop useful products by means of powder metallurgy. As early as 1870, the fundamental idea of a self-lubricating bearing was disclosed in a patent by Gwynn[9] and was the prototype for a large number of later developments in the field. To 99 parts of tin prepared by rasping or filing, one part of petroleum still residue was added, and the mass heated and intimately mixed. The mixture was then pressed to give the shape and solidity desired. It was specifically stated by Gwynn that journal boxes made by this method or lined with the material would allow shafts to run at high speed without other lubrication[10].

There were a number of metal powder producers in the nineteenth century, most of them producing flake powders, but a virtual monopoly in the field was held by Sir Henry Bessemer from about 1840 to 1885, when he retired from the business[11]. The process was a secret one and remained so for almost his entire business career, and the profits were so large that they financed the development of the Bessemer process for making steel. Essentially, the method was one of machining very fine filaments from solid metal bars and passing the filaments through rolls to flatten and break them into flat tabular particles. Precautions were taken to prevent sticking and give a high polish to the powder by adding a very small amount of olive oil. The powder was graded by means of an air blast in a tunnel about 40 feet long and 2½ feet wide, the finest powder fraction being collected in silk bags attached to the end of the tunnel. Bessemer's powder metals included copper, and most of the common alloys of copper.

Even with the relatively large scale production of flake metal powders by Bessemer up to 1885, and the subsequent preparation of powder metals by stamp mills which pulverized the metal by severe working, there was very little actual commercial manufacture of solid compacts from powder metals.

The electric lamp industry provided the stimulus for further study in the search for a metallic filament to replace the carbon filament first used. This culminated in the production of the tungsten filament[10,12] and indicated the technique to be applied in the development of the other refractory metals as well as the production of cemented carbides, electrical contacts, and electrode materials.

Even with the promise shown by this development and the production of other ductile heavy metals, there was little other commercial activity in powder metallurgy as late as 1915–1920.

Various types of porous bearings had received sporadic attention, and, in 1921, a new porous bronze bearing was described[13]. The material was a bronze having finely divided graphite uniformly distributed throughout the mass. It was prepared by mixing the oxides of tin and copper with graphite, compressing the mass and heating. There was reduction of the oxides by the graphite and partial diffusion of the copper and tin to give a porous bronze structure in which excess graphite was uniformly distributed in amounts as high as 40 per cent by volume. In addition, there was sufficient porosity for the introduction of 2 to 3 per cent of oil. Later developments utilized the metal powders rather than the oxides[14], and porous bearings in a variety of compositions and forms have constituted a large part of the total production of powder metallurgy products over the years. Of considerable influence on the design and utilization of this type of bearing has been the demand by the automotive industry for large quantities of small bearing parts. Many of these parts are at inaccessible places, and the value of a self-lubricating surface is apparent. As suggested previously, these bearings are not all of the simple pressed porous alloy structure described, but many are complicated such as those having a steel backing coated with a porous sponge alloy of copper-nickel in which the voids are impregnated with Babbitt metal[15].

A later development, and one which has had tremendous industrial significance, was the production of cemented carbides[17,18,19] and their use in cutting tools, dies, and hard surfaced parts of many types. Essentially these consist of finely divided tungsten carbide particles bonded by cobalt, or in some few instances, nickel or iron. Other carbides such as those of tantalum, titanium, or columbium may be added to impart special properties.

Powder metallurgy is admittedly an art that has progressed more rapidly than the science, but the gap is being closed by investigations of a fundamental nature. Much of the lack of correlated information in the field has been due, in part, to an understandable reluctance of the manufacturers to divulge information on their processes to competitors, and largely, as well, to the narrow specialized uses that apparently discouraged a general systematic investigation of the problems involved. Within the past ten or fifteen years, mainly through the efforts of producers of metal powders, research of a fundamental nature has been stimulated. Another factor has been the large scale adoption of the powder metallurgy process by the automobile industry for use in the preparation of many different parts. The field is still narrow and specialized, but the art has progressed to the point where powder metal parts are competing, in some instances, with parts made by the standard melting, casting, and machining procedures.

As in many similar situations where rapid expansion has occurred, there has been a tendency, not as yet based on actual performance, to oversell the product. This is a sign of healthy activity on the part of the exploiters in the field, but a somewhat unwise course for industry as a whole to pursue. That there are limitations to powder metallurgy and many serious problems unsolved, is generally now recognized, and there is a tendency toward more conservative evaluation of the potentialities of the process.

It is the purpose of the remainder of this article to describe some of the common methods of preparing metal powders, to explain the fundamental principles involved in powder metallurgy, to describe the advantages and limitations of the process, and to indicate the type of product that may be expected.

Manufacture of Metal Powders

Metal powders are made in a variety of ways, each method of preparation being suited to the metal being treated or to the end product desired. Experience has shown that no one type of metal powder can serve all the projected uses in industry, so it is not surprising that there have been developed numerous methods for the preparation of metal powders, each of which has advantages for certain types of work, and which may or may not be suited for other uses[11,16]. Listed below are some of the common methods which have been developed for producing metals and alloys in powder form. No attempt is made here to discuss these methods in detail or to point out the relative hazards[20] involved in the various processes. It is worthy of note, however, that many metal powders in a finely divided state have such a large surface area in proportion to their bulk that they are usually subject to rapid oxidation, so rapid in many instances that they constitute an explosion hazard. Care must therefore be exercised throughout in the preparation of these powders, and many must be prepared and stored in inert atmospheres.

1. *Machining*

Machining of metals to produce powder has been mentioned above in connection with the process of Bessemer. A relatively coarse powder is produced. The cost of production is usually high, and the powder use is limited to a few special applications such as dental alloys where no fines or dust are allowable, and where the high cost of the alloy itself justifies the extra cost of this method.

2. *Milling*

By the use of various types of mills such as stamp mills, jaw crushers, gyratory crushers, impact, and ball mills, both brittle and malleable metals can be reduced to powder. The friable metals tend to produce angular, jagged, particles of irregular shape while the malleable metals usually produce flakes. Because of the lubricant necessary with malleable metals to prevent the flakes from welding together, this type of powder is not greatly used for molding metal parts. The grease or other lubricant interferes with proper sintering, and there is an additional disadvantage of flakes in that low strength laminated or layered structures result in the pressing operation. The flake powders are more generally used as pigments in the paint industry where their flat surface is an asset for good coverage.

A special type of mill, the Eddy Mill, can be used for malleable metals to give particles of suitable shape, fineness, and purity for the manufacture of sintered briquettes. Essentially, the mill consists of a chamber wherein are mounted two fans facing one another and operating at high speeds in opposite directions. The metal is introduced into the chamber in relatively small pieces, (e.g. $\frac{1}{4}$–$\frac{1}{2}$ inch lengths of 0.05 inch diameter wire) which, by collision with one another in the fan blasts, become very finely pulverized. The process can be accurately controlled and a variety of shapes, angular, flake, or pebble, can be produced as desired.

3. *Shotting*

Metal shot can be prepared by dropping the molten metal from a small opening through air or an inert atmosphere into water. If the method is controlled properly, a fairly fine shot can be produced. On the whole, however, this process in powder metallurgical work is confined largely to preparing intermediate size particles for further reduction by other methods.

4. *Atomization*

For metals having relatively low melting points, atomization provides a convenient method of producing fine particles. The molten metal is forced through a small nozzle orifice and broken up by a stream of compressed air, steam, or inert gas. The process can be controlled rather closely by proper choice of nozzle, pressure and temperature of the gas used, and the rate of metal flow. As a rule, it is applied to metals melting below 700° C. such as lead, lead alloys, zinc, and aluminum; but copper, having a much higher melting point, has also been successfully treated in this manner. The product can be drawn off and collected in standard dust collector systems, and is suitable for many types of powder compacting.

5. *Carbonyl Process*

Both nickel and iron under suitable temperature and pressure conditions will react with carbon monoxide to form the respective carbonyls[22]. From these carbonyls, the metals can be obtained by a reverse of the process decomposing the compound to the metal and the monoxide. The virtue of the process lies in the shape of particle, which appears to be almost spherical, the purity, and the control which can be exercised in particle size. The method has been used for years in the Mond process for making nickel shot, but, until recently, foreign producers exercised almost a complete monopoly on the manufacture of fine powders from carbonyl. Within the last few years, iron carbonyl powder has been produced on a large scale in this country in several different grades suited to industrial needs. The iron powder is a specialty product commanding a higher price than that produced by most other methods, but because of superior properties it has been used extensively in the electrical industry, particularly in the communications field for various types of magnetic cores.

6. *Condensation of Vapor*

Metals which have low boiling points can be vaporized and the vapor then condensed in powder form. These include zinc, magnesium, and cadmium. The powders so produced are used mainly in the chemical industry.

7. *Reduction of Chemical Compounds*

Metal powders whose characteristics can be varied over a wide range are prepared in large quantities by reduction of compounds of the metal with hydrogen or other reducing gases at temperatures below the melting point. The oxide of the metal is most generally utilized for the purpose, and among the metals produced are copper, nickel, iron, cobalt, molybdenum, and tungsten. The type and shape of the metal powder is governed somewhat by the compound from which it is reduced, so that, within limits, these factors are controllable by proper choice of compound.

8. *Electrolytic Deposition*

Metals can be electrodeposited in several ways to obtain powder depending upon the plating conditions. A hard, brittle deposit may be obtained which can be further crushed or ground to small particles, or a soft sponge, or even the metal in powder form can be produced. The powder is usually dendritic in shape and requires further treatment for use in molding. This generally comprises some sort of milling or grinding operation, and an annealing treatment to eliminate hydrogen and soften the powder.

9. *Other Methods*

Other methods for the preparation of metal powders include chemical precipitation, granulation, alloy formation and removal of an alloying constituent (such as platinum-arsenic, platinum-mercury, and gold-sulphur previously discussed), and the hydride process[67]. The last mentioned method is probably the only one of these which is of more than academic interest for powder metallurgy uses.

Hydrides can be formed of many metals, those of titanium, zirconium, thorium, hafnium, columbium, and tantalum being of particular interest since they are reported to be stable at room temperature. They are produced in 300 mesh size or finer, have the appearance of metal, and begin to dissociate into hydrogen and the pure metal in vacuum or non-oxidizing atmospheres above 350° C. The hydrides can be mixed with other metal powders, and, when compacted and sintered, slowly release hydrogen which creates a protective atmosphere around the metal particles and sometimes acts to remove oxide films already present.

Despite the number of methods known for producing metal powders, the bulk of the powders used on a large scale are produced by only three methods[23]: electrolytic deposition, atomization, and reduction of metal salts by gases. The carbonyl process produces a specialty product as does the hydride process, and, while both have their uses, the amount consumed is probably small in relation to that prepared by the other methods.

The Powder Metallurgy Process

As has been indicated in the introduction, there are a number of definite steps in the powder metallurgy process which may be summarized as follows:

1. Selection of the powder or powders best suited for production of the part under consideration.
2. Proper mixing. (If more than one type of powder is being used)
3. Pressing. (Sometimes followed by pre-sintering)
4. Sintering. (Sometimes followed by an impregnating operation)
5. Coining or Sizing operation if necessary.

Each of these important operations is discussed in somewhat more detail below:

1. *Selection of Powder*

When the actual metal or alloy composition has been decided upon, there are a number of factors which must be considered in the selection of the type of powder itself. An essential characteristic is purity[23] because in the powder metallurgy process impurities cannot be slagged off as in most melting processes, and may interfere with pressing and sintering operations. Oxide films, for example, may prevent good contact between metal particles. Clean surfaces are essential if ductility, and high tensile and shear strength are required in the finished article. In most cases, there is a definite limit set for objectionable impurities in a given powder, but in some instances materials normally classed as impurities are deliberately added to obtain a desired result. An example is the addition of thorium dioxide to tungsten as later described in the section on types of metal powder products.

The physical properties of the metal powders are also determining factors in their selection. These include particle shape, size, hardness, particle size distribution, flow characteristics, apparent density of loose powder, and particle grain structure.

Particle shape and size are governed largely by the method of production of the powder as has been suggested previously. The carbonyl process yields spherical particles, for example, while other methods produce particles that are angular, acicular, spongy, flat, rounded, granular, dendritic or otherwise irregular.

The hardness depends largely upon the metal itself, its purity, and the method of preparation. Hardness, in addition to shape of the particle, will be reflected in the amount of pressure required to obtain a given density in a finished part, and is a factor in the economics of die cost because of its influence on die life.

Particle size distribution in a metal powder is of great importance although no particular specification can be set up at present. The problem of size distribution and shape has been treated in some detail by W. D. Jones[24] and others, especially as concerned with interstitial volume or porosity. If all particles were cubes of the same size and could be placed in perfect order with the cube faces matching identically, there would be a minimum of porosity in the powder and in the pressed part. This is obviously impossible of attainment. In practice, packing is not systematic, but random, and even if identically sized cubes could be obtained, the voids between particles would be appreciable. In addition to the porosity resulting from the random packing, there are cavities which are due to bridging action of the particles themselves. This bridging is not due to irregular or angular particle shape, but can occur quite easily with spherical particles. Shaking or compressing the powder tends to destroy the bridges or arches and allow denser packing. As the powder is shaken down there is rotation of particles until corresponding surfaces come in contact and relatively dense packing is obtained. Such a rotation may not be present, however, during the rapid stroke in a die, and the particles cannot seek corresponding surfaces. In this case, there is a deformation of the particles pressed against one another so that there may be an actual keying, and the smaller particles may be pressed into the voids to produce the same result of denser packing. With a distribution of particle size, the voids between larger particles can be filled with smaller particles and, in practice, that is what is sought. The problem of setting up specified sizes or particle size distribution for powder metallurgy methods is not easy, however, because of practical complications arising in the pressing and sintering operations. Pore size rather than total porosity then becomes the problem, since, in sintering, only the smaller pores may become closed. At present, the manufacturer of metal powders cannot guarantee his particle size distribution, nor can the user determine and specify exactly what he needs. The grades can be approximated, only, and the types required must be determined in an empirical manner[23].

The apparent density (or loading weight) is the ratio of weight in grams to volume in cubic centimeters of powder, measured according to some specified method of filling a designated receptacle. It is of considerable practical importance since it has effect on several of the operations of powder metallurgy, especially that of pressing the compact. The lower the apparent density of a powder as compared with the actual density of the solid metal, the greater will be the volume of powder required to produce a briquette of given size. This necessitates deeper dies and longer plungers than for denser materials, and for very low apparent densities may become a serious design problem. Powders can usually be supplied in a range of densities, and the proper powder selected for use. For proper blending and mixing of different metal powders for producing solid metal parts, it is advisable to select grades having comparable apparent densities. An example of the use of a low-density copper powder may be cited. For the manufacture of starting brushes in the electrical industry, copper powder and carbon powder are mixed together and compressed. By using copper powder of a low apparent density, approaching that of the carbon (1.2), good blending is assured and the danger of segregation eliminated[23].

Low rate of flow of metal powders interferes with automatic pressing operations and may make it necessary to install vibrating equipment on the feeder hopper or even on the die itself. Rate of flow is influenced by particle size distribution, particle shape, and amount of absorbed moisture.

2. *Mixing*

When only one metal is to be pressed and sintered, there is usually no necessity for mixing since the powder as received from the manufacturer is generally well blended. Where several batches of the same metal of different particle size distribution are to be added, or where different metal powders are to be used, it is necessary to mix them thoroughly prior to pressing and sintering. This may be done in any of the standard type mixers with the precaution, in some instances, of providing against oxidation of the powders.

3. *Pressing*

For preparation of the compacts, the pressing operation may be done at either ordinary or elevated temperatures. The majority of parts produced, however, are pressed at room temperature. The presses[25,26] which now are designed primarily for this type of work may be of the mechanical or hydraulic types for high production rates with modifications for rapid plunger strokes as required.

The dies are generally of hardened steel having the inner surfaces highly polished by lapping with polishing rouge in the direction of the plunger stroke so that any fine scratches that remain are in the direction of ejection of the pressed part[26]. In some instances where parts are made from highly abrasive particles, the dies are made of or lined with hard carbide materials. Die depth depends upon the apparent density of the powder being pressed, but the usual ratio of depth to part thickness is approximately 3 to 1. The greater die depth required for powders of lower density introduces the complications of friction at the die sides, unevenness of pressure distribution, and internal friction of the powder itself. There is almost no lateral flow in the powder mass, a condition which limits the shapes that can be pressed.

Pressure used varies from 5 to over 100 tons per square inch, in general, and is an important factor in limiting the size of parts that can be made by the powder process.

Following pressing, a powder compact may sometimes be given a pre-sintering treatment below the normal sintering temperature in order to increase its strength to facilitate handling, or to remove lubricants or binders which might cause difficulties later.

4. *Sintering*[24,27,28]

Sintering is the fundamental process in powder metallurgy whereby solid bodies are bonded by atomic forces.

Theoretically it is possible to obtain bonding by bringing the powder particles into so close contact with one another that the atomic forces of cohesion may become operative. But this occurs only when the respective atoms of such adjacent particles are distant in the order of magnitude of the crystal interatomic spacings; this is a condition against which there are many obstructions. Visually and even microscopically smooth particles have surfaces which are extremely jagged with respect to interatomic spacings and crystal planes. Then not large, flat areas representing large numbers of atoms, but only successive points representing relatively very small groups of atoms can be brought into sufficiently intimate contact. Moreover, even this small contact may be reduced by the presence of oxide films.

An increase of pressure will improve the bonding of such powders since the particles are deformed and pressed against one another to give increased surface contact. At the same time, rupture of the oxide films may occur with subsequent closer contact of the metal particles. This is the general case for pressed powder compacts, or "green compacts" as they are designated. There is frequently a surprising strength associated with such pressed parts but, on the whole, a heat treatment is necessary to produce a material approaching the strength and solidity of a cast or wrought metal part.

The heating of pressed powder briquettes is usually done in an inert, reducing, or neutral atmosphere, or in vacuum. The temperature used is determined by the metal powders comprising the compact, and by the properties desired in the final product. The melting point is not exceeded for any of the components of the mixture except in those instances where such fusion of a minor constituent is desired, as, for example, in the production of cemented carbides. No definite temperature may be set for the heat treatment, but general practice is to treat at a temperature about two-thirds that of the melting point of the metal or alloy being fabricated. Higher temperatures are frequently used, however, and may be only slightly below the melting point.

The effect of heat is possibly that of causing increased surface diffusion and plasticity. The atoms on the surface of metal particles possess considerable mobility far below the melting point, and the surface energy at elevated temperatures may be appreciable. Where particles are in contact surrounding a void, flow of metal is in such a direction as to increase the area of contact.

When the sintering temperature is within the recrystallization range of the metal or metal alloy powder being treated, marked structural changes may occur. Recrystallization takes place at sites of plastic strain. Since these sites are regions of contact between particles, new crystallites form and grow into the adjacent particles so that a new series of grain boundaries is formed. The numerous cavities or voids present in the structure are not completely filled in or sealed in this operation. This could not occur without change of overall dimensions of the compressed mass. The voids may be present at the new boundaries or even enclosed in the crystallites, and produce a non-homogeneous sintered metal of relatively weak structure susceptible to sudden shock. By a high temperature treatment just below the melting point, or by alternate working and annealing, the voids can be closed and the metal consolidated to a dense, strong mass.

Surface oxide films which interfere with the sintering operation may sometimes be destroyed by treatment of the powder compact in a reducing atmosphere. If the oxide cannot be reduced in this manner, the pure metal can only be obtained by sintering operations if the oxide has a higher vapor pressure than the metal[29].

Gases, either adsorbed, dissolved, entrapped, chemically bound, or resulting from chemical action, may interfere with sintering and the general rule is to avoid them if possible in attempting to produce solid metal.

Following sintering, there is sometimes a treatment for impregnating a porous structure with some material designed to confer special properties on the compact. Pressed and sintered bearings may, for example, be impregnated with oil, and a strong, porous network of tungsten may be impregnated with copper by suitable means to produce spot and line welding electrode material having high compressive strength associated with good heat and electrical conductivity.

5. *Coining or Sizing*

Although the dimensional tolerances of sintered metal parts can be rather closely controlled, it may be advantageous to control final size and improve surface structure by a coining operation consisting in re-pressing the compact in a die of suitable size.

The Modern Field of Powder Metallurgy

Most of the developments and uses of metal powders described thus far, it should be noted, have been concerned with products which could not be produced in any other way than by powder metallurgy processes. This, in fact, has been the principal field of powder metallurgy. Porous bearings with uniformly distributed porosity could not possibly be fabricated by any of the standard melting and casting techniques, nor could the carbide cutting tools be likewise manufactured.

In general, the powder metallurgy process has been applied under conditions as outlined below[30,31,32]:

1. Production of refractory metals such as tungsten, tantalum, columbium, and molybdenum.
2. Development of structures not practical by other methods. These include telephone and radio cores, and articles requiring uniform or controlled porosity such as porous bearings and metallic filters.
3. Preparation of metals to include uniformly distributed non-metals.
4. Preparation of samples comprising a metal with another metal or metals which would be immiscible in the molten state, or which do not form alloys.
5. Preparation of samples of two or more metals where one component has a low boiling point.
6. Fabrication of products that can be made more economically by the powder process than by other methods[14].

Considerable work has been done by the automotive industry and others in developing products from powder metals that fall into class 6 above. There are many instances where automatic pressing and continuous annealing operations on small parts in quantity have made the process economically feasible for competition with the standard casting method. There are many factors involved in determining whether parts should be thus fabricated, and these will be described at greater length in the section on limitations of the powder method.

With the advent of increased production for war purposes, the powder process has, in many instances, been utilized to insure a steady supply of many small parts needed for ordnance. The use of powder metallurgy has released machines and mechanics for other types of work, and because of the speed and ease of setting up for production, it has often been possible for suppliers of small parts to adhere to schedules they could not otherwise meet[33]. In addition, because of the low metal loss connected with the powder process, there is considerable saving of scarce or strategic material.

To the six general classes of materials listed above, can then be added another class that can best be described as utilitarian. The powder method has been used as an expedient to supplement and extend normal production methods without regard to cost. However, it has often proved itself to be economically competitive, and in many cases, has effected considerable savings over normal production methods[33].

The intensified war production schedules have opened the larger field that has been long predicted by powder metallurgists, that of using the powder method to displace the conventional methods of making many parts not in the classification of specialty products. Even under the abnormal war conditions, however, there are indications that progress along these lines will not be rapid and the early promise shown has not been completely realized. Progress has been made, nevertheless, but many of the developments and products are known only to those workers actually engaged in producing parts for the wartime program, and only when the story of the progress made can be told, will complete evaluation of the process be possible.

It is the belief of some metallurgists, as yet realized commercially with only a few special items, that parts can eventually be prepared by powder methods with properties superior to those obtained by melting, casting, and working techniques. At least one investigator reasoned that, since sintered tungsten is stronger than fused tungsten, iron or steel prepared similarly should show the same superiority[34]. Actual studies conducted using relatively high compacting pressures indicate that both iron and steel can be prepared by powder methods with tensile properties better than those obtained on the some materials made by fusion processes.

Typical Powder Metallurgy Products

Most of the materials produced by powder metallurgy prior to about 1940 are well known; some have already been mentioned in this article, but for convenience are included in the following descriptions of typical products. Others of more recent development owe their immediate existence to the demands of wartime production, and, while some have been described in some detail in the technical literature, many have had only brief mention. Some typical parts made by powder methods are shown in Figures 1, 2, and 3.

1. *Cemented Carbides*[17,18,19,35]

Although tungsten carbide was produced many years ago and was found to be extremely hard, it was so brittle and low in strength that its use commercially where advantage could be taken of the high degree of hardness was not possible. About 20 years ago, it was discovered that the addition of a small amount of metallic constituent, such as cobalt, to the tungsten carbide powder would yield a hard, relatively strong compact after sintering. During the heating operation, there is partial melting with some solution of the carbide by the cobalt; and on cooling the cementing material produces the required strength.

The method of preparing the powders, compacting, and sintering has undergone considerable improvement since the first carbide materials were made. Essentially, in outline, the process consists of first preparing the tungsten carbide powder, mixing it with cobalt powder and ball milling the mixture until proper grain size is obtained and the carbide particles are coated with a thin layer of the cementing metal. In this treatment, other carbides are added as required. Following the milling operation, the mixed powders are pressed in suitable molds and given a pre-sintering heat treatment to increase the strength for handling and to remove, by volatilization, lubricants which may have been used to facilitate pressing. After the pre-sintering operation, the compact can be cut to desired shapes quite readily. The sintering treatment which follows is carried out at about 1400°–1500° C. with the pressed parts placed in carbon boats or on carbon slabs and heated in a suitable neutral or reducing atmosphere. There is considerable shrinkage in dimensions in this sintering treatment which gives a product that is hard, dense, sound, and strong. Any further shaping is done by grinding or lapping operations.

The cemented carbides have many uses usually falling into the three general classes of die materials, cutting tool materials, and wear and corrosion resistant materials.

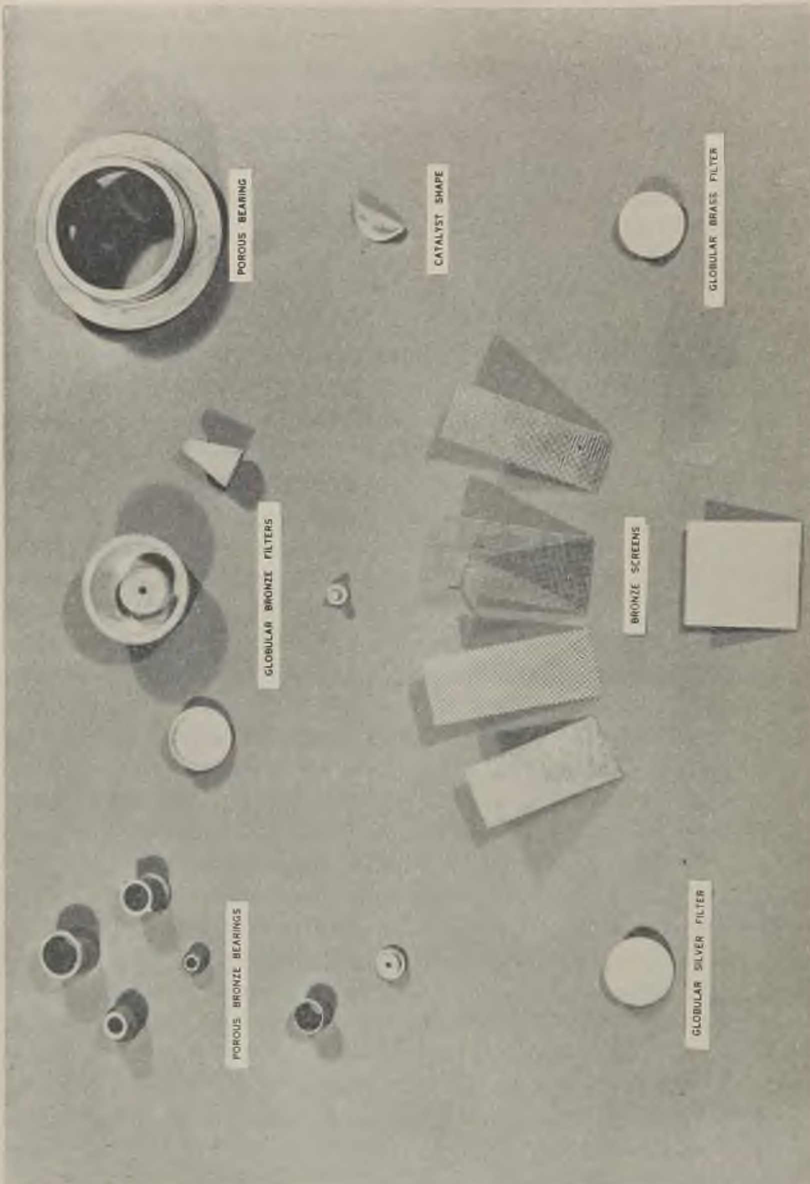

Fig. 1—Some porous parts made by powder metallurgy[23]

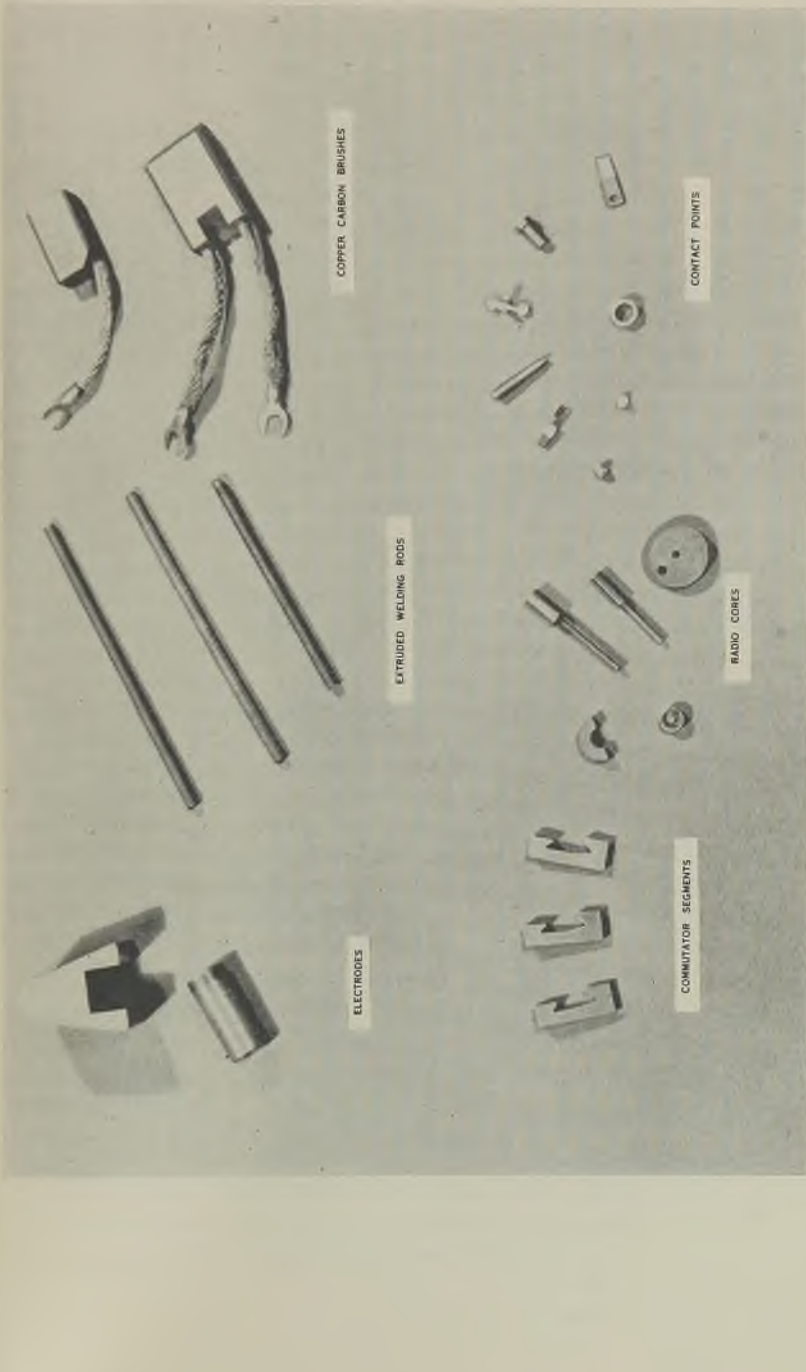

Fig. 2—Some electrical parts made by powder metallurgy[43]

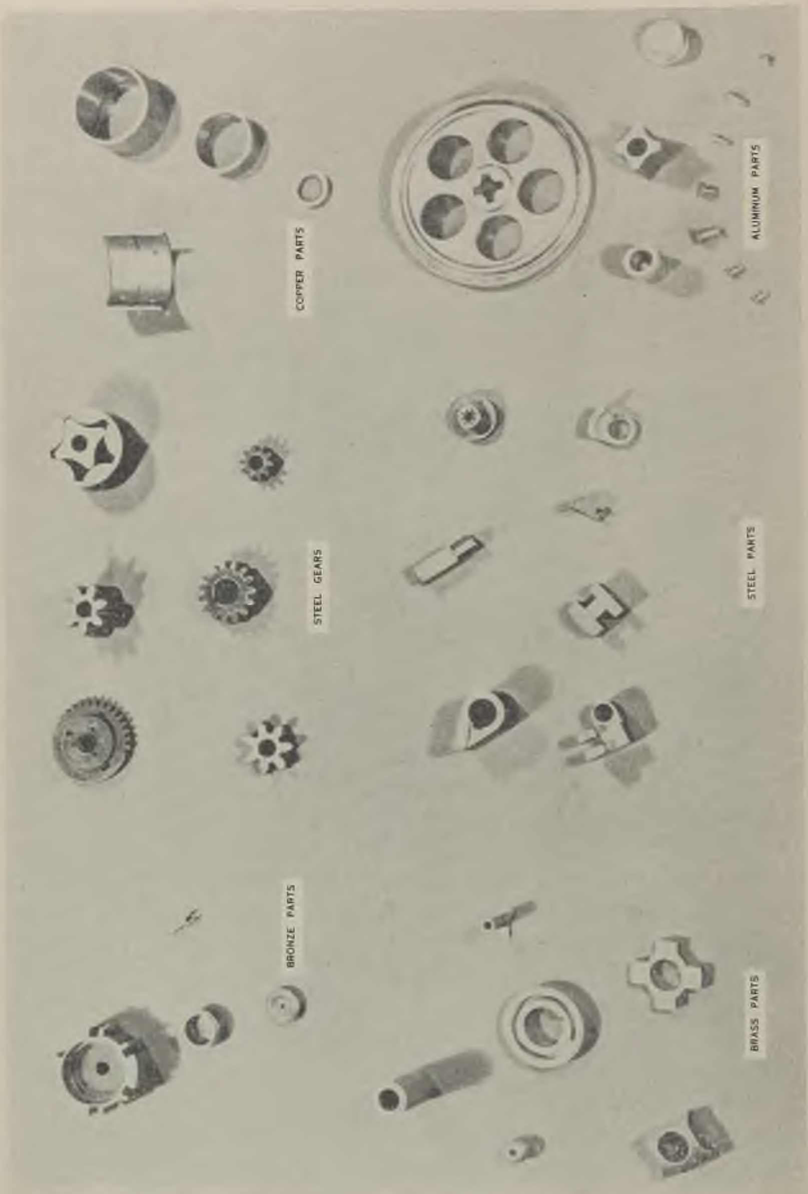

Fig. 3—Some machine parts made by powder metallurgy[23]

The die materials are usually the simpler tungsten carbide compositions and can be used to advantage for extruding, drawing, sizing, and other operations where the shape or dimensions of the article being worked is changed but where no metal is removed in the operation. The tungsten carbide can be used in this way for shaping many types of metals and alloys and this has been a major use of the product.

Cemented carbides, either the simple type or the mixtures, depending on the application, have been successfully used as cutting tips on a variety of tools, and for a number of different materials. This use has increased steadily due to the remarkable increase in production achieved. Decrease in cost of the tips and parts during recent years has further stimulated use.

Wear and corrosion resistant parts include gauges, guides of many types, pump valves for abrasive materials, sandblast nozzles, burnishing tools and dies, and many others where utilization of the superior properties is indicated.

One use recently reported[36] has been that of cemented tungsten carbide for bullet cores in ammunition for anti-tank weapons used by the enemy in the desert warfare in Africa. The material has about twice the density of steel and is much harder, and, although not greatly resistant to shock under normal conditions, becomes quite effective under the high pressures attained during striking and penetrating armor plate.

2. *Porous Bearings*

Porous bearings, always a large runner in the powder metallurgy field, have been described in the section on the historical development. Where the bearings are impregnated with oil, there is usually sufficient to last the lifetime of the assembly, but provision can readily be made for supplying additional oil if needed by utilizing the capillary action of the interconnecting pores to draw oil from a reservoir in contact with the bearing wall. In such assemblies, there is always a film of oil for the shaft to run on in contrast to normal bearings where an oil film does not coat the shaft until run for some time.

3. *Motor Brushes and Commutator Segments*

Numerous types of current collector brushes are now made by powder methods. Copper powder can be added to the graphite mixture, and the desired part pressed and sintered below the melting point of copper to develop a strong, high conductivity brush of longer life for use against copper surfaces. Greater wear resistance may be obtained by adding zinc, tin, or nickel to the mixture. Improvement in operating smoothness may be attained by the incorporation of lead[14,23].

The brushes can be pressed around pigtail conductor wire inserts to insure good contact for the lead wire and eliminate attachment problems.

Commutator segments, resistance rings, and rotor bars in squirrel-cage motors, have been successfully produced from copper by powder metallurgy methods[37].

4. *Refractory Metals*

Because of high melting points, the refractory metals, of which tungsten, molybdenum and tantalum are the most important, are prepared by powder methods. The preparation of each is similar, with the technique differing only in certain details where the characteristics of the individual metals require it[38].

With tungsten[39], the ore is treated by chemical methods to yield pure tungstic oxide which is then reduced by hydrogen at 650°–950° C. to give tungsten powder with a particle size range from 0.5 to 8 microns. As with other metal powders, care is exercised throughout to maintain high purity. After proper mixing and blending, the powder is compressed and the briquette given a pre-sintering treatment at 1000°–1200° C. to give sufficient strength for further handling. The resulting bar is then clamped in electrodes in a suitably designed hydrogen chamber, where acting as a resistance heater, heavy electric current is passed through it. The compact shrinks, the density increases, and a relatively solid bar results which can then be hot-worked. During the swaging or rolling, the working temperature can be gradually decreased until there is sufficient ductility by control of grain size to draw the material cold.

For tungsten used in lamp filaments, certain additions such as thorium oxide, or compounds of sodium or potassium mixed with such relatively non-volatile materials as SiO_2, Al_2O_3, or ThO_2 are intimately mixed with the tungstic oxide prior to reduction. These additions are effective in controlling grain growth and insuring proper grain boundary orientation for producing "non-sag" coiled filament. Essentially, the sodium and potassium compounds promote large grain growth while the others, such as thorium oxide, inhibit grain growth under the conditions of wire fabrication. When the material is drawn in wire form, the thoria particles form elongated stringers in the direction of drawing and tend to prevent grain growth across the wire while allowing exaggerated growth along the axis of the wire. The resulting structure of long grains with boundaries forming acute angles with the longitudinal axis of the wire is ideally suited for the coil type of lamp filament.

Molybdenum and tantalum are prepared in much the same manner as tungsten, although tantalum sintering and annealing must be conducted in high vacuum because of the ability of the metal to absorb and retain gases at high temperatures.

5. *Heavy Alloy*

"Heavy alloy" is the name applied to a group of alloys composed of tungsten, copper, and nickel having a density of 16 grams per cc. or greater[40,41]. They were originally developed for fabricating the containers and nozzles for radium units, but have such interesting properties that a number of other uses have become evident. Specific properties depend upon the composition, but generally the tungsten comprises about 90 per cent of the alloy.

One of the best compositions claimed is that of 90 tungsten-7.5 nickel-2.5 copper which has properties as listed below:

Tensile Strength	90,000 psi
Yield Point	83,000 psi
Elongation in 1 inch	4%
Elastic modulus	32×10^6 psi
Brinell hardness	250–290
Density	16.3–17.0 gms. per cc.
Coefficient of expansion	5.6×10^{-6}
Thermal conductivity	0.25 c.g.s. units

The alloys are prepared by mixing the metal powders dry, adding a small amount of wax, in benzol solution, mixing until the solvent has evaporated, and then pressing to shape. The compact is heated slowly to about 1000° C. and then sintered at a higher temperature at which the nickel and copper particles fuse, and the tungsten is not only wet by the liquid, but actually dissolved. The fine particles are thus dissolved, but tungsten is reprecipitated on certain nuclei to develop large rounded grains. The solution and redeposition continue until the original fine tungsten particles are replaced by grains approximately 100 times the original particle diameter. The alloy thus consists of tungsten particles in a cementing phase of copper-nickel-tungsten.

There is a shrinkage of up to 20 per cent, and the resulting compact is relatively free of porosity.

The alloy has good machining properties and can be treated much like many cast alloys. It has good corrosion resistance and can take a variety of surface finishes.

In addition to its use in X-ray and radium work, its high density and strength make it attractive for use as a counterweight material in high-speed motor setups of many types.

6. *Electrical contacts and electrode materials*

Powder metallurgy can be utilized to fabricate material composed of two or more metals without any appreciable alloying so that the characteristics of each of the components may be retained to a large degree. This has opened a large field for electrical contacts and welding electrodes made by using compositions where the refractory nature of materials such as tungsten, molybdenum, nickel, or graphite can be retained, while good electrical conductivity may be obtained with copper and silver[14,32,42].

Another type of material with good spark quenching properties is the combination of silver and cadmium oxide, which, because no alloying results, also has high electrical conductivity[43].

The contact materials may be made by any of the suitable powder techniques. One method is to press and sinter the powder composition sought, with or without final sizing or shaping of the part. Another method that is utilized for making tungsten-copper compositions consists in pressing a bar from tungsten powder and sintering at 1300° C. in hydrogen. The tungsten thus forms a strong porous structure which can then be impregnated with copper. This may be accomplished by placing the part in a graphite boat with copper, heating above the melting point of the latter, and allowing the voids to be filled by capillary action.[44]

No single contact material is satisfactory for all purposes, and a number of different combinations have been developed. These include silver-tungsten, copper-tungsten, silver-graphite, silver-molybdenum, cemented tungsten carbide, and copper-nickel-tungsten. They are used in many installations such as circuit breakers, welding machines, relays, and many types of industrial control equipment.

7. *Alnico magnets*

Many Alnico magnets of small size have been produced commercially by powder methods[45,46]. Magnets made in this manner are fine grained in contrast to the relatively coarse grained material obtained by casting methods. The material is uniform throughout with no cold shuts, cracks, blow holes or grain boundary segregation so that a more uniform flux density is obtained. Of particular interest are the close dimensional tolerances which can be maintained in the powder method and the small amount of grinding required in finishing. The composition can be held much more closely than for the cast alloy.

The process is limited economically to the production of small samples. Large samples can be prepared by conventional methods at a cost that would not allow sintered products to compete.

The presence of a highly oxidizable element (9–13 per cent of aluminum) presented difficulties when attempts were first made to prepare Alnico by sintering pressed compacts. To overcome this oxidation, the aluminum is added in the form of alloy powder of 50 aluminum-50 iron composition prepared by crushing and ball milling a casting of the brittle material[47]. In such form, there is practically no oxidation of the aluminum under the sintering conditions which prevail.

Another method to minimize or eliminate oxidation in sintering operations utilizes, in addition to the 50 aluminum-50 iron powder, approximately 2 per cent of titanium hydride incorporated in a powder mixture of aluminum-iron-nickel[48]. Decomposition of the hydride commences at about 450° C. with release of nascent hydrogen so that during the sintering operation, oxidation is prevented and part or all of any oxide already present may be reduced.*

8. *Metal filters and screens*

Related to the porous metal type of bearing and prepared in much the same way are the metal filters and screens made by powder methods[3,49]. Bronze, copper-nickel alloys, or pure nickel may be utilized, and porosities up to 80% by volume may be obtained. These filters have been used to advantage in the chemical industry for filtering strong alkaline solutions and other liquids of many kinds. One reported application is as a fuel filter 5 inches long and 2 inches in diameter for a Diesel engine[3].

Generally, the filter part can be bonded to steel or copper and made an integral part of the apparatus in which it is to function.

In the manufacture of the filters, the prosity can be accurately controlled. In addition to the methods of producing porous parts as previously described, a highly porous metallic mass can be prepared by sintering the component metal powders (sometimes with volatile additions) in the uncompacted condition using a protective atmosphere and a temperature determined by the type of powders used[50].

9. *Alloys having special properties dependent on close control of composition*

There are some alloys for special purposes where accurate control of composition and reproducibility of composition are of primary importance. Two such materials are: low-expansion alloys for metal to glass seals, and thermocouple wire for temperature measurement.

An alloy of 54% iron-28% nickel-18% cobalt having approximately the same coefficient of expansion as certain grades of glass is normally prepared by melting and casting procedures. This alloy can be prepared by sintering methods, however, with the same physical characteristics, but with closer composition control and less contamination[44].

Alloys of nickel-molybdenum and nickel-tungsten have been prepared

* The need for titanium hydride in the preparation of alloys of this type, and the effect of the hydride in controlling oxidation has been the subject of some discussion[48]. Its use is mentioned here only as a variation of the method described above and apart from any effects it may have on the magnetic properties of the alloys to which it is added.

by powder methods for use as thermocouple elements[44]. When these are used with nickel wire as the second element, the couples can operate at temperatures up to 1300° (Ni-Mo) and 1400° C. (Ni-W). Ease of preparation and not reproducibility of composition was probably the main factor in the fabrication of these two types of thermocouple elements since the compositions reported are in the range where relatively large changes in composition produce little variation in thermoelectric voltage.

10. *Parts for Ordnance*

As has already been mentioned, many powder metal parts are being manufactured for use in equipment of the Armed Services, and, while in some instances the parts are made by powder methods only because of expedience, it should be noted that, in all cases definite specifications must be met before acceptance, and a powder metal part that does not meet the rigid requirements has no more chance of acceptance than has an inferior part made by other methods.

Among the parts which have been successfully produced are copper and brass rotating bands for projectiles[36]. While the cost of the powder metal bands is greater than that of bands made in the normal manner from copper or brass tubing, they compare favorably in actual performance in firing tests both as to behavior on the projectile and wear on the gun barrel.

Improvement of the strength of porous metal bearings has been a factor in their adoption for use in anti-aircraft guns where they may operate under severe conditions. It has been reported that 100 parts are thus utilized in a single gun installation[51].

Another item reported to be in production is an iron powder part of an elevating hand mechanism for both the .30 and .50 caliber anti-aircraft machine guns[36]. Knurling of the outer surface of the ring part and the marking off of degrees are performed on the part in a coining blow.

11. *Sintered Iron Parts*

Prior to the wartime demands for sintered iron parts, there had been developed a fairly extensive field for peacetime uses particularly in the automotive industry. Bearings had been manufactured for some time and, following this, production had extended to the fabrication of oil pump gears, door catches, cams, and other parts where very high strength is not essential. In general, these sintered iron parts have mechanical properties similar to those of cast iron, but considerable range in properties may be obtained by proper selection of raw material and treatment. Grading of parts from iron powder into three classes according to the type of product and properties has been outlined as follows[52,53]:

Type A Materials having mechanical properties similar to ordinary cast iron suitable for applications where stresses are very low.

Type B Materials similar to Type A but having improved tensile strength, a definite yield point, and a noticeable elongation.

Type C Materials having mechanical properties approaching ordinary malleable iron, suitable for applications where stresses, including impact, are moderate.

Prior to 1941, the iron powder used commercially for pressed and sintered parts was of Swedish origin because that was the only powder available in quantity, quality, and at a price which allowed competition economically with established methods of production. Domestic iron powders are now available, however, that are superior to those formerly imported.

Of the sintered iron products manufactured in this country, an interesting example is a small gear for automobile oil pumps[27]. This gear was formerly made by machining cast iron blanks but was adapted for powder metal production because of greater ease in fabrication at less cost and more satisfactory operation. The gear teeth must be true involute curves with surfaces such that noisy operation and binding are prevented. All of these characteristics can be readily obtained by pressing and sintering, while more difficulty is encountered with cast gears because of the intricate machining work involved. The sintered gear avoids these expensive machining operations, and the teeth have so much better surface finish, and mesh so accurately, that noisy operation is avoided. In addition, the associated porosity is helpful in that oil impregnation assists in smoother and quieter operation.

The pressed gears are lighter in weight than the cast gears, and while the mechanical properties are not of high order, they are satisfactory for the use.

12. *Cladding and Duplexing*

Powder methods are useful in cladding, duplexing, or any of the processes whereby one metal or alloy may be coated with another for protective purposes, to obtain special properties as in bimetal strip, to obtain hard surface layers on strong, tough backing material, or to obtain a thin layer of relatively high-cost metal of desirable properties on a suitable low-cost backing strip.

For fabrication of bimetal, layers of the respective component metal powders may be placed in the die in the desired proportions and compacted. Upon sintering, an alloy bond is formed between the layers, and the briquette may be rolled or otherwise worked to the desired thickness[50,54]. An advantage of this type of bimetal fabrication is the use of alloy bonding at the interface instead of a solder which might limit the operating temperature of the material[14].

13. *Metallic Friction Materials*[14,55]

The ordinary type of friction material for brake linings, clutch facings, and similar uses is generally composed of asbestos with an organic type of binder. Under normal operating conditions, this type of material is quite satisfactory, but where severe conditions of operation are encountered, the heat generated at the braking surfaces may be sufficient to decompose the binder and cause rapid wearing of the friction facing.

By powder methods, however, a metallic matrix can be formed with admixtures of friction producing ingredients to give a facing that is capable of withstanding the high temperatures generated under severe operating conditions. The exact composition of the facing is determined by the requirements, and a number of different metallic and non-metallic materials are used. Generally, however, the basic ingredient of the matrix is copper to which may be added such modifying metals as tin, lead, zinc or iron. The friction-producing powder is generally an abrasive such as silica or emery which is varied in amount according to the coefficient of friction that is desired.

The metallic elements may constitute only about 50 per cent of the part by volume with the other 50 per cent represented by non-metallic ingredients and pores. In consequence, therefore, the facing is weak and brittle and is usually bonded to a strong backing plate.

The friction materials are prepared in the normal manner by mixing suitable powders, compressing in suitable form, (usually as thin annular rings) and sintering. The sintering operation is generally performed so that the part is bonded to the backing plate at the same time. Finishing operations are then performed to adjust the facing to size and proper shape for use.

14. *Cores for Inductance Coils for Telephone and Radio*[56,57]

Although the manufacture of cores for induction coils for telephone and radio use does not fit into the field of powder metallurgy as more strictly defined in the Introduction, the procedure is in many ways so similar to the processes described above, and the product of such interest, that a brief description is included in this review.

The coils in communication circuits may operate over a wide range of frequencies from voice frequencies up to millions of cycles per second.

By the use of a finely divided magnetic powder, the particles of which are insulated from one another, the eddy current losses in the cores can be reduced to a level low enough for satisfactory use.

The first metal powder used for cores in the telephone industry was electrolytic iron. This was later superseded by more suitable magnetic materials such as the permalloys.

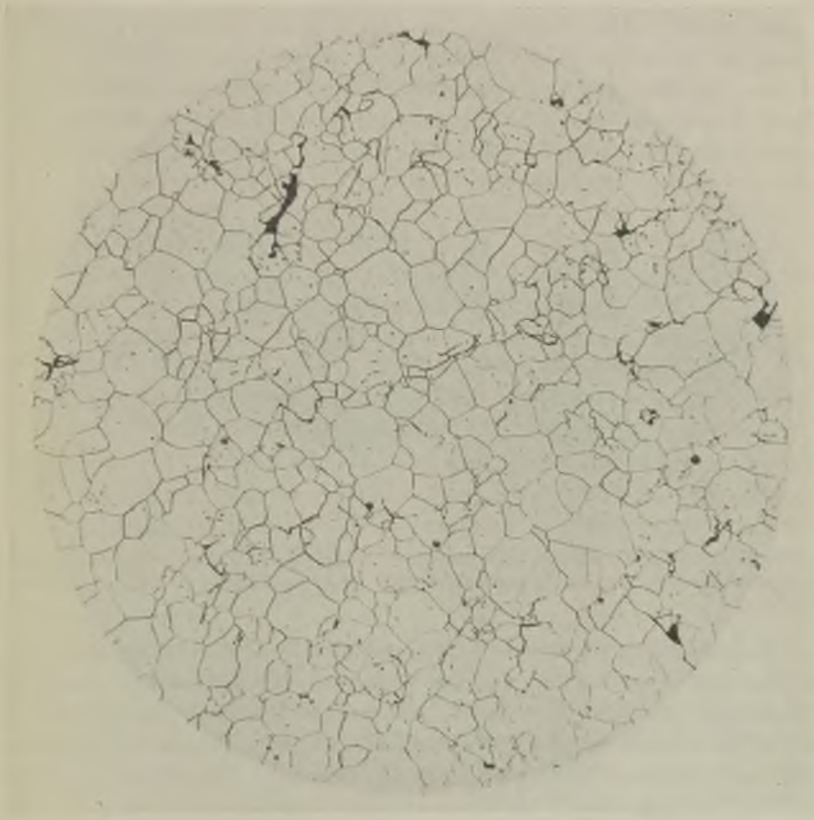

Fig. 4—Brittle molybdenum-permalloy, as rolled to produce fine, equiaxed grain. Magnified 130 diameters.[57]

The procedure utilized to obtain the permalloy powder is worthy of note. Ingots of the desired composition are prepared by melting and casting in the normal manner with, however, the addition to the melt of a small amount of sulphur which acts as an embrittling agent to facilitate pulverization. The sulphur exists as microscopic films of complex sulphides at the crystallite boundaries. At normal temperatures these films are brittle, but at elevated temperatures are either malleable or dissolve in the iron-nickel solid solution. The alloy can therefore be hot-rolled to small section under controlled conditions to develop a desired grain size, and then cold-worked to separate the individual crystals. Grain size depends upon the degree of refinement in the hot-rolling operation and upon the distribution of the sulphide film around the grain boundaries. Final pulverization is accomplished in an attrition mill, and the product is generally annealed to soften the particles.

The powder is then treated to cover each of the particles with an insulating film that is generally of the ceramic type. The cores are then pressed at about 100 tons per square inch to develop proper density and strength. There is no sintering treatment performed on this type of material after pressing, but the cores are generally annealed to remove pressing strains and restore magnetic quality.

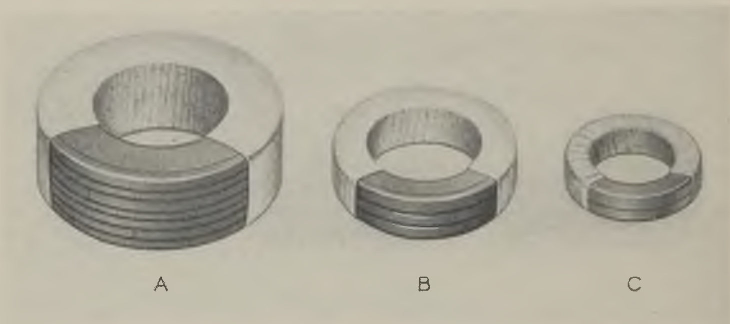

Fig. 5—Relative size of cores for a given duty in a telephone circuit. A is a core made of electrolytic iron powder; B is made of 80% Ni-permalloy powder; C is 2-81 Mo-permalloy.[66]

This powder metal process is thus different from those previously described and is one of the specialty group of materials which cannot be prepared by any other methods. Except for the deliberate coating of the metal particles with an insulating film, and the avoidance of a sintering operation, however, the procedure is that normally followed in preparing powder metal articles.

In addition to the permalloys described, a number of other magnetic powders are used in pressed core form for various applications. These include electrolytic iron, carbonyl iron, and several types of magnetic oxides. Carbonyl iron, in particular, has been used extensively for radio cores where the spherical shape and small size of the particles have been factors in their successful utilization.

Advantages of the Powder Metallurgy Process

Throughout this paper, numerous advantages of the powder metallurgy process have been indicated as well as some of the limitations. Outlined below in somewhat more detail are these considerations and others which enter into an evaluation of the process as a whole. In those instances where a product cannot be made in any way except by powder methods, evaluation is easy. But for those products which must compete with standard methods of fabrication, the problem is more complex, and generalizations cannot always be applied.

The following are some of the advantages of the powder metallurgy process:

1. High purity of the metal content of the finished product can be maintained. Control of the manufacture of the powders enables producers to supply metals that generally run well above 99 per cent purity, and often as high as 99.99 per cent for some metals such as tungsten, tantalum, and zirconium[23]. Opportunity for additional impurity pickup is slight under the conditions prevailing in the pressing and sintering operations, so that the original metal purity is retained, and may even be improved by oxide reduction or removal of volatile impurities.
2. Composition of the product can be accurately controlled and reproduced[30,44]. There are no losses due to oxidation or slagging as in melting processes so that the metal content can be quite readily fixed.
3. Structures, alloys, or materials not possible of fabrication by any other method can be produced by powder methods[29,30,49,58]. These have been adequately described and include porous bearings, sintered carbides, refractory metals such as tungsten and tantalum, and combinations of metals, and of metals and non-metals that do not alloy.
4. High production rates[58,61,65], especially on small parts, can be attained by use of automatic presses of the pill tabletting type and of continuous type sintering furnaces. One order of forty million small parts required by the Navy was produced at the rate of 520 pieces per minute by powder methods[64].

   Larger size articles cannot be produced at any such rate because of press limitations which may necessitate hand operation, but with pressed iron parts, high rate of production is one of the factors that allows the process to compete with other standard methods of manufacture.
5. A wide range of certain physical properties can be obtained for any particular material being fabricated[58,62]. Control can be exercised over such properties as density, porosity, grain size, and strength by variation of the type and size of powder particles, die pressure, and sintering time and temperature.

   In some instances such as small Alnico magnets, structures developed may have better mechanical properties than the same material in cast form[44,45,46,47]. The same type of fine-grain structure developed in laboratory samples of iron parts compacted at high pressures and sintered at relatively low temperatures also exhibit superior tensile properties[34].

6. The powder method of manufacture may be more economical in many instances due to factors such as rapid quantity production, lower labor costs, ease of setting up for manufacture, conservation of material, and elimination of machining operations[30,62]. A reported instance of analysis of the normal cost of producing approximately one hundred different units used in a piece of Ordnance equipment revealed that powder metal parts effected a saving of about 70 per cent[33].
7. Rather close dimensional tolerances[30,58,61] on small or medium size parts up to about two inches major dimension can be secured, averaging ± 0.001 inch. Closer tolerances of ± 0.0005 inch are attainable and may be even smaller on special production jobs. On larger parts, the tolerance may be in the order of ± 0.002 inch. Frequently, however, accuracy of dimensions is attained only through a coining or re-pressing operation of the sintered part.
8. There is usually very little material waste associated with powder metal parts manufacture since there is little or no scrap loss[23,58,62]. Powder losses generally run below 0.5 per cent[59]. In melting and casting operations on small parts, on the other hand, the sprues and risers may be several times the weight of the finished casting. In addition, machining operations on cast parts may remove from 10 to 50 per cent of the metal, and while most of it is recoverable as scrap, it represents a loss in the manufacturing process[62].
9. Highly skilled labor is not required for most operations in the powder method[33,59]. Except for the construction of the necessary dies and die parts, semi-skilled labor may be used. This is of value in industrial plants producing parts for Ordnance because skilled mechanics who would normally be required for machining operations can be made available for other work.
10. Tooling costs are relatively low in comparison with other high-production methods, and less time is usually required to set up for production[33]. Secondary operations such as machining of the sintered products may be eliminated or greatly reduced.

Limitations and Problems of the Powder Process

As has been indicated in several sections of this review, there has been a recent shift in emphasis in the type of product made by powder methods, and in addition to those materials that are difficult or impossible to make by other methods, parts are now being manufactured in direct competition with those made by conventional, established procedures.

Under these circumstances, economy of production, in addition to technical feasibility, becomes a major factor in the utilization of the process. Of the numerous limitations of the process, some are inherent and definitely limit its application while others are incidental and susceptible to certain measures of control. The more important of these limitations and problems are outlined below:

1. The cost of metal powders is high in comparison with metal for other methods of producing similar parts, and availability of suitable powders is another problem[44,63]. Both cost reduction and availability have received considerable attention in recent years, and with increased use of metal powders and the large-scale powder production entailed, substantial price reductions have been effected and a wider variety of types of powder have been made avilable. The development of domestic sources of supply of a satisfactory low-cost iron powder to replace Swedish sponge iron is an example of a successful attempt to overcome a limitation of the process[53].

   In a final analysis, metal powder costs must be balanced against overall costs before a raw material cost standard can be set up.
2. Die expense[14,44,61,63] is high, especially for large and complicated parts and for high pressures. New dies are required for each part of different shape and size, and each die must be installed and carefully adjusted for operation. With the entry of the powder metallurgist to the low cost part field, there will be need for more complicated dies to meet the competition of intricately shaped parts produced by casting methods. The tool cost, however, for the powder process is generally lower for a given part than with other processes. Die cost may range from about $150 for small simple parts up to $1800 or more for large parts or complicated shapes[33].
3. Sintering furnaces pose many problems in the production of powder metal parts[14]. Close temperature control and uniformity are essential for control of dimensional changes in compacts. The fabrication of iron or alloy steel parts requiring higher temperatures than have been previously utilized in the industry add to the difficulties of furnace design.
4. The size and form of powder metal products is limited[44,62,63]. Large samples require huge presses to obtain the desired compacting pressures and both tool and press costs increase. Increase in size of compacts leads to a non-uniform distribution of pressure and may adversely affect the shape and dimensions of the article in the sintering

operation. Large presses are usually not of the automatic type, which means hand operation with lower production rates and increased cost. Low apparent density of most metal powders affects die design and limits the thickness of parts produced. A compression ratio of about 3 to 1 is generally assumed, which means mold depth must be at least 3 times the thickness of the finished compact. Other factors of die design are noted under item 7 of this section.

5. The powder process is essentially one of mass production, and a reasonable number of parts must, in general, be fabricated or the costs per unit will be excessive.
6. On a production basis, powder metal structural parts generally have relatively low elongation, tensile strength and impact strength[14,44,63]. The mechanical properties of a sintered part depend to some extent on its density, which itself is a function of the type of powder used, the compacting pressure, and the sintering treatment. Because of the voids normally present in powder metal parts, the ultimate properties cannot be expected to be as good as those obtained on cast and wrought materials[62].
7. There are a number of design limitations for powder metallurgy parts[11,44,61,62].
   a. Sharp corners should be avoided and internal angles should have fillets.
   b. Large and abrupt changes in thickness of parts should be avoided, as should uneven cross sections.
   c. Re-entrant angles, grooves, and undercuts cannot be molded, and if required, must be machined in an extra operation. Internal and external threads, and holes at right angles to the central hole or perpendicular to the axis of pressing, likewise cannot be pressed, and must be machined.
   d. Length of pressed parts must be comparable to the cross-section area because of pressing limitations. A long section may have a soft central portion of low density.
   e. There is almost no flow of metal powders during compacting because of friction between particles, and between particles and the die walls[60,62].
8. Although powder parts can be produced to close dimensions by careful control of the compacting and sintering operations and by coining or re-pressing the sintered pieces, tolerances should, in general, be fairly liberal if costs are to be kept down[14,61]. Close dimensional tolerances may necessitate machining operations to meet specifications. Eccentricity of cylindrical parts may be controlled fairly closely, but concentricity may be troublesome because there must be clear-

ance between die parts and plungers, and the clearances may be cumulative[60].

9. There is a lack of technical information available for engineers and designers. Tests on metal powders and finished parts have not been standardized, and until such standardization has been achieved the metal powder consumer and the ultimate user of the sintered parts have no check on the respective products. This situation is now being remedied.
10. There are some thermal limitations that may cause difficulties in the sintering process in certain instances[63]. Some oxides can be reduced only at temperatures above the melting point of the metal itself and prevent effective welding of the powder particles.
11. Metal powders in a fine state of subdivision are readily combustible and must be treated as potential fire and explosion hazards[20,62]. Zirconium, magnesium, aluminum, and titanium are the most inflammable with iron, manganese, zinc, silicon, tin, and antimony, moderately inflammable. Precautions must be taken to keep dust out of the air in the mixing and pressing rooms, not only because of the explosion hazard, but also because of possible toxic effect on workers.
12. Deterioration of metal powders may occur in storage due to oxidation or absorption of moisture with subsequent chemical reaction to change the composition[62].

Conclusion

This correlated review of some of the more common aspects of powder metallurgy is presented to provide information on an increasingly important production method. The review makes no pretense of complete coverage of the subject, and many important topics such as hot pressing, press and furnace design and operation, sintering atmospheres, and die design and operation have not been described. These and other more specialized topics that are beyond the scope of this paper may be found in the appended list of references.

Acknowledgment

The authors have drawn freely from many of the articles on powder metallurgy published during the past ten years. Wherever possible, reference is made to the original source of the topic material or to associated articles where more complete information may be found. To these sources listed below, the authors are indebted for much of the material presented in this review.

The authors express appreciation to Mr. Charles Hardy for permission to use his pictures of powder metal parts shown in Figs. 1, 2, and 3.

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Abstracts of Technical Articles by Bell System Authors

Automatic Ticketing of Telephone Calls.[1] O. A. FRIEND. In January a new arrangement of dial central office equipment was placed in service at Culver City, California, designed to enable subscribers to dial for themselves their short-haul toll calls to other exchanges within the Los Angeles metropolitan area. These calls were formerly placed with an operator, who completed and timed the call and wrote a ticket used for billing. The new equipment controls the automatic completion of the dialed call, identifies the calling line, and prints a ticket showing the calling and called numbers and other information needed for billing. The arrangement applies to the step-by-step switching system and employs senders capable of routing these calls efficiently through a metropolitan trunking network. It affords operating economy together with faster and more convenient service.

Noise Figures of Radio Receivers.[2] H. T. FRIIS. A rigorous definition of the noise figure of radio receivers is given in this paper. The definition is not limited to high-gain receivers, but can be applied to four-terminal networks in general. An analysis is made of the relationship between the noise figure of the receiver as a whole and the noise figures of its components. Mismatch relations between the components of the receiver and methods of measurements of noise figures are discussed briefly.

Structural Features of Buna S—Relation to Physical Properties.[3] A. R. KEMP and W. G. STRAITIFF. The non-symmetry in the chain structure of Buna S hydrocarbon is discussed in relation to the prevention of crystallization and the impeding of cross linking during vulcanization. This lack of chain symmetry is put forward to account for the poor quality of Buna S vulcanizates in comparison with corresponding vulcanizates prepared from natural rubber. Fractionation data on a regular benzene-soluble crude Buna S indicates the presence of an objectionable broad range of polymer sizes. It is shown that the lowest-molecular-weight polymer fractions in Buna S are not chemically bound in the vulcanizate but remain soluble in chloroform. By removing most of this low polymer from Buna S, the chloroform extract of its vulcanizate decreases accordingly. Vulcanizates were prepared from high- and low-molecular-weight fractions of Buna S. The high fractions were tough, dry, and difficult to handle on the mill; the

[1] *Elec. Engg., Transactions Section*, March, 1944.
[2] *Proc. I. R. E.*, July, 1944.
[3] *Indus. & Engg. Chem.*, August, 1944.

lower-molecular-weight fractions were soft and sticky. The tensile strength of vulcanizates from the high fraction was somewhat greater than that of the whole polymer, but the modulus was considerably increased. For the low-molecular-weight polymer both tensile and modulus values were much lower. Vulcanizates prepared by mixing natural rubber and gutta-percha hydrocarbons show lower strength than either of the hydrocarbons separately tested in the same formula.

Contributors to this Issue

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