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NUMBER 1

Transatlantic Communications — An Historical Resume MERVIN J. KELLY AND SIR GORDON RADLEY	1
Transatlantic Telephone Cable System—Planning and Over-All Performance E. T. MOTTRAM, R. J. HALSEY, J. W. EMLING AND R. G. GRIFFITH	7
System Design for the North Atlantic Link H. A. LEWIS, R. S. TUCKER, G. H. LOVELL AND J. M. FRASER	29
Repeater Design for the North Atlantic Link T. F. GLEICHMANN, A. H. LINCE, M. C. WOOLEY AND F. J. BRAGA	69
Repeater Production for the North Atlantic Link H. A. LAMB AND W. W. HEFFNER	103
Power Feed Equipment for the North Atlantic Link G. W. MESZAROS AND H. H. SPENCER	139
Electron Tubes for the Transatlantic Cable System J. O. McNALLY, G. H. METSON, E. A. VEAZIE AND M. F. HOLMES	163
Cable Design and Manufacture for the Transatlantic Submarine Cable System A. W. LEBERT, H. B. FISCHER AND M. C. BISKEBORN	189
System Design for the Newfoundland-Nova Scotia Link R. J. HALSEY AND J. F. BAMPTON	217
Repeater Design for the Newfoundland-Nova Scotia Link R. A. BROCKBANK, D. C. WALKER AND V. G. WELSBY	245
Power-Feed System for the Newfoundland-Nova Scotia Link J. F. P. THOMAS AND R. KELLY	277
Route Selection and Cable Laying for the Transatlantic Cable System J. S. JACK, CAPT. W. H. LEECH AND H. A. LEWIS	293
<hr/>	
Bell System Technical Papers Not Published in This Journal	327
Recent Bell System Monographs	335
Contributors to This Issue	338

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Transatlantic Communications— An Historical Resume

By DR. MERVIN J. KELLY* and SIR GORDON RADLEY†

(Manuscript received July 30, 1956)

The papers that follow describe the design, manufacture and installation of the first transatlantic telephone cable system with all its component parts, including the connecting microwave radio-relay system in Nova Scotia. The purpose of this introduction is to set the scene in which this project was undertaken, and to discuss the technical contribution it has made to the development of world communications.

Electrical communication between the two sides of the North Atlantic started in 1866. In that year the laying of a telegraph cable between the British Isles and Newfoundland was successfully completed. Three previous attempts to establish transatlantic telegraph communication by submarine cable had failed. These failures are today seen to be the result of insufficient appreciation of the relation between the mechanical design of the cable and the stresses to which it is subjected as it is laid in the deep waters of the Atlantic. The making and laying of deep sea cables was a new art and designers had few experiments to guide them.

During the succeeding ninety years, submarine telegraph communication cables have been laid all over the world. Cable design has evolved from the simple structure of the first transatlantic telegraph cable — a

* Bell Telephone Laboratories. † British Post Office.

stranded copper conductor, insulated with gutta-percha and finished off with servings of jute yarn and soft armoring wires — to the relatively complex structure of the modern coaxial cable, strengthened by high tensile steel armoring for deep sea operation. The coaxial structure of the conducting path is necessary for the transmission of the wide frequency band width required for many telephone channels of communication. The optimum mechanical design of the structure for this first transoceanic telephone cable has been determined by many experiments in the laboratory and at sea. As a result, the cable engineer is confident that the risk of damage is exceedingly small even when the cable has to be laid and recovered under conditions which impose tensile loads approaching the breaking strength of the structure.

The great difference between the transatlantic telephone cable and all earlier transoceanic telegraph cables is, however, the inclusion of submerged repeaters as an integral part of the cable at equally spaced intervals and the use of two separate cables in the long intercontinental section to provide a separate transmission path for each direction. The repeaters make possible a very large increase in the frequency band width that can be transmitted. There are fifty-one of these submerged repeaters in each of the two cables connecting Clarenville in Newfoundland with Oban in Scotland. Each repeater provides 65 db of amplification at 164 kc, the highest transmitted frequency. The working frequency range of 144 kc will provide thirty-five telephone channels in each cable and one channel to be used for telegraph traffic between the United Kingdom and Canada. Each cable is a one-way traffic lane, all the "go" channels being in one cable and all the "return" in the other.

The design of the repeaters used in the North Atlantic is based on the use of electron tubes and other components, initially constructed or selected for reliability in service, supported by many years of research at Bell Telephone Laboratories. Nevertheless, the use of so many repeaters in one cable at the bottom of the ocean has been a bold step forward, well beyond anything that has been attempted hitherto. There are some 300 electron tubes and 6,000 other components in the submerged repeaters of the system. Many of the repeaters are at depths exceeding 2,000 fathoms ($2\frac{1}{4}$ miles) and recovery of the cable and replacement of a faulty repeater might well be a protracted and expensive operation. This has provided the incentive for a design that provides a new order of reliability and long life.

On the North Atlantic section of the route, the repeater elements are housed in flexible containers that can pass around the normal cable

laying gear without requiring the ship to be stopped each time a repeater is laid. The advantages of this flexible housing have been apparent during the laying operations of 1955 and 1956. They have made it possible to continue laying cable and repeaters under weather conditions which would have made it extremely difficult to handle rigid repeater housings with the methods at present available.

A single connecting cable has been used across Cabot Strait between Newfoundland and Nova Scotia. The sixteen repeaters in this section have been arranged electronically to give both-way amplification and the single cable provides "go" and "return" channels for sixty circuits. "Go" and "return" channels are disposed in separate frequency bands. The design is based closely on that used by the British Post Office in the North Sea. Use of a single cable for both-way transmission has many attractions, including that of flexibility in providing repeated cable systems, but no means has yet been perfected of laying as part of a continuous operation the rigid repeater housings that are required because of the additional circuit elements. This is unimportant in relatively shallow water, but any operation that necessitates stopping the ship adds appreciably to the hazards of cable laying in very deep water.

The electron tubes used in the repeaters between Newfoundland and Scotland are relatively inefficient judged by present day standards. They have a mutual conductance of 1,000 micromhos. Proven reliability, lower mechanical failure probability and long life were the criteria that determined their choice. Electron tubes of much higher performance with a mutual conductance of 6,000 micromhos are used in the Newfoundland-Nova Scotia cable, and it is to be expected that long repeated cable systems of the future will use electron tubes of similar performance. This will increase the amplification and enable a wider frequency band to be transmitted; thus assisting provision of a greater number of circuits. If every advantage is to be taken of the higher performance tubes, it will be necessary to duplicate (or parallel) the amplifier elements of each repeater, in the manner described in a later paper, in order to assure adequately long trouble-free performance. This has the disadvantage of requiring the use of a larger repeater housing.

During the three years that have elapsed since the announcement in December, 1953 by the American Telephone and Telegraph Company, the British Post Office, and the Canadian Overseas Telecommunication Corporation, of their intention to construct the first transatlantic telephone cable system, considerable progress has been made in the development and use of transistors. The low power drain and operating voltage required will make practicable a cable with many more sub-

merged repeaters than at present. This will make possible a further widening of the transmission band which could provide for more telephone circuits with accompanying decrease in cost per speech channel or the widened band could be utilized for television transmission. Much work, however, is yet to be done to mature the transistor art to the level of that of the thermionic electron tube and thus insure the constancy of characteristics and long trouble-free life that this transatlantic service demands.

The present transatlantic telephone cable whose technical properties are presented in the accompanying papers, however, gives promise of large reduction in costs of transoceanic communications on routes where the traffic justifies the provision of large traffic capacity repeatered cables. The thirty-six, four-kilocycle channels which each cable of the two-way system provides, are the equivalent of at least 864 telegraph channels. A modern telegraph cable of the same length without repeaters would provide only one channel of the same speed. The first transatlantic telegraph cable operated at a much slower speed, and transmitted only three words per minute. The greater capacity of future cables will reduce still further the cost of each communication circuit provided in them. Such considerations point to the economic attractiveness, where traffic potentials justify it, of providing broad band repeatered cables for all telephone, telegraph and teletypewriter service across ocean barriers.

The new transatlantic telephone cable supplements the service now provided by radio telephone between the European and North American Continents. It adds greatly to the present traffic handling capacity of this service. The first of these radio circuits was brought into operation between London and New York in 1927. As demands for service have grown, the number of circuits has been increased. We are, however, fast approaching a limit on further additions, as almost all possible frequency space has now been occupied. The submarine telephone cable has come therefore at an opportune time; further growth in traffic is not limited by traffic capacity.

Technical developments over the years by the British Post Office and Bell Telephone Laboratories have brought continuing improvement in the quality, continuity and reliability of the radio circuits. The use of high frequency transmission on a single side band with suppressed carrier and steerable receiving antenna are typical of these developments. Even so, the route, because of its location on the earth's surface, is particularly susceptible to ionospheric disturbances which produce quality deterioration and at times interrupt the service completely.

Cable transmission will be free of all such quality and continuity limitations. In fact, service of the quality and reliability of the long distance service in America and Western Europe is possible. This quality and continuity improvement may well accelerate the growth in transatlantic traffic.

The British Post Office and Bell Telephone Laboratories are continuing vigorous programs of research and development on submarine cable systems. Continuing technical advance can be anticipated. Broader transmission bands, lower cost systems and greater insurance of continuous, reliable and high quality services surely follow.

Transatlantic Telephone Cable System — Planning and Over-All Performance

By E. T. MOTTRAM,* R. J. HALSEY,† J. W. EMLING*
and R. G. GRIFFITH‡

(Manuscript received October 10, 1956)

The transatlantic telephone cable system was designed as a link connecting communication networks on the two sides of the Atlantic. The technical planning of the system and the objectives set up so that this role would be fulfilled, are the principal subjects of this paper. Typical performance characteristics illustrate the high degree with which the objectives have been realized. Optimum application of the experience of the British Post Office with rigid repeaters and the Bell System with flexible repeaters, together with close cooperation among three administrations, have played a large part in achieving the objectives.

INTRODUCTION

The transatlantic telephone cable system was planned primarily to connect London to New York and London to Montreal, and thus serve as an interconnection between continent-wide networks on the two sides of the Atlantic. Thus, the system has to be capable of serving as a link in wire circuits as long as 10,000 miles, connecting telephone instruments supplied by various administrations and used by peoples of many nations. This role as an intercontinental link has, therefore, been a controlling consideration in setting the basic objectives for the system.

The end sections of the system utilize facilities which are integral parts of the internal networks of the United States, Great Britain and Canada, but the essential new connecting links, extending between Oban, Scotland, and the United States-Canada border, and forming the greater part of the system, were built under an Agreement between the joint owners — the American Telephone and Telegraph Company and its subsidiary the Eastern Telephone and Telegraph Company (operating in Canada), the British Post Office, and the Canadian Overseas

* Bell Telephone Laboratories. † British Post Office. ‡ Canadian Overseas Telecommunication Corporation.

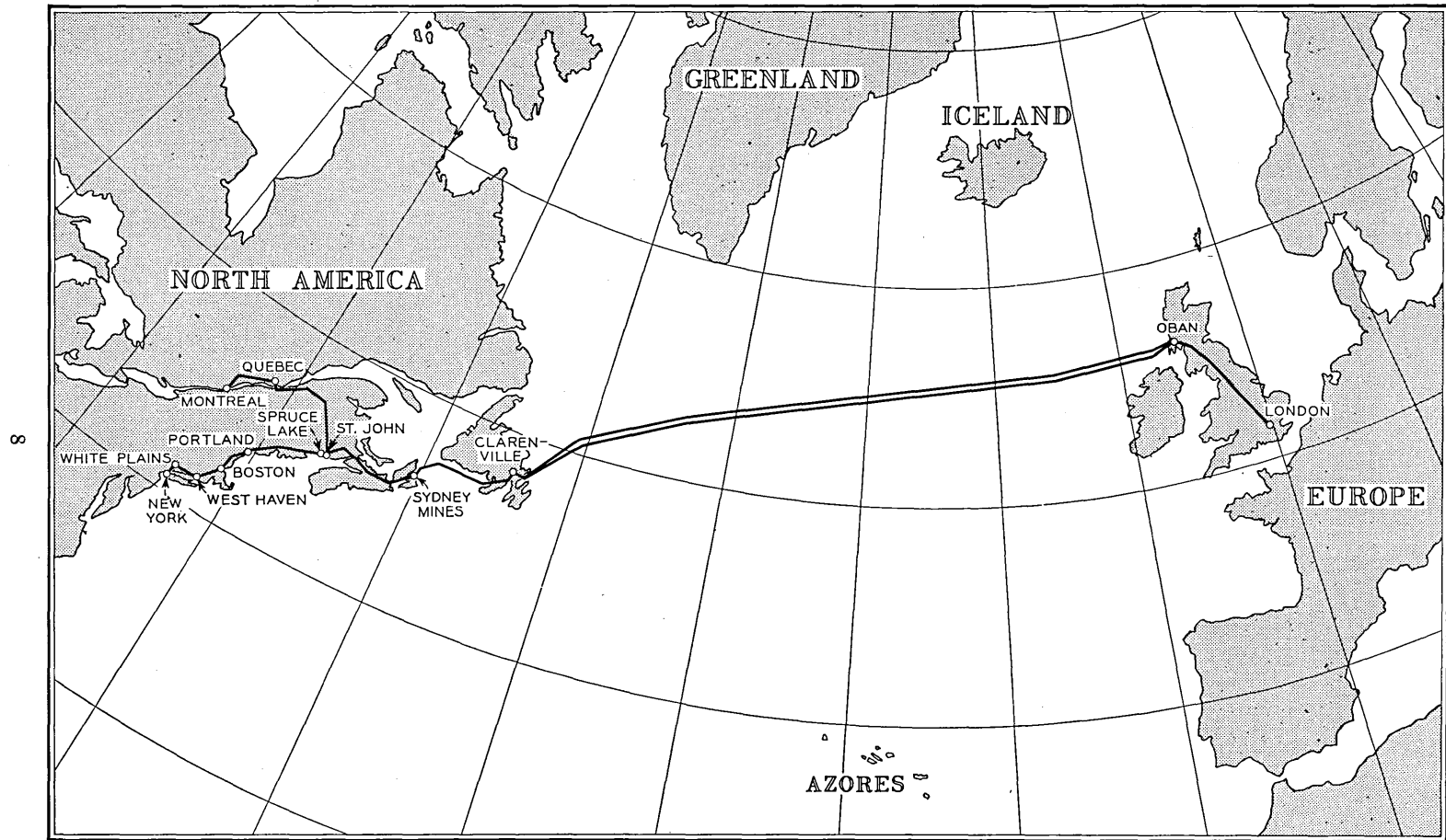


FIG. 1 — Route of the transatlantic submarine telephone cable system.

Telecommunication Corporation. It is thus the joint effort of three nations.

In planning the system, the main centres of interest were, naturally, the two submarine cable sections, Scotland to Newfoundland, and Newfoundland to Nova Scotia, each of which had to meet a unique combination of requirements imposed by water depth, cable length and transmitted bandwidth.

OVER-ALL VIEW OF THE SYSTEM

The transatlantic system provides 29 telephone circuits between London and New York, six telephone circuits between London and Montreal, and a single circuit split between London — New York and London — Montreal; this split circuit is available for telegraph and other narrow band uses. There are also 24 telephone circuits available for local service between Newfoundland and the Mainland of Canada, and there is considerable excess capacity over the radio-relay link that crosses the Maritime Provinces of Canada.

A map of the system is shown in Fig. 1; the facilities used, together with the approximate route distances are shown in Fig. 2. It will be seen that the over-all lengths of the London to New York and London to Montreal circuits are 4,078 and 4,157 statute miles respectively. Seven of the New York to London circuits are permanently extended to European Continental centres — Paris, Frankfurt (2), Amsterdam, Brussels, Copenhagen and Berne. The longest circuit is thus New York to Copenhagen, 4,948 miles.

Starting at London, which is the switching centre for United Kingdom and Continental points, 24-circuit carrier cables provide two alternative routes to Glasgow and thence to Oban by a new coaxial cable. Between London and Oban the two routes are fed in parallel at the sending ends, so a changeover can be effected at the receiving ends only. At a later date, an alternative route out of Oban will be provided by a new coaxial cable to Inverness.

From Oban a deep-sea submarine link connects to Clarenville, Newfoundland. This link is in fact two parallel submarine cables, one used for east-to-west transmission, the other for transmission in the reverse direction. Each cable is roughly 1,950 nautical-miles in length and lies at depths varying between a few hundred fathoms on the continental shelf and about 2,300 fathoms at the deepest point. Each cable incorporates 51 repeaters in flexible housings which compensate for the cable attenuation of about 3,200 db at the top frequency of 164 kc. These

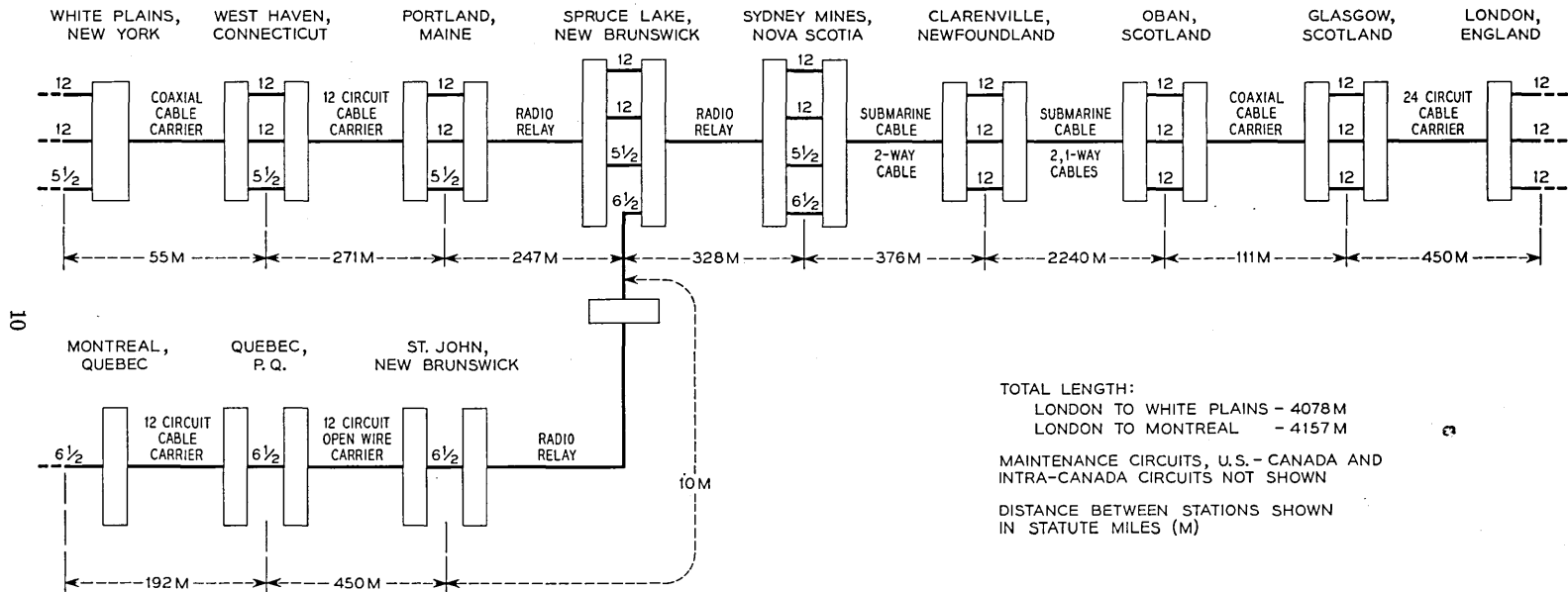


FIG. 2— Facilities used for the transatlantic submarine telephone cable system. Maintenance circuits, U.S.-Canada and intra-Canada circuits are not shown.

cables carry 36 telephone circuits plus maintenance circuits and establish the present maximum capacity of the transatlantic system.

At Clarenville, connection is made with Sydney Mines, Nova Scotia, by a second cable system which goes 63 statute-miles over land to Terrenceville, Newfoundland, and thence about 270 nautical-miles in coastal waters at a depth of about 250 fathoms. Although this system is partly on land, it is basically a submarine system in design, the two portions differing only in the protection of the cable. In this link, the two directions of transmission are carried by the same cable, a low-frequency band being used from west-to-east and a high-frequency band in the opposite direction. In addition to the necessary maintenance circuits, a total of 60 two-way circuits are provided, 36 being used for transatlantic service, and the remainder being available for service between Newfoundland and the Mainland. Sixteen two-way repeaters in rigid containers provide close to 1,000 db gain at this system's top frequency of 552 kc.

From Sydney Mines, transmission is by radio-relay to the United States-Canada border and thence to Portland, Maine; this system operates at about 4,000 mc and includes 17 intermediate stations. From Portland, standard 12-circuit carrier and coaxial cable facilities are used to connect with White Plains, New York, the American switching center 30 miles north of New York City, where connection is made to the Bell System network.

The Montreal circuits leave the radio-relay route at Spruce Lake, a relay station near the Border, from which point a short radio spur connects to St. John, New Brunswick, thence to Quebec on a 12-circuit open-wire carrier system and thence to Montreal on a 12-circuit cable carrier system.

BACKGROUND TO THE SUBMARINE CABLE SYSTEMS

The submarine cable sections have been built upon a long background of experience. Some of the cable laying and design techniques go back to the early telegraph cables of almost a century ago, and Lord Kelvin's analysis of the laying process is still the standard mathematical treatise on the subject. It is also interesting to note that the firm which provided most of the cable is a subsidiary of the organization that manufactured and laid the first successful transatlantic telegraph cable some 90 years ago.

In addition to the long experience in submarine telegraphy, the transatlantic system has drawn on over a quarter of a century of experience of telephone cable work in the British Post Office and the Bell System.

Experience in these two organizations has been quite different, but each in its own way has been invaluable in achieving today's system.

British Experience

In Great Britain, communication to the Continent dominated the early work in submarine telephony and led to systems providing relatively large numbers of circuits over short cables laid in shallow water. Early systems were un-repeated, but the advantages of submerged repeaters were apparent. Experimental work, started in 1938, culminated in the first submerged repeater installation in an Anglesey-Isle of Man cable in 1943. Currently, there are many repeaters in the various shallow water cables radiating from the British Isles.

These repeaters, although of a size and mechanical structure well suited to shallow water applications, are not structurally suited to Atlantic depths. In 1948, the Post Office began to study deep water problems, and the first laying tests of a deep-water repeater housing were conducted in the Bay of Biscay in 1951. This housing was rigid, like the shallow-water ones, but smaller and double-ended so that the repeater was in line with the cable. Thus the rotation of the repeater, which accompanies the twisting and untwisting of the cable as tension is increased and decreased during the laying operation could be tolerated. The housing now used by the British Post Office is basically the same as this early deep-water design, although minor modifications have been made to improve the closure and water seals.

A serious study of transatlantic telephony was begun by the Post Office in 1950 when a committee was set up to report on future possibilities of repeated cables. As a result, it was decided in 1952 to engineer a new telephone cable to Scandinavia, 300 nautical-miles in length, as a deep-water prototype, even though the requirements of depth, length, and channel capacity all could have been met by existing shallow-water designs.

All of the Post Office submarine systems are alike in that they use but a single cable, the go and return paths being carried by different frequency bands. The adoption of this plan was greatly influenced by the conditions under which the art developed. Because North Sea and Channel cables were highly subject to damage from fishing operations, it was desirable to limit the effects of such damage as much as possible. A single cable system is obviously preferable under these circumstances to a system using separate go and return cables which could be put out of service by damage to either cable. Since these systems were designed for shallow

water use, the additional container size required for two-way repeaters was of no great moment compared to the advantages of a single-cable system.

United States Experience

In the United States, the cable art developed under very different circumstances. There was, of course, need for communication to Cuba, Catalina, Nantucket and other off-shore locations, some of which involved conditions similar to those existing around the British Isles. The application of carrier to several of these cables occurred at an early date, but the repeater art was not directed at these shallow water applications.

For many years, telephone communication to Europe had been an important goal and some thirty-five years ago a specific proposal was made by the Bell System to the Post Office for a single, continuously-loaded, nonrepeated cable to provide a single telephone circuit across the Atlantic.

This system was never built, partly because of the economic depression of the early thirties and partly because short-wave radio was able to meet current needs. Cable studies and experiments in the laboratory and field were continued, however, and largely influenced subsequent developments. It was at this time that the physical structure of the cable now used in the transatlantic system was worked out. It was also at this time that the harmful effects of physical irregularities in the cable were demonstrated. As cables are laid in deep water, high tensions are developed which unwrap the armor wires that normally spiral about the central structure. As tension changes during the laying process, twisting and untwisting occurs which is harmless if distributed along the cable. But obstructions in the cable which prevent rotation, or any other process such as starting and stopping of the ship which tends to localize twisting, are likely to cause kinking of cable and buckling of the conductors.

By 1932, electronic technology had advanced to a point where serious consideration could be given to a wideband system with numerous long-life repeaters laid on the bottom of the ocean and powered by current supplied over the cable from sources on shore.

The hazardous effects of obstructions in the cable, demonstrated in early laying tests, indicated that the chances of a successful deep-sea cable would be greatest if the repeaters were in small-diameter, flexible housings which could pass through laying gear without stopping the ship and without restricting the normal untwisting and twisting of the

cable. The structure ultimately evolved, consisting of two overlapping layers of abutting steel pressure rings within a flexible waterproof container, was an important influence on the electrical design, since it placed severe limitations on size and placement of individual components.

Because these repeaters were to lie without failure for many years on the ocean bottom, it was necessary either to provide a minimum number of components of the utmost reliability, or to provide duplicate components to take over in case of failure. The size limitation favored the former approach. Similarly, the need for small size and minimum number of components militated against the use of two-way repeaters with their associated directional filters.

Out of these considerations grew the Bell System approach to solving the transatlantic problem by the use of two cables, each with built-in flexible amplifiers containing the minimum number of components of utmost reliability and a life objective of 20 years or better.

It was not until the end of World War II that such a system could be tried. At this time it was decided to install a pair of cables on the Key West-Havana route to evaluate the transatlantic design which had evolved in the prewar years. After further laying trials, this plan was completed in May, 1950, with the laying of two cables. Each of these had three built-in repeaters lying at depths up to 950 fathoms. These cables, each about 120 nautical-miles in length, carry 24 telephone circuits. They have now been in continuous service for over six years without repeater failure or evidence of deterioration.

EARLY TRANSATLANTIC TECHNICAL DECISIONS

Early in 1952, negotiations concerning a transatlantic cable were again opened between the American Telephone and Telegraph Company and the British Post Office. As indicated above, at that time each party had been laying plans for such a system. Thus it became necessary to evaluate the work on each side of the Atlantic to evolve the best technical solution.

To do this, a technical team from the Post Office visited Bell Telephone Laboratories in the fall of 1952 to examine developments in the United States. The work of the preceding 30 years was reviewed in detail with particular emphasis on the development and manufacture of the 1950 Key West-Havana cables. This was followed by a visit to the Post Office by a Bell Laboratories' team to review similar work in Great Britain. Again the review was comprehensive, covering shallow-water systems as well as plans for deep-water repeaters. Each visit was characterized by a frankness and complete openness of discussion that is perhaps unusual in international negotiations.

As is apparent from the previous discussion, it was found that the basic features of a deep-water design had been completed by the Bell System. Not only had many of the components been under laboratory test for many years, but a complete system had been operating for 2½ years between Havana and Key West. To use a phrase coined at the time, the design had proven integrity.

Because of the years of proof and the conservative approach adopted to assure long life, the design was far from modern. The electron tubes, for example, had characteristics typical of tubes of the late 1930's, when, in fact, they were designed. Similarly, other components were essentially of prewar design.

The Post Office, on the other hand, had pioneered shallow-water repeaters and were pre-eminent in this field. Their deep-water designs were still evolving and had not yet been subjected to the same rigorous tests as the Bell System repeaters. This later evolution, however, made possible a much more modern design. The electron tubes, for example, had a mutual conductance of 6,000 micromhos as compared to about 1,000 in the Bell System repeater, and thus had a potentiality for much greater repeater bandwidths.

It was apparent from these reviews that only the American design was far enough advanced to assure service at an early date. It also appeared to have the integrity so essential to such a pioneering and costly effort as a transatlantic cable. On the other hand, the more modern Post Office design had many elements of potential value. If deep-water laying hazards could be overcome and proof of reliability established, it gave promise of greater flexibility and economy for future systems.

It was on these grounds that Dr. Mervin Kelly for the Bell System and Sir Gordon Radley for the Post Office jointly recommended that the Bell System design be used for the long length and great depths of the Atlantic crossing and the Post Office design be used for the Newfoundland-Nova Scotia link where the shallower water afforded less hazard and better observation of this potentially interesting design. The decision to use the Post Office design was subject to technical review after deep-sea laying tests and further experience with circuits and components. This review, made in June of 1954, confirmed the soundness of the original recommendation.

SYSTEM PLANNING

Planning of the individual systems began as soon as the technical decision just mentioned had been reached. By the time administrative agreements had been reached and the contract signed on November 27, 1953, both parties were ready to set up system objectives and an

over-all system plan. This work, too, was accomplished by a series of technical meetings held alternately in the United States and the United Kingdom, with additional meetings in Canada.

At the first of these meetings, a decision of far-reaching importance was made. It was agreed that each technical problem would be solved as it arose in so far as possible on the best engineering basis, putting aside all considerations of national pride. Adherence to this principle did much to forward the technical negotiations.

The initial joint meeting was also responsible for establishing most of the basic performance objectives of the system. The target date for opening of service, December 1, 1956, had been settled even earlier and was, in the event, bettered by nearly 10 weeks.

Service Objectives

A statement of the manner in which the system would be used and the services to be provided was a necessary preliminary to establishing performance objectives.

It was agreed that the system should be designed as a connecting link between the North American and European long distance networks. As such it should be capable of connecting any telephone in North America (ordinarily reached through the Bell System or Canadian long distance networks) with any telephone in the British Isles or any telephone normally reached from the British Isles through the European continental network. The system would be designed primarily for message telephone service but consideration would be given to the provision of other services such as VF carrier telegraph, program (music), and telephotograph as permitted by technical and contractual considerations. It was also agreed that the two submarine cable links should be so planned that it would be possible to utilize the full bandwidth in any desired manner in the future. Thus, for example, repeater test signals should be outside the main transmission band.

All elements in the submarine cable systems were to be planned for reliable service over a period of at least 20 years.

Transmission Objectives

The term "objective" was used advisedly in describing the aims of the system. It was agreed that such objectives were not ironclad requirements but rather desirable goals which it was believed practical to attain with the facilities proposed. Reasonable departure from these goals, however, would not be reason for major redesign.

Since the transatlantic circuits were to connect two extensive networks, the broad objective was to add as little loss and other forms of impairment as practical. To this end, they were to be designed essentially to the standards of international circuits as defined by the C.C.I.F.* and of circuits connecting main switching points in national networks, as for example, "Regional Centers" in the Bell System network and "Zone Centers" in the Post Office network.

The possibility of increasing the circuit capacity of the system by using channel spacings less than 4 kc was obvious. It was decided, however, to adopt, initially at least, the 4-kc spacing commonly used by long distance systems on both sides of the Atlantic. This would make possible the use of standard multiplexing arrangements, and it was believed that the number of circuits provided would be adequate for the first few years of operation. It would undoubtedly be desirable to increase the number of circuits in later years, but a decision on the method to be used was left until completion of exploratory work on several methods which promised capacity increases with less degradation than narrow-band operation.

The decision to use standard terminal equipment led naturally to acceptance of the principle that the 36 circuits across the Atlantic would be assembled as three 12-channel groups in the range 60-108 kc and the 60 circuits between Newfoundland and Nova Scotia as five 12-channel groups and thence as a supergroup in the range 312-552 kc. These are standard modulation stages in the multiplexing arrangements for broad-band carrier system on both sides of the Atlantic. Two of the 12-channel transatlantic groups would be connected to New York and the third would be split to provide $6\frac{1}{2}$ circuits to Montreal and $5\frac{1}{2}$ to New York in accordance with the Agreement.

To provide for program circuits, three eastbound and three westbound channels in each of the three transatlantic groups would be made available when required; equipment would be provided to replace either two or three 4-kc message telephone channels by a music channel. In order to avoid the agreed group pilot frequencies and to provide service to Montreal, it was agreed to utilize the frequency bands 68-76 kc and 64-76 kc in the 12-channel groups for this purpose. Terminals of British Post Office design would be used at all points for translation between program and carrier frequencies. The normal Bell System terminals could not be used since they occupy the frequency ranges 80-88 kc and

* The International Consultative Committee on Telephony (C.C.I.F.) bases its recommendations on a circuit 2,500 km (1,600 miles) in length, with implied pro rata increases for noise impairment.

76-88 kc which are not compatible with the split group arrangement or with the 84.08 kc end-to-end pilot.

Net Loss

The nominal 1,000-cycle net loss objective between London and New York for calls switched to other long distance trunks at each end (i.e., the via net loss) was set at 0.5 db. For calls terminating at either New York or London, the loss would be increased by switching a 3.5-db pad in London, as recommended by the C.C.I.F., and a 2-db pad at New York as standard in the Bell System. Thus a New York to London call would have a net loss of 6 db.

Variations from these nominal net losses owing to temperature effects, lack of perfect equalization and regulation, etc., are to be expected and a standard deviation of 1.5 db was set as the objective for such variations in the absence of trouble. The allocation of this variation to the various links is shown in Table I.

It is interesting to note that a smaller variation was allocated to the submarine links than to the over-land links. It was believed that the more stable environment on the ocean floor would make it possible to meet the rather small variation assigned to these links.

While these loss variations are consistent with normal long distance trunk objectives, they would not be satisfactory if compandors were found necessary to meet the noise objectives, and it was agreed that any of the links lying between such compandors would have to meet objectives half as large as those in Table I.

Frequency Characteristics

For telephone message circuits, the frequency characteristic recommended by the C.C.I.F., Fig. 3, was adopted with the expectation that it could be bettered by a factor of two, since channel equipments would be included at the circuit terminals only, as described later.

TABLE I—STANDARD DEVIATIONS OF NET LOSS OBJECTIVE

Link	Standard Deviation (db)
New York-Portland.....	0.75
Portland-Sydney Mines.....	0.75
Sydney Mines-Clarenville.....	0.5
Clarenville-Oban.....	0.5
Oban-London.....	0.75
Total (Assuming rms addition)	
New York-London }.....	1.5
Montreal-London }.....	

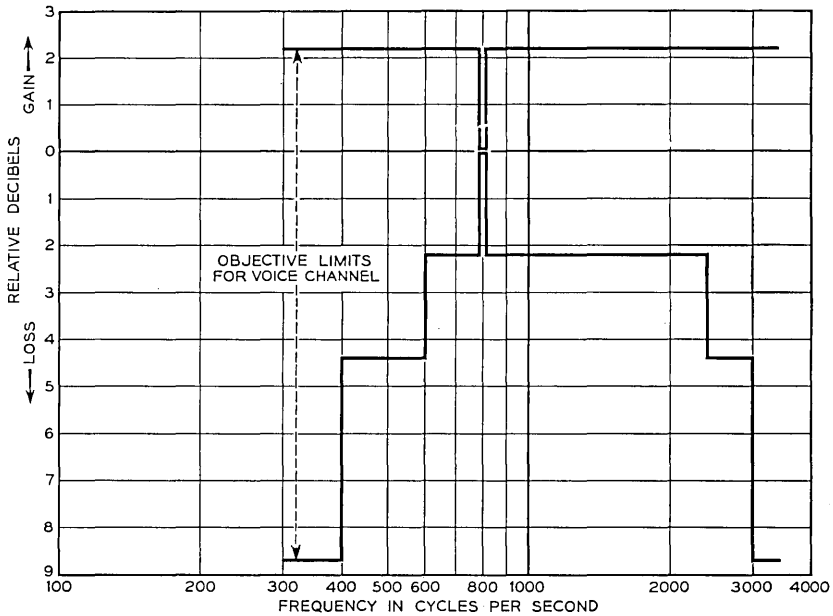


Fig. 3 — C.C.I.F. objectives for frequency characteristic of voice channel.

No specific objectives were agreed upon for the frequency characteristics of the 12-channel groups as such, but there was an expectation that ± 2 db could be achieved except for frequencies adjacent to the filters in the split group.

For program channels, the C.C.I.F. recommendations were also adopted in respect of the two-band (6.4 kc) and three-band (10 kc) arrangements. To meet the requirements of these channels and of telegraphy, an overall frequency stability objective of ± 2 cycles was adopted.

Noise and Crosstalk

Noise objectives were established to be reasonably consistent both with Bell System and C.C.I.F.* objectives for circuits of transatlantic length.

The objective for the rms circuit noise at a zero level point in the

* The methods specified by these two bodies for the assessment of circuit noise differ in three respects, the units employed, the frequency weighting employed, and the fraction of the busy hour for which the specified noise may occur. The meters concerned are the Bell System 2B noise meter (F1A weighting network) reading in dba and the C.C.I.F. psophometer (1951 weighting network) reading in millivolts across 600 ohms. The relationship between readings on the two meters is discussed in a later paper and it will suffice here to note that, for white noise $\text{dbm (CCIF)} = \text{dba (Bell)} - 84$.

TABLE II — RMS NOISE OBJECTIVES IN BUSY HOUR

Link	Approx. mileage	Noise dba
New York-Sydney Mines } Montreal-Sydney Mines }	1,000	31
Sydney Mines-Clarenville.....	400	28
Clarenville-Oban.....	2,000	36
Oban-London.....	500	28
Total		
New York-London } Montreal-London }		38

busy hour was agreed as 38 dba (i.e. -46 dbm or 3.9 mv). This was allocated between the various links as in Table II.

For the program channels, the agreed noise objective was -50 dbm as measured on a C.C.I.F. psophometer with a 1951 program weighting network.

Statistical data on probable speech levels and distributions at London and New York terminals were provided as a basis for repeater loading studies.

Early planning studies indicated that these objectives would probably be met on all, or nearly all channels without resort to companders. If, as the system aged, the noise increased owing to increasing misalignment, the use of companders would offer a means for reducing message circuit noise below the objectives.

The minimum equal-level crosstalk loss between any two telephone channels was set at 56 db for any source of potentially intelligible crosstalk. For channels used for VF telegraph, the equal-level crosstalk loss between go and return directions was set as a minimum of 40 db; for all program channels the minimum crosstalk attenuation would be 55 db.

Restrictions of Telegraph and Other Services

Since the system was being designed primarily for message telephone service, it was agreed that a channel used for any other service should not contribute more to the system rms or peak load than if this channel were used for message telephone, except by prior agreement between Post Office, Bell System and Canadian Overseas Telecommunication Corporation engineering representatives.

Signalling Objectives

In order to conserve frequency space, it was decided to transmit all calling and supervisory signals within the telephone channel bands and,

to avoid transmission degradation, it was agreed that the signaling power and duration would not amount to more than 9 milliwatt-seconds in the busy hour at a zero level point; this would not contribute unduly to the loading of the system.

It was agreed that, for initial operation, ringdown signaling would be employed, but the system design should be such as to permit the use of dialing at a later date.

Echo Suppressors

Echo control was considered essential, since the via net loss of the transatlantic circuits would be only 0.5 db, with a one-way transmission time of 35 milliseconds. Echo suppressors would be provided initially at New York and Montreal only, and arrangements made in London to cut out such suppressors as may be fitted there on Continental circuits, when these are used for extension of the transatlantic circuits. It was recognized, however, that other suppressors might be encountered in the more remote parts of Continental and United States extensions. The general problem of how best to arrange and operate echo suppressors on very long switched connections is one which remains for consideration later.

Maintenance and Operating Services

Telephone Speaker and Telegraph Printer Circuits

The need for telephone and telegraph circuits for maintenance and administration was recognized, and it was agreed to provide the following circuits on the submarine links at frequencies immediately outside the main transmission bands where inferior and somewhat uncertain characteristics might be expected (Fig. 4):

(a) A 4-kc band, possibly sub-standard in regard to noise, equipped with band splitting equipment (EB Banks) to provide two half-bandwidth telephone (speaker) circuits, and

(b) two frequency-modulated telegraph (printer) circuits.

These circuits would be extended over the land circuits to the terminal stations by standard arrangements as needed and would be used to provide the following facilities:

(I) An omnibus speaker circuit connecting the principal stations on the route, including Montreal.

(II) A speaker circuit for point-to-point communication between the principal stations — i.e., non-continuous.

(III) A direct printer circuit between London and White Plains.

(IV) An omnibus printer circuit as (I) above.

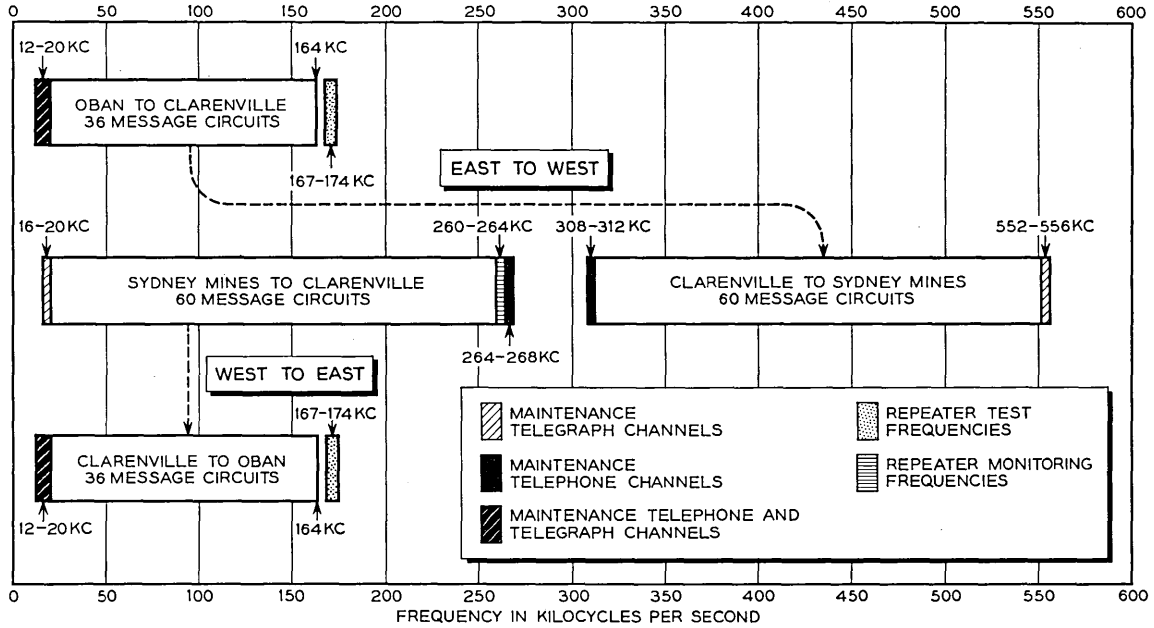


Fig. 4—Frequency allocations in submarine cable links.

Repeater Test Frequencies

In each submarine cable link, test frequency bands were required for monitoring repeater performance; and these are indicated in Fig. 4.

Pilot Frequencies

It was agreed to provide pilot facilities throughout the route for line-up maintenance and regulation purposes. In addition to the usual pilots on the inland networks, there would be provided:

(a) a 92-kc pilot in each 12-channel group, continuous only in a particular section of the route and fitted with a recording voltmeter at the receiving end of that section, and

(b) an 84.08-kc overall pilot in each 12-channel group as recommended by the C.C.I.F. This would transmit continuously over the entire route and would be monitored and recorded at every main station.

Connections between Component Links

At the time that the objectives were being established, a far-reaching decision was made to employ channel equipment at London, New York, and Montreal only, and to adopt the frequency band 60–108 kc as the standard frequency for connecting the various parts of the over-all system. By adopting this band as standard for the transatlantic system, it also became possible to interconnect readily with land systems at each end.

This agreement also facilitated decisions on responsibility for design and manufacture of equipment. For example, it became logical to define each submarine system as the equipment between points where the 60–108-kc band appeared, i.e., the group connecting frames. Thus, these systems would include not only the cable, repeaters, and power supplies, but also the terminal gear to translate between 60–108 kc and line frequency of the submarine system. It also became logical to assign responsibility for manufacture of all of this equipment to the administration responsible for the specific system design, i.e., responsibility for the Oban-Clarenville link to the Bell System and the Clarenville-Sydney Mines link to the Post Office.

THE REALIZATION OF THE SYSTEM

With decisions reached on the system objectives and interconnecting arrangements, it became possible to lay out jointly a detailed over-all plan and for each administration to proceed with developing and engineering the links under its jurisdiction.

There was an understanding that there should be no deliberate attempt to make the characteristics of one link compensate for those of another, and so it would be incumbent on the administrations to produce the best possible group characteristic on each link.

The overall plan for the system, as finally developed, is shown in Fig. 2. Except for the necessity to split one of the three transatlantic groups in each direction to provide $6\frac{1}{2}$ circuits to Montreal and $5\frac{1}{2}$ to New York, which required specially designed crystal filters, no unusual circuit facilities were required.

Special equipment arrangements were called for at Sydney Mines and Clarendville to provide security for the Montreal-London circuits where they appeared in the same office with White Plains-London circuits. In these cases, a special locked room was constructed to house the equipment associated with the channel group containing the Canadian circuits.

The details of how the two all-important submarine cable links were designed and engineered to meet their individual objectives are given in companion papers. The efficiency and integrity of these two links are the highest that could be devised by engineers on both sides of the Atlantic.

Finally, each section of the connecting links was lined-up and tested individually before bringing them all together as an integrated system.

OVER-ALL PERFORMANCE OF THE SYSTEM

The system went into service on September 25, 1956, so soon after completion of some of the links that it was not possible to include all the final equalizers. Nevertheless, after completion of the initial overall line-up, the performance has been found to meet very closely the original objectives. The system went into service without the use of compandors on any of the telephone circuits, but compandors are included in the program equipment. At the time of writing, only the 2-channel program equipment is available for use.

Frequency Characteristics of 12-channel groups

Fig. 5 shows the frequency characteristic of one of the 12-channel groups, link by link and over-all, measured at group frequencies corresponding to 1,000 cycles on each channel. In both of the complete London-New York groups the deviation from flat transmission is within ± 1.5 db, and some further improvement is to be expected when the equalization is finalized. For the split group, the characteristics are similar except for the effect of the splitting filters.

Variation of Over-all Transmission Loss

The system has, of course, only been completed for a short time, but the indications so far are that the standard deviation of the transmission loss, as indicated by the 84.08-kc group pilots is well within the objective of 1.5 db. Alarms operate when the received pilot level deviates by ± 4 db and, so far, these alarms have not operated under working conditions.

Frequency Characteristics of Telephone Circuits

Fig. 6 shows the measured frequency characteristic of a typical circuit in the two directions of transmission as measured in the through and terminated conditions. Half the C.C.I.F. limits are met on most circuits.

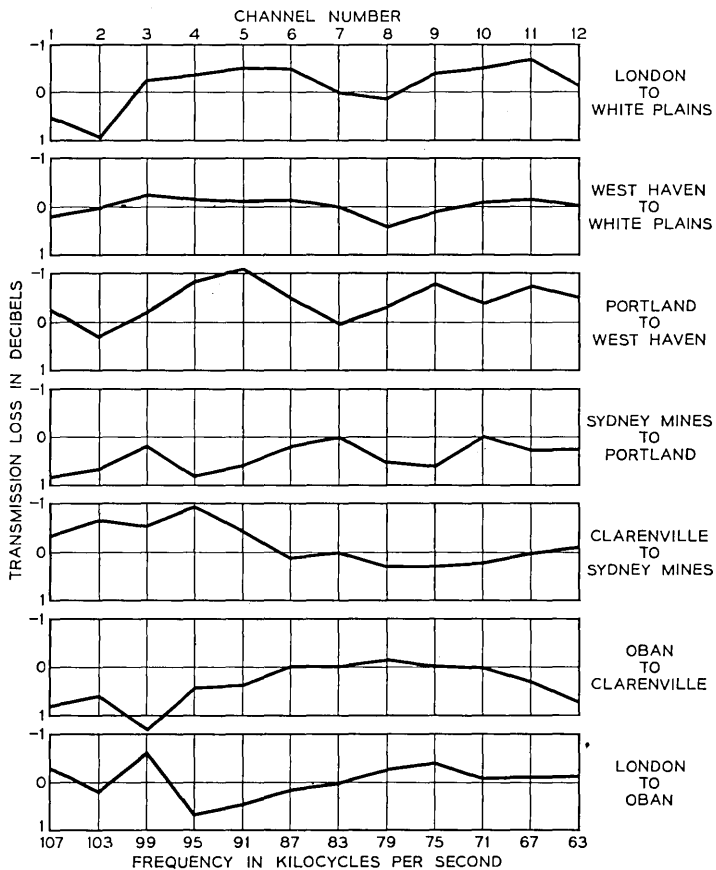


Fig. 5 — Frequency characteristic of typical London-New York channel group. (Measured at group frequencies corresponding to 1,000 cycles.)

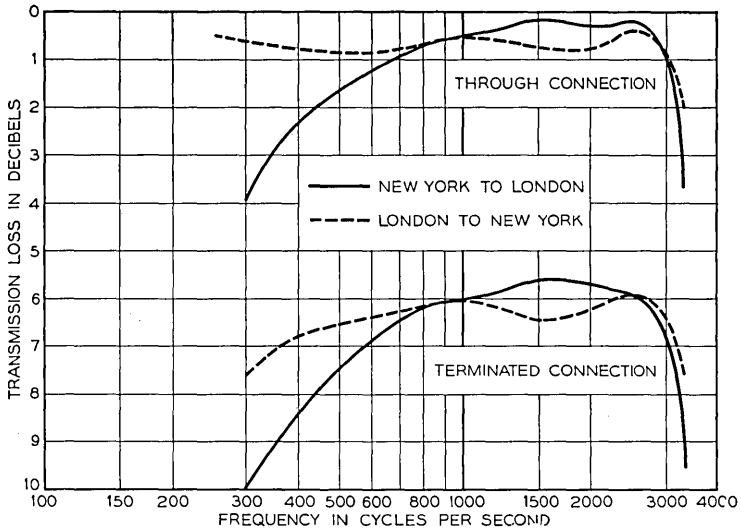


Fig. 6 — Frequency characteristic of typical telephone circuit.

Circuit Noise

The circuit noise, referred to a zero level point is as follows:

London-New York	Best 30 dba;	worst 36 dba
New York-London	Best 29 dba;	worst 41 dba
London-Montreal	Best 30 dba;	worst 33 dba
Montreal-London	Best 30 dba;	worst 31 dba

Two circuits at present exceed the objective of 38 dba in the New York-London direction only; the higher noise levels refer to the high frequency channels in the Oban-Clarenville cable. After additional data on the effect of cable temperature variations are accumulated, refinements will be made in the equalization and adjustment of levels on the Oban-Clarenville link. It is expected that the two worst channels can then be made to meet the objectives — still without the use of companders.

Frequency Characteristics of Program Channels

Fig. 7 shows the measured frequency characteristic of a London-New York program channel; this is typical.

Telegraph Channels London-Montreal

In the Agreement it was envisaged that at least six 50-baud telegraph channels could be provided in each direction in the Canadian half circuit. In fact, eleven such channels have been provided using carriers spaced

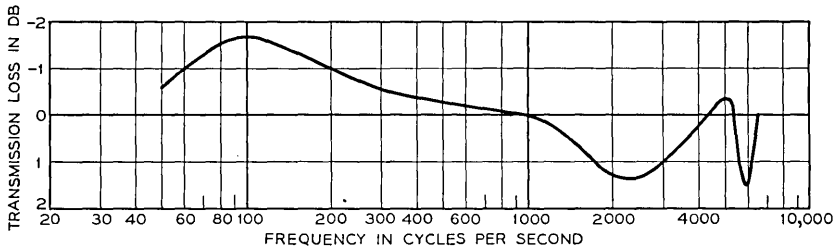


Fig. 7 — Frequency characteristic of typical program channel, London-New York.

at 120 cycles and frequency modulation. The telegraph distortion due to the cable system with start stop signals is about 4 per cent in every case, thus making the circuits suitable for switched connections, without regeneration, up to the same limits as inland systems.

Tests over the system indicate that the channel speed can be raised satisfactorily to 80 bauds on at least ten of the channels. By the adoption of synchronous working, it appears that time division multiplex systems can be operated on these ten channels to double their capacity at a later date.

CONCLUSION

The transatlantic cable system has presented unique problems in system planning and design. It has been necessary to design the system to connect the facilities of many countries and to provide for cable communication of unprecedented length. But the stringent design objectives necessary to meet these requirements have not been the only challenge to the designer. It has been necessary to meet these objectives with a system which for over 2,000 miles of its length could not be altered to the slightest extent once it had been placed on the ocean bottom. Except for the adjustments which can be made at the shore terminals of the submarine links it has not been permissible to make any of the multitude of small design changes, substitutions and adaptations which are so commonly required in new systems to achieve the design objectives.

The success achieved in meeting the original objectives is a measure of the realism of the early planning as well as the diligence with which the project was carried forward to completion and is a tribute to all who took part in planning, designing and building the system.

The accomplishment of getting into commercial service a working system with many complex links six weeks after the final splice was dropped overboard, and nearly ten weeks ahead of schedule, is a further tribute to the close cooperation of the technical people of three nations.

System Design for the North Atlantic Link

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J. M. FRASER,*

(Manuscript received September 7, 1956)

The purpose of this paper is to examine the design and performance of the North Atlantic link, including consideration of factors governing the choice of features, a description of the operational design of the facility, and an outline of those measures available for future application in the event that faults or aging require corrective action.

DESCRIPTION OF LINK

That portion of the transatlantic system¹ which connects Newfoundland and Scotland consists of a physical 4-wire, repeatered, undersea link of Bell Telephone Laboratories design, with appropriate terminal and power feeding equipment in cable stations at Clarenville and at Oban.

The various elements comprising the link are shown in block form in Fig. 1. The termination points at each end of the link are the Group Distributing Frames (GDF), where the working channels are brought down in three groups to the nominal group frequency band 60–108 kc. At the west end, this point provides the interconnection between the North Atlantic and the Newfoundland-Nova Scotia links. At the east end, it is the common point between the North Atlantic link and the standard British toll plant over which the circuits are extended to London.

Two separate coaxial cables connect Clarenville with Oban, one handling east-to-west transmission, the other west-to-east. Each is about 1,940 nautical miles long. A total of 102 repeaters are installed in the two cables, at nominal intervals of 37.5 nautical miles. The cables also contain a number of simple undersea equalizers which are needed to bring system performance within the specified objectives.

The working spectrum of each cable extends from 20 to 164 kc, pro-

* Bell Telephone Laboratories.

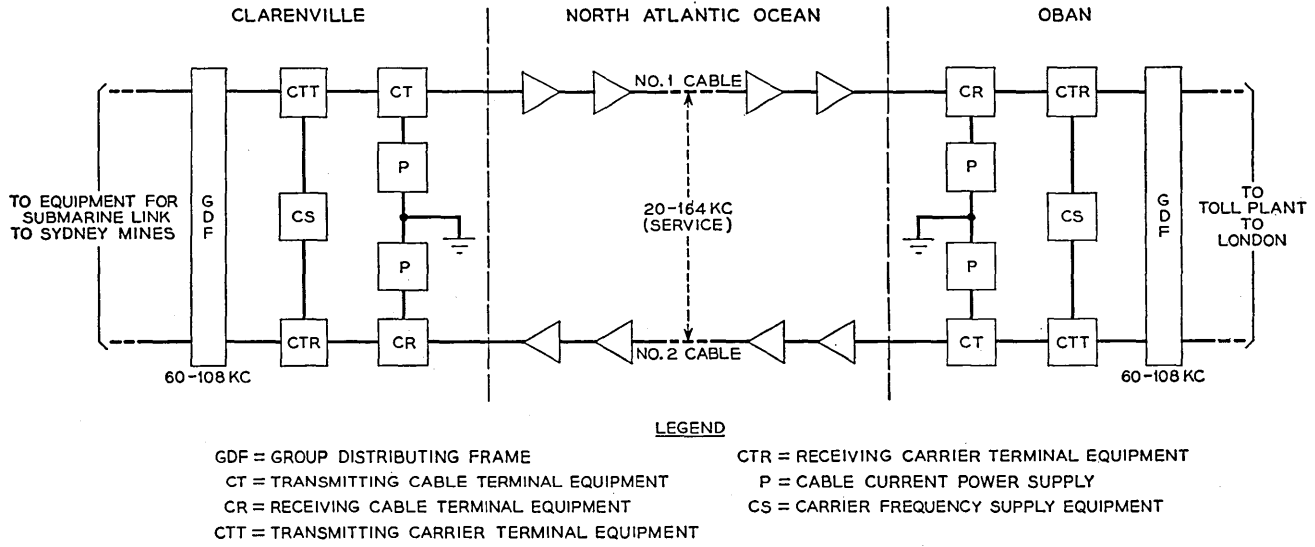


Fig. 1 — Schematic — North Atlantic link.

viding for 36 4-kc voice message channels. Below this band are assigned the telephone (speaker) and telegraph (printer) circuits needed for maintenance and administration of the facility. Above the working band, between 167 and 174 kc, are the crystal frequencies, which permit evaluation of the performance of each repeater individually from the shore stations.

The signal complex carried by the cables is derived in the carrier terminals from the signals on the individual voice frequency circuits by conventional frequency division techniques such as are employed in the Bell System types J, K and L broadband carrier systems manufactured by the Western Electric Company. (See Fig. 2.) These signals are applied to the cable through a transmitting amplifier which provides necessary gain and protects the undersea repeaters against harmful overloads. At the incoming end of each cable, a receiving amplifier provides gain and permits level adjustment.

Shore equalizers next to the transmitting and receiving amplifiers insert fixed shapes for cable length and level compensation. Adjustable units provide for equalization of the system against seasonal temperature changes on the ocean bed, and some aging.

The power equipment at each cable station includes (a) regular primary power with Diesel standby, (b) rotary machines for driving the cable current supplies, with battery standby, (c) battery plants for supplying the carrier terminal bays, and (d) last but by no means least in complexity, the cable current supplies themselves. These latter furnish regulated direct current to a series loop consisting of the central conductors of the two cables, with their repeaters. A power system ground is provided at the midpoint of the cable current supply at each cable station.

FACTORS AFFECTING SYSTEM DESIGN

General

A repeatered submarine cable system differs from the land-wire type of carrier system in two major respects. First, the cost of repairing a fault, and of the concurrent out-of-service time, is so great as to put an enormous premium on integrity of all the elements in the system and on proper safeguards in the system against shore-end induced faults. Second, once such a system is resting on the sea-bottom it is accessible for adjustment only at its ends. These two restrictions naturally had a profound influence on the design of the North Atlantic link.

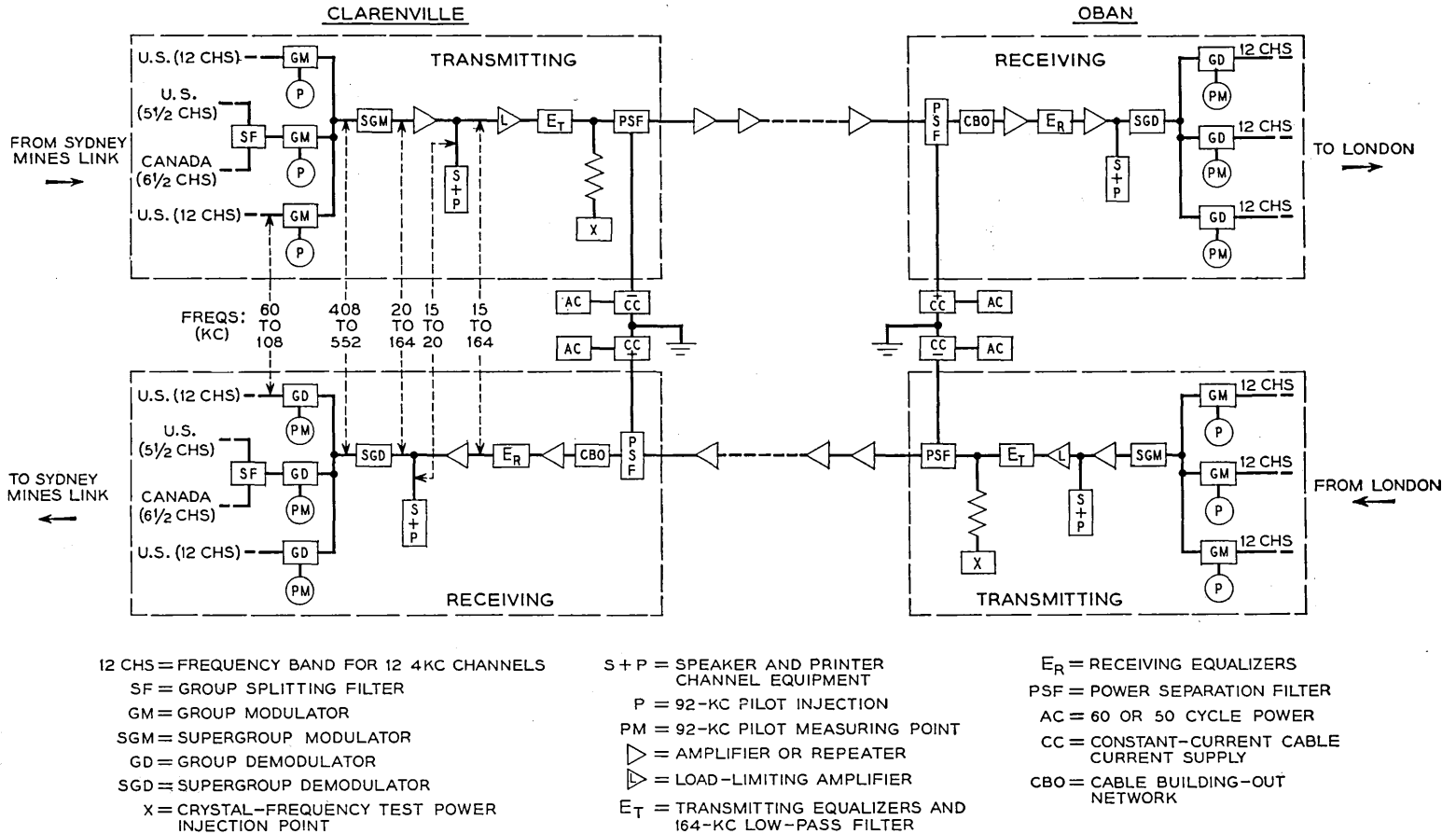


Fig. 2 — Block schematic of terminals — North Atlantic link.

Proven Integrity

Assurance of reliability dictated use of elements whose integrity had actually been proved by successful prior experience in the laboratory or in the Bell System. This resulted in adoption of a coaxial cable structure explored by the Laboratories soon after the war, field tested in the Bahamas area in 1948 and applied commercially on the USAF Missile Test Range project¹³ in 1953. It also resulted in specification of a basic flexible repeater design which had been under test in the Laboratories since before the war and had been in use on the Key West-Havana submarine cable telephone system⁴ since 1950.

Cable

The cable adopted was the largest which had actually been successfully laid in deep water, and its size afforded an important benefit in the form of reduced unit attenuation. The structure and characteristics of this cable are covered in detail in a companion paper.² Suffice it to point out here that by its adoption for the North Atlantic link, there were specified for the system designers (a) the attenuation characteristic of the transmission medium, (b) the influence on this of the pressure and temperature environments, (c) the unit contribution of the cable to the resistance of the power loop, and (d) the impedances faced by the repeaters.

Repeater

The adaptation³ of the basic Key West-Havana repeater design to the present project likewise presented the system designers with certain restrictions. Most important, the space and form of the long, tubular structure limited the size of the high voltage capacitors in the power separation filters, and thus their voltage rating, to the extent that this determined the maximum permissible number of repeaters. Likewise the performance of the repeater circuit was at least partially defined because of several factors. One was the effect of the physical shape on parasitic capacitances in the circuit, which in turn reacted on the feedback and hence on modulation performance, gain-bandwidth and the aging characteristic. Use of the Key West-Havana electron tube influenced the above factors and also tended to fix the input noise figure and load capacity.

System Design

In similar respects, the principle of proven integrity reacted into the broad consideration of system design. For instance, in a long system

having many repeaters in tandem, automatic gain control (gain regulation) in the repeaters provides an ideal method for minimizing the amount of the total system margin which must be allocated to environmental loss variations. However, this would have required adoption of elements of unproved integrity which might have increased the probability of system failure. So the more simple and reliable alternative was adopted — fixed gain repeaters with built-in system margins.

System Inaccessibility

The inaccessibility of the undersea system for periodic or seasonal adjustment and the decision to avoid automatic gain regulation were major factors in the allocation of system margins between undersea and shore locations. To avoid wasting such a valuable commodity as margin, required the most careful consideration of means of trimming the system during laying. Equalization for control of misalignment in the undersea link is a function of the match between cable attenuation and repeater gain. Generally speaking, these are fixed at the factory. Very small unit deviations from gain and loss objectives could well add to an impressive total in a 3,200-db system. Accordingly, it was necessary to plan for periodic adjustment of cable length during laying, and where necessary, insertion of simple mop-up undersea equalizers at the adjustment points.

DESIGN OF HIGH-FREQUENCY LINE

Terminology

The high-frequency line, as the term is used here, includes the cable, the undersea repeaters, the undersea equalizers, and the shore-station power separation filters, transmitting and line-frequency receiving amplifiers, and associated equalizers.

Repeater Spacing and System Bandwidth

As in most transmission media, the attenuation of the cable increases with increasing frequency. Hence the greater the bandwidth of the system, the greater the number of repeaters needed.

In this system, powered only from its ends, the maximum permissible number of repeaters and thus the repeater spacing is determined by a dc voltage limitation, as explained in a later section.

With the repeater spacing fixed, and the type of cable fixed, the required repeater gain versus frequency is known to the degree of accuracy that the cable attenuation is known. The frequency band which

can be utilized then depends on repeater design considerations, including gain-bandwidth limitations, signal power capacity and signal-to-noise requirements.

The early studies of this transatlantic system were based on "scaling up" the Havana-Key West system.⁴ In these studies, consideration was given to extending the band upward as far as possible by using compandors⁵ on the top channels, thus lightening the signal-to-noise requirements on these channels by some 15 db provided they are restricted to message telephone service.

As the repeater design was worked out in detail, however, it became evident that a rather sharp upper frequency limit existed. This resulted from the parasitic capacitances imposed by the size and shape of the flexible repeater, the degree of precision required in matching repeater gain to cable loss in such a long system, and the feedback requirements as related to the requirement of at least 20 years' life.

These limitations resulted in the decision to develop a system with 36 channels of 4-kc carrier spacing, utilizing the frequency band from 20 to 164 kilocycles per second.

Signal-to-Noise Design

Scaling-up of Key West-Havana System

The length of the North Atlantic cable was to be about 16 times that of the Havana-Key West system. The number of channels was to be increased as much as practicable. The length increase entailed an increased power voltage to ground on the end repeaters. Increase in length and in number of channels entailed increased precision in control of variations in cable and repeaters. Work on these and other aspects was carried on concurrently, to determine the basic parameters of the extended system.

Increasing cable size decreases both the attenuation and the dc resistance, and in turn the voltage to ground on the end repeaters. It was soon decided that the largest cable size which could be safely adopted was the one used in the Bahamas tests. This has a center-conductor seabottom resistance of about 2.38 ohms per nautical mile. It consumes about 28 per cent of the total potential drop in cable plus repeaters.

Number of Repeaters

As indicated earlier, the factor which emerged as controlling the number of repeaters was the dc voltage to ground on the end repeaters. Considerations which entered into this were: voltage which blocking capacitors could safely withstand over a life of at least 20 years; volt-

age which other repeater elements such as connecting tapes between compartments could safely hold without danger of breakdown or corona noise; initial power potential and possible need for increasing dc cable current later in life to combat repeater aging; allowance for repair repeaters; and a reasonable allowance for increased power potential to offset adverse earth potential.

- Let R = dc resistance of center conductor (ohms/nautical mile)
 L = length of one cable* (nautical miles)
 E_{rep} = voltage drop across one repeater at current I
 I = ultimate (maximum) line current (amperes)
 N = ultimate number of submerged repeaters, in terms of equivalent regular repeaters
 n = allowance for repair repeaters, in terms of number of regular submerged repeaters using up same voltage drop.
 E_m = maximum voltage to ground at shore-end repeaters at end of life, and in absence of earth potential.
 S = spacing of working regular repeaters (nautical miles)

Then for the ultimate condition

$$2E_m = LIR - 2SIR + NE_{rep} \quad (1)$$

in which the term $2SIR$ accounts for the sum of the cable voltage drops on the two shore-end cable sections; the sum of their lengths is assumed, for simplicity, to equal $2S$. This equation also neglects a small allowance (less than 0.6 volt per mile) for the voltage drop in cable added to the system during repair operations. Also

$$S(N - n + 1) = L \quad (2)$$

because the repeater spacing is determined by the number of working regular repeaters. From (1) and (2),

$$2E_m = LIR + NE_{rep} - 2LIR/(N - n + 1) \quad (3)$$

The allowance n for repair repeaters was determined after studies of cable fault records of transoceanic telegraph cables, including average number of faults per year and proportion of faults occurring in shallow water. If the fault occurs in shallow water — as is true in most cases† — the net length of cable added to the system and the resulting attenuation increase, are small. Several shallow-water faults might be permis-

* The length of a cable is greater than the length of the route because of the need to pay out slack. The slack allowance, which averages 5 per cent in deep water on this route, helps to assure that the cable follows the contour of the bottom.

† Because of trawler activity, ship anchors and icebergs.

sible without adding a repair repeater. Therefore it was decided to let $n = 3$. Since the repair repeater is a 2-tube repeater while the regular repeater has 3 vacuum tubes, $n = 3$ corresponds to about 5 repair repeaters per cable.

To determine the maximum voltage E_m , it was necessary to consider blocking capacitors and earth potentials.

Based on laboratory life tests, the blocking capacitor developed has an estimated minimum life of 36 years at 2,000 volts. It is estimated that life varies inversely as about the fourth power of the voltage. The potential actually appearing on these capacitors is determined by the distance of the repeater from shore, the power potential applied to the system, and the magnitude and polarity of any earth potential.

Earth potential records on several Western Union submarine telegraph cables were examined. These covered a continuous period from 1938 to 1947, including the very severe magnetic storms of April, 1938, and March, 1940. It was judged reasonable to allow a margin of 400 volts (200 volts at each shore station) for magnetic storms during the final years of life of the system.

With an assumed maximum voltage of 2,300 volts on the end repeaters due to cable-current supply equipment, and 200 volts per end as allowance for the maximum opposing earth potential which the system would be permitted to offset without automatic reduction of the cable current, the voltage across the end repeater in late years of life (i.e., after line current had been increased to offset aging) would normally be 2,300 and would infrequently rise to 2,500. On the rare occasions where earth potential would rise above twice 200 volts, the cable current would be somewhat reduced and the transmission affected to a reasonably small extent. In the early years of life when the cable-current supply voltage would normally be about 2,000 volts, an opposing earth potential of twice 500 volts could be accommodated without affecting cable current; according to the telegraph cable records this would practically never occur. With conditions changing in this way over the years, the life of the blocking capacitors in the end repeaters was calculated to be satisfactory.

Accordingly E_m was established as 2,300 volts.

The system length L was estimated as about 1,985 nautical miles and the ultimate current I was estimated as 0.250 amperes, with a corresponding ultimate E_{rep} of about 62.8 volts.

Substituting in (3),

$$N = 55$$

$$N - n = 52 \text{ working repeaters}$$

$$S = 37.4 \text{ nautical miles.}$$

From a later estimate of $L = 1,955$ nautical miles, S calculates to be 36.9. The repeater design was based on this spacing in the deep sea temperature and pressure environment. Subsequently, after better knowledge had been obtained of the cable attenuation in deep water, the actual repeater spacing for the main part of the crossing was changed to about 37.4 nautical miles for the eastbound (No. 1) cable and 37.6 for the westbound. Only 51 repeaters were required in each cable.

Number of Channels

The number of channels which could be transmitted was determined by the upper and lower boundary frequencies. In this system, the bottom frequency was established at 20 kc, primarily because of the loss characteristics of the power separation filters.³

Preliminary studies were made to estimate the usable top frequency. For a system having a fixed number of repeaters, this frequency falls where the maximum permissible repeater gain equals the loss of a repeater section of the cable — which varies approximately as the square root of frequency. The repeater gain is the difference between the repeater input and output levels. The minimum permissible transmission level at the repeater input depends on the random noise (fluctuation noise) contributed by cable and repeaters, and on the specified requirement for random noise. The maximum permissible transmission level at the repeater output may depend on the modulation noise contributed by the repeaters below overload, or on overload from the peaks of the multi-channel signal complex. In this system, overload was found to be the controlling factor.

An important consideration was to provide enough feedback in the repeater so that at the end of 20 years the accumulated gain change (Mu-Beta effect) in all the repeaters would not cause the signal-to-noise performance to fall outside limits. The usable feedback voltage was scaled from the Havana-Key West design according to the relation that this voltage varies inversely as the $\frac{2}{3}$ power of the top frequency. Electron tube aging was estimated from laboratory life tests on Key West-Havana type tubes.

Concurrently, detailed theoretical and experimental studies were being conducted on the transmission design of a repeater suited to transatlantic use with the chosen type of cable, as discussed in a companion paper.³ Intimate acquaintance with the repeater limitations led to a decision in 1953 to develop a system with a working spectrum of 144 kc (36 channels) and a top frequency of 164 kc. Use of compandors would not increase this top frequency appreciably.

Computed Noise

When the repeater design was established, the remaining theoretical work on signal-to-noise consisted in refining the determination of the repeater output and input levels; computations of system noise, and comparison of this with the objectives to establish the margin available for variations; and determination of the necessary measures in manufacturing and cable laying so that these margins would not be exceeded by the deviations from ideal conditions which would occur. These deviations assumed great importance, because they tended to accumulate over the entire length of the system, and because many of them were unknown in magnitude before the system was actually laid.

The repeater levels and the resultant system noise were computed as follows:

It was recognized that the output levels of different repeaters would differ somewhat at any given frequency. The maximum allowable output level of the highest-level repeater was computed by the criterion that the instantaneous voltage at its output grid would be expected to reach the load-limit voltage very infrequently. This is the system load criterion established by Holbrook and Dixon.⁶ It premises that in the busy hour, the load-limit voltage (instantaneous peak value) should be reached 0.001 per cent of the time, or less. It is probable that the level could be raised 2 db higher than the one computed in this way without noticeable effect on intermodulation noise.

An important factor in the Holbrook-Dixon method is the talker volume distribution. Because of the special nature of this long circuit, a careful study was made of the expected United States talker volumes.

First, recent measurements of volumes on long-distance circuits were examined for the relation between talker volume and circuit length. They showed a small increase for the longer-distance circuits. This relation was extrapolated by a small amount to reach the 4000-mile value appropriate to the New York-London distance.

Second, an estimate was made of the probable trends in the Bell System plant in the next several years, which might affect the United States volumes on transatlantic cable calls.

The result of this was a "most probable U. S. volume distribution". This distribution, which had an average value of -12.5 vu at the zero level point, with a standard deviation of 5 db, agreed very well with one furnished by the Post Office and based on calls between London and the European continent. A further small allowance was then made for the contribution of signaling tones and system pilots which brought the resultant distribution to an average value of -12 vu at zero level of the

system (the level of the outgoing New York or London or Montreal switchboard), and a standard deviation of 5 db. It is approximately a normal-law distribution (expressed in vu), except that the very infrequent high volumes are reduced by load limiting in the inland circuits.

The other data needed for system load computations are the number of channels, and the "circuit activity", i.e., the per cent of time during the busy hour that the circuit is actually carrying voice in a given direction (eastbound or westbound). The circuit activity value used in designing United States long-distance multi-channel circuits is 25 per cent; for the transatlantic system, 30 per cent was used.

The peak value of the computed system multi-channel signal is the same as the peak value of a sine wave having an average power of +17.4 dbm at the zero transmission level point of the system.

This value, together with the measured sine-wave load capacity of the undersea repeater, determines the maximum permissible output transmission level of the repeater. The measured sine-wave load capacity is about +13.5 dbm at 164 kc. Hence the maximum permissible output transmission level for the 164-kc channel is $+13.5 - 17.4 = -3.9$ db.

If the relative output levels of the various submarine repeaters were precisely known, the highest-level repeater could have an output transmission level of -3.9 db at 164 kc. An allowance of about 2 db was made for uncertainty in knowledge of repeater levels, giving -6 db as the design value for the maximum repeater output level at 164 kc.*

The repeater has frequency shaping in the circuit between the grid of its output tube and the cable. The maximum repeater output at lower frequencies is smaller than at 164 kc, but the maximum voltage on the output grid, from an overload standpoint, is approximately constant over the 20 to 164 kc band.

The transmission level of the maximum level repeater output is thus determined, based on load considerations. Another factor which might limit this level is modulation noise. This was found to be less of a restriction than the load limitation, however.

With the output level determined, the random noise and the modulation noise for the system can be computed. The random noise computation is made on the assumption that all repeaters are at the same level, and then a correction is made for the estimated differences in levels of the various repeaters. The equation is

$$N_0 = N_{in} + G - TL + 10 \log n + d_r$$

* At the time of writing, the No. 1 cable (eastbound) is set up with a somewhat lower maximum output level than this; the safe increase in level will be determined later.

where N_0 = system random noise, in dba,* referred to zero transmission level

N_{in} = random noise per repeater in dba, referred to repeater input level

G = repeater gain in db

TL = transmission level of repeater output

n = number of undersea repeaters

d_r = db increase in noise due to differing output levels of the various repeaters as compared to the highest level repeater.

At the top frequency of 164 kc, $TL = -6$ db as seen above, $G = 60.7$ db, and N_{in} is about -55.5 dba, which corresponds to a noise figure of about 2 db. Hence for 52 repeaters,

$$N_0 = -55.5 + 60.7 - (-6) + 10 \log 52 + d_r = 28.4 + d_r$$

At lower frequencies, the noise power referred to repeater input is greater because part of the equalization loss is in the input circuit; the repeater gain is less, to match the lesser loss of a repeater section of cable; and the repeater output level is lower on account of the equalization loss from output grid to repeater output. This is shown in Table I.

TABLE I

Channel	N_{in} = Approx. Input Noise, dba	G = Approx. Repeater Gain, db	TL = Approx. Output Trans Level, db	N_0 = Resulting Noise dba
Top Freq.	-55.5	60.7	-6	$28.4 + d_r$
Middle.	-53	45	-11	$20.2 + d_r$
Bottom Freq.	-46	22	-19	$12.2 + d_r$

In order to estimate d_r (which is a function of frequency) before the cable was laid, the factors were studied which might contribute to differences between the levels of the various repeaters. Estimates were made of probable total misalignment — by which is meant the level difference between highest-level and lowest-level repeaters. These values together with estimates of the resulting noise increases, are shown in Table II. This is based on the assumption that the repeater levels would be distributed approximately uniformly between highest and lowest. The position of a repeater along the cable route is not significant.

* "dba" is a term used for describing the interfering effect of noise on a speech channel. Readings of the 2B noise meter with F1A weighting may be converted to dba by adding 7 db. dba may be translated to dbm (unweighted) by noting that flat noise having a power of 1 milliwatt over a 3,000-cycle band equals approximately +82 dba, and that 1 milliwatt of 1,000-cycle single-frequency power equals +85 dba.

TABLE II

Channel	M = Estimated Misalignment	d_r = Resulting Noise Increase	N_0 = Resulting System Random Noise (Approx.)
Top.....	12 db	7.4 db	36 dba
Middle.....	10 db	6.0 db	26 dba
Bottom.....	6 db	3.4 db	16 dba

A study was made of the expected intermodulation noise. This noise is affected by repeater level differences, by talker volumes, and by circuit activity. It has a time distribution, the most attention being given to the root-mean-square modulation noise in the busy hour.

Modulation noise was computed in two ways: by the Bennett method,⁷ and by the Brockbank-Wass method.⁸ Results by the two methods are in fairly good agreement. The values computed by the Bennett method are shown in Table III.

Because noise powers, not dba, are additive, these values of modulation noise would contribute only a very small amount to the total noise in the deep-sea cable system, as previously stated.*

Other possible contributory sources of noise in the deep-sea cable system are noise in the terminals, noise picked up in the shore lead-in cables, and corona noise in the repeaters. The system has been designed so that the expected total of these is small. Hence the estimate of total deep-sea cable system noise, made before cable-laying, gave the values shown in Table IV, to the nearest db.

Misalignment Control

Objective

Since the noise objective for the deep sea cable link was set as 36 dba in the joint meetings of the British Post Office and Bell System Representatives¹, the above estimate of system noise led in turn to the objective that the system be manufactured and laid in such a way that the misalignment, including effects of seasonal temperature change, should be no greater in the top channel than the value assumed in the estimate, which was 12 db. Half of this was allotted to initial misalignment and half to effects of temperature change. Greater misalignments were permissible at lower frequencies.

* The following table for adding two noises expressed in dba shows the magnitudes of the increases:

db difference between larger and smaller noises	2	4	6	8	10	15	20
Resulting db to be added to larger noise to get sum of the two	2.1	1.4	1.0	0.6	0.4	0.1	0+

TABLE III

Channel	Weighted Noise in dba at Zero Transmission Level		
	Second Order Products	Third Order Products	Total
Top.....	8.2	8.5	11.3
Middle.....	0.2	3.8	5.4
Bottom.....	-1.8	2.5	3.9

TABLE IV

Channel	Estimated System RMS Noise at 0 db Transmission Level	
	dba	dbm (Psophometer†)
Top.....	36	-48
Middle.....	26	-58
Bottom.....	16	-68

† The psophometer is the C.C.I.F. circuit noise meter. On message telephone circuits, dbm (psophometer) + 84 = dba using C.C.I.F. 1951 weighting and Bell System F1A weighting.

Control of this misalignment required extensive consideration in the equalization design of the system.

Causes of Misalignment

The basic causes of misalignment can be grouped as follows: those producing unequal repeater levels when the system is first laid; those resulting from changes in cable loss produced by changes in sea-bottom temperature; and those from aging of the cable or repeaters.

There are a large number of possible causes of initial misalignment. While the cable and repeaters were manufactured within very close tolerances to their design objectives, they could not exactly meet those objectives. In addition, the cable loss as determined in the factory must be translated to the estimated loss on sea-bottom, and the length of each repeater section must be tailored in the factory so that its expected sea-bottom loss will best match the repeater gain. Possible sources of error in this process include: uncertainty in temperature of the cable when it is measured in the factory, and in its temperature on the sea-bottom; uncertainty in temperature and pressure coefficients of attenuation; changes in cable loss between factory and sea-bottom conditions, not accounted for by pressure and temperature coefficients.

These latter changes in cable loss were called "laying effect". The determination of the magnitude of laying effect, and its causes, are dis-

cussed in the paper on cable design.² Suffice it to say here that after measuring the loss of a length of cable in the factory and computing the sea-bottom loss, the computed result was a little greater than the actual sea-bottom loss. The difference, i.e., the laying effect, was approximately proportional to frequency, and was greater for deep-sea than for shallow-water conditions. Its existence was confirmed by precise measurements on trial lengths of cable, made early in 1955 in connection with cable-laying tests near Gibraltar.

Laying effect had been suspected from statistical analysis of less precise tests of repeater sections of cable generally similar to transatlantic cable, as measured in the factory and as laid in the vicinity of the Bahamas. However, the repeater design had of necessity been established before the Gibraltar test results were known. The consequence was a small systematic excess of repeater gain over computed cable loss, approximately proportional to frequency, and amounting at the top frequency to about 0.04 db per nautical mile on the average, for deep-sea conditions, and about 0.025 db per mile for shallow-water conditions. While this difference appears small, it would accumulate in a transatlantic crossing of some 1,600 miles of deep sea and 350 miles of relatively shallow sea, to about 75 db at the top frequency. This would be enough to render almost half of the channels useless if no remedial action were taken.

After the system is laid, changes in cable loss or repeater gain may occur. These may be caused by temperature effects and by aging of cable or repeaters.

Comprehensive studies* of the expected amounts of temperature change were made both before and after the 1955 laying. These gave an estimate of 0 to ± 1 degree F annual variation in sea-bottom temperature in the deep-sea part of the route (about 1,600 nautical miles) and perhaps $\pm 5^\circ$ F on the Continental shelves (about 330 nautical miles). Use of these figures leads to a ± 5 -db variation in system net loss at 164 kc from annual temperature changes. If the deep-sea bottom temperature did not change at all, the estimated net loss variation due to temperature would be about half of this.

Control of Misalignment

The first line of defense against variations leading to misalignment was the design and production of complementary repeaters and cable. This is discussed in companion papers.

* Factual data on deep sea bottom temperatures are elusive. Many of the existing data were acquired by unknown methods under unspecified circumstances, using apparatus of unstated accuracies. Statistical analysis of selected portions of the data leads to the quoted estimates.

Signal-to-noise changes from undersea temperature variations were minimized by providing adjustable temperature equalizers at both the transmitting and the receiving terminals, and devising a suitable method of choosing when and how to adjust them.

Partial compensation for laying effect was carried out at the cable factory by slightly lengthening the individual repeater sections. In the 1955 cable, where the factory compensation was based on early data, the increased loss compensated for about two-fifths of the laying effect at the top frequency. In the 1956 cable, which had the benefit of the 1955 transatlantic experience, the compensation was increased to nearly twice this amount. Since the loss of the added cable is approximately proportional to the square root of frequency and the laying effect is approximately directly proportional to frequency, the proportion of laying effect compensated varied with frequency, and a residual remained which had a loss deficiency rising sharply in the upper part of the transmitted band.

The remainder of the laying effect, which was not compensated for in the factory, as well as other initial variations, were largely compensated by measures taken during cable laying at intervals of 150 to 200 miles. The whole length of the cable was divided into eleven "ocean blocks", each either four or five repeater sections long. At each junction between successive ocean blocks, means were provided to compensate approximately for the excess gain or loss which had accumulated up to that point.

These means were twofold. The first means was adjustment of the length of the repeater section containing the junction. For this purpose, the beginning of each block, except the first, was manufactured with a small excess length of cable. This was to be cut to the desired length as determined by shipboard transmission measurements.

The second means was a set of undersea equalizers. These equalizers were fixed series networks, encased in housings similar to the repeater housings but shorter.

Before the nature of the laying effect was known, it had been planned to have equalizers with perhaps several shapes of loss versus frequency; but to combat laying effect, nearly all were finally made with a loss curve sloping sharply upward at the higher frequencies, as shown in Fig. 3.* Because the equalizer components had to be manufactured many months in advance and then sealed into the housings, last minute designs of undersea equalizers were not practical. The proven-integrity principle prevented use of adjustable units. Because the equalizers were series-

* This characteristic was based on a statistical analysis of the data on some similar cable laid for the Air Force project.

type, each block junction was located at approximately mid-repeater section to minimize the effects of reflections between equalizer and cable impedances.

The actual adjustments at block junctions were determined by a series of transmission measurements during laying, as described in the companion paper on cable laying.⁹ Six equalizers were used at block junctions in the 1955 (No. 1) cable, and eight in the 1956 (No. 2) cable.

The result of all the precautions taken to control initial misalignment was, in the 1955 cable, to hold the initial level difference between highest and lowest-level repeaters to about 6 db near the top frequency and to values between 4 and 9 db at lower frequencies, the 9 db value occurring in the range 50 to 70 kc where there is noise margin. In the 1956 cable, the level difference was about 4 db at the top frequency, and from 2 to 7 db elsewhere in the band.

Shore Equalization

The equalization to be provided at the transmitting and receiving ends of the North Atlantic link had these primary functions:

1. For signal to noise reasons, to provide a signal level approximately flat with frequency on the grid of the third tube of the undersea repeaters.
2. To equalize the system so that the received signal level is approximately constant over the transmitted band.
3. To keep the system net loss flat, regardless of temperature variations in the ocean. (A change of 1° F in sea-bottom temperature would cause the cable loss to change by 2.8 db at 160 kc and less than this at lower frequencies. The amplifiers are relatively unaffected by small temperature changes.)
4. To provide overload protection for the highest level repeater.
5. To incorporate some adjustment against possible cable aging.

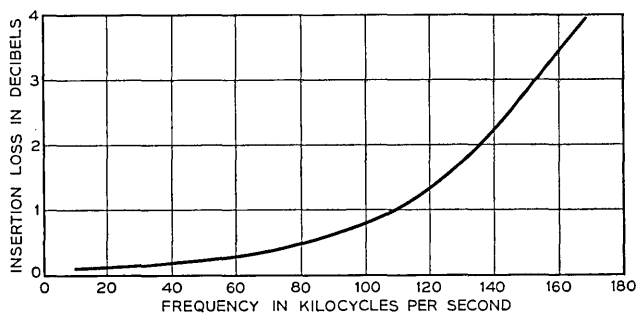


Fig. 3 — Undersea equalizer — loss-frequency characteristic.

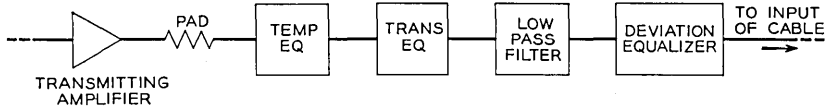


Fig. 4 — Transmitting equalizers — block schematic.

A portion of the transmitting terminal is shown in block schematic form in Fig. 4. All of the equalizers are constant resistance, 135 ohm unbalanced bridged-T structures. Their functions are as follows:

Transmitting Temperature Equalizer — It was estimated that the cable loss change from temperature variations would not exceed ± 5 db at the top of the transmitted band. The change in cable loss versus frequency due to temperature variations is approximately the same as if the cable were made slightly longer or shorter, and so the temperature equalizer was designed to match cable shape. Temperature equalizers are used both in the transmitting and receiving terminals to minimize the signal-to-noise degradation caused by temperature misalignment. Each equalizer provides a range of about ± 5 db at the top of the band, the loss being adjustable in steps of 0.5 db by means of keys. See Fig. 5.

This range might appear to be more than necessary, but it must be borne in mind that the sea bottom temperature data left much to be desired in precise knowledge of both average and range.

Transmitting Equalizer — The transmitting equalizer was so designed that with the temperature equalizer set at mid-range and with repeaters that match the cable loss, the signal level on the grid of the output tube of the first repeater would be flat with frequency. The loss-frequency characteristic is shown on Fig. 6.

L.P. Filter — This filter transmits signals up to 164 kc and suppresses by 25 db or more, signals in the frequency range from 165 to 175 kc. Its purpose is to prevent an accidentally applied test tone from overloading the deep sea repeaters should such a tone coincide with the resonance

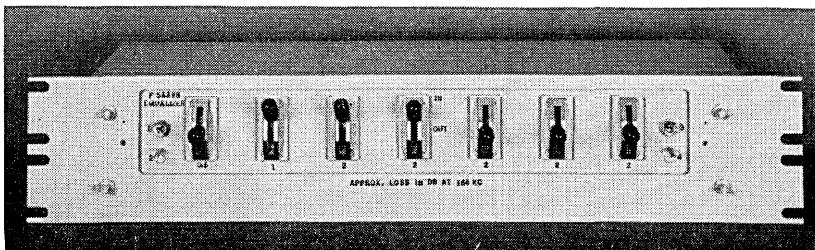


Fig. 5 — Transmitting temperature equalizer.

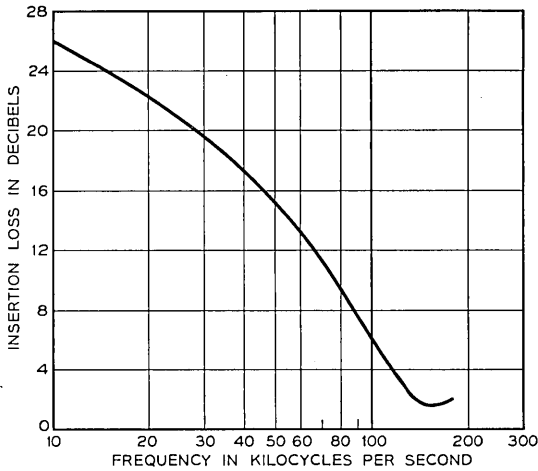


Fig. 6 — Transmitting equalizer — loss-frequency characteristic.

of the crystal used in a repeater for performance checking. The gain of a repeater to a signal applied at the resonance frequency of its crystal is about 25 db greater than at 164 kc.

Deviation Equalizer — The transmitting deviation equalizer is used to protect the highest level repeater from overload. The design is based on data obtained during the laying indicating which repeater was at the highest level at the various frequencies. The characteristic of this equalizer is shown on Fig. 7.

A portion of the receiving terminal is shown in block schematic form on Fig. 8. The generalized function of the equalizers is to make the signal level flat versus frequency at the input to the receiving amplifier No. 2. The specific functions of the various equalizers are as follows:

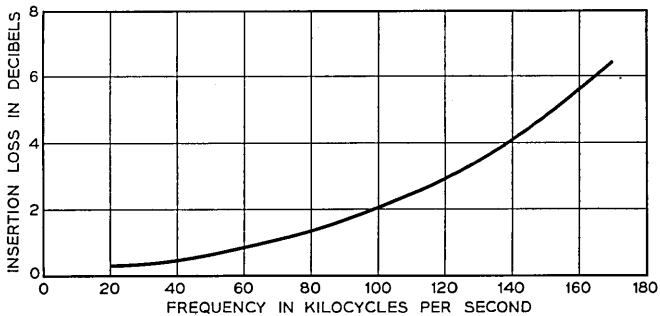


Fig. 7 — Transmitting deviation equalizer — loss-frequency characteristic.

Cable Length Equalizer — In planning the system, an estimate was made of how far the last repeater (receiving end) would be from the shore. Considerations of interference and level dictated a maximum distance not exceeding approximately 32 miles. For protection against wave action, trawlers and similar hazards, the repeater should be no closer than about five miles. To take care of this variation, a cable length equalizer was designed that is capable of simulating the loss of 10 miles of cable, adjustable in 0.5 db steps at the top of the frequency band. Two of these could be used if needed. Once the system is laid, this equalizer should require no further adjustment unless it is used to take care of cable aging or a cable repair near shore.

Receiving Fixed Equalizer — This is the mop-up equalizer for the system. A final receiving equalizer, Fig. 9, has been constructed for the first crossing. Another, tailored to the No. 2 cable, will be designed on the basis of data taken after completion.

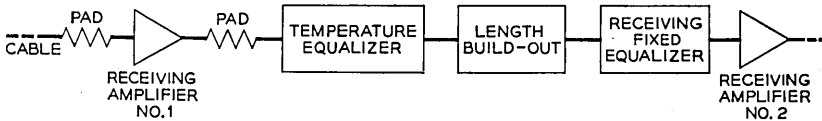


Fig. 8 — Receiving equalizers — block schematic.

Receiving Temperature Equalizer — The receiving temperature equalizer is identical with the transmitting temperature unit.

OPERATIONAL DESIGN

General

The operational design of a transmission system considers the supplementary facilities which are needed for operation of the main transmission facility, for its supervision and for its maintenance. In the present instance, these facilities include the cable station power plants for driving the carrier terminals and high frequency line, the carrier terminals themselves and their associated carrier supply bays, the telephone and telegraph (speaker and printer) equipments needed for maintenance, supervision and administration of the overall facility, the pilots, protection devices and alarms and the maintenance and fault locating equipment.

Power Supplies

With the exception of the plants for cable current supply, the power plants at Clarendville and Oban are relatively conventional, and follow telephone office techniques which are standard for the telephone adminis-

tration of the particular side of the Atlantic on which they are located. They will not be discussed here, although it might be well to point out that the equipment supply for the Bell equipment is direct current, obtained from floated storage batteries, while the supply for the Post Office equipment is alternating current from rotary machines driven normally from the station ac supply, with storage battery back-up.

The cable current supplies for the North Atlantic link¹⁰ are complex and highly special. It is pertinent to discuss here briefly the requirements which beget this complexity. To assist in this, an elementary schematic of the cable power loop is shown in Fig. 10.

The following main requirements governed the design of these plants:

1. Constant maintenance of uniform and known current in the power loop.
2. Protection of HF line against faults induced by failures in power bays.
3. Protection of HF line against damage from power voltage surges caused by faults in the line itself.

Maintenance of constant and known operating current in the line is very important from the standpoint of system life because of the dependence of the rate of electron tube aging on the power dissipated in the heaters.¹¹

The principal factor which tends to cause variations in the line current is the earth potential which may appear between the terminals of the system. This potential may be of varying magnitude and of either po-

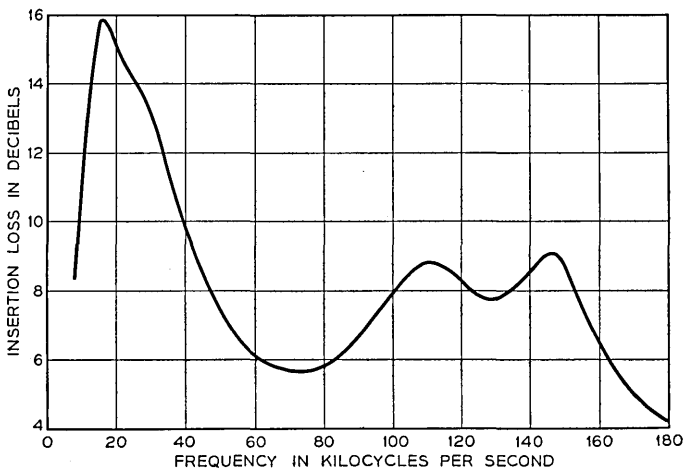


Fig. 9 — Receiving fixed equalizer — loss-frequency characteristic.

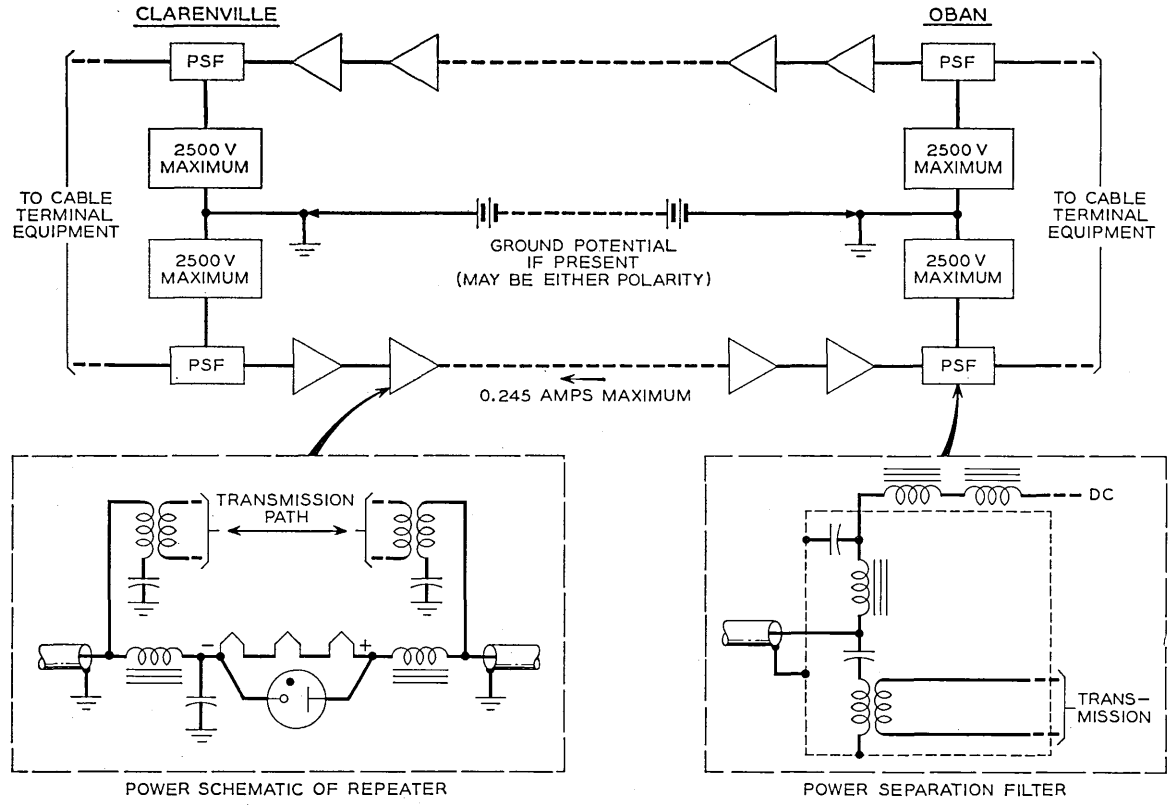


Fig. 10 — Cable power loop — elementary schematic.

larity. Consequently, it may either aid or oppose the driving potential applied to a particular cable. The power circuit regulation is such that the presence of an aiding potential will be completely compensated, while opposing potentials will be compensated only to the degree possible with the maximum of 2,500 volts applied by the terminal plants. Beyond this point, the line current will be allowed to drop, so as to avoid excessive potential across the power filter capacitors in the shore end repeaters.

Line faults caused by failures or misoperation of the power supplies must be carefully guarded against. Such failures might result in surges on the line, or excessive voltage or current. Protection against surges takes the form of retardation coils in the terminal power separation filters, which limit the rate of current change to tolerable values.

Failure of the capacitors in these filters could also create dangerous surges. The protection here takes the form of a large voltage design margin.

Faults in the HF line of importance from the power feed standpoint are short circuits to ground, and opens. The former tend to result in excessive currents, the latter, excessive voltages. Very fast acting protection in the terminal power bays is required to cope with these, and series electron tube regulators provide the means.

Terminal Plan

The plan of design of transmission terminal equipment, shown in Fig. 2, was based on the following objectives:

- (a) Use of standard, or modified standard equipment as far as possible.
- (b) To facilitate supply and maintenance of standard equipment, use of Bell System equipment in North America and Post Office equipment in the United Kingdom.
- (c) Provision of full duplicate equipment and means for quick shift between regular and alternate.
- (d) Provision of special equipment to fit Canadian requirements.
- (e) Provision for ample order-wire (speaker and printer) equipment, partly because there is no alternate undersea route.
- (f) Provision of no automatic loss regulation, because the loss changes are so slow; provision of three link pilot frequencies as a basis for manual regulation.

Much of the equipment is standard. This includes group modems, group connectors, pilot supply, frequency-shift telegraph equipment for printer circuits, etc. Supergroup modulators are modified standard coaxial carrier equipment. The channel modems for speaker and printer circuits are a combination of Type-C open-wire carrier active equipment,

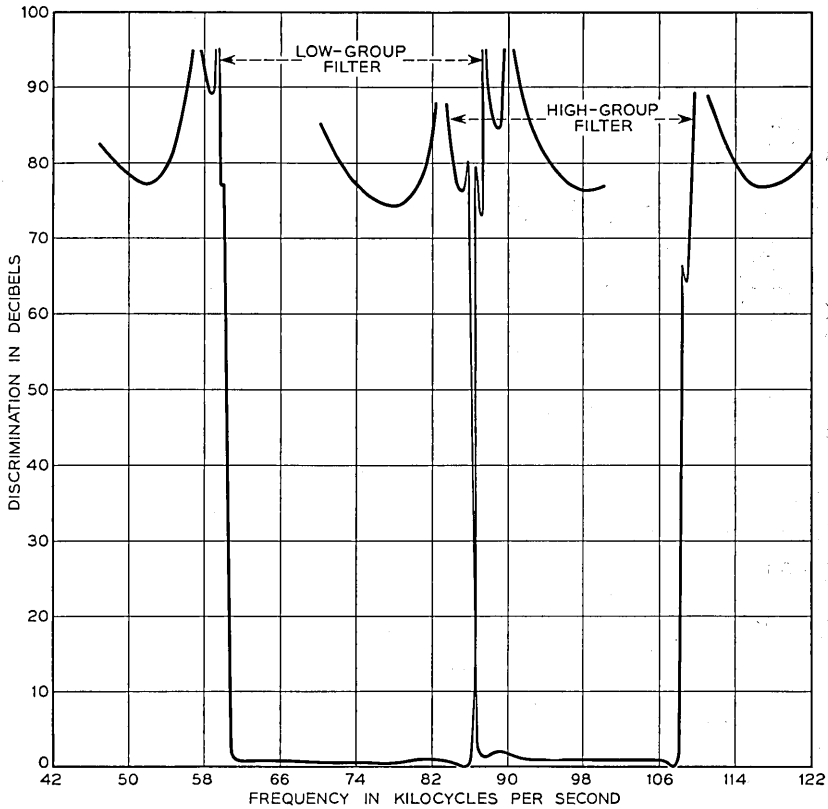


Fig. 11 — Splitting filters — loss frequency characteristic.

and filters designed for a military carrier system. The transmitting output amplifier is a modified version of one used in the Havana-Key West submarine cable system terminals; the modifications include broader frequency band, lower modulation and sharper overload cutoff. As in the coaxial carrier system, hybrid coils are provided at points in the Bell equipment where quick patching is needed.

The agreed Canadian bandwidth quota is 26 kc,¹ corresponding to six and one-half message telephone channels. The split between the 6½ Canadian channels and the remaining 5½ U.S. channels in the "split group" was accomplished by specially-designed group-frequency splitting filters, with very sharp cutoff. The loss-versus-frequency characteristics of these filters are shown in Fig. 11. The resulting Canadian half telephone channel next to the cut-apart was broad enough to accommodate

twelve frequency-shift telegraph channels with 120-cycle carrier telegraph spacing. It is planned to use one of these for automatic regulation of the other eleven. The U.S. half channel is at present unassigned.

Two telephone order wires (speakers) and two teletype order wires (printers) are provided for maintenance and administration purposes.

The two speakers occupy a 4-kc telephone channel which is the lower sideband of 20 kc on the line. The 4-kc band is divided into halves by Bell Type-EB split-channel equipment, which yields two narrow-band telephone channels. One of these is reserved for a "local" Clarenville-Oban circuit, available at all times to the personnel at these terminals. It constitutes a cleared channel which could be of great benefit in emergencies which might arise. The other narrow-band telephone channel, the "omnibus speaker", is extended through to other control points including the system metropolitan terminals.

The two printer circuits are frequency-shift voice-frequency telegraph channels, occupying line frequencies just below 16 kc. These are both brought to dc at Clarenville and Oban, and extended by carrier telegraph to the metropolitan terminals. One is normally a "through" circuit with teletypewriters at the metropolitan terminals only, and the other is an "omnibus" circuit with teletypewriters connected at Oban, Clarenville and other control points, permitting message interchange between all connected points.

92-kc group frequency pilots are transmitted over the Clarenville-Oban link only, and blocked at its ends. The line frequencies corresponding to the 92-kc group frequencies are 52, 100 and 148 kc. These pilots are used for manual regulation and maintenance of the Clarenville-Oban link. Information derived from them governs the manual setting of the temperature equalizers. The sending power of the 92-kc pilots is regulated to within ± 0.1 db variation with time.

84.080-kc group frequency pilots also appear on this link. These, however, are system pilots applied at the metropolitan terminals. They are useful for evaluation of overall system performance and for quickly locating transmission troubles.

Alarms are provided in the manner usual for multi-channel telephone systems. A special feature of the pilot alarm system is the "alarm relay channel", a third voice-frequency carrier telegraph channel just below the printer channels in line frequency. If all three eastbound 92-kc pilots fail to reach Oban, a signal is transmitted over the westbound cable which brings in a major alarm at Clarenville, and vice versa. This major alarm would provide news of a cable failure immediately to the transmitting cable terminal station. Failure of the pilot supply would, of course, give

the same alarm. The alarm relay channel circuit is arranged so that if it fails it does not give the major alarm.

A special alarm system for the cable current supply is described in the companion paper on that equipment.¹⁰

Fault Location

Length and inaccessibility have always imposed difficult requirements on fault locating techniques for undersea cable systems. Before the advent of repeatered systems, much effort was expended on use of impedance methods — i.e., those involving resistance and electrostatic capacitance measurements to locate a fault to ground, or a break.* Some work has been done also on magnetic pickup devices towed along the route by a ship.

With the advent of undersea repeaters, the problem has become even more difficult, both because of the effect of the repeater elements on impedance measurements, and because a fault may interrupt transmission without affecting the dc loop.

It has been necessary, therefore, to reassess the whole problem of fault location.

Location of Faults Affecting the DC Power Loop

Three types of measurement are made on submarine cables at present:

(a) Center conductor resistance, assuming a short circuit or a sea water exposure at some point, which might be either a fault or a break.

(b) Dielectric resistance, assuming a pinhole leak through the dielectric and a sea water exposure.

(c) Electrostatic capacitance, assuming a center conductor break insulated from sea water.

By these methods, faults and breaks in non-repeatered cables can be located although the accuracy of determination, and indeed the practical success of the operation, is dependent on the nature of the fault, the situation with respect to earth potential, the skill of the craftsman and many other factors.

The presence of cold repeaters in the circuit adds considerably to the difficulty, both because of the resistance/temperature characteristic of the electron tube heaters (153 in series with each cable) and because of polarization effects exhibited by the castor oil capacitors in the trans-

* In the literature, "fault location" is a generalized term encompassing the field. A "fault" is an exposure of the cable conductor to the sea without a break in the conductor. A "break" is an interruption of the conductor with or without exposure to the sea.

atlantic repeaters. These capacitors have a storage characteristic which varies with the magnitude of applied voltage, duration of its application and the temperature.

Because of this, the usual methods of fault location are expected to give results of doubtful accuracy and so a new approach is being made to the problem. The results of the work to date are beyond the scope of this paper.

Location of Transmission Faults

The previous section deals with the situation where the dc power loop has been opened or disturbed. Of equal importance is the location of transmission faults when the power loop is intact.

For this purpose, use is made of the discrete frequency crystal provided in each repeater.³ This crystal is effectively in parallel with the feedback circuit of the amplifier, and at its resonant frequency the amplifier has a noise peak of the order of 25 db, with an effective noise band of about 4 cycles. When one repeater fails, it is possible to recognize the noise peak of each amplifier from the receiving end back to the failed unit. The noise peaks from the faulty unit and all preceding amplifiers will be missing, indicating location of the trouble. Noisy amplifiers can be singled out by an extension of the technique.

Testing and Maintenance

Routine testing and maintenance activities at Oban and Clarenville can be divided into four parts: for the carrier terminals, for the station power equipment, for the cable current power units and for the high frequency line. Usual methods apply and the usual types of existing test equipment were provided with one exception.

The exception is a newly designed transmission measuring system. The system employs a decade type sending oscillator with continuous tuning over the final 1-kc range. Provision is built-in for precise calibration of output level. The receiving console contains a selective detector functioning as a terminating meter of 75-ohm input impedance, and can measure over the range - 120 to 0 dbm. Coils are supplied to permit measuring over 135-ohm circuits. The detector can be calibrated for direct reading when used as a terminating meter.

The system covers a frequency range of 10 kc to 1.1 mc. It is useful, therefore, for measuring much of the standard British and U.S. designed carrier terminal equipment as well as for normal line transmission measurements over both the North Atlantic and Cabot Strait (Newfoundland-Nova Scotia) submarine lines.

A special transmission measuring set is provided in the receiving console which facilitates measurements in the crystal frequency region 166–175 kc. This set is used for evaluating the performance of individual repeaters from shore. As an oscillator, it is capable of delivering an output of up to +8 dbm into a 75-ohm load, with exceptional frequency stability and finely-adjustable, motor-driven tuning. This is useful in locating and measuring the narrow-band response peaks of individual repeater crystals. The oscillator frequency is varied in the region of a particular peak, and the received power is measured at the peak frequency and at nearby frequencies. At the peak frequency, the crystal removes nearly all feedback in the repeater. Changes in repeater internal gain can thus be determined from shore.

As a detector, the set can measure from -110 to -60 dbm in a bandwidth of about 2 cycles. This enables it to measure crystal noise peaks which may be spaced as closely as 50 cycles apart. To reduce the random variations in such narrow-band noise, a "slow integrate" circuit, of the order of 10 seconds, is provided. Thus the crystal noise peaks can be compared in magnitude with the system noise level at closely adjacent frequencies.

ASSEMBLY AND TEST OF SYSTEM

General

Assembly and initial testing of the North Atlantic link occupied a span of about three years. Because of the geographical and political factors involved the job was a difficult one and required close cooperation among individuals in many different organizations on both sides of the ocean.

Clarenville

The cable station at Clarenville houses the carrier terminal, cable terminating and power equipment at the junction of the North Atlantic and Cabot Strait links. It was designed by United States architects from requirements furnished by A. T. & T. engineers and was approved by the other parties to the enterprise. The building was constructed by a Canadian firm under the supervision of a Canadian architect. The equipment was put in place and connected by installers of the Northern Electric Company and tested by representatives of Bell Telephone Laboratories, Eastern Telephone and Telegraph Company, Northern Electric Company and the British Post Office.

As Newfoundland is an island, shipments of equipment and supplies

to Clarenville were carried by sea or air to St. John's where they were trans-shipped by rail to Clarenville.

Oban

The cable station at Oban was executed by British contractors from designs drawn up by the British Post Office. Its equipment was installed by a British electrical contracting firm. Two Western Electric Company installers were present at Oban during the installation of the American-made cable terminating equipment and cable current supply bays to provide necessary liaison and interpretation of drawing requirements. The Oban equipment was tested by representatives of the British Post Office, Bell Telephone Laboratories and the firm that did the installing.

Here too, it was necessary to ship by boat or air, with subsequent trans-shipment by train and by truck.

Undersea Link

Perhaps the most interesting phase of all was the handling of the undersea section. The actual laying is described elsewhere, but much effort was required before the cable ship ever left the dolphins at the cable manufacturing plants.

Most of the cable was manufactured at the plant of Submarine Cables, Ltd., at Erith, on the Thames about fifteen miles downstream from London. A smaller quantity of cable was manufactured by Simplex Wire and Cable Corporation at its plant in Newington, N.H. As the cable was completed it was coiled in repeater section lengths in huge tanks. The ends of each repeater section were left available at a "splicing platform" where the repeaters, manufactured at Hillside, N.J., were spliced in. Spliced repeaters were located in water filled troughs for protection against overheating while testing.

All repeaters were armored by Simplex at Newington. This involved their transportation by truck from the Western Electric shop at Hillside where the flexible repeaters were manufactured, to Newington. While this sounds simple it was actually a very carefully planned and controlled operation because of the need to avoid subjecting the units to any but the most necessary and unavoidable hazards. Consequently, the truck used for the purpose was specifically selected for size and construction and was provided with a heating unit in the body. The route was carefully surveyed in advance for unusual hazards and the truck speed was limited to a very modest value.

After the repeaters were armored, those to be incorporated in Simplex-made cable were spliced at Newington. Those destined for application in

British-made cable were shipped by truck, following the same precautions, to Idlewild Airport in New York. From there they proceeded by special freight plane — one or two at a time — to London Airport. Here they were again trans-shipped by truck to Erith.

The repeaters were housed in shipping cases¹² of a very strange shape and considerable size. These cases were provided with max-min thermometers and with impactograph devices that would record the maximum acceleration to which the repeaters had been subjected.

When ship loading time arrived, the cable and its contained repeaters were transported over a system of sheaves from the tanks of the cable manufacturer to the tanks on shipboard. This process offered no particular obstacle so far as the cable itself was concerned, but the requirement against unnecessary bending of the repeater meant that a great deal of special attention had to be given to avoiding unnecessary deviations from a straight run, and to lifting the repeaters around sheaves where the direction of the loading line changed materially. Auxiliary protection was provided on each repeater in the form of angle irons with flexible extensions on each end which served to restrict any bending to the core tube region of the repeater and safely limited the magnitude of the bends in this region.³ One further precaution was observed — that of energizing the repeaters during the loading process. This accomplished two things. First, it permitted continuous testing; second, it reduced the hazards of possible damage to the electron tubes during loading, as the tungsten heaters are much more ductile when hot and the glassware of the tube is more resistant to shock and vibration.

SYSTEM PERFORMANCE

General

At the time of this writing, the No. 2 cable has just been laid, but the No. 1 cable has had eleven months of successful life under test, a pre-service period of probably greater duration than has been granted to any land system of comparable length and cost. It has been under constant observation and test, largely by the people who will operate it when it goes into service. The pre-service measurements have been much more extensive, in quantity and scope, than the routine tests which will be made after the system goes into service.

Net Loss Tests

Net Loss versus Frequency

Results of measurements in June, 1956, on the No. 1 cable are shown in Figs. 12 and 13. The former covers the equalized high-frequency line.

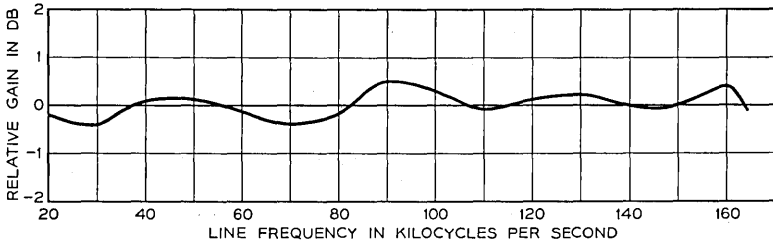


Fig. 12 — Gain versus line frequency — No. 1 cable.

Fig. 13 gives the corresponding group-to-group frequency response of the deep-sea link. These frequency characteristics will vary a little from time to time, depending partly on the change since the last adjustment of the temperature equalizer.

Note that while the slope in gross cable loss between 20 and 164 kc is about 2,100 db, the net loss of the equalized high frequency line over this band varies only about 1 db.

Net Loss versus Time

The net loss of the undersea system (cable plus repeaters) has decreased slowly since the system was laid. The decrease is approximately cable shape, proportional to the square root of frequency. In a year it has amounted to about 5 db at the top frequency. In the early months the change was almost directly proportional to time, but later the rate slowed, as shown in Fig. 14.

The changes shown in the figure are due partly to change in cable temperature and partly to slow aging of the cable. Detailed studies of repeater crystal frequency changes have resulted in only an approximate separation into temperature effects and aging. However, it seems reasonable to assume that at the end of a one-year cycle there would be little

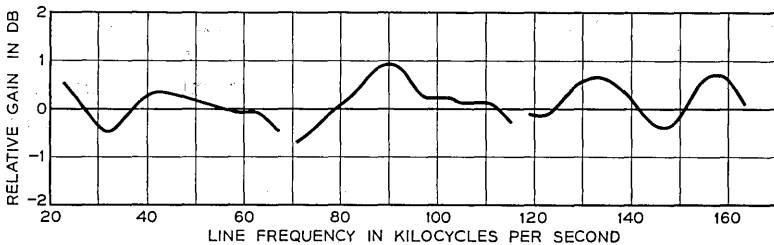


Fig. 13 — Group to group frequency response — No. 1 cable.

if any net change in the cable temperature averaged over the whole cable length. The greatest possibility of change would be in the shallow-water sections, and crystal measurements indicate that at the end of a year the average temperature of the shallow-water sections returned nearly to its initial value. Hence about 5 db seems chargeable to one year's aging. Extrapolation into the future, however, is uncertain. Theoretical considerations lead to the idea that the rate of cable aging should decrease.

Information on long-term change in transmission loss of previous cables is very limited. The Havana-Key West cables were accurately measured just after laying, and again five years later. The change in that system due to aging is very small, if indeed there is a change. That cable is generally like the transatlantic, though it is smaller and has a perhaps significant difference in construction of the central conductor.

The above applies to the net loss of the undersea part of the system only. The group-to-group net loss variation with time of the Clarendville-Oban link has been held within a much smaller range by temperature equalizer adjustments. Practices have been worked out which it is believed will hold the in-service variation with time to a fraction of a db.

Net Loss versus Carrier Frequency Power Level

Single-frequency tests of carrier frequency output power versus input power were made, up to a test power a little below the estimated overload of the highest-level repeater. An increase of 0.1 db in system net loss occurs at a power 2 to 3 db below the load limit of the transmitting amplifier. This is about 15 or 16 db above the expected rms value of the in-service system busy hour load. The 0.1 db change is presumably due to the cumulative effect of smaller changes in several of the undersea amplifiers.

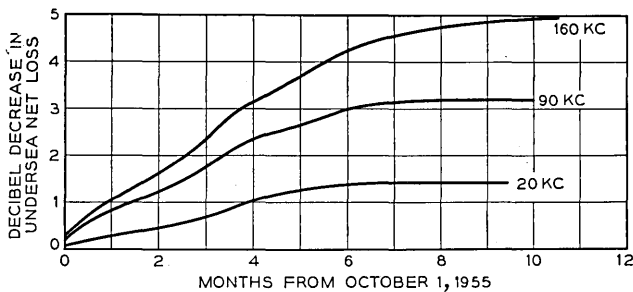


Fig. 14 — Change in system gain in first eleven months.

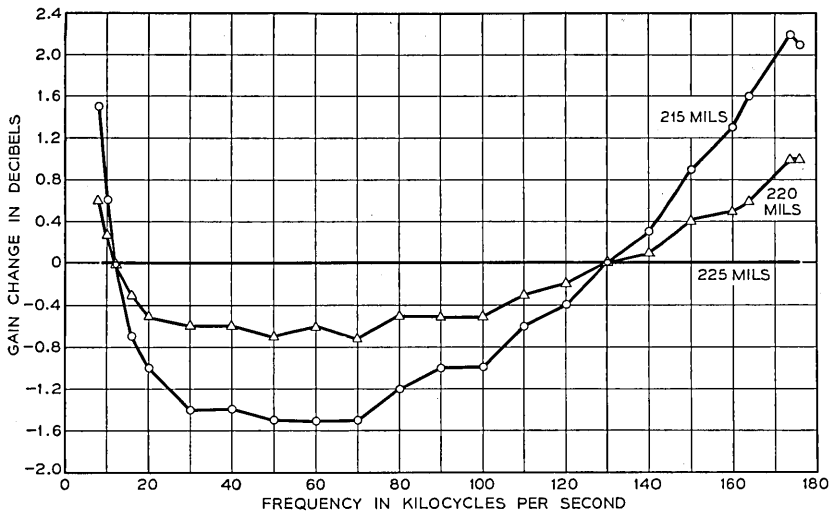


Fig. 15 — Effect of cable current on system gain — No. 1 cable.

Net Loss versus DC Cable Current

Changes in cable current affect the repeater gain to a slight extent, the amount depending on the magnitude and phase of the feedback in the repeater as a function of frequency. Measured changes in the loss of the 2,000-mile system, for currents of 5 and 10 milliamperes less than the normal value of 225 milliamperes, are shown in Fig. 15. Under normal conditions the automatic control will hold the cable current variation within ± 0.5 milliampere.

The shape of the curve on Fig. 15 is almost the same as that computed in advance from laboratory measurements on model repeaters.

System Noise

Shown in Fig. 16 are values of noise on the No. 1 cable system measured in the Fall of 1955 and again in the Spring of 1956. The noise increase is compatible with the decrease in undersea system net loss during this period. To prevent overload, the loss in the transmitting temperature equalizer has to be increased as the undersea loss decreases; this lowers the levels of the various parts of the undersea system by various amounts.

The noise shown in the top channel exceeds the 36 dba objective by a small amount. The excess can be recovered, if necessary, by certain changes in the terminals without recourse to companders.

Fig. 16 shows also the noise on the No. 2 cable system shortly after

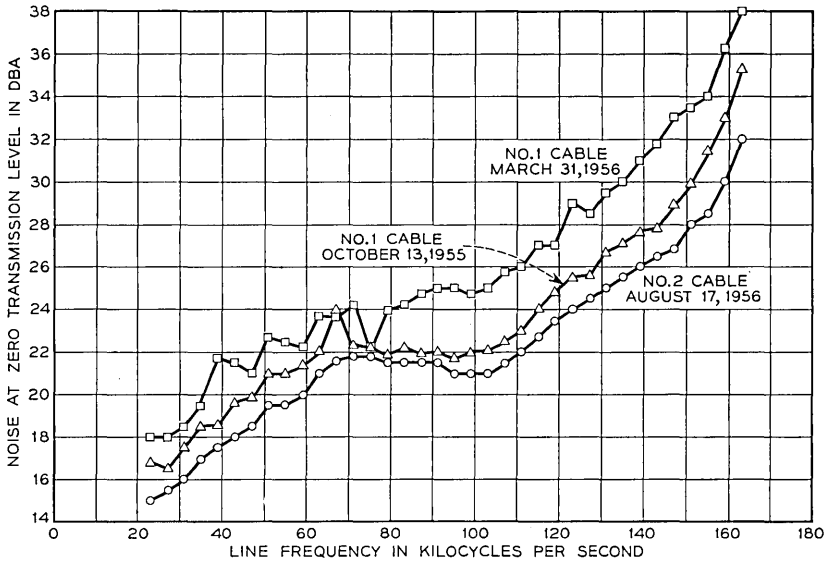


Fig. 16 — System noise.

completion of laying. The noise is lower than on the No. 1 cable. This is because results of experience on the No. 1 cable were utilized in better choice of cable repeater section lengths and in better equalization while laying the 1956 cable.

Modulation Tests

Two-tone modulation tests of second and third order products were made, using a large number of successive frequency combinations. The highest level modulation products were at least 60 db below the 1-milliwatt test tones, at zero transmission level. This is approximately the value computed before the system was laid. Most of the modulation products were down substantially more than 60 db. Probably various causes contributed to the good performance, including the effect of misalignment in lowering repeater levels, and small propagation-time differences which minimize in-phase addition of third-order products from successive repeaters.

Telegraph Transmission Tests

At present writing, telegraph tests have been made only on the printer (telegraph order wire) channels, and without a system multi-channel

load. With the proposed specific telegraph level (STL) of -30 db (i.e. telegraph signal of -30 dbm per telegraph channel at 0 db telephone transmission level), the telegraph distortion was too low to measure reliably; it was possible to send clear messages under test conditions with a signal 36 db weaker than this.

Crystal Tests

All of the peaks of noise at the crystal resonance frequencies were easily discernible.

The crystal gain values all lay in the range from 23.6 to 27.2 db, with 60 per cent of them lying in the range from 25 to 26 db. Crystal gain, as used here, is the difference between the system gain at a repeater crystal frequency and the average of the gains at 50 cycles above and below this frequency; the latter value is approximately the gain if the crystal were absent. No significant changes in crystal gain have occurred in eleven months of system life, and none were expected. These measurements are to be continued over the years, as an indication of electron tube aging, as explained in the companion paper on the repeater.³

A series of measurements of the frequency of each of the 51 repeater crystals versus time has been made. (Any of these frequency determinations can be checked on the same day within ± 0.1 cycle with the special test apparatus and techniques used.) The crystals were designed to be extremely stable in frequency, so that measurements on one repeater, made at the land terminal, would not be affected by the combined effect of 50 other crystals at 100-cycle spacings. The crystal frequency varies only about $-\frac{1}{2}$ cycle per degree Fahrenheit increase in sea-bottom

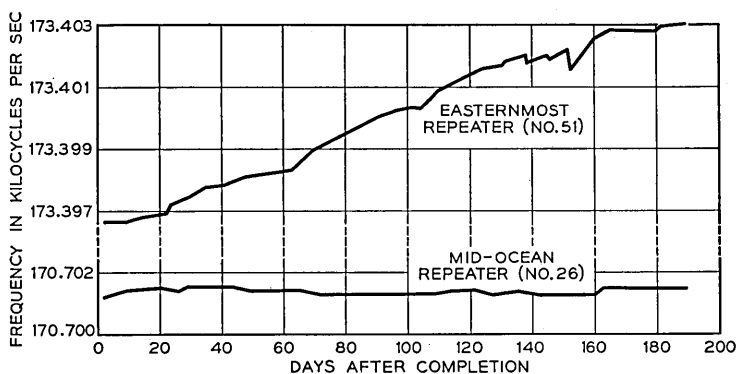


Fig. 17 — Resonant frequency versus time — shore and deep sea crystals.

temperature. The change in frequency due to crystal aging in 11 months under the sea is considered to lie in the range 0 to -0.4 cycle.

Although the crystals were not designed as sea-bottom temperature indicators and are within a repeater housing, it seems likely that with precise techniques and, after some further stabilization, some uniquely accurate information on change of sea-bottom temperature will be obtainable.

In accordance with previous oceanographic knowledge of sea-bottom temperature, the frequency changes have been larger in the crystals near shore. The greatest change has been in the repeater nearest Oban. This is about 17 miles from shore and in water only about 50 fathoms deep. Its frequency change, and that of a typical deep-sea repeater, are shown in Fig. 17.

FUTURE CONSIDERATIONS

Spare Equipment for Cable Stations

In a system as far-flung geographically as this one, and as important, much thought must be given not only to the supplies needed for routine replacement of expendable items, but also to major replacements necessitated by fire or other causes. Accordingly, a schedule of spare equipment has been established, divided into two groups — “shelf” and “casualty”.

Shelf spares are carried in the station itself, and include items such as dial lights, electron tubes and dry cell batteries, which have limited life in normal service. These are maintained in the cable station in quantity estimated as adequate for two years of operation.

Casualty spares embrace those major, essential frames and equipments without which the system cannot be operated. There are two subdivisions: those which are in common use in the telephone plant and are, therefore, available by “cannibalization”, and those which are special to the project, like the cable current supplies and the cable terminating bays. The common-use items are not stocked as casualty spares. Spares of the special items have been built and are stored in locations remote from the cable stations. In event of catastrophe, these can be drawn out and flown as near the point of need as possible, for onward-shipment by available means.

Spare Equipment for the Undersea Link

Although every effort has been made to produce a trouble-free system, the underwater link is still subject to the hazards of trawlers, icebergs,

anchors and submarine earthquakes or land slides. There must be considered, too, the possibility of fault from human failure.

So it is necessary to contemplate the replacement of a length of cable, or a repeater or equalizer. For such contingency, spare cable of the various armor types has been stored on both sides of the Atlantic. Spare repeaters and equalizers are also available.

In addition, a spare called a "repair repeater" has been stocked. Need for this arises from the fact that except in very shallow water, a repair cannot be effected without the addition of cable over and above the length which was in the circuit initially. The amount of cable which must be added is a function of water depth, condition of the sea at the time of the repair, and the amount of cable slack available in the immediate vicinity of the point in question.

When excess cable is introduced in amount sufficient to significantly reduce the system operating margins, its loss must be compensated. Hence, the repair repeater.

A repair repeater is a two-tube device, essentially like a regular repeater although its impedances are designed to match the cable impedances at input and output ends. However, its gain is sufficient to offset only about 5.3 miles of cable. A second type of repair repeater is under consideration, to compensate for about 15 miles of cable.

Long-Term Aging

General

In a system with some 3,200-db gross loss at its top frequency between points which are accessible for adjustment, a long-term change in loss of only one per cent would have a profound effect on system performance.

For this reason, the repeater design included careful consideration of net gain change over the years.³ The degree of control over aging is such that in a period of at least 20 years, and perhaps much longer, the estimated change in 51 repeaters might total 8 db added gain at the top frequency. The gain variation with frequency would be proportional to either curve of Fig. 15, and the rate of aging would be slower in earlier than in later years.

Estimates of cable aging are discussed in the section on "Net Loss Tests."

Means of Combatting Aging

The effects of aging would become important on the top channels first. Remedial measures to improve signal-to-noise, especially in the top

channels, include: possible increase of transmission level at input of the final transmitting and load limiting amplifier in the transmitting terminal; pre-distortion ahead of this amplifier; compandors; increase of dc current; and undersea re-equalization in later years. This last would be very expensive, and so it is necessary to examine fully the possibilities of the other measures.

The penalty for increasing the transmission level at the input of the transmitting amplifier is more peak-chopping and modulation-noise peaks. The improvement that could be realized in this way is probably fairly small.

Pre-distortion is accomplished by inserting ahead of the transmitting amplifier a suitable shaping network adjusted for gain in the top part of the band and loss at lower frequencies. A complementary network (restoring network) is placed at the receiving terminal. This measure would improve signal-to-noise in the uppermost part of the band and reduce it in lower channels which have less noise. Some 3-db improvement might be thus realized in the top channel.

Compandors would give an effective signal-to-noise improvement of up to about 15 db for message telephone service, but none for services such as voice-frequency telegraph. Compandors would be applied only to those channels needing them. They halve the range of talker volume, but also double the transmission variations between compressor and expander, and thus tend to require some increase in the overall channel net loss. The program (music) channels are already equipped with compandors which use up a part of the obtainable advantage.

If the combination of such measures netted an effective message signal-to-noise improvement of 20 db in the top channel, this would counter-balance aging of some 28 db in this channel, if the aging were uniformly distributed along the system length. Thus considerable aging could be handled without undersea modification.

ACKNOWLEDGEMENTS

A system of the complexity of the one described obviously results from teamwork by a very large number of individuals. However, no paper on this subject could be written without acknowledgement to Dr. O. E. Buckley and J. J. Gilbert and O. B. Jacobs, now retired from Bell Telephone Laboratories. All of the early and fundamental Bell System work on repeatered submarine cable systems, and the concept of the flexible repeater, came from these sources and from their co-workers. Messrs. Gilbert and Jacobs have also contributed to the present project.

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Repeater Design for the North Atlantic Link

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F. J. BRAGA*

(Manuscript received October 8, 1956)

Some of the considerations governing the electrical and mechanical design of flexible repeaters and their component apparatus are discussed in this paper. The discussion includes description of the feedback amplifier and the sea-pressure resisting container that surrounds it. Examples are given of some of the extraordinary measures taken to ensure continuous performance in service.

INTRODUCTION

Repeaters for use in the transatlantic submarine telephone cable system had to be designed to resist the stresses of laying, and to withstand the great pressures of water encountered in the North Atlantic route. In anticipation of the need for such a long telephone system in deep water, development work was started over 20 years ago on the design of a flexible repeater that could be incorporated in the cable and be handled as cable by conventional cable ship techniques. Successful completion, in 1950, of the design and construction of the 24-channel Key West, Florida-Havana, Cuba system,³ led to the adoption of similar repeaters designed for 36 channels for the North Atlantic link discussed in companion papers.^{1, 2}

Repeater transmission characteristics determine, to a large extent, the degree to which system objectives can be met. In this repeater, significant characteristics are:

(a) *Noise and Modulation*. These were established by the circuit configuration and by the use of the conservative electron tube⁸ developed for the Key West-Havana project.

(b) *Initial Misalignment*, or mismatch of repeater gain and cable loss throughout the transmitted band of frequencies. A match within 0.05 db was the objective. This affected both the design and the precision required in manufacture.

* Bell Telephone Laboratories.

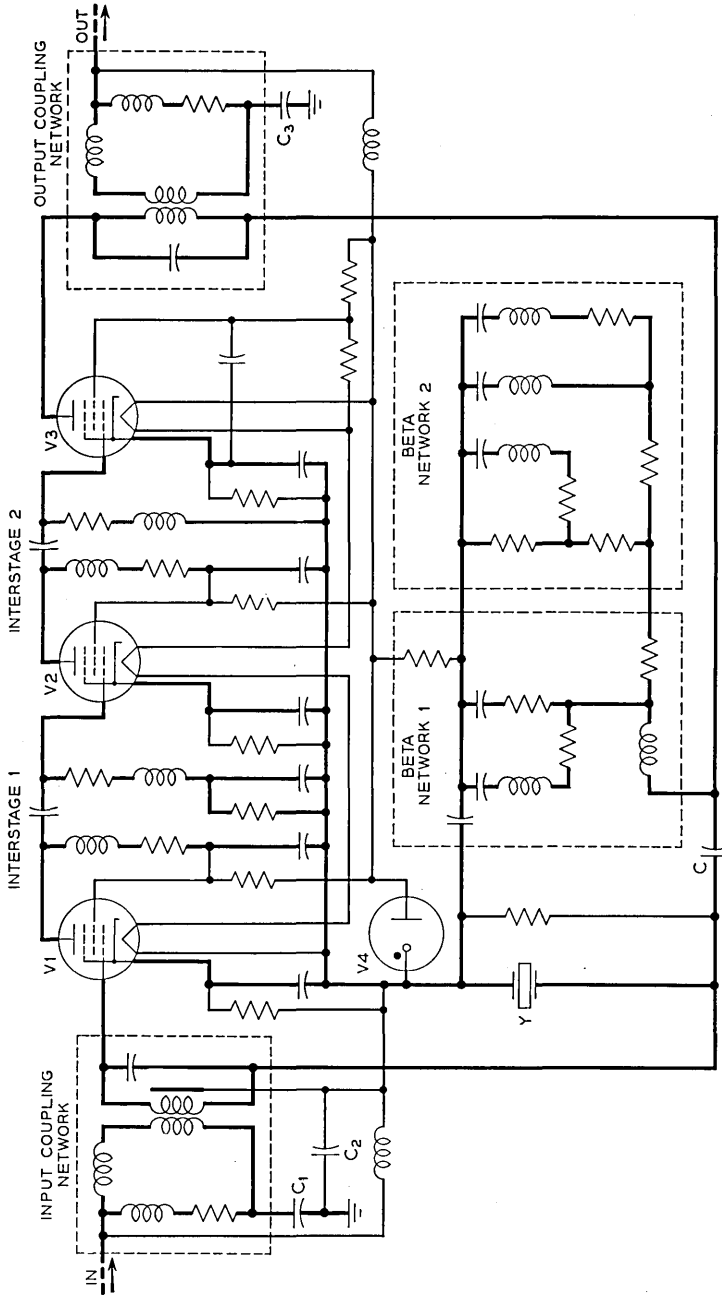


Fig. 1 — Repeater schematic.

(c) *Aging*. As electron tubes lose mutual conductance with age, repeater feedback decreases, repeater gain changes, and misalignment is affected. Decrease in feedback increases the gain at the higher frequencies so that the signal input must be reduced to prevent overloading, resulting in a signal-to-noise penalty. Gain increase is inversely proportional to the amount of feedback; in these repeaters, 33 to 34 db of feedback was the objective to keep this source of misalignment in bounds.

Because repeaters are inaccessible for maintenance, facilities are provided to enable the individual repeater performance to be checked from the shore end. This feature also permits a defective repeater to be identified in the event of transmission failure.

REPEATER UNIT

The repeater, for the sake of discussion, may be divided into two parts, (1) the repeater unit, which contains the electron tubes and other circuit components and (2) the water-proof container and seals which house the repeater unit.

Circuit

The circuit of the repeater unit is shown in Fig. 1. It is a three-stage feedback amplifier of conventional design with the cathodes at ac ground. The amplifier is connected to the cable through input and output coupling networks. Each coupling network consists of a transformer plus gain-shaping elements and a power separation inductor.

The coupling networks directly affect the insertion gain as do the two feedback networks. The design of these networks controls the insertion gain of the amplifier. The required gain (inverse of cable loss) is shown in Fig. 2. The 39 db shaping required between 20 and 164 kc is divided approximately equally among the input and output coupling networks and the feedback networks.

The interstage networks are of conventional design. The gain of the first interstage is approximately flat across the band. The second interstage has a sloping characteristic, the gain increasing with frequency. The gain shaping of these networks offsets the loss of the feedback networks so that the feedback is approximately flat across the band.

Plate and heater power is supplied to the repeater over the cable.⁴ The plate voltage (approximately 52 volts) is obtained from the drop across the heater string. The dc circuits are isolated from the container by the high voltage blocking capacitors C_1 , C_2 and C_3 .

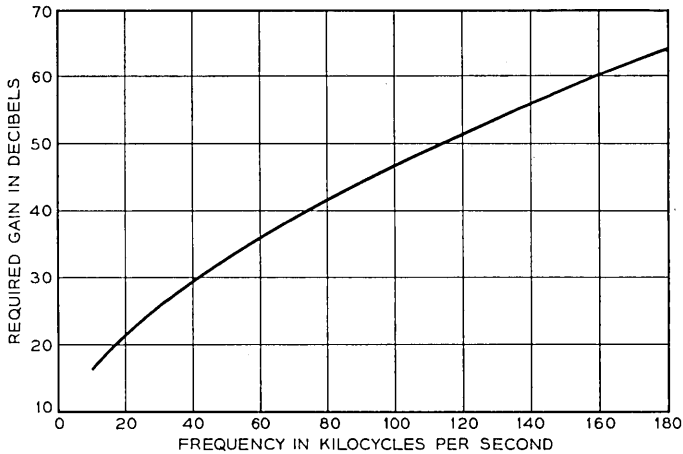


Fig. 2 — Required insertion gain.

Gain Formula

The circuit of Fig. 1 may be represented by a simplified circuit consisting of an input coupling network, a three stage amplifier, an output network and a feedback impedance Z_β as shown in Fig. 3. From this figure it can be shown that the insertion gain of the repeater is given by:⁶

$$e^\theta = \frac{2e^{\theta_1}e^{\theta_2}Z_c}{Z_\beta} \left[\frac{\rho_i\rho_0g_{mT}Z_1Z_2Z_\beta}{1 - \rho_i\rho_0g_{mT}Z_1Z_2Z_\beta} \right] \quad (1)$$

when $Z_\beta \ll g_{mT}Z_pZ_gZ_1Z_2 \gg (Z_0 + Z_p)$ and where

$$\rho_i = \frac{Z_g}{Z_i + Z_g} \quad \text{and} \quad \rho_0 = \frac{Z_p}{Z_0 + Z_p}$$

are "potentiometer terms". The gain of the input network is defined as $e^{\theta_1} = V/E_i$; where V is the open circuit voltage of the input network with E_i as the source, and the gain of the output network is defined as $e^{\theta_2} = i/I_1$. This expression may be put in familiar form by recognizing that $\rho_i\rho_0g_{mT}Z_1Z_2Z_\beta$ is $\mu\beta$, the feedback around the loop. Hence

$$e^\theta = \frac{2e^{\theta_1}e^{\theta_2}Z_c}{Z_\beta} \left[\frac{\mu\beta}{1 - \mu\beta} \right] \quad (2)$$

Equation (2) shows that the insertion gain of the repeater is the product of five factors, namely:

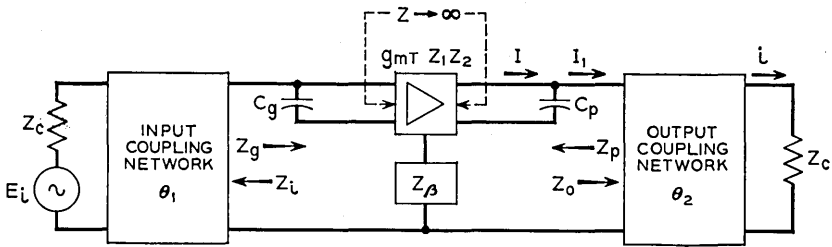
- (1) e^{θ_1} — the gain of the Input Network
- (2) e^{θ_2} — the gain of the Output Network
- (3) Z_c — the cable impedance
- (4) Z_β — the feedback impedance
- (5) $(\mu\beta/1 - \mu\beta)$ — the $\mu\beta$ effect term

It should be noted that a number of simplifying assumptions have been made. For example, the effect of grid plate capacitance has been neglected. In addition the β circuit has been assumed to be a two terminal impedance whereas it is actually a four terminal network. However, in the pass band and over a large part of the outband of the repeater these simplifications give a very good approximation to the true gain of the repeater.

In the pass band $(\mu\beta/1 - \mu\beta)$ is very nearly unity so that the gain controlling factors are e^{θ_1} , e^{θ_2} , and $1/Z_\beta$ assuming that Z_c is fixed.

Coupling Networks

The input and output networks are essentially identical. The networks are of unterminated design and therefore do not present a good termination to the cable at all frequencies which results in some ripple in the system transmission characteristic at the lower edge of the band and makes the repeater insertion gain sensitive to variations in the cable impedance. However, this arrangement has the advantage of maximum



V = OPEN CIRCUIT VOLTAGE OF INPUT COUPLING NETWORK WITH E_i AS THE SOURCE

θ_1 = GAIN OF INPUT COUPLING NETWORK DEFINED AS $e^{\theta_1} = V/E_i$

θ_2 = GAIN OF OUTPUT COUPLING NETWORK DEFINED AS $e^{\theta_2} = i/I_1$

$Z_1 Z_2$ = INTERSTAGE IMPEDANCES

g_{mT} = PRODUCT OF g_m OF THREE AMPLIFIER TUBES

Fig. 3 — Simplified amplifier circuit.

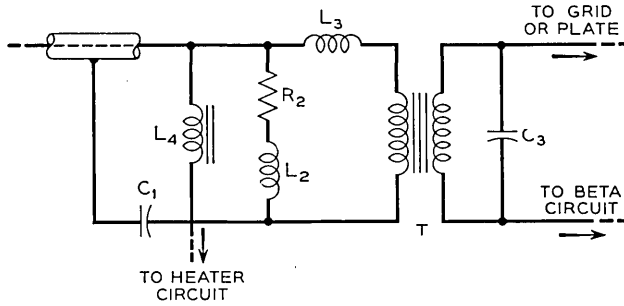
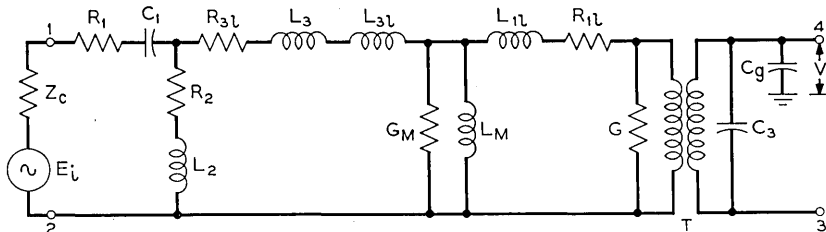


Fig. 4 — Coupling network.

signal to noise performance, highest gain, and most effective shaping with a minimum of elements. A minimum of elements is important in view of the space restrictions imposed by the flexible repeater structure. The sensitivity of the gain to variation in impedance is minimized by close manufacturing control of the cable and networks.

The schematic of a coupling network is shown in Fig. 4 and the equivalent circuit in Fig. 5. Capacitor C_1 and inductor L_4 are part of the power separation circuit. The effect of L_4 in the transmission band is negligible and it has been omitted from the equivalent circuit. However C_1 is in the direct transmission path and has a small effect at the lower edge of the band so that it becomes a design parameter. The combination R_2, L_2 controls the low-frequency gain shaping of the network. Inductor L_3



- | | |
|---|---------------------------------|
| C_1 — HIGH VOLTAGE BLOCKING CAPACITOR | L_M — MUTUAL |
| C_g — GRID CATHODE CAPACITANCE | G_M — CONDUCTANCE OF MUTUAL |
| C_3 — HIGH SIDE CAPACITANCE | G — HIGH SIDE CONDUCTANCE |
| Z_c — CABLE IMPEDANCE | L_3 — LEAKAGE BUILD-OUT |
| R_1 — RESISTANCE OF C_1 | T — IDEAL TRANSFORMER |
| R_{1l} } — RESISTANCE OF LEAKAGE | R_2 } — LOW FREQUENCY SHAPING |
| R_{3l} } | L_2 } — ELEMENTS |
| L_{1l} } | |
| L_{3l} } — LEAKAGE (LOW SIDE) | |

Fig. 5 — Equivalent circuit of coupling network.

builds out the leakage inductance of the transformer and together with capacitor C_3 controls the shaping at the top end of the band. These elements are adjusted during manufacture of the networks to provide the desired shaping.

The equivalent circuit is an approximation to the true transformer circuit. By standard network analysis techniques the ratio V/E_i , the gain of the network, can be obtained. The agreement between measurements and computation is sufficiently close, several hundredths of a db, to insure that the representation is good.

Each coupling network is designed to provide approximately one-third of the total shaping required, or 13 db. While these networks are

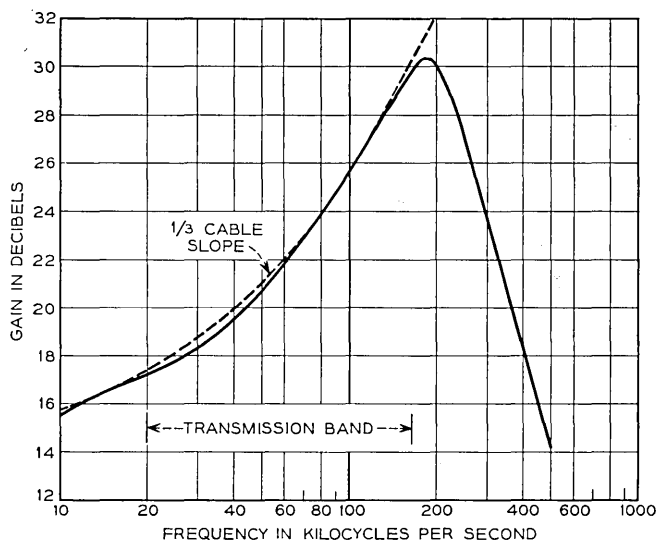


FIG. 6 — Gain of input coupling network.

outside the feedback path, the impedances which they present to the amplifier are important factors in the feedback design. It can be seen from Fig. 3 that at the amplifier input the proportion of the feedback voltage which will be effective in producing feedback around the loop is dependent upon the potentiometer division between the grid-cathode impedance of the first tube and the impedance looking back into the coupling network. The greater the gain shaping of the network, the greater the potentiometer loss. The maximum gain which can be obtained from the coupling network is limited by the capacitance across the circuit. This capacitance cannot be reduced without increasing the

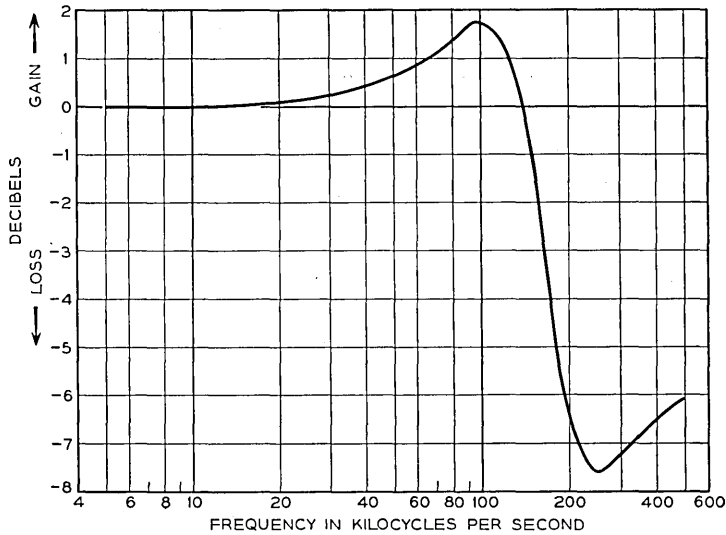


Fig. 7 — Input potentiometer term.

potentiometer loss, and seriously limiting feedback. In this design an acceptable compromise is made when the ratio of network capacitance to grid-cathode capacitance has been fixed at 1.2 as suggested by Bode.⁶ The gain through the input network and the deviation from one-third cable shape is shown in Fig. 6. A typical potentiometer term is shown in Fig. 7

Similar considerations apply to the output network with the further restriction that the impedance presented to the output tube should be about 40,000 ohms at the top edge of the band for optimum modulation performance.

The coupling networks have a temperature characteristic which must be taken into account in the insertion gain of the repeater. The characteristic is due to variations in the resistance of C_1 and R_2 with temperature. This amounts to 0.005 db per degree F at 20 kc, decreasing with frequency, becoming negligible above 80 kc.

Beta Circuit

The beta or feedback network is designed to complement the combined characteristics of the input and output coupling networks and mop-up residual effects, such as those due to $\mu\beta$ effect and coupling network temperature coefficients. The network also provides the dc path for the output tube plate current.

The configuration of the beta circuit is shown in Fig. 8. In the pass band it is a two terminal network whose impedance varies from about 300 ohms at 20 kc to 70 ohms at 164 kc. It consists of essentially two parts. The elements to the left of the dotted line provide the major portion of the shaping. With these the repeater is within ± 0.7 db of the required gain. The series resonant circuits to the right of the dotted line reduce this to the ± 0.05 db set as the objective.

The mopping up elements are connected to the main portion of the beta circuit through a resistance potentiometer R_1 , R_2 and R_3 . This scales the elements of the resonant circuits to values which would meet mounting space and component restrictions.

Built-in Testing Features

The crystal Y and capacitor C , Fig. 1, in the feedback path provide the means for checking the repeater from the shore station. The crystal is a sharply tuned series-resonant shunt on the feedback path which reduces the feedback at the resonant frequency and produces a narrow peak in the insertion gain characteristic of the repeater. The feedback reduction, and hence the peak gain, is controlled by the potentiometer divider formed by the reactance of the capacitor and the series resonant resistance of the crystal. The crystal and capacitor are chosen so that substantially all the feedback is removed from the repeater. With no feed-

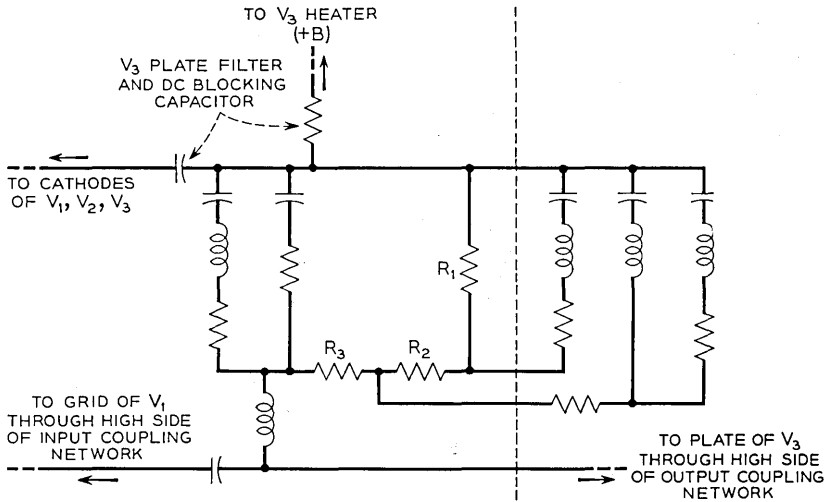


Fig. 8 — Beta network.

back the peak gain is proportional to the mutual conductance of the three tubes.

At frequencies well off resonance the impedance of the crystal is high so that no reduction in feedback results. Periodic measurements of gain at the resonant frequency relative to measurements made at a frequency off resonance will show any changes in the tubes. The crystal frequency is different for each repeater so that by measuring the gain from the shore stations at the various crystal frequencies it is possible to monitor the performance of the individual repeaters.

The increase in gain at the peak is approximately 25 db. The crystal frequencies, spaced at 100-cycle intervals, are placed above the normal transmitted band between 167 and 173.4 kc.

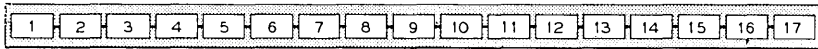
Thermal noise always present at the input to the repeater, is also amplified over the narrow band of frequencies corresponding to the peak gain in each repeater so that at the receiving end of the line there are a series of noise peaks, one for each repeater. Should a repeater fail, the noise peaks of all repeaters between the faulty repeater and the receiving end will be present and those from repeaters ahead will be missing. By determining which peaks are missing the location of the failed repeater can be determined. It is obvious that to locate a faulty repeater the power circuit must be intact. To guard against power interruption owing to an open electron-tube heater, a gas tube V4, Fig. 1, is connected across the heater string as a bypass.

Loop Feedback

The design of the feedback loop follows conventional practice. The restrictions that limit the amount of feedback that can be obtained in the transmitted band are well known.⁶ Broadly speaking, the figure of merit of the electron tubes and the incidental circuit capacitances determine the asymptotic cutoff which limits the amount of feedback that can be obtained in the band. With the flexible repeater circuit, capacitances are rather large because of the severe space restrictions and physical length of the structure. Transit time of 1.8° per megacycle per tube and a like amount for the physical length of the feedback loop reduced the available feedback by 2 db.

Margins of 10 db at phase cross-over and 30° at gain cross-over were set as design objectives. While these may seem to be ultraconservative in view of the tight controls placed on components and the mechanical assembly, it should be borne in mind that the repeaters are inaccessible and repairs would be costly.

Modulation and tube aging considerations require a minimum feed-



- | | |
|------------------------------|------------------------------|
| 1 INPUT TERMINAL | 10 VACUUM TUBE (THIRD STAGE) |
| 2 INPUT BLOCKING CAPACITOR | 11 OUTPUT NETWORK |
| 3 GROUNDING CAPACITOR | 12 BETA NETWORK (1) |
| 4 CRYSTAL | 13 BETA NETWORK (2) |
| 5 INPUT NETWORK | 14 GAS TUBE |
| 6 VACUUM TUBE (FIRST STAGE) | 15 DRYER |
| 7 FIRST INTERSTAGE NETWORK | 16 OUTPUT BLOCKING CAPACITOR |
| 8 VACUUM TUBE (SECOND STAGE) | 17 OUTPUT TERMINAL |
| 9 SECOND INTERSTAGE NETWORK | |

Fig. 9 — Repeater make-up.

back of 33–34 db. With the restrictions noted above and the effect of the potentiometer terms on the available feedback, the top edge of the band is limited to about 165 kc with the desired feedback.

Mechanical Design

To provide a flexible structure the repeater unit is assembled in a number of longitudinal sections mechanically coupled by helical springs and electrically interconnected by means of bus tapes. The assembly is composed of 17 sections. Figs. 9 and 10 show the repeater make-up and an assembled unit.

The sections consist of the circuit component, or components, mounted in machined plastic forms and enclosed in a plastic container which in turn is enclosed in a housing of the same material.* The sections contain circuit components grouped functionally such as input coupling network, interstage, electron tube, or high voltage blocking capacitor. In the case of the feedback network it was necessary to mount the network in two sections because of the large numbers of components involved. A typical network, container and housing are shown in Fig. 11.

The bus tapes are placed in grooves milled in the outer surfaces of the

* The material used is methyl methacrylate which was chosen for its physical and chemical stability and good machinability.

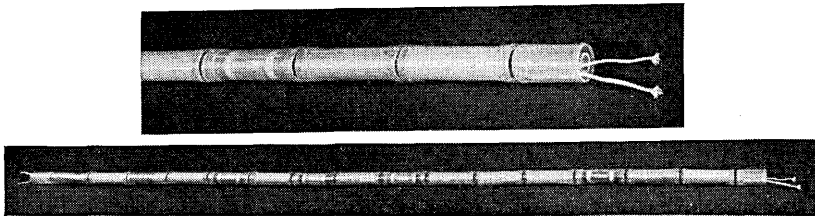


Fig. 10 — Overall view of the repeater unit.

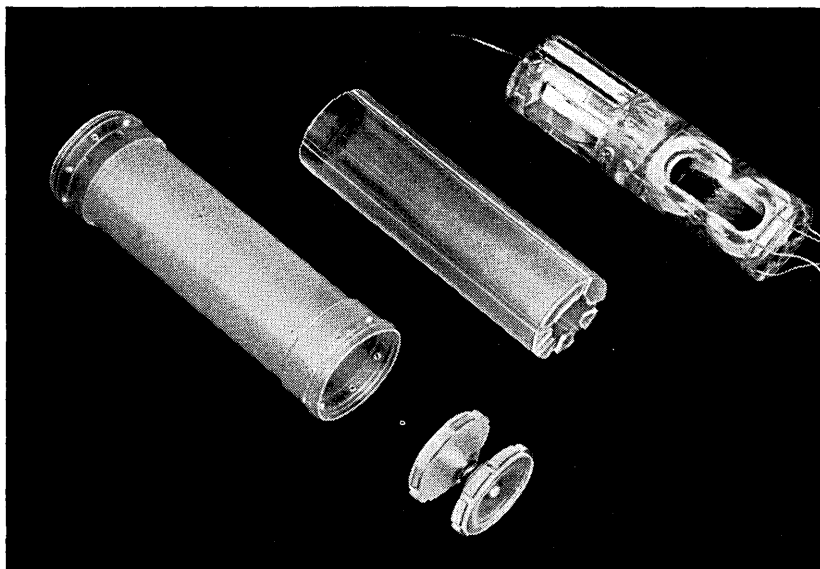


Fig. 11 — Network section.

section containers. Wiring spaces are machined into the ends of the containers for connecting network leads to the bus tapes. The housing is placed over the container and the buses and is closed by a plastic coupler plate which also forms part of the intersection couplers. The coupler plates are fastened to the housing with plastic pins.

Between sections the bus tapes are looped toward the longitudinal axis of the repeater unit. The dimensions of the loop are rigidly controlled so that as the unit is flexed during bending of the repeater, the loops always return to their original location between sections and do not short to each other or the metal outer container. The bus tapes have either an electrical connection or lock at one end of each section to eliminate any tendency of the tapes to creep as the repeater unit is flexed.

The buses consist of two copper tapes in parallel to guard against opens should one tape break. The design of the connections to the buses is such that once the section is closed there can be no disturbance of the tapes or network leads in the vicinity of the electrical connections. The bus-type wiring plan was chosen as the best arrangement for the long structure in keeping with the stringent transmission requirements. Electrically adjacent but physically remote components can thus be inter-

connected with careful control of the parasitic capacitances and couplings to insure reproducibility from unit to unit in manufacture.

COMPONENTS

The development of passive components for use in the flexible repeater presented a number of unusual problems, the most important being: (1) the extreme reliability, (2) the high degree of stability, (3) the limitations on size and shape and, (4) an environment of constant low temperature.

The repeaters for the transatlantic system contain a total of approximately 6,000 resistors, capacitors, inductors and transformers. If we are to be 90 per cent certain of attaining the objective of 20 years service without failure of any of these components, the effective average annual failure rate for the components must be not more than 1 in a million. To assure this degree of reliability by actual tests would require more than 400 years testing on 6,000 components. Obviously some other approach to insure reliability is required. The most obvious avenue, that of providing a large factor of safety, was not open because of space limitations.

Fortunately, with only one exception, the passive components do not wear out. Thus the approach to reliability could be made by one or more of the following:

1. The use of constructions and materials which have been proved by long use, particularly in the Bell System.
2. The use of only mechanically and chemically stable materials.
3. The use of extreme precautions to avoid contamination by materials which might promote deterioration.
4. Special care in manufacture to insure freedom from potentially hazardous defects.

The philosophy of using only tried and proved types of components dictated the use of wire wound resistors, impregnated paper and silvered mica capacitors and permalloy cores for inductors and transformers. While newer and, in some ways, superior materials are known, none of these possessed the necessary long record of trouble-free performance. In some cases, particularly in resistors, this approach resulted in more difficult design problems and also in physically larger components. While the ambient conditions in the repeater, i.e., low temperatures and extreme dryness, are ideal from the standpoint of minimizing corrosion or other harmful effects of a chemical nature, the materials used in the fabrication of components were nevertheless limited to those which are in-

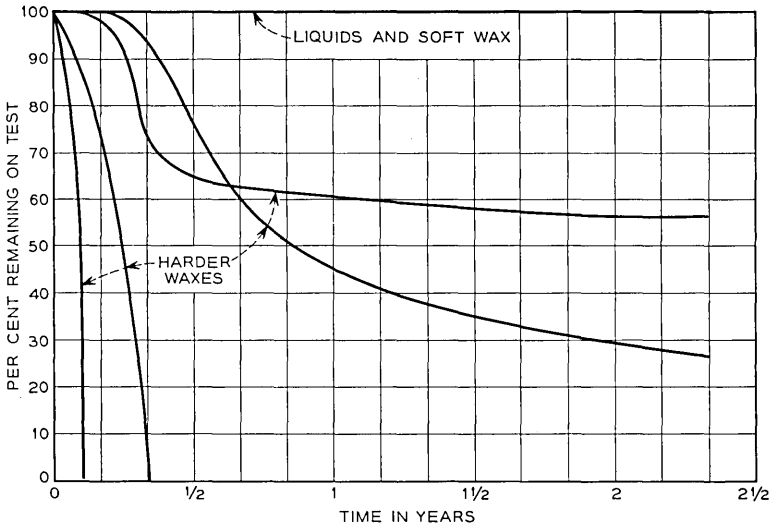


Fig. 12 — Accelerated life tests on paper capacitors with various impregnants at room temperature (60° to 80°F).

herently stable and nonreactive. In addition, raw materials were carefully protected from contamination from the time of their manufacture until they were used, or, wherever possible, they were cleaned and tested for freedom from contaminants just prior to use. Unusually detailed specifications were prepared for all materials.

The effort to achieve extreme reliability also influenced or dictated a number of design factors such as the minimum wire diameters used in wound apparatus, the use of as few electrical joints as possible and the use of relatively simple structures. These limitations resulted in the use of unencased components in most instances. Wherever possible, the ends of windings were used as terminal leads to avoid unnecessary soldered connections. This injected the additional hazard of lead breakage owing to handling during manufacture and inspection. This hazard was minimized in most instances by providing the windings with extra turns which were removed just before the component was assembled in the network. Thus, the lead wires in the final assembly had never been subjected to severe stress. Where this technique was impracticable, special fixtures and handling procedures were used to prevent undue flexing or stressing of lead wires.

As mentioned above there was one type of passive component in which life is a function of time and severity of operating conditions. These are the capacitors, especially those subject to high voltages. Because of this

and the fact that the physical and electrical requirements dictated the use of relatively high dielectric stress in these capacitors, a program of study covering a wide range of dielectric materials was undertaken about 1940. This study showed that none of the usual solid or semisolid materials used to impregnate paper capacitors were suitable for continuous use at sea bottom temperatures. Typical results of this program are shown in Figs. 12 and 13. These curves show the performance of capacitors operating at approximately 1.8 times normal dielectric stress at both sea bottom and room temperatures. It is evident that even semisolid impregnants are inferior to liquids at the lower temperature. The need for the maximum capacitance in a given space restricted the field still further, so that the final choice was a design using castor-oil-impregnated kraft paper as the dielectric.

It is well established that the life of impregnated paper capacitors is inversely proportional to the fourth to sixth power of the voltage stress; or

$$\frac{L_1}{L_2} = \left(\frac{V_2}{V_1}\right)^p$$

where p ranges from 4 to 6. This fact permits the accumulation of a large amount of life information in a relatively short time. In order to insure

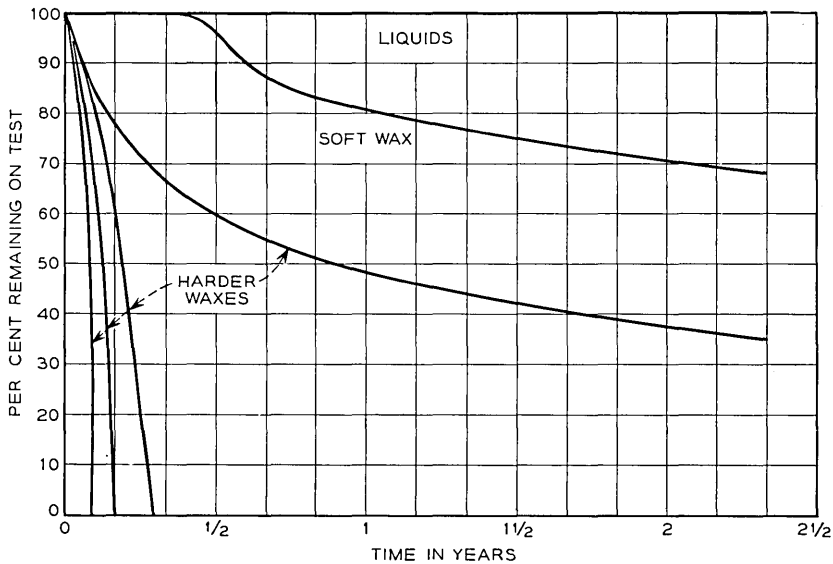


Fig. 13 — Accelerated life tests on paper capacitors with various impregnants at 40°F.

that the capacitor design selected would provide the degree of reliability required, a number of capacitors were constructed and placed on test at voltage stresses ranging from $1\frac{1}{2}$ to $2\frac{1}{4}$ times the maximum stress expected in service. From the performance of these samples, a prediction of performance under service conditions can be made as follows:

The total equivalent exposure in terms of capacitor years at the maximum service voltage can be computed for the samples under test by the following summation:

$$T = N_1 T_1 \left(\frac{V_1}{V_s} \right)^p + N_2 T_2 \left(\frac{V_2}{V_s} \right)^p + \cdots + N_r T_r \left(\frac{V_r}{V_s} \right)^p \quad (1)$$

where N_1, N_2, \cdots, N_r are the number of samples on test at voltage stresses V_1, V_2 and V_r , T_1, T_2, \cdots, T_r are the total times of the individual tests and V_s is the maximum voltage stress under service conditions.

If, as has been the case in the tests described above, there has been only one failure in the total exposure T , we can estimate from probability equations the limits or bounds within which the first failure will occur in a system involving a given number of capacitors operating at a voltage stress V_s . These equations are:

$$\text{probability of no failures in exposure } T = e^{-(T/L)} \quad (2)$$

probability of more than one failure in exposure time $T =$

$$1 - \left(1 + \frac{T}{L} \right) e^{-T/L} \quad (3)$$

where T is obtained from (1) and L is the total exposure in the same units as T for the service conditions. The solutions of (2) and (3) for L using any desired probability give the maximum and minimum exposures in capacitor-years, within which the first failure may be expected to occur under service conditions.

However, since the voltage on the capacitors varies from repeater to repeater, it is necessary to determine the equivalent exposure of the system in terms of capacitor-years per year of operation at the maximum service voltage in order to estimate the time to the first failure in the system. This is obtained from (1) for one-half of one cable by substituting the supply voltage at each repeater for V_1, V_2 , etc., the maximum service voltage for V_s and the number of capacitors per repeater for N . The total exposure for a two cable system is then 4 times this figure. With the data which has been accumulated and the number of capacitors and voltages of the transatlantic system, we estimate with a probability of being correct nine times in ten that the first "wear-out" failure of a

capacitor in the transatlantic system will not occur in less than 16 years nor more than 600 years.

There is, of course, the possibility of a catastrophic or early failure due to mechanical or other defects not associated with normal deterioration of the dielectric. Such potential failures are not always detected by the commonly used short-time over-voltage test. Thus, for submarine cable repeaters, all capacitors subjected to dc potentials in service are subjected to at least $1\frac{1}{2}$ times the maximum operating voltage for a period of four to six months before they are used in repeaters. Experience indicates that this is adequate to detect potential early failures. The results of this type of testing on submarine cable capacitors is an indication of the care used in selecting materials and manufacturing the capacitors. Only one failure has occurred in more than 3,000 capacitor-years of testing.

An important aspect of the control of quality of components is the control of the raw materials used in their manufacture. For the transatlantic project, this was accomplished by rigid specifications, thorough inspection and testing, supplemented in some cases by a process of selection.

This can be illustrated by the procedure used for selecting the paper used as the dielectric in capacitors. The Western Electric Company normally inspects many lots of capacitor paper during each year. Those lots which were outstanding in their ability to stand up under a highly accelerated voltage test were selected from this regular inspection process. These selected lots were then subjected to a somewhat less highly accelerated life test. Paper which met the performance requirements of this test was slit into the proper widths for use in capacitors. Sample capacitors were then prepared with this paper and so selected that they represented a uniform sampling of the lot at the rate of one sample for approximately each three pounds of paper. These samples were impregnated with the same lot of oil to be used in the final product. Satisfactory completion of accelerated life and other tests on these samples constituted final qualification of the paper for production of capacitors. Relatively few raw materials were adaptable to such tests or required such detailed and exhaustive inspection as capacitor paper. But the attitude in all cases was that the material be qualified not only as to its primary constituents or characteristics but also as to its uniformity and freedom from unwanted properties.

To a considerable extent, stability of components is assured by the practice of using only those types of structures which have long records of satisfactory field performance. However, in some cases, a product far

more stable than usual was required. This was true of the high voltage capacitors where other requirements dictated the use of impregnated paper as the dielectric but where the degree of stability required was comparable to that expected of more stable types of capacitors. In so far as possible, stability was built into the components by appropriate design but, where necessary, stabilizing treatments consisting of repeated temperature cycles were used to accelerate aging processes to reach a stable condition prior to assembly of the repeaters. Temperature cycling or observation over periods up to six months were used also to determine that the components' characteristics were stable.

Exceptional inspection procedures followed to insure reliability and stability are described in detail in a companion paper.⁷

As mentioned earlier, the design and construction of components was simplified by omitting housings or containers, except for oil impregnated paper capacitors. Adequate mountings for the components were obtained in several ways. Mica capacitors were cemented to small bases of methyl methacrylate which were in turn cemented in suitable recesses in network structures. Inductors and transformers were cemented directly into recesses in the network housings. Fig. 14 illustrates some of these structures and their mounting arrangements. On the bottom is a molybdenum permalloy dust core coil in which a mounting ring of methyl

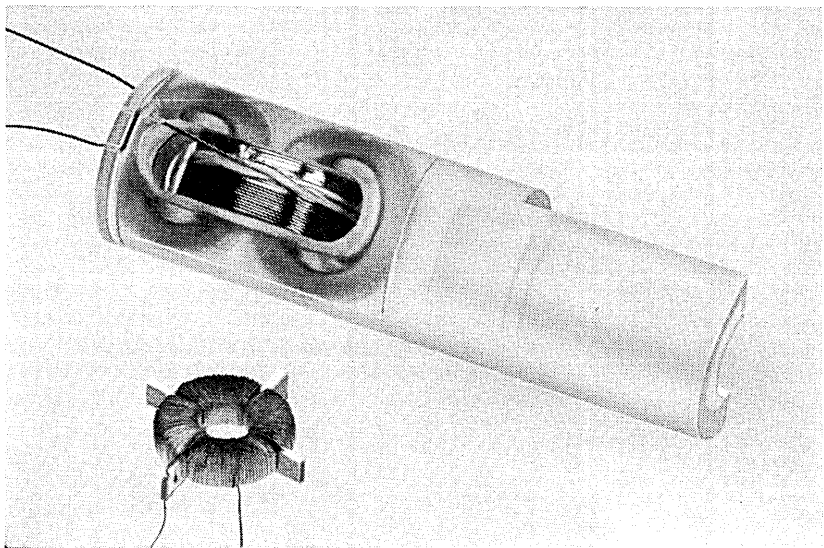


Fig. 14 — Mounting for molybdenum permalloy dust core coils.

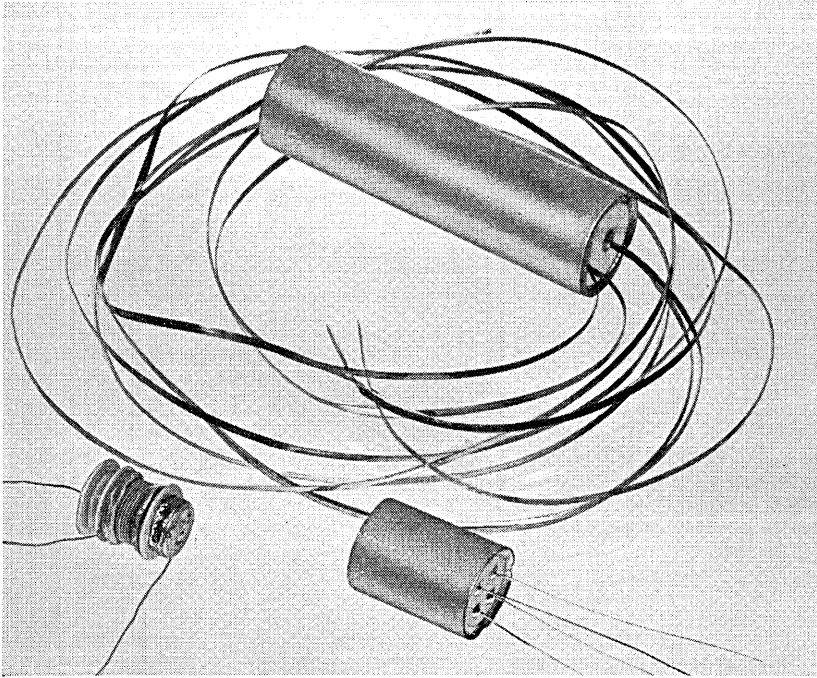


Fig. 15 — Capacitor and resistor capacitor combinations.

methacrylate provided with radial fins is secured around the core by tape and the wire of the winding. Such inductors were mounted by cementing the projecting fins into slots arranged around a recess in the network housing. On top is an inductor which, for electrical reasons, required a core of greater cross-section than could be accommodated in the network when made by the usual toroidal construction. In this case, the effective cross-section of two cores was obtained by cementing the cores in a "figure-8" position and by applying the winding so that it threads the hole in both cores. With these constructions, the cement used to secure the inductors does not come into contact with the wire of the winding which is thereby not subject to strains produced by curing of the cement.

For economy of space and also to reduce the number of soldered connections, many of the components' structures contain two or more elements. Inductors and resistors were combined by winding inductors with resistance wire. Separate adjustment of inductance and resistance were obtained by adjusting turns for inductance and the length of wire in a

small "non-inductive" winding for resistance. The inductor on the bottom in Fig. 14 illustrates one type in which the non-inductive part of the winding is placed on one of the separating fins. In some cases, capacitors and resistors were also combined. Fig. 15 shows two of these. The capacitor at the bottom right contains three capacitances and a single resistance in the same container. This construction requires that the resistor parts be capable of withstanding the capacitor drying and impregnation process and also that the resistor contain nothing which would be harmful to the capacitor. The capacitor on the left in this figure is housed in a ceramic container on which is wound a resistor. The capacitor at the top is a high-voltage type which, aside from electron tubes, represents the largest single component used in the repeater. In this capacitor, the tape terminals which contact the electrodes are brought out through the ceramic cover and are made long enough to reach an appropriate point so as to avoid additional soldered connections. Such special designs introduced many problems in the manufacture of the components. However, the improved performance of the repeater and the increase in the inherent reliability of the overall system fully justified the greater effort which was required for the production of such specialized apparatus.

POWER BY-PASS GAS TUBE*

The fault locating means, referred to previously, requires that the power circuit through the cable be continuous. To protect against an open circuit in the repeater, such as a heater failure, an additional device is required to bypass the line current. This bypass must be a high resistance under normal operating conditions since any current taken by this device must be supplied through preceding repeaters. If an open circuit occurs the bypass must carry the full cable current. At full current, the voltage drop should be small to avoid excessive localized power dissipation in the repeater. The device should recover when power is removed so that false operation by a transient condition will not permanently bypass the repeater.

A gas diode using an ionically heated cathode has been used to meet these requirements. By making the breakdown voltage safely greater than the drop across the heater string, no power is taken by the tube under normal repeater operation. In the event of an open circuit in the repeater, the voltage across the tube rises and breakdown occurs. Full cable current is then passed through the gas discharge. Removal of power

* Material contributed by Mr. M. A. Townsend.

from the cable allows the tube to deionize and recover in the event of false triggering by transients. The cathode is a coil of tungsten wire coated with a mixture of barium and strontium oxide. A cold cathode glow discharge forms when the tube is first broken down. This discharge has a sustaining voltage of the order of 70 volts. The glow discharge initially covers the entire cathode area. Local heating occurs and some parts of the oxide coating begin to emit electrons thermionically. This local emission causes increased current density and further increases the local heating. The discharge thus concentrates to a thermionic arc covering only a portion of the coil. The sustaining voltage is then of the order of 10 volts.

Mechanically the tube was designed to minimize the possibility of a short circuit resulting from structural failure of tube parts. Fig. 16 shows the construction of the tube. The glass envelope and stem structure which had previously been developed for the hot cathode repeater tubes were used as a starting point for the design. The anode is a circular disk of nickel attached to two of the stem lead wires. To provide shock resistance the supporting stem leads are crossed and welded in the center. To protect against weld failure, a nickel sleeve is used at each end of the cathode

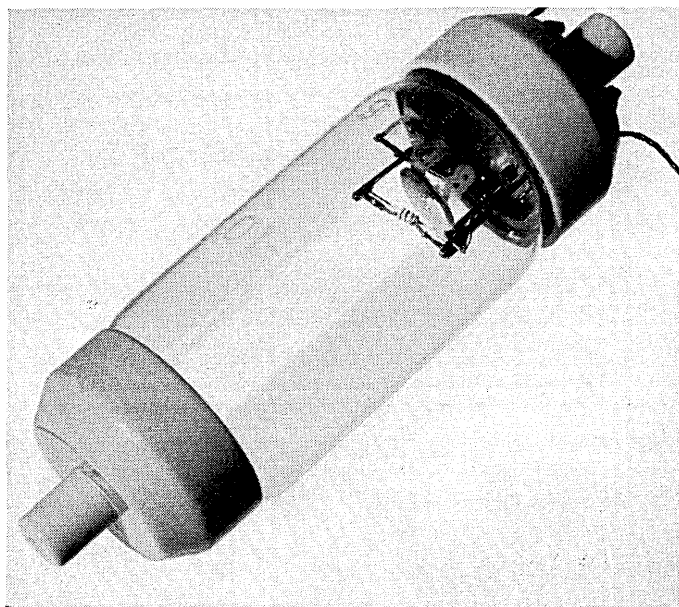


Fig. 16— The power by-pass gas tube.

coil. It is crimped to hold the coil mechanically in place and then welded at the end for electrical connection. At the end of the coil as well as in all other places where it is possible, a mechanical wrap is made in addition to spot welding. An additional precaution is taken by inserting an insulated molybdenum support rod through the center of the cathode coil. The filling gas is argon at a pressure of 10 mm Hg. To provide initial ionization, 1 microgram of radium in the form of radium bromide was placed on the inside of the tube envelope. All materials were procured in batches of sufficient size to make the entire lot of tubes and carefully tested before being approved for use. The tubes were fabricated in small groups and a complete history was kept of the processing of each lot.

For detailed study of tube performance, a number of electrical tests were made. These involved measurements of breakdown voltage, operating voltage as a glow discharge at low current, current required to cause the transition to a thermionic arc, the time required at the cable current to cause transition to the low voltage arc, and the sustaining voltage at the full cable current.

All tubes were aged by operating at 250 milliamperes on a schedule which included a sequence of short on-off periods (2 min. on, 2 min. off) followed by periods of continuous operation. A total of 150 starts and 300 hours of continuous operation were used. Following this aging schedule the tubes were allowed to stabilize for a few days and then subjected to a 2-hour thermal treatment or pulse at 125°C. It was required that no more than a few volts change in breakdown voltage occur during this thermal pulse before a tube was considered as a candidate for use in repeaters.

After aging and selection as candidates for repeaters, tubes were stored in a light-tight can at 0°C. Measurements were made to assure stability of breakdown voltage and breakdown time.

The quality of each group of 12 tubes was further checked by continuous and on-off cycling life tests. The fact that none of these tubes has failed on the cycling tests at less than 3,500 hours and 1,500 starts and no tube on continuous operation has failed at less than 4,200 hours gives assurance that system tubes will start once and operate for the few hours necessary to locate a defective repeater. Long-term shelf tests of representative samples at 70°C and at 0°C give assurance of satisfactory behavior in the system.

CONTAINER AND SEALS

The design of the flexible enclosure for the flexible repeater unit is basically the same as it emerged from its development stages in the

1930's. It is virtually identical to the structure of the repeaters manufactured by the Bell Telephone Laboratories for the cables laid in 1950 between Key West and Havana.³

The functions of the enclosure are to protect the repeater unit from the effects of water at great pressure at the ocean bottom; to provide means of connecting the repeater to the cable before laying; and to be slender and flexible enough to behave like cable during laying. How these functions are met in the design may be more readily understood by reference to Fig. 17.

The repeater unit, described earlier, is surrounded by a two-layer carcass of steel rings, end to end. The rings are surrounded in turn by a copper tube $1\frac{3}{4}$ inches in diameter and having a $\frac{1}{32}$ -inch wall.

When a repeater is bent during laying by passing onto the cable-ship drum, the steel rings separate at the outer periphery of the bend and the copper tube stretches beyond its elastic limit. As the repeater leaves the drum under tension the rings separate and the copper stretches on the opposite side, leaving the repeater in a slightly elongated state. At the ocean bottom, hydraulic pressure restores the repeater to its original condition with rings abutted and the copper tube reformed.

The system of seals in each end of the tube consists of (1) a glass-to-Kovar seal adjacent to the repeater unit, (2) a rubber-to-brass seal seaward from the glass seal, and (3) a core tube and core sleeve seal seaward from the rubber seal.

The glass seal, although capable of withstanding sea bottom pressures, is primarily a water vapor barrier and a lead-through for electrical connection to the repeater circuit. In service it is normally protected from exposure to sea pressures by the rubber seal.

The rubber seal, capable of withstanding sea bottom pressures, is indeed exposed to these pressures for the life of the repeater, but is not exposed to sea water. It is likewise a lead-through for electrical connection from the cable to the glass seal.

The core sleeve seal is an elastic barrier between sea water on the outside and a fluid on the inside. This fluid, polyisobutylene, is a viscous honey-like substance, chemically inert, electrically a good insulator, and a moderately good water vapor barrier. It fills the long thin annular space outside the cable core and inside a copper core tube and thus becomes the medium of transmitting to the rubber seal the sea pressure exerted on the core sleeve. It can be seen that the core sleeve seal has nominally no pressure resisting function and no electrical function.

The same fluid is also used to fill the space between the glass and rubber seals. Voids at any point in the system of seals are potential hazards to long, trouble-free life. Empty pockets, for instance, lying between the

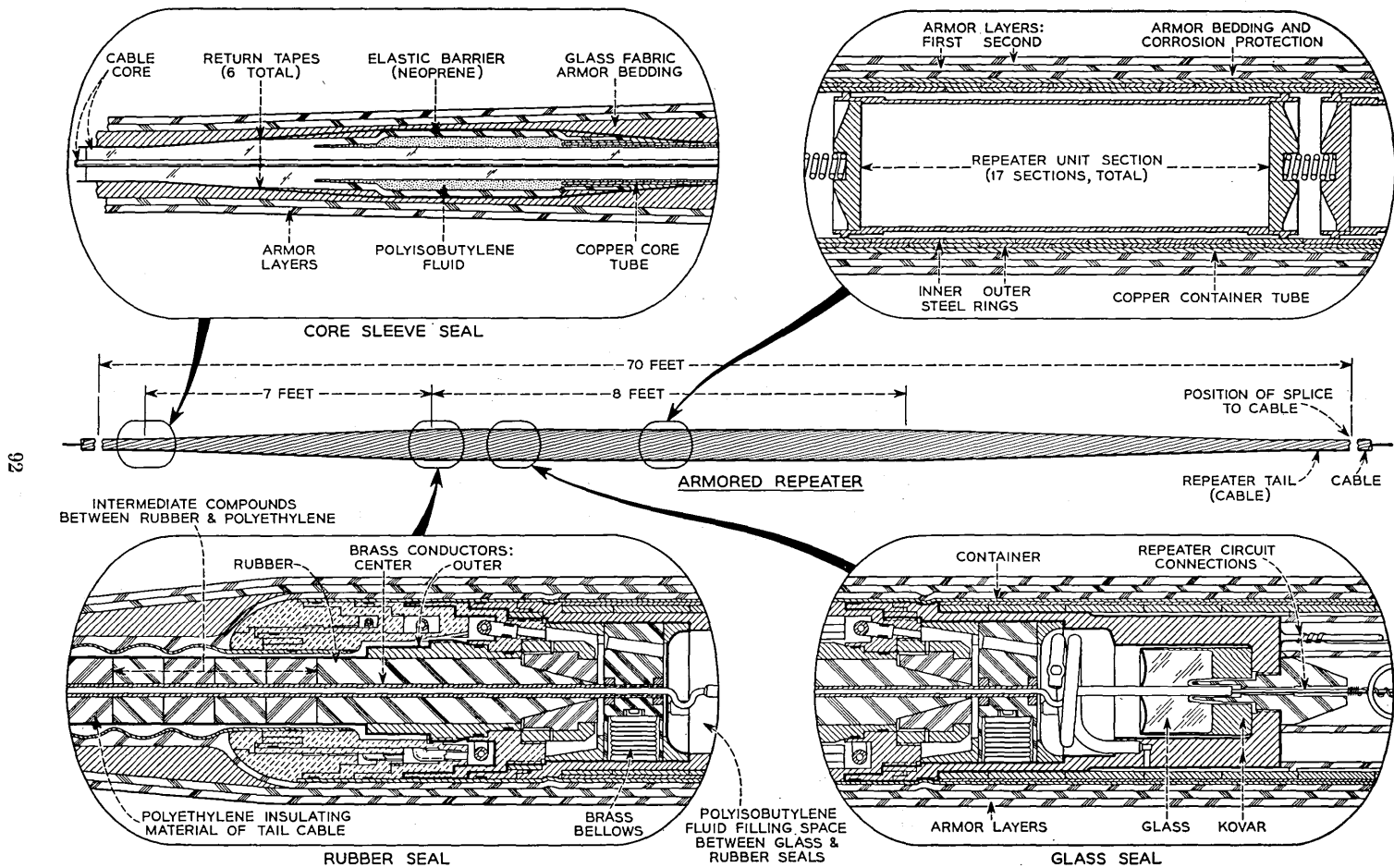


Fig. 17 — Details of container and seals.

central conductor and the outer conductor, or container, are capable of becoming electrically conducting paths if filled with water vapor. As pointed out in companion papers,^{2, 4} the voltage between the repeater (and cable) central and outer conductors is in the neighborhood of 2,000 volts at the ends of the transatlantic system.

The filling of the seal interspace with a liquid would defeat one function of the rubber seal if special features were not provided in the rubber seal design. Very slight displacement of the rubber seal toward the glass seal because of sea pressure, or resulting from reduction in volume owing to falling temperature, would otherwise build up pressure in the liquid and on the glass seal. We avoid this by providing a kind of resilience in the interspace chamber. Three small brass bellows, partly compressed, occupy fixed cavities in the chamber. They can compress readily and maintain essentially constant conditions independent of external pressures and temperatures.

The entire repeater assembly enclosed in copper is approximately 23 feet long. Tails of cable at each end make the total length about 80 feet before splicing. The central conductor of each cable tail is joined to the rubber seal central conductor, with the insulation molded in place in generally the same manner as in cable-to-cable junctions elsewhere in the system. The outer-conductor copper tapes of the cable tails are electrically connected to the copper core tubes.

The copper region is coated with asphalt varnish and gutta percha tape to minimize corrosion. Over this coating bandage-like layers of glass fabric tape are built up to produce an outer contour tapering from cable diameter at one end up to repeater diameter and back down to cable diameter at the opposite end. The tape covering is saturated with asphalt varnish. This tape is primarily a bedding for the armor wires that are laid on the outside of both cable tails and repeater to make the repeater cable-like in its tensile properties and capable of being spliced to cable.

In the region of the repeater proper where the diameter is double that of cable, extra armor wires are added to produce a layer without spaces. Also, to avoid subjecting the repeater to the torque characteristically present in cable under the tensions of laying, a second layer of armor wires of opposite lay is added over the first layer. This armoring process is so closely related to the armoring of cable core in a cable factory that it is performed there.

Materials

Following the same design philosophy applied to the repeater components, the materials of construction of the repeater container and seals

were chosen for maximum life, compatibility with each other, and for best adaptability to the design intent. Specifications particularly adapted to this use were set up for all of the some 50 different metals and non-metals employed in the enclosure design. In general, the methods established for proving the integrity of the materials are more elaborate than usual commercial practice. In most instances, such as that of copper container tubes, the extraordinary inspection for defects and weaknesses with its resulting rejection rate, resulted in high cost for the usable material.

TESTING

A substantial part of the development work on the repeater enclosure was concerned with devising tests that give real assurance of soundness and stability. It is beyond the scope of this paper to discuss how each part is tested before and after it is assembled but certain outstanding tests deserve mention.

Steel Ring Tests

Each of the inner steel rings, before installation, is required to pass a magnetic particle test to find evidence of hidden metallurgical faults. Each ring is later a participant in a group test under hydraulic pressure simulating the crushing effect of ocean bottom service but exceeding the working pressures. The magnetic particle test is repeated.

Helium Leak Tests

Both glass and rubber seal assemblies, before being installed in repeaters, are required to undergo individual tests under high-pressure helium gas. Helium is used not only because its small molecules can pass through smaller leaks than can water molecules but because of the excellent mass spectrometer type of leak detectors commercially available for this technique. While helium is applied at high pressure to the outer wall of the seal, the inner wall is maintained under vacuum in a chamber joined with the leak detector. The passage of helium through a faulty seal at the rate of 10^{-9} milliliters per second can be detected. Stated differently, this is 1 milliliter of helium in 30 years. The relation of water-leak rate to helium-leak rate is dependent on the physical nature of the leak, but if they were assumed to be equal rates, the amount of water which might enter a tested repeater in 20 years would be 0.66 grams. A desiccant within the repeater cavity is designed to keep the

relative humidity under 10 per cent if the water intake were five times this amount.

After glass seals are silver brazed into the ends of the copper tube of the repeater the helium test is repeated to check the braze and to re-check the seal. For this test the entire repeater must necessarily be submerged in high pressure helium. Obviously, in order to sense a possible passage of the gas from the outside to the inside, the leak detector vacuum system must be connected to the internal volume of the repeater. For this and other reasons a small diameter tube that by-passes the seal is provided as a feature of the seal design. After the leak integrity of the repeater is established by this means for all but the access tube, this tube is then used as a means of vacuum drying the repeater and then filling it with extremely dry nitrogen. Following this, the tube is closed by welding and brazing. This closure is then the only remaining leak possibility and is checked by a radioisotope leak test.

Radioisotope Leak Test

Of various methods of detecting the passage of very small amounts of a liquid or a gas from the outside to the inside of a sealed repeater, a scheme using a gamma-emitting radioisotope appeared to be the most applicable.

The relatively small region of the welded tube referred to above is surrounded by a solution of a soluble salt of cesium¹³⁴. With the entire repeater in a pressure tank, hydraulic pressure in excess of service pressures is applied for about 60 hours. The repeater is removed from the tank, the radioactive solution is removed and the test region is washed by a special process so as to be essentially free from external radioactivity. A special geiger counter is applied to the region. If there has been no leak the gamma radiation reads a low value. If an intake has occurred of as much as one milligram of the isotope solution, the radiation count is about four to five times greater than that of the no-leak condition. The rate of leak indicated is an acceptable measure of soundness of the repeater closure.

The helium and subsequent isotope leak tests are made on a repeater not only when its glass seals are installed but are performed again on each rubber seal after it is brazed in place.

Electrical Tests

Prior to assembly into the repeater the various networks are tested under conditions simulating as nearly as is feasible the actual operating

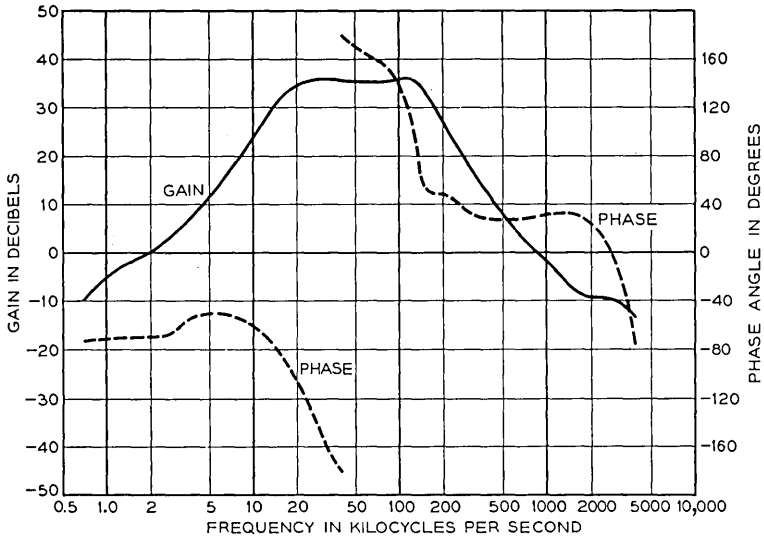


Fig. 18 — Mu Beta gain and phase.

conditions of the particular network. The input and output coupling networks and the beta networks enter directly into the insertion gain and hence are held to very close limits. To ensure meeting these limits elements which go into a particular network are matched and adjusted as a group before assembly into the network.

Repeater units are tested for transmission performance both before and after closing. These tests consist of; mu-beta measurements (simultaneous measurements of gain and phase of the feedback loop); noise; modulation; insertion gain at many frequencies; exact frequency of the fault location crystal and crystal peak gain. Modulation and crystal frequency measurements are made with the repeater energized at 225 milliamperes cable current and also at 245 milliamperes as a check on the ultimate performance of the whole system initially and after aging.

PERFORMANCE OF REPEATERS

The phase and gain characteristics of the feedback loop of the repeater are shown in Fig. 18. It will be noted that at the upper edge of the band the feedback is a little less than the 33-34 db set as the objective. Additional elements could have been used in the interstages to increase the feedback but the return per element is small. Since any element is a potential hazard, the lower feedback is acceptable.

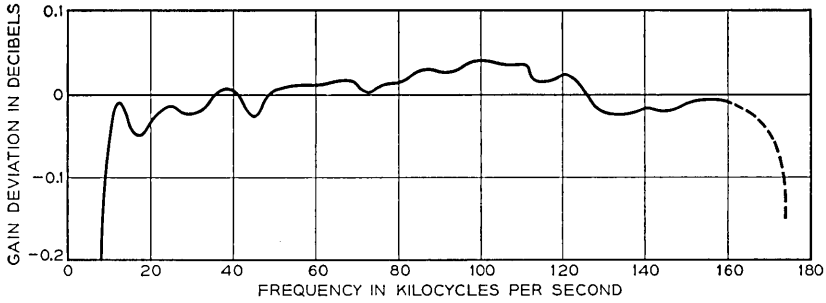


Fig. 19 — Repeater deviation from 36.9 NM design cable.

The deviation of the insertion gain of the repeater from the loss of 36.9 nautical miles of design cable⁵ at sea bottom is shown in Fig. 19. This is well within the objective of ± 0.05 db.

It has been pointed out that the repeater input and output impedance do not match the cable impedance. This results in ripples in the system frequency characteristic due to reflections at the repeater. These are shown in Fig. 20.

The noise performance of the repeater is determined by the input tube and the voltage ratio of the input coupling network. Amplifier noise referred to the input is shown in Fig. 21. At the upper frequencies the

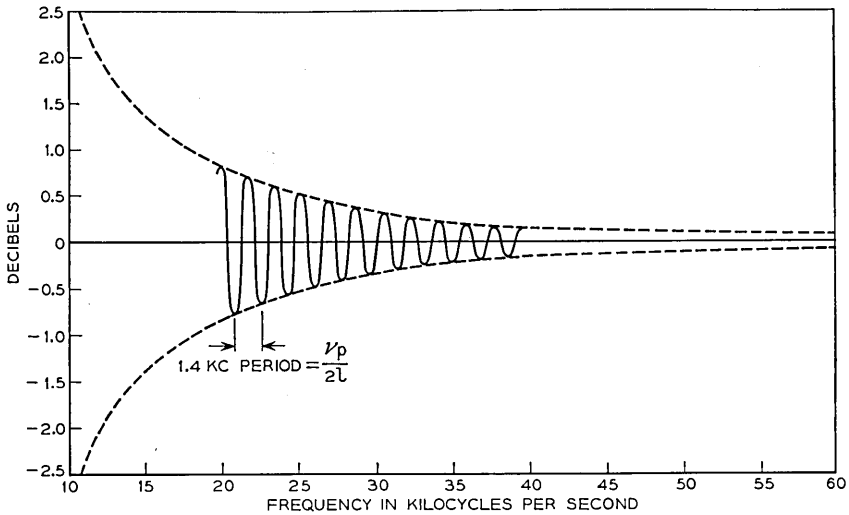


Fig. 20 — Interaction ripple for TAC system.

repeater contribution to cable noise is very small. At the lower frequencies, while the repeater noise is considerably greater than thermal noise, this does not degrade performance because of the lower cable attenuation at these frequencies.

MANUFACTURING DRAWINGS

Because of the extraordinary nature of many of the manufacturing problems associated with undersea repeaters it was determined at the outset that a so-called single-drawing system would be used. For this reason, considerably more information is supplied than is normal. The effect is illustrated best in the rather large number of drawings that consist of text material outlining in detail a specific manufacturing technique. Such drawings specify the devices, supplies and work materials needed to perform an operation, and the step-by-step procedure. Of course, these papers are by no means a substitute for manufacturing skill. Primarily they insure the continuance of practices proved to be effective with the Havana-Key West project.

REPAIR REPEATER

The "repair repeater," used to offset the attenuation of the excess cable which must be added in making a repair, is basically the same general design as the line repeater. It employs a two-stage amplifier, designed to match the loss of 5.3 nautical miles of cable to within ± 0.25 db. The larger deviation compared to the line repeater is permissible since few repair repeaters are expected to be added in a cable. The input

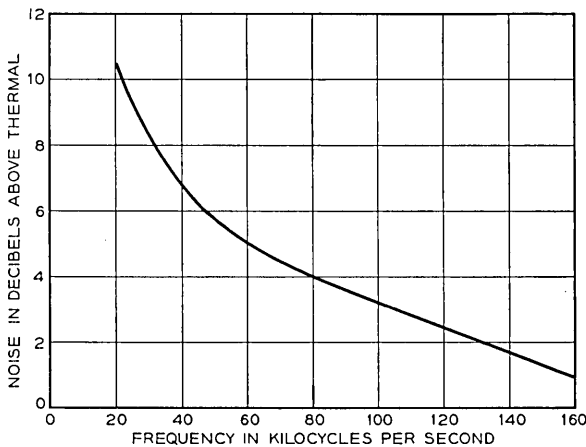


Fig. 21 — Repeater noise.

and output impedances match the cable. As in regular repeaters a crystal and gas tube are provided for maintenance testing. The crystals give approximately 25 db increase in gain and are placed between 173.5 and 174.1 kc so as not to duplicate any frequencies used in the line repeaters. The crystal frequency spacing is 100 cycles.

Wherever possible the same components and mechanical details are used in the repair repeaters as in the line repeaters. When changes in design were necessary, these were modifications in the existing designs rather than new types. Capacitors are like those of line repeaters. Except for the length of the container, the enclosure is identical to the line repeater.

Noise and overload considerations restrict the location of a repair repeater to the middle third of a repeater section.

UNDERSEA EQUALIZERS

Even though the insertion gain of the line repeater matches the normal loss characteristic of the cable rather closely, uncertainties in the knowledge of the attenuation of the laid cable can lead to misalignment which, if uncorrected, would seriously affect the performance of the system. Misalignment which has cable loss shape can be corrected by shortening or lengthening the cable between repeaters at intervals as the cable is laid. Other shapes, however, require the addition of networks or equalizers in the line.

With these factors in mind a series of undersea equalizers were designed. The loss shapes were chosen on the basis of a power series analysis of expected misalignments. The designs were restricted to series im-

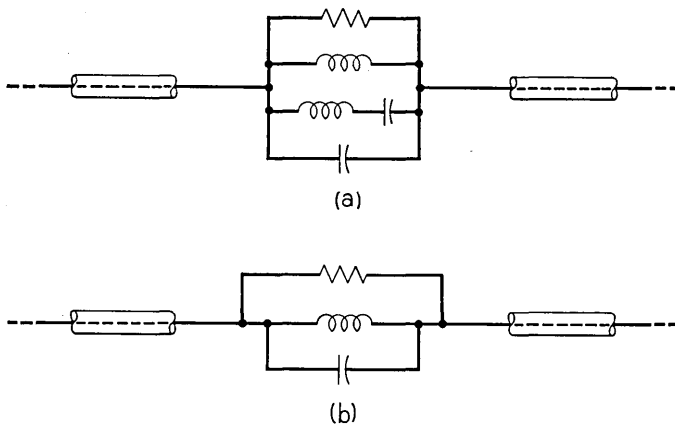


Fig. 22 — (a) Schematic of Type IV equalizer. (b) Schematic of Type V equalizer

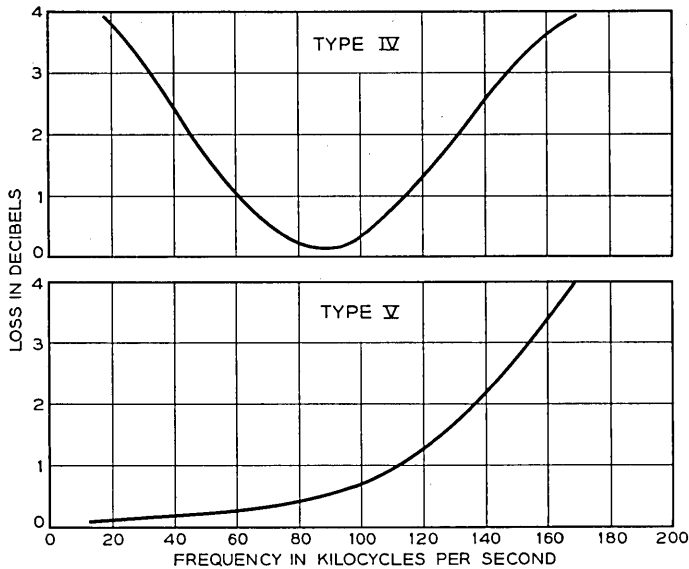


Fig. 23 — Equalizer loss characteristics.

pedance type equalizers to avoid the necessity for shunt arms and the accompanying high-voltage blocking capacitor required to isolate the cable power circuits. This restriction confines the ultimate location of the equalizers to the middle portion of repeater sections to minimize the reaction of the poor repeater impedance on the equalizer characteristic. The dc resistance of equalizers is low so that material increase of the system power supply voltage is not required.

The configuration of two of the equalizers are shown in Fig. 22. The loss characteristics are shown in Fig. 23. Each equalizer has a maximum loss spread in the pass band of about 4 db which represents a compromise between keeping the number of equalizers low and at the same time keeping the misalignment within tolerable limits.

The components used are modifications of the repeater components. The mechanical construction is identical to the repeater except that with the smaller number of elements, the container is materially shorter than a repeater.

ACKNOWLEDGMENTS

Scores of individuals have contributed to the development of these repeaters, some leading to basic decisions, some creating, adapting and

perfecting both electrical and mechanical designs. Many of these people have furnished the continuing drive and enthusiasm that are so essential for a team of engineers and scientists having divergent interests. It is nearly impossible to assign relative importance to the work of transmission engineers, apparatus designers, mathematicians and research scientists in the fields of materials and processes. Equally difficult is any realistic appraisal of the work of all of the technical aides and shop personnel whose contributions are so significant to the final product. The authors of this paper, in reporting the results, therefore acknowledge this large volume of effort without listing the many individuals by name.

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Repeater Production for the North Atlantic Link

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Production of submarine telephone cable repeaters, designed to have a minimum trouble-free life of twenty years, required many new and refined manufacturing procedures. Care in the selection and training of personnel, manufacturing environment, inspection, and testing, were of great importance in the successful attainment of the ultimate objective. Although quality of product has always been of major significance in Western Electric Company manufacture, building electronic equipment for use at the bottom of the ocean, where maintenance is impossible and replacement of apparatus extremely expensive, required unusual manufacturing methods.

MANUFACTURING OBJECTIVE

Late in 1952, the manufacture of flexible repeaters for the North Atlantic Link of the transatlantic submarine telephone cable system was allocated to the Kearny Works of Western Electric Company.

In accordance with established practice in initiating radically new products and processes, production of these repeaters was assigned to the Engineer of Manufacture Organization rather than to regular manufacture in the telephone apparatus shops. The job — to produce 122 thirty-six channel carrier repeaters and 19 equalizers capable of operating satisfactorily at pressures up to 6,800 pounds per square inch on the ocean floor, with minimum maintenance, for a period of at least twenty years. Initial delivery of repeaters was required for March, 1954, less than a year and a half after the project started.

GENERAL PHILOSOPHY

Quality has always been the prime consideration in producing apparatus and equipment for the Bell System. There is an economical breaking point, however, beyond which the return does not warrant the abnormal

* Western Electric Company.

expenditures required to approach theoretical perfection. The same philosophy applies to all manufactured commodities, be they automobiles, airplanes or telephone systems. In general, all of these products are physically available for preventive and corrective maintenance at nominal cost. With electronic repeaters at the bottom of the ocean, maintenance is impossible and replacement would be extremely expensive.

The general philosophy adopted at the inception of the project was to build integrity into the product to the limit of practicability. To do this, a number of fundamental premises were established, which form the foundation of all operations involved:

1. Manufacturing environment would be provided which, in addition to furnishing a desirable place to work, could be kept scrupulously clean and free from contamination.

2. The best available talent would be screened and selected for the particular work involved.

3. Wage payments would be based on day work, rather than on an incentive plan basis, because production schedules and the complexity of the operations did not permit the high degree of standardization essential to effective wage incentive operation.

4. A sense of individual responsibility would be inculcated in every person on the job.

5. Training programs would be established to thoroughly prepare supervisors, operators, and inspectors for their respective assignments before doing any work on the project.

6. Inspection, on a 100 per cent basis, would be established at every point in the process which could, conceivably, contribute to, or affect the integrity of the product.

PREPARATION FOR MANUFACTURE

Manufacturing Location

It appeared desirable to set up manufacture in a location apart from the general manufacturing area. Experience gained to date has satisfied us that this was the correct approach, since it provided a number of advantages:

1. Administration has been greatly facilitated by having all necessary levels of supervision located in the immediate vicinity of the work.

2. It was necessary for the people on the job to acquire and maintain a new philosophy of perfection in product, rather than a high output at an "acceptable quality level." This was easier at a separate location, since only one philosophy was followed throughout the plant.

3. Engineering, production control, service and maintenance organizations were located close to actual production and had no assignments other than the project.

4. The small plant, due to its semi-isolation, tends to produce a very closely knit organization and good teamwork.

A large number of manufacturing locations were examined and the one selected was a one-story modern structure in Hillside, New Jersey, which provided a gross area of 43,700 square feet.

The entire plant was air conditioned; in most cases, the temperature was controlled to minimum 73 degrees F, maximum 77 degrees F. The air was filtered through two mechanical and one electrostatic filters. Relative humidity was maintained at maximum 40 per cent in all but one area — the capacitor winding room — in which it was necessary to maintain maximum 20 per cent humidity to avoid mechanical difficulty with capacitor paper. While most of the air was recirculated, the air from the cafeteria, cleaning room, locker and toilet rooms was exhausted to the

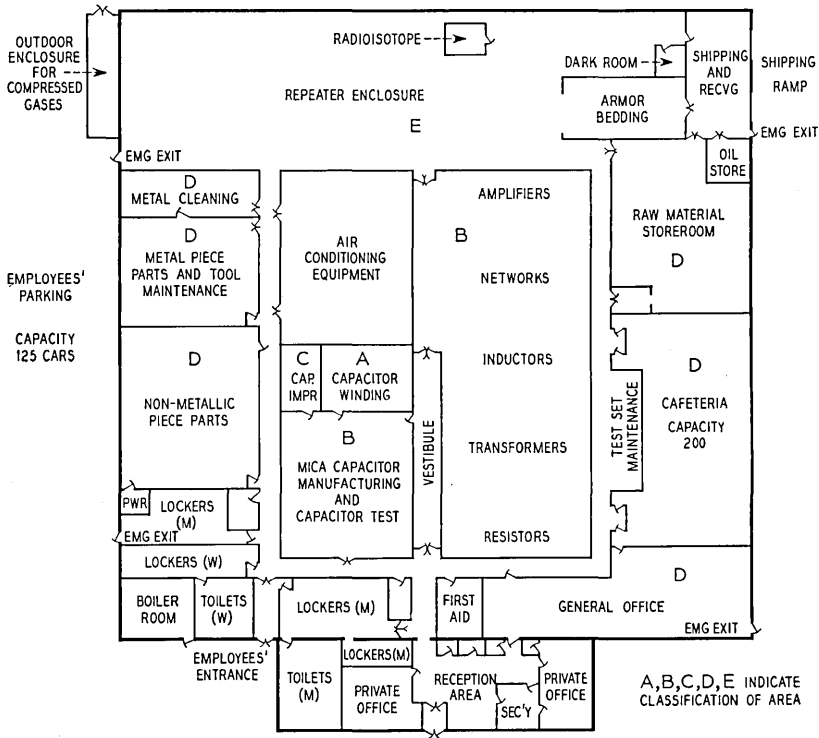


Fig. 1 — Plant layout.

outside atmosphere. Two separate air conditioning systems were in use. One, of 300 tons capacity, provided for most of the plant, while a smaller unit of 30 tons capacity served the capacitor winding, testing, and impregnating rooms. Each installation had its own air filtering and conditioning equipment.

Plant Layout

The plant layout is illustrated in Fig. 1. All working areas, with the exception of the repeater enclosure area, were individually enclosed, and walls from approximately four feet above the floor were almost entirely of reinforced glass. This arrangement facilitated supervision by other than first-line supervisors, who were located with the groups, and provided a means of viewing the operations by the many visitors at Hillside, without contaminating the critical areas or disturbing the operators.

Analysis of Design for Facilities and Operations

In analyzing the design for manufacture there were, of course, numerous instances where conventional methods and facilities were entirely adequate for the job. Since their inclusion would contribute little to this article, we shall confine the description to those cases which are new or unusual.

Collaboration with Bell Telephone Laboratories in Preparation of Manufacturing Information

Early in 1953 a coordination committee was established, consisting of representatives from the various Laboratories design groups and Western engineers, which met on a bi-weekly basis during the entire period preceding initial manufacturing operations. These meetings provided a clearing house for questions and policies of a general nature for this particular project and served to keep all concerned informed as to the progress of design and the preparations for manufacture.

It is customary, during the latter stages of development of any project at the Laboratories, for Western engineers to participate in the preparation of manufacturing information as an aid in pointing the design toward the most economical and satisfactory production methods and facilities. Since the decision to use the Bell System repeater in the Transatlantic system was based on the performance of the Key West-Havana installation, and the fact that changes in design would require further

trials over an extended period of time, only minor changes to facilitate manufacture were made. Further, since some experience had been gained by the Laboratories in producing repeaters for that installation, it was decided to "pool" effort in preparing the manufacturing process information, which is normally Western's responsibility. Close cooperation of the two groups, therefore, has resulted in the production of repeaters which are essentially replicas of those in the initial installation except for the internal changes necessary to increase transmission capacity from 24 to 36 channels.

Other Western Electric Locations and Outside Suppliers

During the development work on the Key West-Havana repeaters, the Hawthorne Works of Western Electric had furnished the molybdenum-permalloy cores for certain inductors, the Tonawanda Plant had furnished mandrelated resistance wire, and the Allentown Plant had fabricated the glass seal subassemblies. Since the experience gained in this development work was extremely valuable in producing the additional material required for the Transatlantic system and since the facilities for doing the work were largely available, these various locations were asked to furnish similar material for the project. Although the Kearny Crystal Shop had not been involved in the Key West-Havana project, arrangements were made there to make the crystals for this project, since facilities were available, along with considerable experience in producing precision units.

Subcontracted Operations

While it was believed, initially, that all component parts for repeaters should be manufactured by Western Electric, critical analysis indicated that it was neither desirable nor economical in certain cases. One of the outstanding examples in this category is the hardened and ground chrome-molybdenum steel rings that constitute the strength members in the repeater and sustain the pressures developed on the ocean bottom. Purchasing the many large and varied machine tools and associated heat treating equipment necessary to produce these parts would have required a substantial capital expenditure and additional manufacturing space. Arrangements, therefore, were made with a highly qualified and well equipped supplier to produce the rings, using material furnished by Western, which had been previously inspected and tested to very stringent requirements.

The situation attending the manufacture of a relatively small number of comparatively large copper parts used in the rubber and core tube seals was much the same. Here, again, the large size machine tools and additional manufacturing space, required for only a short time, would have increased the over-all cost of the project considerably. These parts, therefore, were subcontracted in the local area and inspection was performed by Hillside inspectors.

A safeguard, in so far as integrity is concerned, was provided by the fact that these were individual parts that could be reinspected at the time of delivery. No subassembly operations that might possibly result in oversight of a defect, were subcontracted.

Manufacturing Conditions

Two major problems confronted us in planning the manufacture of repeaters. First, to produce units that were essentially perfect; and second, to prevent the contamination of the product by any substance that might degrade its performance over a long period of time. In approaching both of these objectives, it was realized that the product had a definite economic value which the cost of production should not exceed. In many cases, therefore, it was necessary to rely on judgment, backed by considerable manufacturing experience, in determining when the "point of no return" had been reached in refining processes and practices.

The initial approach to this phase of the job was to classify, with the collaboration of Bell Telephone Laboratories, all of the manufacturing operations involved as to the degree of cleanliness required. In setting up these criteria, it was necessary to evaluate the importance of contamination in each area and the practicability of eliminating it at the source or to insure that whatever foreign material accumulated on the product was removed.

A representative case is the machining of piece parts. While the shop area is cleaner, perhaps, than any similar area in industry, the very nature of the work is such that immediate contamination cannot be avoided since material is being removed in the form of chips and turnings, and a water soluble oil is used as a coolant. In this instance, however, the parts can be thoroughly cleaned and their condition observed before leaving the area. Conversely, in the case of an operation such as the assembly of paper capacitors into a container which is then hermetically sealed, it is vitally necessary to insure that both the manufacturing

area and the processes are free from, and not conducive to producing, particles of material which are capable of causing trouble.

The various classifications established for the production areas include specific requirements as to temperature, relative humidity, static pressure with respect to adjacent areas, cleanliness in terms of restrictions on smoking and the use of cosmetics and food, and the type and use of special clothing.

Special Clothing

Employees' clothing was considered one of the most important sources of contamination for two reasons; first, for the foreign material that could be collected upon it and carried into the manufacturing areas, and second, that various types of textiles in popular use are subject to considerable raveling and fraying.

After considerable study of many types of clothing for use in critical areas, the material adopted was closely woven Orlon, which has proved to be acceptably lint-free. The complete uniform — supplied at no cost to employees — consists of slacks and shirts for both male and female employees, Orlon surgeon's caps for the men and nylon-visored caps for the women. In addition shoes, without toecap seams, were provided. Nylon smocks were furnished to protect the uniforms while employees moved from locker rooms to the entrance vestibule. Two changes of clothing were provided each week, and the laundering was done by an outside concern.

Employees to whom this special clothing was issued were paired for locker use. Both kept their uniforms and special shoes in one locker and their own clothes and shoes in the other. This prevented the transfer to the uniforms of any foreign material that might exist on the street clothing. At the entrance vestibule to the A, B, and C areas (Fig. 1) the employees were required to clean their shoes in the specially designed facilities provided and to wash their hands in the wash basins installed for this purpose. Smocks were then removed and hung on numbered hooks that line the walls at the end of the vestibule. Employees were then permitted to go to their work positions within the inner areas. At any time that it was necessary for employees to leave the work areas for any purpose, they were required to put on their smocks in the vestibule and upon their return, to go through the cleaning procedure again.

Employees in the other areas were provided only with smocks, mainly for the protection of their clothes since the work involved could soil or stain them but could not be contaminated from the clothing.

Cleaning

Schedules were established for cleaning the areas at regular intervals, the frequency and methods depending upon the type of manufacturing operations and the activity. Usually, the vinyl plastic floors were machine scrubbed and vacuum dried. Walls, windows and ceilings were cleaned by hand with lint-free cloths. Manufacturing facilities such as bench tops, which were linoleum covered, were washed daily. Test sets, cabinets, test chambers and bench fixtures were also cleaned daily. Hand tools were cleaned at least once a week by scrubbing with a solution of green soap, rinsing in distilled water, followed by alcohol and then dried in an oven.

Dust Count

Since it was impossible to determine what contaminating material in the form of air-borne particles might be encountered from day to day, and what the effect might be during the life of the repeaters, the general approach to this problem was to control, so far as possible, the amount of dust within the plant.

In order to verify, continuously, the over-all effectiveness of the various preventive measures, dust counts were made in each classified area at daily intervals, using a Bausch and Lomb Dust Counter. This device combines, in one instrument, air-sampling means and a particle-counting microscope. Over a two-year period it has been possible to maintain, in certain areas, a maximum dust count of between 2,000 and 3,500 particles per cubic foot of air with a maximum size of 10 microns. Control checks, taken outside the building at the employees' entrance, generally run upwards of 25,000 particles per cubic foot, a good portion of which are of comparatively large size.

PRODUCTION AND PERSONNEL

Equipping the plant, obtaining and installing facilities, and selecting and training personnel proceeded on a closely overlapped basis with receipt and analysis of Bell Telephone Laboratories' product design information. Because of the critical nature of the product, provisions were made not only for the most reliable commercially available utilities and services, but also for emergency lighting service in some areas. Maintenance and service staffs had to be built up rapidly as the supervisory and manufacturing forces were being developed.

"Qualification" of All Personnel

Before employees were assigned to production work they were required to pass a qualification test established by the inspection organization to demonstrate satisfactory performance. Programs were, therefore, set up for "vestibule" training and qualification of new employees. This activity was carried on by full-time instructors who had been trained by Western and Bell Laboratories engineers. Training was carried out in two stages:

1. (a) The employee received instruction and became acquainted with equipment and requirements. (b) A practice period in which the employee developed techniques and worked under actual operating conditions, with all work submitted to regular inspection.

2. A qualification period in which the employee was required to demonstrate that work satisfactory for project use could be produced.

The main objective during stage 1 was progressive quality improvement and in stage 2 the maintenance of a satisfactory quality level over an extended period of time. Employees made a definite number of units at acceptable quality levels in order to qualify. The number of units required for training varied with the type of work and the ease with which it was mastered.

All personnel were required to pass qualification tests before being assigned to production work and were restricted to that work unless trained and qualified for other work. Employees trained on more than one job were requalified before being returned to a previous assignment.

Records of the performance of individual operators started in the training stage were continued after the employees were assigned to production work. The performance record of the operators was based on results obtained during the inspection of their work, while that of the inspectors was based on special quality accuracy checks of their work.

Personnel Selection

It was apparent that the new manufacturing techniques, including the cleanliness and quality demands, would necessitate that all shop supervisors and employees be very carefully selected. It also appeared (and this was subsequently confirmed) that after the careful selection and training of supervisors, long training periods would be required for specially selected shop employees.

In selecting first line shop supervisors, such factors as adaptability, personality, and ability to work closely with the engineers were of paramount importance. For the parts and apparatus included in their re-

sponsibility, they were required to thoroughly learn the design, the operations to be performed, the facilities to be used, the data to be recorded, the cleanliness practices to be observed — and in most cases, prepare themselves to be able to do practically all of the operations, because subsequently they had to train selected operators to perform critical operations to very high quality standards under rigidly controlled manufacturing conditions. As shop supervisors and employees were assigned to the manufacture of repeaters, they were thoroughly indoctrinated in the design intent and the new philosophy of manufacture.

Standard ability and adaptability tests were used in a large number of cases to assist in proper selection and placement of technicians. Tests for finger and hand dexterity; sustained attention; eyes, including perception and observation; and reaction time of the right foot after a visual stimulus. (The latter test was relatively important for induction brazing operations.) Other requisite considerations were a high degree of dependability and integrity, involving intellectual honesty and conscientious convictions; capability of performing tedious, frustrating, and exasperating operations against ultra-high quality standards, verifying their own work; perseverance and capability to easily adapt to changes in assignment and occupation or the introduction of design changes. We considered whether or not they would stand up under “fishbowl” operations, wherein they would receive a considerable amount of observation from high levels of Western Electric Company and Bell System management and other visitors. Also, could they duplicate high quality frequently after qualifying for a particular operation?

During the period of repeater manufacture, the number of employees rose from less than 50 in January, 1954, to a maximum of 304 by February, 1955, after which there was a gradual reduction to a level of about 265 employees for six months and then a gradual falling off as we were completing the last of the project. In the period from May to December, 1954, between 30 and 45 employees were constantly in training prior to being placed on productive work. During 1955 this decreased to practically no employees in training during the midpart of the year and thereafter training was required merely to compensate for a small labor turnover and employee reassignment. It is significant that labor turnover was very low and attendance was exceptionally good during the life of the Hillside operations.

Personnel Training

The original plan, which was generally followed, was to prove in the tools for each phase of the job, followed by an intensive program of train-

ing. Indoctrination of laboratory technicians could be considered as "vestibule training" in that they were acclimated to the area and conditions, given oral instruction in the work, then given practice materials and demonstrations and, when qualified, were started on making project material. To do this, extra supervisors were required at the beginning of the job. A supervisor trained a few employees, qualified some of them, and began work on the project. Another supervisor was then required to train additional employees who, as they became qualified, were transferred to the supervisor responsible for making project apparatus. Additional testing of the employees, instruction and reinstruction and, in some cases, retraining were required. In practically all cases, we were able to fit an employee selected for work at Hillside into some particular group of operations. The extra emphasis on selection and training created a well-balanced team that later resulted in considerable flexibility. During all of this training our supervisors worked closely with engineers and inspectors who understood the design intent and the degree of perfection required.

At the beginning, each technician was trained for only one operation of a particular job, such as (1) winding Type X capacitors or (2) impregnating all paper capacitors or (3) winding Type Y transformers and so became an expert on this one operation. Later, the tours of duty for many technicians were broadened to cover several operations.

Communications

To keep employees informed, we occasionally assembled the entire group, presenting informative talks on current production plans and our future business prospects. Motion pictures were shown of the cable laying ships and the operations of cable splicing and cable laying. A display board, showing all of the repeater components, was mounted on the wall of the cafeteria. This informed the operators just where the parts were used in apparatus; also, just where their products went into the wired repeater unit, and how all electrical apparatus was enclosed against sea pressure in the final repeater. In small groups, all of the employees at Hillside were given a short guided tour of the plant to see the facilities and hear a description of the operations being performed in each area. These communications were extended to everyone at the Hillside Plant, including those who did not work directly on the product. It was our conviction that the maintenance men, boiler operators, oilers, station wagon chauffeur, janitors, and clerical workers in the office were all interested and could do a better job if kept informed of the needs and progress of the project.

Scheduling

Capacity was provided at the Hillside Shop to manufacture a maximum of 14 repeaters in a calendar month. This envisioned 6-day operation with some second and third shift operations; due allowance was made for holidays and vacations, so that the annual rate would be approximately 160 enclosures per year. (An enclosure is either a repeater or an equalizer.)

Some of the facilities and raw materials were ordered late in 1953. This ordering expanded early in 1954 and continued through 1955 to include parts to be made by outside suppliers and the parts and apparatus to be made at Hillside. Apparatus designs were not all available at the beginning of the job, and the ultimate quantities required were also subject to sharp change as the project shaped up, thus further complicating the scheduling problem.

Because of the time and economic factors involved, coupled with the developmental nature of the product and processes, one of the most difficult and continuing problems was the balancing of production to meet schedules. For this task, we devised "tree charts" for the apparatus codes and time intervals in each type of repeater or equalizer for each project. Each chart was established from estimates of the time required to accomplish the specified operations and the percentage of good product each major group of operations was expected to produce.

RAW MATERIALS

Many of the specifications were written around the specific needs of the job and embodied requirements that were considerably more stringent than those imposed on similar materials for commercial use. As a result, it was necessary for many suppliers to refine their processes, and, in some cases, to produce the material on a laboratory basis.

One example is the container, or repeater enclosure, which consists, in part, of a seamless copper tube approximately $1\frac{3}{4}$ inches in diameter having a $\frac{1}{32}$ -inch wall and approximately 8 feet long. This material was purchased in standard lengths of 10 feet. The basic material was required to be phosphorous deoxidized copper of 99.80 per cent purity. The tubing, as delivered, had to be smooth, bright, and free from dirt, grease, oxides (or other inclusions including copper chips), scale, voids, laps, and slivers. Dents, pits, scratches, and other mechanical defects could not be greater than 0.003 inch in depth. The tubing had to be concentric within 0.002 inch and the curvature in a 10-foot length not exceed $\frac{1}{2}$ inch to facilitate assembly over the steel rings.

Only one supplier was willing to accept orders for the tubes, and only on the basis of meeting the mechanical requirements on the outside surface. To establish a source of supply, it was necessary to accept the supplier's proposal on the basis that some of the tubes produced could be expected to meet requirements on the inside as well as the outside surface. Inspection of the inside surface was performed with a 10-foot Bore-scope.

The supplier then set aside, overhauled, and cleaned a complete group of drawing facilities for this project. In addition, a number of refinements were made in lubrication and systematic maintenance of tools. After all refinements were made and precautions taken, however, the yield of good tubes in the first 400 produced was less than 1.0 per cent. Consultations with Western and Bell Laboratories' engineers, and with the supplier's cooperation, raised the yield to approximately 50 per cent.

Procurement of satisfactory mica laminations for capacitors introduced an unusual problem. The best grade of mica available in the world market was purchased which the supplier, under special plant conditions, split and processed into laminations. Despite care in selection and processing, only 50 per cent of the 250,000 laminations purchased met the extremely rigid requirements for microscopic inclusions and delaminations, and less than 8 per cent survived the capacitor manufacturing processes.

A large number of the parts, and the most complex, are made from methyl-methacrylate (Plexiglass). At the time manufacture began, there was little, if any, experience or information available on machining this material to the required close tolerances and surface finish. Consequently, considerable pioneering effort was expended in this field before satisfactory results were obtained.

The methacrylate parts cover a wide range of size and complexity — from $1\frac{1}{2}$ -inch diameter by $4\frac{7}{8}$ -inch long tubular housing to tiny spools $\frac{1}{8}$ -inch diameter and $\frac{1}{16}$ -inch long. Most of the parts are cylindrical in shape with some semicylindrical sections that must mate with other sections to form complete cylinders. Others have thin fins, walls, flanges and projections. Five representative parts are shown in Fig. 2.

Methyl-methacrylate has a tendency to chip if tools are not kept sharp and care is not used in entry or exit of the tool in the work, particularly in milling. In some cases, it is necessary, with end-milling, to work the cutter around the periphery of the area for a slight depth so that subsequent cuts will not break out at an unsupported area. Normally, with a sharp cutter and a 0.010-inch finish cut, and a slow feed, chipping will not result. High-speed steel tools with zero rake were used for turning

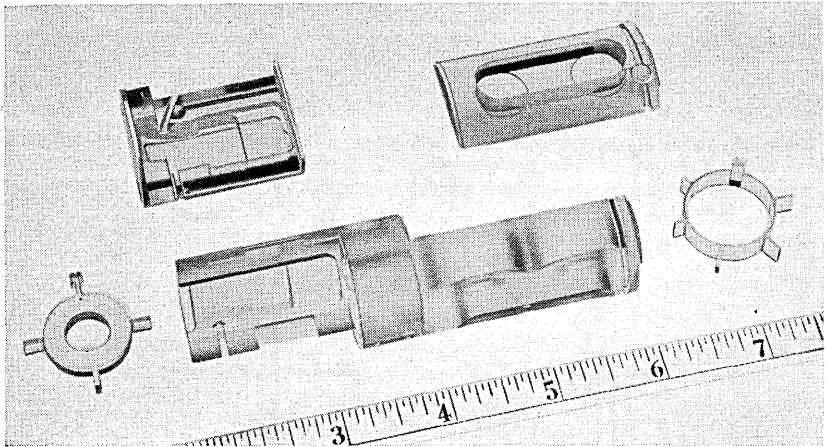


Fig. 2 — Methyl methacrylate parts.

and boring operations. Standard high-speed milling cutters and end mills were used for milling except for the cutting edges, which are honed to a fine finish. A clearance angle of 7 degrees for milling and 10 degrees to 15 degrees for lathe work was found most satisfactory. In lathe work, the general rule was light feeds (0.003 inch–0.005 inch) and small depth of cut. However, the depth of cut could be safely varied over a wide range depending upon many factors, such as type of part, quality of finish, machine and tool rigidity, effective application of coolant, and tooling to support and clamp the part. In one operation of boring a $1\frac{3}{16}$ -inch diameter by $4\frac{1}{8}$ -inch deep blind hole within ± 0.002 inch, the boring terminates in simultaneously facing the bottom of the hole square with its axis. A cut $\frac{1}{32}$ -inch deep with a light feed was taken with a specially designed boring tool with the coolant being fed through the shank to the cutting edge. All completely machined parts were annealed for 12 hours at 175° F.

HIGHLIGHTS IN ASSEMBLY AND BRAZING

Repeater units are encased in hardened steel rings which previously had been tested at 10,000 pounds per square inch hydraulic pressure. This pressure is approximately 50 per cent higher than the greatest pressure expected at ocean bottom. The steel rings were encased in a copper sheath and closed at each end with a glass-to-Kovar seal, with the central conductor coming through the glass to the outside. The copper sheath was then shrunk to the steel rings and glass seals using 6000 pounds per

square inch hydraulic pressure, and the glass seal was then high-frequency brazed to the copper sheath.

To keep the ocean bottom pressure off the glass seals and also to terminate the cable insulation, a rubber seal is brazed in to the copper container tube adjacent to each glass seal. This rubber seal consists of rubber bonded to brass, which has been brazed to the copper portion of the seal. The rubber terminates in polyethylene through five steps of compounds containing successively less rubber and more polyethylene. The polyethylene can be readily bonded by molding to the polyethylene insulation of the cable. The central conductor passes through a central brass tube in the rubber seal, which is also bonded to the rubber.

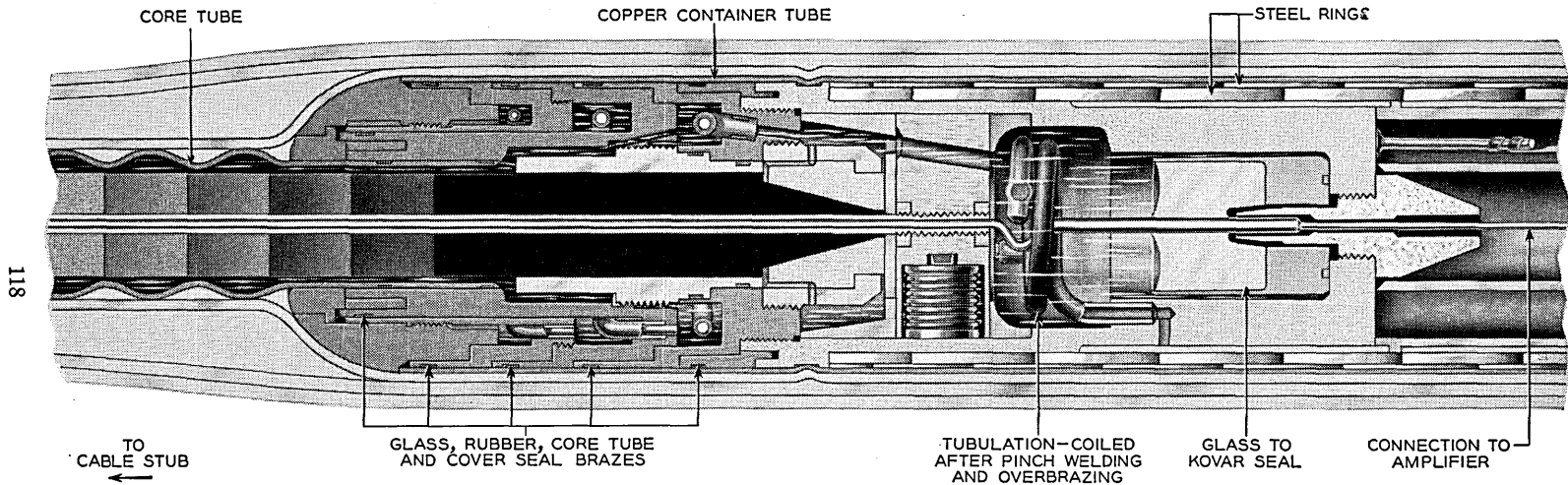
To protect the rubber seals from the deleterious effects of salt water immersion for long periods of time, a copper core tube is brazed over each rubber seal. The core tube is arranged to equalize the pressure inside and out when submerged at ocean bottom pressure. This is accomplished with a bulge of neoprene filled with polyisobutylene, on the far end of the core tube, which transmits the pressure to the inside of the core tube seal.

To make doubly sure that no salt water reaches the rubber seal, a copper cover is brazed into the container outside the core tube connector on each end. This cover is also brazed to the core tube connector. The interstice between each of the above four seals is filled with polyisobutylene, which is viscous and inert and has very good insulating qualities.

Each end of the repeater closure (Fig. 3) contains five successive brazed joints. Any one of these ten brazes, if not perfect, could cause the loss of the repeater closure and jeopardize the entire repeater. All of these brazes were made with the repeater in a vertical position to insure an even distribution of the brazing alloy fillet around the joint.

An upending device was provided at the pit brazing location to raise the repeater on its carrier to a vertical position with either end up and move it into position for brazing. The repeaters were brought into the brazing area on an overhead monorail and an electric hoist. The shorter repeater assemblies, before core tube and cable stub assembly, were upended by hand and brazed from a raised platform.

It was necessary to make all of these brazes by high-frequency induction heating, since the heat must be intense, contained within a very narrow band, evenly distributed, and the area protected from oxidation by a somewhat reducing atmosphere. The heat must be very intense since the time interval for the shortest braze was 10 seconds maximum and the longest was 30 seconds. A large part of the heat was dissipated



F. 3 — Repeater seals.

by being conducted at a high rate from the copper parts to the water in the cooling jackets used to contain the heat in a very narrow band.

Circulating cooling water within a jacket prevented heat from being conducted down the copper container tube to the preceding seals or to the repeater unit. This water-cooled jacket was positioned only $\frac{3}{8}$ inch below the inductor, and the water was in intimate contact with the container tube, which is sealed off at both ends with rubber "O" rings. In addition, for the glass seal braze, the glass inside the seal cavity was kept covered with water during the heat cycle. The water was fed in and siphoned out to a constant level which was kept under observation by the operator and the inspector to make sure that the glass was covered at all times. The rubber seal was also water jacketed on the inside of the seal to prevent deleterious effects of the heat on the rubber insulation around the central conductor. The inner cover braze was quenched before the 10-second maximum interval had expired to insure that the heat did not penetrate to the polyisobutylene at a sufficient rate to deteriorate it or the rubber inside.

Distribution of the heat around the container tube at the braze area was controlled by locating the work in the inductor so that the color came up essentially evenly all the way around and at the proper level to bring a fillet up to the top of the braze joint within the allowable time limit. The time limit was determined by experiment so that none of the previously assembled parts were damaged by the heat. This determination of the proper heat pattern and the prevention of overheating required the development of considerable skill on the part of the operator. The variables encountered made it essential to rely on an operator to control the heat rather than to utilize the timer with which the induction heating equipment is normally controlled.

The area to be heated for brazing was protected from oxidation by enclosing it in a separable transparent plastic box and flooding the interior with a gas consisting of 15 per cent hydrogen and 85 per cent nitrogen. This atmosphere is somewhat reducing and not explosive. The brazing surfaces of the parts were chemically cleaned immediately before assembly and extreme care was exercised to keep them clean until brazed.

The container tube was shrunk to the respective glass, rubber, core tube, and cover seals using hydraulic pressure so that the surfaces to be brazed and the brazing alloy were in intimate contact within the brazing area. If the parts were clean and kept from oxidizing by the protective atmosphere, the alloy would flow upward by capillary action and form a fillet around the top of the seal, impervious to any leak.

The braze in each case was then leak tested with a helium mass-spec-

trometer type leak detector. A gas pressure of helium at least 25 per cent greater than the maximum pressure to be encountered at ocean bottom was used. In addition, a radioisotope was used to test the effectiveness of the final tubulation pinch welds and overbrazes which were kept open for the leak tests under high pressure helium. These tests were made with water pressure about 25 per cent greater than the maximum ocean bottom pressure.

The completed repeater was inserted in a chamber 80 feet long; the chamber was then filled with water and the pressure raised to 7,500 pounds per square inch and held at that pressure for at least 15 hours. At the end of this period the closure had to show no sign of crushing or leaking.

The repeater unit sealed in the closure must be extremely dry to function properly. Any water vapor which might remain after the closure is sealed, or enter during the estimated 20-year minimum life, must be scavenged. A sealed desiccator with a thin diaphragm was, therefore, assembled into the repeater unit sections. After completely drying and sealing the repeater unit except for one tubulation, the diaphragm of the desiccator was ruptured by dry nitrogen pressure and with the enclosure filled with dry nitrogen the final tubulation was immediately sealed off. To insure that the diaphragm was actually broken, a microphone was strapped to the outside of the repeater over the location of the desiccator and a second microphone arranged at the end of the closure to pick up background noises. A pen recorder was used to record the sound from the two microphones and also the change in nitrogen pressure. Three simultaneous pips on the chart gave definite indication that the diaphragm had ruptured and that the desiccant had been exposed to the internal atmosphere of the repeater.

QUARTZ CRYSTAL UNITS MANUFACTURED AT KEARNY

The primary purpose of the crystal unit is to provide the means of identifying and measuring the gain of each repeater in the cable. This basic crystal design is in common usage. The exacting specifications for this application, however, imposed many problems and deviations from normal crystal manufacturing processes.

Raw Quartz was specially selected for this crystal unit. The manufacturing process of reducing the quartz to the final plate followed the recognized methods through the roughing operations. Due to the rigid end requirements, the finishing operations were performed under laboratory conditions. Angular tolerances were one-third of normal limits. No evidence of surface scratches, chipped edges or other surface imper-

fections visible under 30X magnification were permitted. This resulted in a process shrinkage five times that experienced in normal crystal plate manufacture.

In this use, the crystal units were required to meet performance tests at currents as low as one-thousandth of a microampere — far below the current values usually encountered. Improved soldering techniques had to be developed for soldering the gold plated phosphor bronze and nickel wires used, because it was found that the electrical performance of the units was directly related to the quality of soldered connections.

Although one-seventh of Western's production of quartz crystal units are in glass enclosures, the applicable techniques in glass working required a complete revision. Glass components such as the stem and bulb purchased from established sources were found to be far below the standard required for this crystal unit. For example, the supplier of the glass tubing used in the manufacture of stems was required to meet raw material specifications that embodied coefficient of thermal expansion, softening point of glass, density, refractive index, and volume resistivity. The glass stems made from this tubing by regular manufacturers were found unacceptable and the processes used by these sources could not be readily adapted to meet the desired specifications. The glass stems contained four lead wires made from 30-mil Grade "A" nickel wire butt welded to 16-mil light borated Dumet wire. To assure the quality of the metal to glass seal, each wire was inspected under 30X magnification for tool marks and other surface imperfections. The finished stem assemblies were inspected under 30X magnification for dimensions, workmanship, cleanliness and minute glass imperfections, then individually stored in a sealed plastic envelope.

The glass bulb in this crystal unit is known as the T921 design commonly used in the electron tube industry. The high quality required, however, made 100 per cent inspection necessary. Examination under 30X magnification resulted in rejected bulbs for presence of scratches, open bubbles, chips and stones. Physical limits for inside and outside diameters as well as wall thickness were causes for additional rejects. Only one per cent of the commercial bulbs were found acceptable, and these were also stored in a sealed plastic envelope.

The final major assembly operation consisted of sealing the glass bulb to the stem which had had the crystal sub-assembly welded to the nickel wires. The techniques for "sealing in" used in quartz crystal or electron tube manufacture were unsuited. Two important factors in this crystal unit, which required the development of new processes, were the proximity of soft soldered connections to the sealing fires and the demands

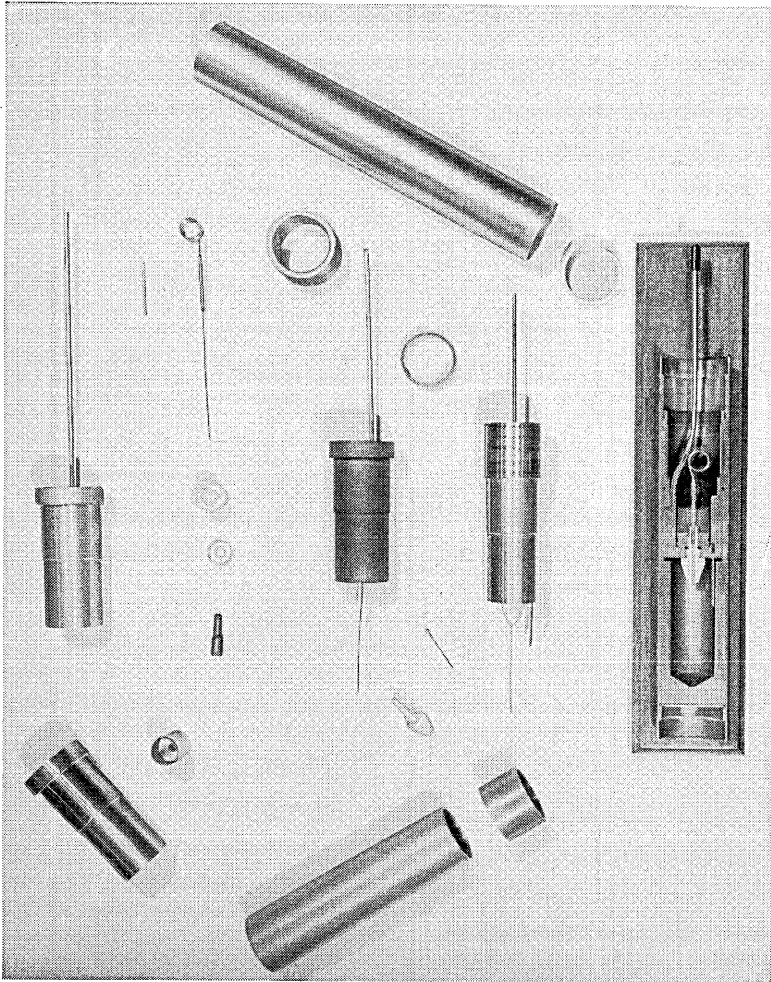


Fig. 4 — Glass to Kovar seal.

that the glass seal contain a minimum of residual tensile stress. These two problems were resolved collectively by performing the sealing operation on a single spindle glass sealing machine. Accurate positioning of the glassware and sealing fires, together with precise timing and temperature controls, achieved the desired results.

Evaluation of residual stresses were made by inspections using a polarimeter and by a thermal shock test. The maximum safe stress was established at 1.74 KG/mm². The thermal shock test required successive immersion of the unit in boiling water and ice water. The electrical characteristics of these units exceeded all others made previously by Western Electric. The ratio of reactance to effective resistance ("Q") was greater than 175,000 — twice that ever previously produced and 17 times that required in the average filter crystal.

Stability for frequency and resistance was assured by a 28-day aging test. During this period, precise daily resonant frequency and resistance measurements were recorded against temperature within 0.1° C. The maximum permissible change was 0.0005 per cent in frequency and +5 per cent to -10 per cent in resistance.

GLASS SEALS MANUFACTURED AT ALLENTOWN

The glass seal used to close each end of the container for the repeaters and equalizers is manufactured at the Allentown Works of the Western Electric Company.

The unit is essentially a glass bead-type seal. It insulates the central conductor of the repeater from the container and serves as a final vapor barrier between the cable and the interior of the repeater. As such, it backs up several other rubber and plastic barriers as shown in Fig. 3.

Fig. 4 shows the various components, subassemblies, and a cross-section of the unit. The unit consists of the basic seal brazed in the Kovar outer shell, to which is brazed a copper extension provided with two brazing-ring grooves. One of these grooves is used in brazing the seal, along with support members, into a length of container tubing in the same manner as the seal is ultimately brazed into the repeater. Packaging of the seal in this manner was necessary to pressure test the seal. Under test, in a specially constructed chamber 10,000 psi of helium gas pressure was applied to the external areas of the packaged glass seal and a mass spectrometer type leak detector was connected through the tubulation to the internal cavity of the packaged unit. In this manner, the interface of the glass to metal seal, the brazed joints, and the porosity of the metal were checked for leakage. The unit is left in this package for delivery to provide protection during shipment. Before the seal could be used,

it was machined from the package by cutting the copper extension to length, leaving the second groove for use in brazing the seal to the repeater and removing the container tubing and the support members.

The basic seal consists of the cup, central conductor and glass. The cup (smaller cylindrical item in the upper lefthand corner of Fig. 4) was machined from Kovar rod. The wall of the cup is tapered from a thickness of 0.025 inch at the base to 0.002 inch at the lip. The last 0.006 inch of the lip is further tapered from this 0.002 inch to a razor edge. The internal surface is better than a 63-micro-inch turned finish and was also liquid honed to give it a uniform matte finish. The central conductor (slim piece in the upper right-hand corner of Fig. 4) was also machined from Kovar rod. Both the cup and central conductor were further processed by pickling, hypersonically cleaning in deionized water, and decarburizing. The glass, a borosilicate type of optical quality, was cut from heavy walled tubing. The glass tubing was hand polished, lapped and etched to remove surface scratches, and to arrive at the specified weight. It was also fire polished and hypersonically cleaned to remove all traces of surface imperfections and to assure maximum cleanliness.

In order to make the basic glass seal, the metal parts had to be oxidized under precisely controlled conditions. For the oxidizing operation, a suitable fixture was loaded with brazed shell-cup assemblies, central conductor assemblies, and a Kovar disc, which had been prepared in precisely the same manner as the cups and central conductors. The disc was carefully weighed before and after oxidizing and the increase in weight divided by the area involved yields the weight gain due to oxidation for each run. Limits of 1.5 to 2.5 milligrams per square inch of oxide were set. This operation was performed by placing the loaded, sealed retort, through which passed a metered flow of dried air, into a furnace for a specified time-temperature cycle.

In the glassing operation the oxidized shell assembly, the carbon mold and the central conductor were placed in a fixture and held in the proper relationship. The carbon mold served to support the glass, while it was being melted, in that section between the cup and central conductor where the glass was normally unsupported. The prepared cut glass tubing was loaded into the Kovar cup and the fixture was sealed into the retort. During the glassing cycle, a constant flow of nitrogen passed through the retort to provide an atmosphere which minimized any reduction or further oxidation of the already carefully oxidized parts. After the proper purging period, the retort was placed in the furnace. In the furnace, the glass melted and formed a bond with the oxidized Kovar of the cup and

central conductor to form the seal. After the specified temperature-time cycle, the retort was removed from the furnace, allowed to partially cool and then placed into an annealing oven.

Vertical furnaces and retorts were used for brazing, decarburizing, oxidizing and glassing. By varying the type of gases flowing into the retorts, atmospheres which are reducing, oxidizing, or neutral were obtained. To provide maximum uniformity of process, separate retorts and holding fixtures were provided for operations involving hydrogen and for air-nitrogen operations, so that a retort or a fixture used for hydrogen treatments was never used for oxidizing or glassing.

PILOT AND REGULAR PRODUCTION

We called our first efforts *Practice Parts and Training*; the next we called Pilot Production. Next, certain items identified as *Trial Laying Repeaters and Oscillators* were manufactured for use in "proving in" the ship laying gear. To prove in manufacturing facilities, a few unequipped housings were made without the usual electrical components normally in a repeater. Similarly, each of the apparatus components and parts required exploratory and pilot effort before regular production could be undertaken.

As might be expected, the manufacturing yield of components meeting all requirements was very low during the early stages of the undertaking. However, substantial improvement was brought about as experience was gained. Comments on some of the production problems, highlights, and yield results, follow.

Paper Capacitors were manufactured only after painstaking qualifying trials and tests had been performed on each individual roll of paper. Cycling and life testing, procurement of acceptable ceramic parts and gold-plated tape and cans, selection and matching of rolls of paper for winding characteristics, and similar problems, all had to be completely resolved to a point of refinement previously unattempted for telephone apparatus.

Composite percentage yield for all operations on paper capacitors is shown in Fig. 5. Yield is shown as the ratio of finished units of acceptable quality to the number of units started in manufacture.

Mica Capacitors were made from only the most meticulously selected laminations, as mentioned earlier. Even the best mica is particularly susceptible to damage in processing. In spite of experience and knowledge of this, the multiple handling of the laminations contributed an unusually high material shrinkage as each separate lamination needed to be cleaned, then handled individually many times through the proc-

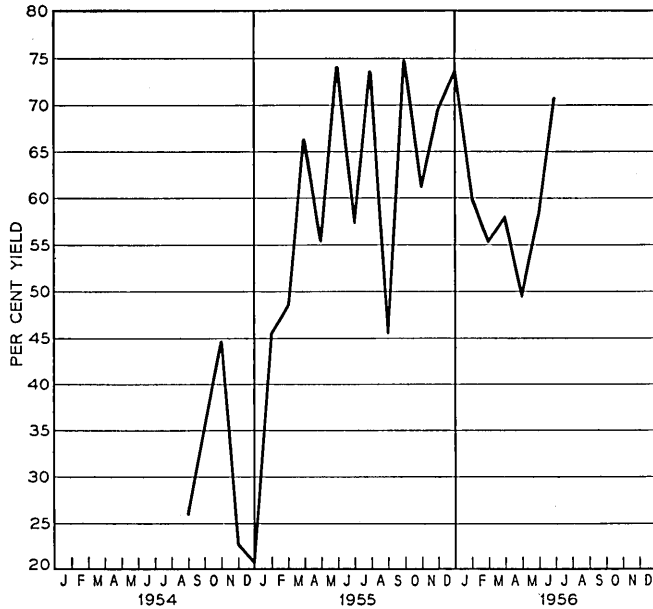


Fig. 5 — Paper capacitor yield.

esses. The art of silk screening was applied to deposit silver paste in a specific area or areas on each side of a lamination. A sharply defined rectangular area was required so that when superimposed one over another the desired capacitance would be obtained. Cementing of mica laminations onto machined methacrylate forms presented some additional problems through the bowing of the mica laminations as the cement cured. Obtaining screens that would give the proper length and width dimensions for the coated area, was another problem. A silk screen woven of strands of silk obviously limits, by the diameter of the threads, the extent to which the dimensions of an opening may be increased or decreased. Beryllium copper U-shaped terminals were used to clamp the layers of mica together into a stack. Control of the pressure used in crimping these terminals was found to be very critical in view of the exceptionally tight limits on capacitance and stability. Fig. 6 shows the composite yield at various times for all mica capacitors.

Resistors. There were three designs of ceramic resistors, which were resistance-wire wound on ceramic spools. These were intended to be assembled into the hole inside the core tube on which the paper capacitors were wound. Special winding machines equipped with binocular

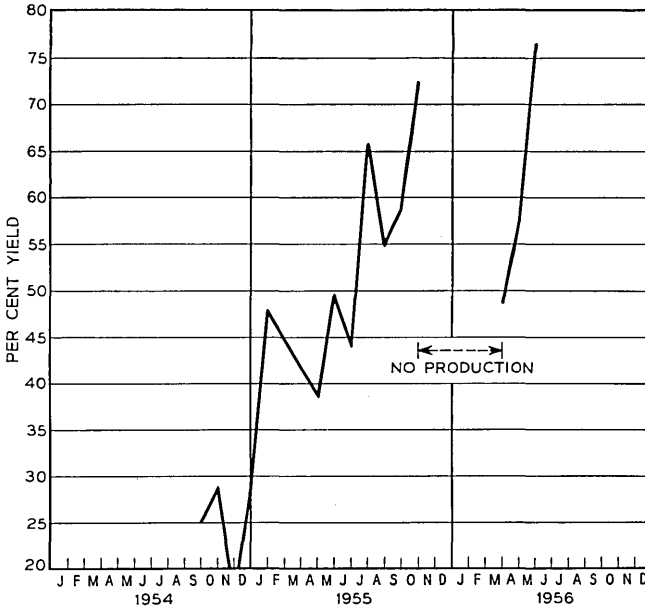


Fig. 6 — Mica capacitor yield.

attachments were necessary to wind these resistors. Other resistors were hand wound on methyl-methacrylate forms, or on the outside of the ceramic containers, for certain types of paper capacitors. Rough adjustments were required of the lengths of resistance wire prior to winding, and close adjustments to resistance values were made after the windings were completed and before leads were attached to resistors. Again it was necessary to provide periodic samples that could be placed on life test by the Laboratories to ascertain that the manufacturing processes were under control. These samples, in all possible cases, were taken from product that would normally be rejected because of some minor defect, but which would not in any way detract from the validity of the life tests. The making of hard solder splices between nichrome resistance wire and gold-plated copper leads, and keeping ceramic parts from coming in contact with metal surfaces and thereby being contaminated because of the ceramic's abrasive characteristics, were two major problems on resistors. Fig. 7 indicates resistor yields.

Inductors comprised 20 different designs, most of which were air core, but there were some for which it was necessary to cement permalloy dust cores into pockets of the methacrylate form, and thereafter using

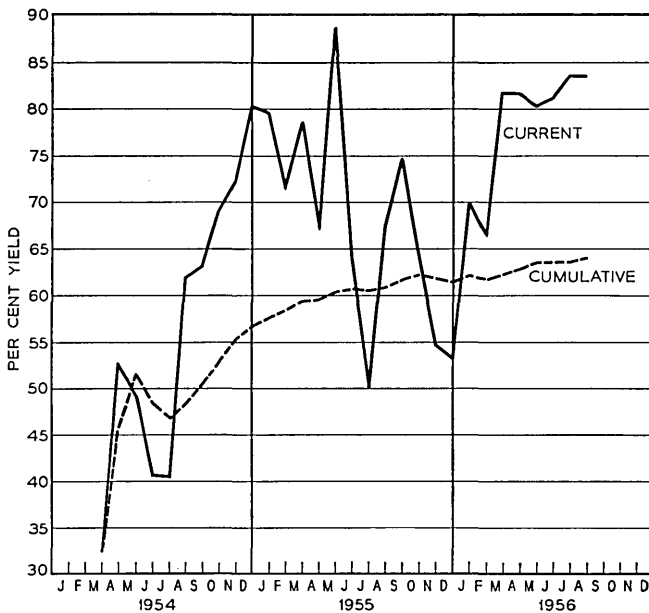


Fig. 7 — Resistor yield.

wire on a shuttle, wind by hand the turns required to produce an inductor. These varied from a very small inductor, smaller in diameter than a pencil, to a fairly large "figure eight" inductor with turns having a major diameter of about $1\frac{1}{4}$ inches. Each layer of a winding was inspected with a microscope to insure that the wire had not been twisted or kinked, or that the insulation was damaged or uneven. Some of the shuttles became fairly long so that they could hold the amount of wire required to make a continuous winding. The operator's handling of this shuttle, as she moved it down around the openings in the methacrylate part, or placed it on a bench to proceed with the interleaving tape, demanded considerable dexterity and concentration to insure that the shuttle was not turned over — which in effect would put a twist in the wire. Although best known means were used to sort cores for their magnetic properties prior to the time a winding was made, the limits on the inductors themselves were so close that subsequently a large number of windings were lost. The best cores that could be selected, plus the best winding practice, could not produce 100 per cent of the inductors within the required limits. Cracking of the insulation on the wire; cementing together of two methacrylate parts or of permalloy cores into pockets of

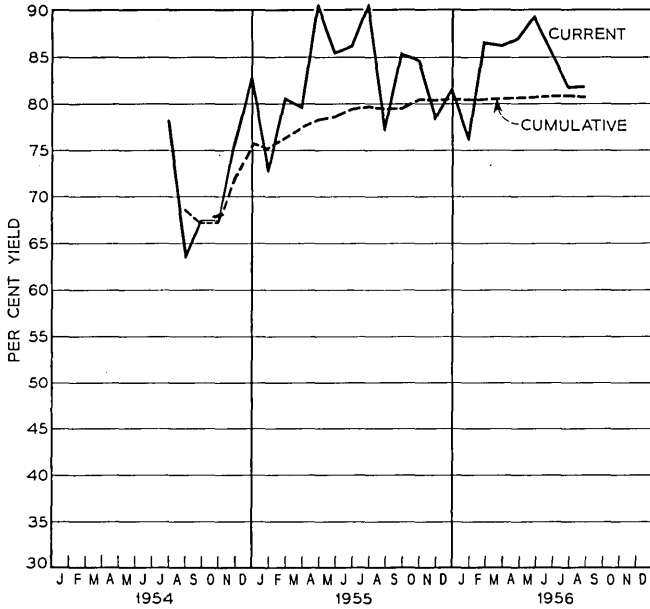


Fig. 8 — Inductor yield.

methacrylate parts, and handling those inductors having long delicate leads, were the most troublesome items on this apparatus. Fig. 8 shows manufacturing yield for inductors.

Networks combined several codes of component apparatus, such as a mica and a paper capacitor, resistor and an inductor. Six networks were used in each repeater unit consisting of two interstage networks, an input, an output, and two beta networks. They demanded a most delicate wiring job in that stranded gold-plated copper wires had to be joined in a small pocket in methyl methacrylate, where a minimum amount of heat can be applied; otherwise the methacrylate is affected. After soldering, a minimum amount of movement of the stranded wire was permitted, inasmuch as the soldered gold-plated copper wire becomes quite brittle.

Repeater Units, are wired assemblies consisting of seventeen sections in which there are six networks, three electron tubes, one gas tube, one crystal, three high voltage capacitors, one dessicator and two terminal sections. The successive build-up of these materials left little chance to make a repair because a splice in a lead was not permissible. It is during this assembly stage that a repeater received its individual identity be-

cause of the frequency of the particular crystal assembled into the unit. A manufacturing yield of 100 per cent was achieved in the assembly and wiring of repeater units.

It was necessary to calibrate the test equipment for this job very closely. Bell Telephone Laboratories and Western Electric worked at length to calibrate the testing details and the test sets for individual networks. Adjustments in components apparatus to bring the network to the fine tolerances required were accomplished by minute scraping of the silvered mica on a mica capacitor or removing turns from wire-wound inductors. The cementing of methacrylate parts, which was a troublesome item on mica capacitors and inductors, also had to be contended with on networks.

PACKING AND SHIPPING COORDINATION

Repeaters were packed in Western Electric specially designed 34-foot long aluminum containers, weighing 1,000 pounds. Forty of these containers were made by an outside firm. Fig. 9 shows two containers tied down in a truck trailer. The repeaters were nested in a pocket of polyethylene bags containing shaped rubberized hair sections in order to cushion the repeaters during their subsequent handling and transportation. The instrumentation required with each case was tested, properly set, and inspected prior to its use on each outgoing case. The instruments were a shock recorder to register shocks in three planes, and a thermometer to register the minimum and maximum temperatures to which the repeater had been exposed. Arrangements were made with a commercial trucking company to provide three specially equipped truck trailers, which could be cooled by dry ice during hot weather and warmed by burning bottled gas during cold weather so as to control temperature within the 20-degree F. to 120-degree F. called for in the repeater specification.

Appointment of a shipping coordinator supervisor added tremendously to the smooth functioning of services and provided the continuing vigilance required to protect repeaters and deliver them to the right place at the right time. His responsibility was to coordinate all the shipping information and arrangements from the time the item was ready for packing at the Hillside plant, through all trucking arrangements to the armoring factory, to the airport, to England, and to follow, with statistical data and reports, each enclosure until we were able to record the date on which the repeater was laid or stored in a depot.

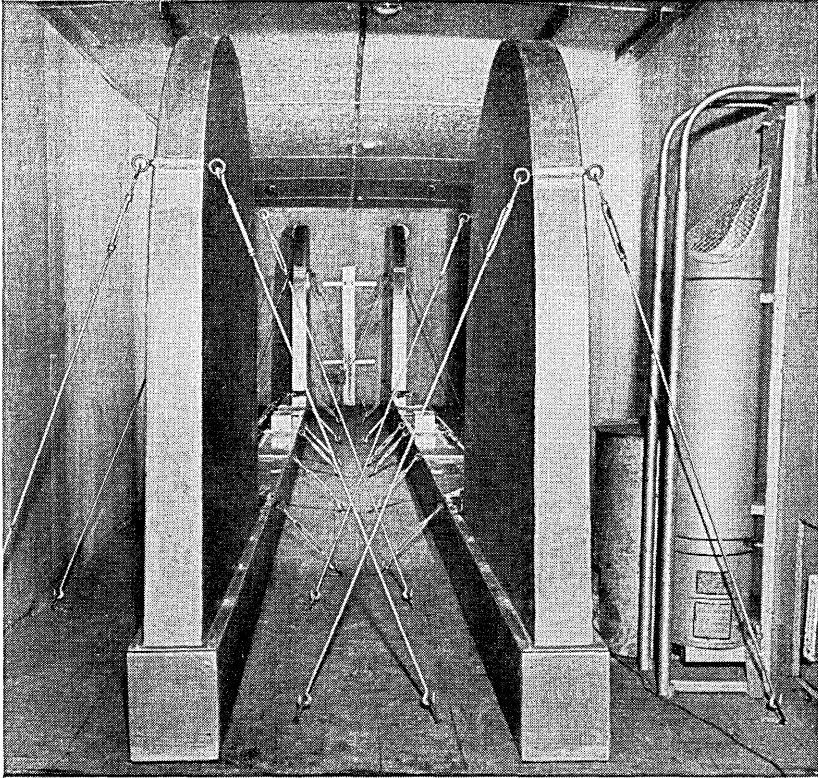


Fig. 9 — Shipping containers.

INSPECTION PLAN AND PROCEDURES

General

It is axiomatic that quality is not obtained by inspection but must be built into the product. However, the Inspection Organization does have the responsibility of certifying that the desired quality exists. Our evaluation indicated that the ordinary inspection "screening" would be inadequate to insure the high degree of integrity demanded and that additional safeguards would have to be provided. These controls were achieved, in a practical way, by:

- (1) Selective placement, intensive training and subsequent qualification testing of all personnel.
- (2) Inspection during manufacturing operations in addition to in-

spection of product after completion, and regulating inspection so that critical characteristics received repetitive examination during the process of manufacture and assembly.

(3) A maintenance program for inspection and testing facilities which provided checks at considerably shorter intervals than is considered normal.

(4) Inspection and operating records and reports that point out areas for corrective measures.

(5) Records of quality accuracy for all inspection personnel as an aid in maintaining the high quality level.

(6) Verification of all data covering process and final inspection as a certification of the accuracy of these data and that the apparatus satisfactorily meets all requirements.

Selection and Training of Inspection Personnel

The quality of a product naturally depends upon the skills, attitude, and integrity of the personnel making and inspecting it. It was realized that in order to develop the high degree of efficiency in the inspection organization necessary to insure the integrity of the product, personnel of very high caliber would be required. These employees would have to be (1) experienced in similar or comparable work, (2) they would have to be precise, accurate and, above all, dependable, (3) in order to reduce the possibility of contamination and damage they would have to be neat and careful, and (4) they would require the ability to work in harmony with other employees, often as a member of a "team," in an environment where their work would be under constant scrutiny.

Most of the inspection employees selected to work at Hillside were transferred from the Kearny Plant and had an average Western Electric service of twelve years. They were hand-picked for the attributes outlined above, and the "screening" was performed by supervision through personal interviews supplemented by occupational tests given by the personnel department. These tests, which are in general use, are designed to evaluate background and physical characteristics, and they were given regardless of whether the employee had or had not previously taken them.

The following group of tests is an example of those given inspectors and testers of apparatus components:

- (1) Electrical — ac-dc theory and application.
- (2) Ortho-Rater — Eye test for phoria, acuity, depth, and color.
- (3) Finger Dexterity — Ability and ease of handling small parts.

(4) Special — Legibility of handwriting, ability to transcribe data and to use algebraic formulae in data computations.

Inspection Plan

The general plan of visual and mechanical inspection consisted of:

(1) Inspection of every operation performed — and in many cases partial operations — during the course of manufacture. This is of particular importance where the quality characteristics are hidden or inaccessible after completion of the operation.

(2) Repeated inspection at subsequent points for omissions, damage and contamination.

(3) Rejection of product at any point where there was failure to obtain inspection or where the results of such inspection had not been recorded.

Most of the visual inspection was performed at the operators' positions to reduce, to a minimum, the amount of handling that could result in damage and contamination.

Visual inspection covered three general categories:

(1) Inspection of work after some or all operations had been completed, such as the machining of parts.

(2) Inspection at those points where successive operations would cover up the work already performed. An example of this is the hand winding of toroidal inductors where each layer of wire was examined under a microscope for such defects as twists, cracks, and crazes in enamel insulation, spacing and overlapping of turns, and contamination before the operator was allowed to proceed with another layer. While being inspected, the work remained in the holding fixture, which was hinged in such a manner as to permit inspection of both top and bottom of the coil. Inductors received an average of 13 and a maximum of 26 visual inspections during winding.

(3) Continuous "over-the-shoulder" inspection, where strict adherence to a process was required or where it was impossible to determine, by subsequent inspection, whether or not specific operations had been performed. In these cases, the inspector checked the setup and facilities, observed to see that the manufacturing layouts were being followed, that the operations were being performed satisfactorily, and that specifications were being met.

ELECTRICAL TESTING

The electrical testing, in itself, was not unusual for carrier apparatus and runs the gamut from dc resistance through capacitance, inductance,

and effective resistance, to transmission characteristics in the frequency band 20-174 kc. What was unusual were the extremely narrow limits imposed and the number and variety of tests involved as compared to those usually specified for commercial counterparts.

The following two examples will serve to illustrate the extreme measures taken to prove the integrity of the product:

(A) One type of Resistor was wound with No. 46 mandrelated nichrome wire to a value of 100,000 ohms plus or minus 0.3 per cent. This resistor received six checks for dc resistance, five for instantaneous stability of resistance and two for distributed capacitance, at various steps in the process which included six days' temperature cycling for mechanical stabilization. This resistor was considered satisfactory, after final analysis of the test results, if: (a) The difference in any two of the six resistance readings did not exceed 0.25 per cent. (b) The change in resistance during cycling was not greater than 0.02 per cent. (c) The "instantaneous stability" (maximum change during 30 seconds) did not vary more than 0.01 per cent. In addition, it was required that the distributed capacitance, minimum 7, maximum 10 mmf, should not differ from any other resistor by more than 2 mmf.

(B) For high voltage paper capacitors, the 0.004-inch thick Kraft paper, which constitutes the dielectric, was selected from the most promising mill lots which the manufacturers had to offer. This selection was based on the results obtained from tests that involve examination for porosity, conducting material and conductivity of water extractions. These tests were followed by the winding and impregnation in Halowax of test capacitors. The test capacitors were then subjected to a direct voltage endurance test at 266 degrees F for 24 hours.

Samples of prospective lots of paper, which have passed the above test, were then used to wind another group of test capacitors that were subsequently impregnated with Aroclor and sealed. 1,500-volt dc was then applied to the capacitors at 203° F for 500 hours. In case of failure, a second sampling was permitted.

After the foregoing tests had been passed, the supplier providing the particular mill lot was authorized to slit the paper. Upon receipt, six special capacitors were wound, using a group of six rolls of the paper being qualified. These capacitors were then impregnated, checked for dielectric strength at 3,000-volt dc, and measured for capacitance and insulation resistance. The capacitors were then given an accelerated life test at 2,000-volt dc, temperature 150° F, for 25 days. Each lot of six satisfactory test capacitors qualified six rolls of paper for use.

Product capacitors were then wound from approved paper, and the dry units checked for dielectric strength at 300-volt dc. Capacitance

was checked and units were then assembled into cans and ceramic covers soldered in place. Assemblies were pressurized with air, through a hole provided for the purpose, while the assembly was immersed in hot water to determine if leaks were present. Capacitors were then baked, vacuum dried, impregnated, pressurized with nitrogen, and sealed off. The completely sealed units were then placed in a vacuum chamber at a temperature of 150° F, 2 mm. mercury, for 3 hours to check for oil leaks. Capacitance was rechecked and insulation resistance measured.

After seven days, capacitors were unsealed to replenish the nitrogen that had been absorbed by the oil, resealed and again vacuum leak tested. An X-ray examination was then made of each individual unit to verify internal mechanical conditions. Capacitors were then placed in a temperature chamber and given the following treatment for one cycle:

16 hours at 150°F; 8 hours at 75°F; 16 hours at 0°F; 8 hours at 75°F.

At the end of ten days, or 5 cycles, the insulation resistance and conductance was measured and a norm established for capacitance.

Capacitors were then recycled for ten days, and, if the capacitance had not changed more than 0.1 per cent, they were satisfactory to place on production life test. If the foregoing conditions had not been met, the capacitors were recycled for periods of ten days until stabilized.

At that time, 10 per cent of the capacitors in every production lot were placed on "Sampling Life Test", which consisted of applying 4,000-volt dc in a temperature of 150°F for 25 days. At the same time, the balance of the capacitors in the lot were placed on production life test at 3,000-volt dc in a temperature of 42°F for 26 weeks. At the end of this time, the insulation resistance was measured and the capacitance checked at 75°F and at 39°F. The difference in capacitance at the two temperatures could not exceed +0.001, -0.005 mf, and the total capacitance could not exceed maximum 0.3726, minimum 0.3674 mf. The capacitance from start to finish of the life test could not have changed more than plus or minus 0.1 per cent.

If all of the preceding requirements had been satisfied, the particular lot of capacitors described was considered satisfactory for use.

The foregoing examples are typical of the procedures evolved for insuring, to the greatest degree possible, the long, trouble-free life of all apparatus used in the repeater.

Radioisotope Test

There were many new and involved tests which were developed and applied to the manufacture of repeaters. One of the most unique is the use of a radioisotope for the detection of leaks under hydraulic pressure.

The initial closure operations consisted of brazing into each end of the repeater housing a Kovar-to-glass seal. These seals are equipped with small diameter nickel tubulations which were used to flush and pressurize the repeaters with nitrogen. After these operations had been performed, one of the tubulations was pinchwelded, overbrazed and coiled down into the seal cavity. The repeater was then placed in a pressure cylinder with the open tubulation extending through and sealed to the test cylinder. A mass spectrometer was then attached to the tubulation and the test cylinder pressurized with helium at 10,000 psi. At the conclusion of this test the repeater was removed from the test cylinder and, after breaking the desiccator diaphragm, the remaining open tubulation was pinchwelded and overbrazed. At this point, it became necessary to determine whether the final pinchweld and overbrazing would leak under pressure.

Since there was no longer any means of access to the inside of the repeater, all testing had to be done from the outside. This was accomplished by filling the glass seal with a solution of radioisotope cesium 134, which was retained by a fixture. The repeater was then placed in a test cylinder and hydraulic pressure applied, which was transmitted to the radioisotope in the fixture. After 60 hours under pressure, the repeater was removed from the cylinder and the seal drained and washed. An examination was then made with a Geiger counter to determine if any of the isotope had entered the final weld.

The washing procedure, after application of the isotope solution, involved some sixty operations with precise timing. In the case of the repeater at the rubber seal stage where both ends were tested, it was desirable that these operations be performed concurrently. This was accomplished by recording the entire process on magnetic tape which, when played back, furnished detailed instructions and exact timing.

RAW MATERIAL INSPECTION

As might be expected, raw materials used in the project were very carefully examined and nothing left to chance. Every individual bar, rod, sheet, tube, bottle or can of materials was given a serial number and a sample taken from each and similarly identified. Each sample was then given a complete chemical and physical analysis before each corresponding piece of material was certified and released for processing. In many cases, the cost of inspection far exceeded the cost of the material. However, the discrepancies revealed and the assurance provided, more than justify the expense.

Detailed records of all raw material inspection were compiled and furnished to the responsible raw material engineer who examined them,

critically, as an additional precaution before the material was released to the shop.

INSPECTION RECORDS

To eliminate, as much as possible, the human element in providing assurance that all prescribed operations had been performed satisfactorily, inspected properly and the results recorded, means were established to compile a complete history of the product concurrent with manufacture. This was accomplished through the provision of permanent data books of semilooseleaf design, which require a special machine for removing or inserting pages.

Each of these books covered a portion of the work involved in producing a piece of apparatus and contained a sequential list of pertinent operations and requirements prescribed in the manufacturing process specifications. Space was provided, adjacent to the recorded information, for both the operator and inspector to affix their initials and the data. A reference page in the front of each book identified the initials with the employees' names. All apparatus was serially numbered and the data were identified accordingly. If a unit was rejected, that serial number was not reused.

These data books, in addition to establishing a complete record of manufacture, provided a definite psychological advantage in that people were naturally more attentive to their work when required to sign for responsibility.

QUALITY ACCURACY

As pointed out previously, every precaution was exercised in selecting and training inspection personnel assigned to the project. However, it was realized at the outset that human beings are not infallible and that insurance, to the greatest degree possible, would have to be provided against the probability of errors in observation and judgment. Quality accuracy evaluation procedures were, therefore, established for determining the accuracy of each inspector's performance.

Quality accuracy checking was performed by a staff of five Inspection Representatives and involved an examination of the work performed by inspectors to determine how accurately it was inspected. Materials which the inspector accepted and those which had been rejected were both examined.

VERIFICATION AND SUMMARY OF DATA

As an added measure of assurance as to the integrity of the product, procedures were established for verifying and summarizing the inspection records for each serially numbered component, up to and including complete repeaters.

Verification involved a complete audit of the inspection records to provide assurance that all process operations were recorded as having been performed satisfactorily, that the prescribed inspections had been made, and that the recorded results indicated that the product met all of the specified requirements. This work was performed by a group of six Inspection Representatives who had considerably experience in all phases of inspection and inspection records.

As the verification of a particular piece of apparatus proceeded, a verification report was prepared which, when completed, contained the most pertinent inspection data, such as:

- (1) Recorded measurements of electrical parameters.
- (2) Values calculated from measurements to determine conformance.
- (3) Confirmation that all process and inspection operations had been verified.
- (4) Identification (code numbers and serial or lot numbers) of materials and components entering into the product at each stage of manufacture.

The verification report usually listed the data for twenty serial numbers of a particular code of apparatus along with the specified requirements. Included, also, was a cross-reference to all the inspection data books involved so that the original data could be located easily. These verification reports were prepared for all apparatus up to and including the finally assembled and tested repeaters.

The following gives an indication of the number of items examined in the verification of one complete repeater:

Items verified in data books	17,593
Items verified on recorder charts	1,142
Calculations verified	1,580
	20,315
Number of entries on verification reports	4,070

Verification reports, in addition to presenting the pertinent recorded data, provided a "field" of twenty sets of measurements from which it was easily possible to spot a questionable variation. For example, it was the adopted practice on this project to examine, critically, any characteristic of a piece of apparatus, in a universe of twenty, which varied considerably from the rest, despite the fact that it was still within limits.

While the number of cases turned up in the verification process which have resulted in rejection of product are relatively few, we believe that the added insurance provided, and the psychological value obtained, considerably outweigh the cost.

Power Feed Equipment for the North Atlantic Link

By G. W. MESZAROS* and H. H. SPENCER*

(Manuscript received September 20, 1956)

Precise regulation of the direct current which provides power for the undersea repeaters in the new transatlantic telephone cable is necessary to maintain proper transmission levels and to assure maximum repeater tube life. The highest possible degree of protection is needed against excessive currents and voltages under a wide variety of possible fault conditions. Furthermore, to minimize the dielectric stresses, a double-ended series-aiding power feed must be used and the balance of these applied voltages must be maintained in spite of substantial earth potentials. This paper describes the design features which were employed to attain these objectives simultaneously, while eliminating, for all practical purposes, any possibility of even a brief system outage due to power failure.

INTRODUCTION

The principal objectives in the power plant design for the Transatlantic cable system were as follows:

1. To stress reliability in order to guarantee continuous dc power to the electron tubes that form an integral part of the submerged repeaters. This is essential, not only to be able to maintain continuous service, but to prevent cooling and contraction of the repeater components, especially the tubes.

2. To provide close dc cable current control to ensure constant cathode temperature and regulated plate and screen potentials for the repeater tubes. These operating conditions are essential both for obtaining maximum life from these tubes and for maintaining constant transmission level.

3. To control and limit the applied dc cable potentials in order to minimize the dielectric stresses. The life of certain capacitors in the repeaters is critically dependent upon these stresses. Moreover, momen-

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tary high potentials increase the chances of corona formation and insulation breakdown.

4. To protect the cable repeaters from the excessive potentials or currents to which they might be subjected after an accidental open or short circuit in the cable.

5. To compensate for earth potentials up to 1,000 volts, of either polarity, that may develop between the grounds at Oban and Clarendville during the magnetic storms accompanying the appearance of sun spots and the aurora borealis.

6. To provide adequate alarms and automatic safety features to ensure safe current and voltage conditions to both the cable and the operating personnel.

DESIGN REQUIREMENTS

Reliable Cable Power

The first basic problem of design was to select a reliable source of dc power for energizing the cable repeaters. Although a string of batteries, on continuous charge, is perhaps the most dependable source of direct current, such an arrangement is not attractive here. A complex set of high-potential switches would be required for removing sections of batteries for maintenance and replacement purposes. Protection of the repeater tubes from damage during a cable short circuit would be difficult. Facilities to accommodate changing earth potentials would be cumbersome. Furthermore, the problem of hazards to personnel would be serious.

The use of commercial ac power with transformers and rectifiers to convert to high potential dc would expose the cable to power interruptions even with a standby diesel-driven alternator, because of the time required to get the engine started. A diesel plant could be operated on a continuous basis, but this prime power source would also present a considerable failure hazard even with the best of maintenance care. The two-motor alternator set, used so successfully in the Bell System's type "L" carrier telephone system, was adopted as representing the most reliable continuous power source available. This set normally operates on commercial ac power, but when this fails, the directly-coupled battery-operated dc motor quickly and automatically takes over the drive from the induction motor, to prevent interruption of the alternator output. Here the storage battery is still the foundation for continuity, but at a more reasonable voltage.

As described later, the possibility of a system outage resulting from fail-

ure of this two-motor alternator set has been essentially eliminated by using two such sets, cross-connected to the rectifiers supplying power to the two cables, with a continuously operating spare for each set, automatically switched in upon failure of the regular set.

The regulating features of the rectifiers will be described in a later section. In the present discussion of reliability it is sufficient to note that series regulating tubes are used, which are capable of acting as high-speed switches, through which two rectifiers can be paralleled. Thus either rectifier can accept instantaneously the entire load presented by the cable. In each regulator the series tubes carrying the cable current are furnished in duplicate and connected in parallel to share the cable load, a single tube being capable of carrying the entire load. These current regulators are operated from separate ac sources to protect against loss of cable power because of failure of one of the sources of ac power.

Cable Potentials

To minimize the cable potentials, half of the dc power is supplied at each end of each cable, the supplies being connected in series aiding. With this arrangement, as shown in Fig. 1, the dc cable potential at one end of each cable is positive with respect to ground while at the other end the potential is negative. This places the maximum potential and risk on the repeaters near the shore ends, which are more readily retrieved, while the repeaters in the middle of the cable, in deeper water, have potentials very near to ground. The power equipment would be simpler with a single-ended arrangement, but at the penalty of doubling the dielectric stresses in the entire system, which would be prohibitive. A balanced power feed could have been attained at the expense of power separation filters in the middle of the cable or a shunt impedance of appropriate size at the midpoint. The resulting complications, in-

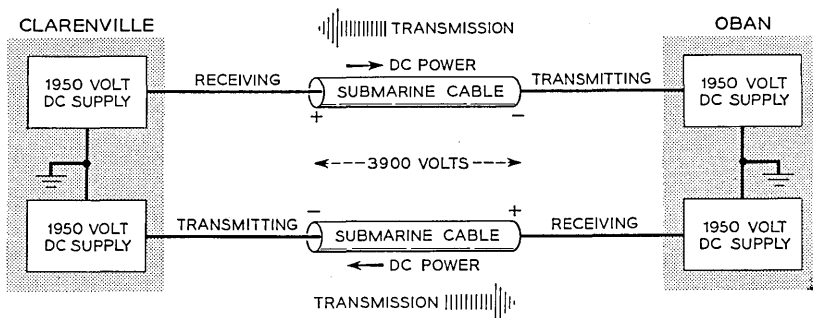


Fig. 1 — Cable voltage supply.

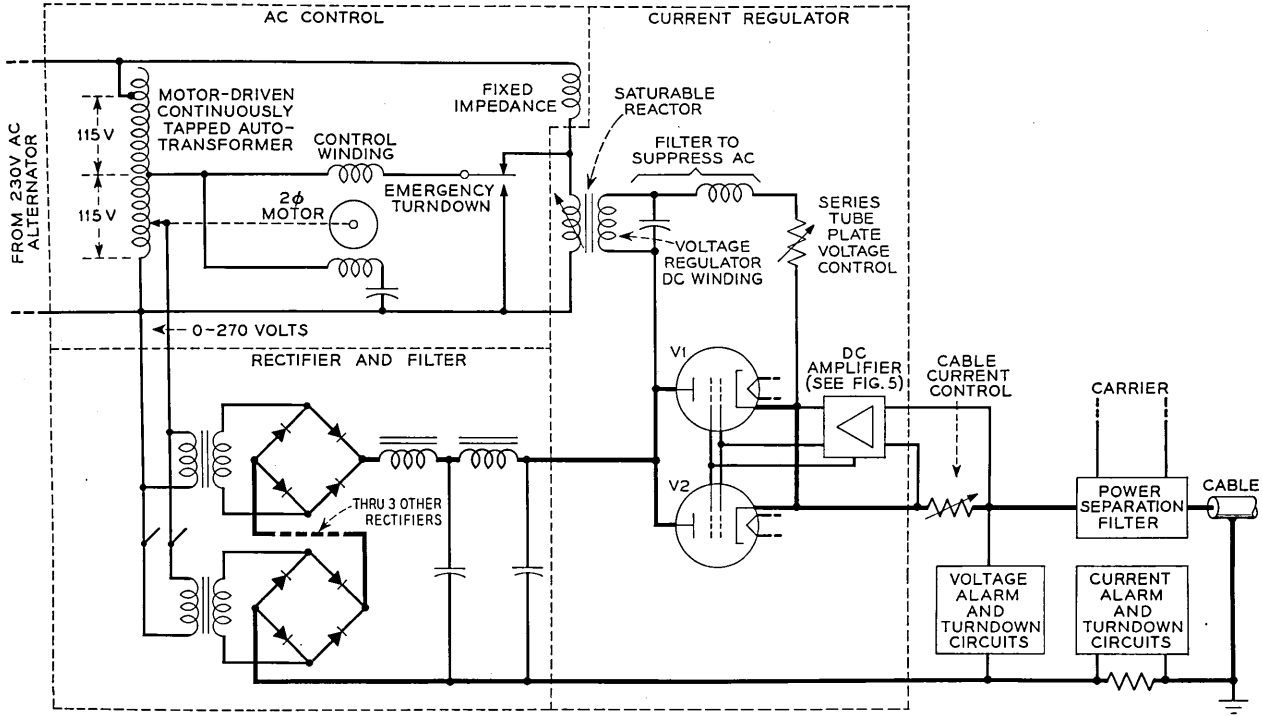


Fig. 2 — Simplified circuit of the regulating system.

cluding difficulty in the location of a cable fault, could not be justified for the sake of simplification of power-plant design and operation.

The requirement that minimum cable potentials be maintained during and after severe earth potential disturbances necessitates variable output voltages from the supplies at both ends, and this introduces problems in continuous voltage balance and regulation stability. The design features which yield the required performance are described in a later section.

DC Cable Current Regulation

The salient requirements in performance of the constant current regulator are listed below:

a. The regulator must have extremely fast response to hold the cable current within a few milliamperes of its nominal value should a short circuit develop in the cable. Thus damage to the heaters of the repeater tubes, as well as excessive induced transient voltages in the repeater transformers is avoided. The probability of a short circuit is higher near the shore ends where the water is shallow and sea traffic a factor. The regulator must be capable of absorbing the reduction in power to the cable, while maintaining current control under normal conditions. This sudden exchange in power from cable to regulator may be as much as 2,000 volts at 0.25 ampere.

b. The cable current should be maintained constant within 0.2 per cent of its nominal value for normal variations in ac supply, gradual earth potential changes, and ambient temperature changes. This degree of regulation allows an adequate safety factor in maintaining a constant transmission level.¹

c. The regulators, in conjunction with the power separation filters and the rectifier filters, must limit the power supply noise at the cable terminals to a peak-to-peak value less than 0.02 per cent of the dc supply potential.

d. The cable current must be adjustable over a range of 225 to 245 milliamperes to compensate for repeater tube aging.²

e. The regulators must operate in parallel in such a way as to ensure continuity of power should one fail or be removed from service for maintenance. This of course implies that regulators can be switched in and out of service without causing surges in the cable current or voltage.

f. The series-aiding arrangement, with rectifiers at each end of the same cable, must be stable.

g. The regulators should be capable of being serviced at low poten-

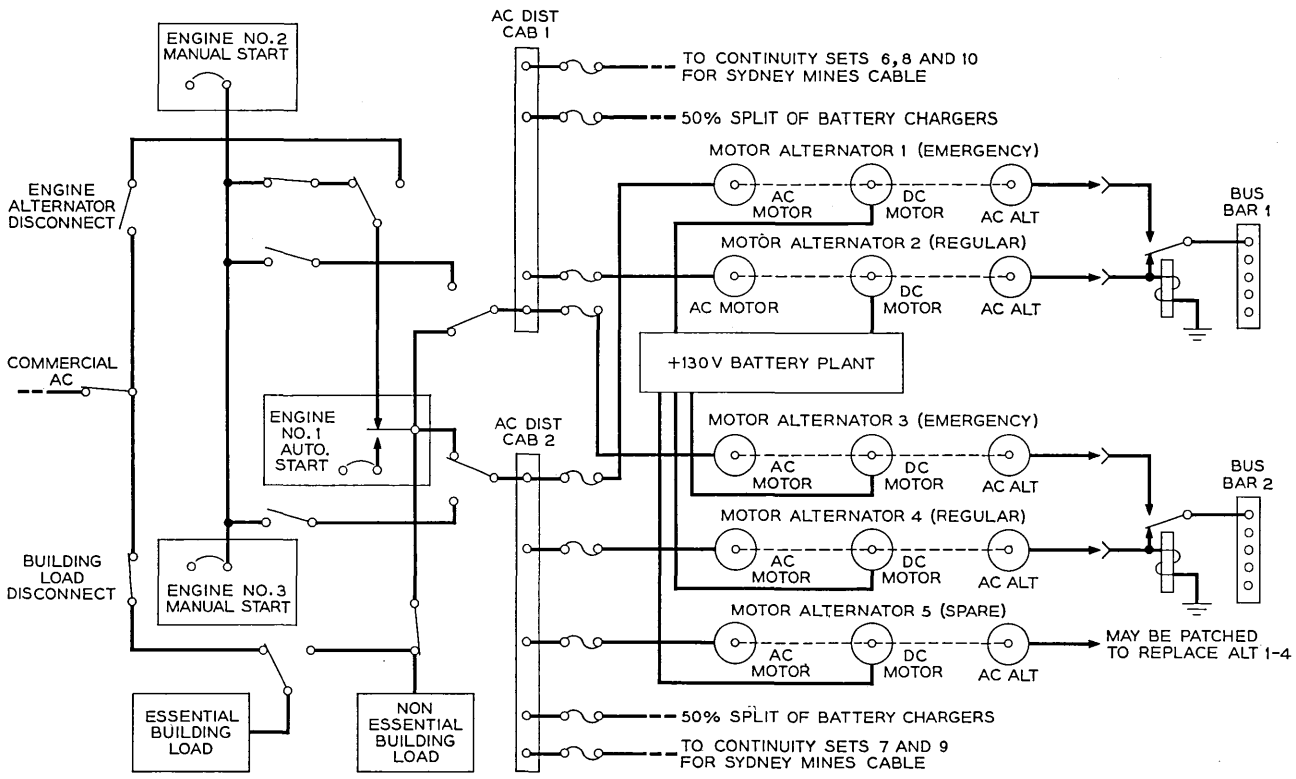


Fig. 3 — Continuous ac power.

tials, when in the test position, in order to protect maintenance personnel.

h. The current regulator should be of the fail-safe type so that impairment of any of the regulator components will not permit excessive rise in cable current. In the event of component trouble, an aural or visual alarm should occur.

It was decided that a high speed electronic constant-current regulator backed up by a slower speed servo system, as shown in Fig. 2 and discussed in detail later, would best meet the above requirements. In this way, fast response with high gain is combined with wide regulating range, yet the efficiency is high and the load-handling capacities of the various components are held to a minimum. With regard to simpler alternatives, the electromechanical type of current regulator, using relays and a motor-driven rheostat, is too slow to protect the repeater tubes from a cable short circuit and its accuracy is insufficient to meet the regulation requirements. The all-magnetic type of regulator is possibly most dependable but it does not readily provide either the speed of response or the wide regulating range needed.

GENERAL DESCRIPTION

Prime and Standby Power Source

Commercial service is considered the normal prime source of power for the cable, although at the Clarendville terminal commercial power was not available at the time of installation. Anticipating this condition, a reserve plant consisting of three 60-kw diesel alternators was installed and the distribution circuits were arranged, as shown in Fig. 3, to provide partial or total use of the commercial service. Initially all cable power was supplied by diesel operation, alternating the prime movers on a weekly basis. These sets are paralleled manually when they are interchanged, to prevent an interruption in the 60-cycle supply. It may be noted that Engine No. 1 is arranged as an automatic standby whether prime power is provided by diesels or by commercial service.

The switching and distribution arrangements are designed to be essentially failure-proof. At Clarendville, for example, two ac distribution cabinets, each capable of being fed from two sources, were provided in separate locations. The normal source through Engine No. 1 control bay can be readily by-passed directly to the manual diesels, should Engine No. 1 control bay be disabled. Furthermore, allocation of charging rectifiers, control circuits, ac motors for continuity sets, etc., has been

made in such a manner that loss of one cabinet alone will have minimum effect on the cable power supplies or office loads. At Oban, where 50-cycle commercial service is normally used, special distribution arrangements have been provided to give maximum power supply reliability, with three manually operated 50-cycle, 90-kw, diesel-alternator sets arranged for standby service. The diesels at this terminal are larger to care for greater local power loads.

Continuous AC Power From Two-Motor Alternators

At both cable terminals, two reliable ac buses supply power to the dc cable regulating bays. Each of these buses is fed from a continuously operated, self-excited, single-phase, 230-volt alternator normally driven by a 3-phase induction motor on the same shaft with a 130-volt dc motor. Each regular alternator is backed-up by a similar emergency alternator running at no load. A fifth motor-alternator is provided which can be used whenever any other set is out of service for routine maintenance or repair.

As alternator loads are essentially constant, and since induction motor speeds are fairly insensitive to power supply voltage variations, alternator outputs are set by fixed adjustments of their field rheostats. Supply voltages are monitored to control automatic transfer to dc motor drive whenever the supply voltage drops below 80 per cent of the normal value. Fig. 4 shows the normal running circuit for an alternator set, with the dc motor connected to the battery through a resistance of 75 ohms inserted in the armature circuit. The field resistance FR is preset so that when the battery is driving the set, the speed matches that of

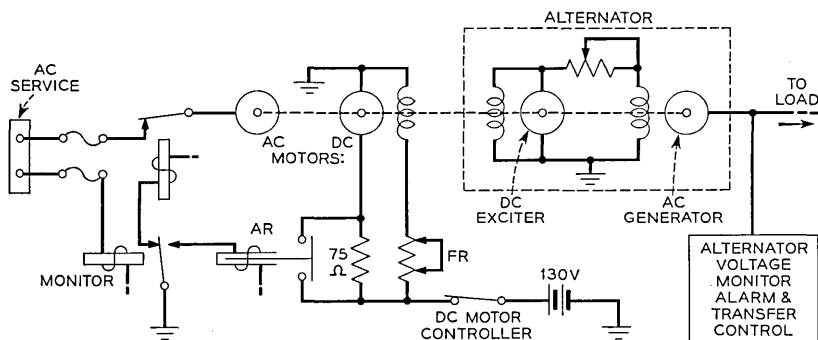


Fig. 4 — Two-motor alternator set.

the ac drive when the battery voltage is at the mean discharge value. During ac drive, the EMF generated in the dc motor armature is a few volts below that of the battery. Accordingly, when the fast acting contactor AR shorts the 75-ohm resistance in the armature circuit, the motor finds itself essentially at the desired operating flux condition and a smooth pickup of drive occurs. Oscillograms indicate that the interval between failure of ac power and operation of contactor AR is less than 0.1 second. During the transfer from ac to dc drive, the change in the nominally 230-volt output is less than 5 volts.

Return to ac drive is delayed approximately 20 seconds after the ac supply voltage has returned to normal to allow time for the ac to stabilize. Fixed field settings for both dc motor and alternator fields provide simple control arrangements without the overspeed or overvoltage hazards which automatic regulators might add. Alternator output is monitored, however, to give alarms for voltage changes exceeding ± 5 per cent and to control transfer to dc drive if the output should drop more than 10 per cent for any reason. When the latter occurs, the machine locks on dc drive. This feature guards against ac motor failure or low ac drive speed because of low supply frequency without low supply voltage.

Failure of the alternator output after transfer to dc drive causes the set to stop and automatically transfer the load to its emergency alternator. This transfer causes a break in the alternator supply to its bus, but cable power is maintained constant by the parallel dc regulating bay fed from the other alternator bus.

Battery Plants and Distribution

Battery power for dc motor drive is supplied from a 66-cell, 1,680-ampere-hour battery at Clarendville and from two 68-cell, 1,680-ampere-hour batteries at Oban. The latter station has double capacity to provide stand-by power for the ac supplies to the inland transmission equipment.

At both cable terminals, control battery for the small alternator plants and the cable dc regulating equipment provides 24 volts and is split so that a fuse or a battery failure on either supply will not interrupt cable power. To guard against so remote a hazard as loss of a common battery for this vital control, two separate 24-volt power plants have been provided with one half of the critical control circuits furnished from each plant.

In addition to supplying dc motor power, the 130-volt battery at Clarendville supplies current to the carrier terminal and test equipment

through voltage dropping resistors which are normally in the circuit to hold the load voltages below a maximum of 135 volts. These resistors are automatically shorted to maintain a minimum load voltage of 125 volts when the battery voltage drops. A voltage detecting relay also steps the fixed field adjustment of each dc motor when the battery nears its final discharge voltage so that dc motor speed is kept within about ± 3 per cent of normal ac drive speed during battery operation. The 66-cell battery is floated at 143 volts by means of voltage regulated rectifiers and, after a discharge, is recharged by automatic operation of a regulated 100-ampere motor-generator set. As indicated in Fig. 3, the rectifiers for this plant are connected so that loss of one service cabinet will still leave sufficient charging capacity to float the load from the other cabinet.

Rectifiers and Associated Controls

As mentioned earlier, each cable is supplied at all times by two regulating bays in parallel, each operating from a separate ac source and each capable of taking over the cable load should the other fail. Thus failure of an alternator supply or of a regulating bay itself will not interrupt the cable power. A spare regulating bay for each cable is arranged for replacing either of the two regular bays and may be connected in parallel with the other two without overloading the associated 2.5-kva alternator.

As shown schematically in Fig. 2, the ac supply to the rectifiers is controlled by a continuously-tapped variable autotransformer, operated normally by a two-phase low-inertia reversible motor, with provision for manual adjustments also. The autotransformer output is stepped up and rectified by a series arrangement of five rectifiers, each to give a maximum of 550 volts for a total of 2,750 volts when the autotransformer is at the upper limit. The high voltage rectifier output is filtered and supplied to the cable through the current regulating unit, cable connecting switch, and common cable control circuit. The cable current is regulated by controlling the plate to cathode drop across the electron tubes through which this current flows. A dc amplifier, which derives its signal from a resistance in series with the total cable current, varies the grid bias of the series regulating tubes. The series tubes have a control-drop range from about 150 volts to the full supply voltage, the dc amplifier being capable of driving the regulating tubes to cut-off. However, to protect the series tubes and to keep them operating at practically a constant plate voltage of 300 volts, a servo system automatically raises and lowers the output from the autotransformer by means of the motor-

driven ac control unit whenever the series tube plate voltage varies more than 25 volts from the normal value. For example, a 2 per cent change in input ac would change the rectifier output of 2,300 volts (corresponding to a cable supply voltage of 2,000 volts) by 46 volts, which would increase the series tube drop to 346 volts. This increase in voltage would raise the signal current through the control winding of a saturable reactor which forms one leg of a balanced bridge in the ac motor control circuit, and thus cause the autotransformer to be driven down, lowering the rectifier output until the series tube drop is restored again to approximately 300 volts.

Overvoltage and Overcurrent Protection and Alarms

While the power for the cable is electronically regulated, protective features are provided to guard against abnormal cable current or voltage. The first order of protection is a ± 2 per cent cable current alarm given by a voltage relay which operates from the drop across a resistor in the ground return circuit to the dc bays. A second voltage relay, set for 5 per cent high cable current, also monitors the current in the ground return side and in conjunction with the current-monitors in the high voltage side, limits the cable current by operating the motor-driven autotransformers until the current is within 5 per cent of normal. The voltage of the ungrounded side, however, is much too high for direct connected voltage or current relays. Therefore, magnetic amplifiers have been used to obtain isolated metering of the cable current. Two of these devices measure the current in the ungrounded side of the common power supply lead to the cables. Of the three current-monitors available, two must operate before turndown functions, to prevent false turndown because of faulty metering.

Voltage protection is provided by means of magnetic amplifiers in shunt across the common power supply to the cable. Here, three monitors are arranged so that any two can reduce power, by means of the turndown control, if the voltage rises to the maximum allowable value for which the voltage relays are adjusted. These monitors draw about 1.5 milliamperes each, but are connected on the supply side of the cable-regulating resistance so as not to affect cable regulation. They guard against excessive voltage resulting from an open circuit where voltages around 4,000 volts could otherwise occur. They also guard against high voltage caused by earth potentials or unbalance between voltages at opposite ends of the cable. When set for a ceiling voltage of 2,600 volts, a maximum of 3,000 volts occurs on open circuit on the first rise, after

which the voltage holds within $2,600 \pm 200$ volts as the turndown relays operate and release to maintain the ceiling voltage. A fourth magnetic-amplifier voltage detecting relay provides an alarm for ± 5 per cent excursions in cable voltage from the normal value. Other alarms are provided to indicate low output in either of the two parallel regulating bays, relay troubles, loss of magnetic amplifier ac control voltage, and fuse failures.

To limit the rate of change in the cable current under short circuit conditions and to reduce the rise in voltage at the repeaters on open circuit failure, an inductance of about 36 henries is connected in series with the cable circuit, and physically close to the cable termination, so that any failure in the power supply would have the advantage of this surge-limiting element.

Metering

Metering of the cable current is a very important part of the power plant design. Not only are the cable current ammeters needed to set the value of current desired, but their ability to indicate absolute current values assists in obtaining stable regulation between the two ends of the cable. The meters provided for this purpose are suppressed-zero, magnetically and statically shielded 150–300 milliamperere, large scale ammeters, with 0.5 per cent accuracy. One of these meters is connected in the ungrounded side and another in the grounded side of the cable supply circuit to provide an accuracy check and to indicate any ground leakage current in the supply circuit. They are connected to highly accurate 1-ohm four-terminal shielded resistors acting as shunts in the cable current circuits with their shunt leads arranged for switching to a calibration box for checking accuracy and for adjustment. This box employs a Weston laboratory standard cell, essentially a single-point potentiometer with the usual galvanometer, acting as a calibration standard at the 225-milliamperere point. Meters calibrated at Oban for 225 milliampereres were expected to be within 0.2 per cent or 0.5 milliamperere of those similarly calibrated at Clarendville, and at present are within about 0.2 milliamperere.

The cable current is also indicated by a recording ammeter. Meters in each regulating bay indicate the division of current between paralleled regulators. These meters have only 1 per cent accuracy but are satisfactory for adjusting load balance between parallel bays and also are used in turnup of power on a particular bay.

Cable voltage is read on a large scale voltmeter reading 0–3,000 volts and having ± 0.25 per cent accuracy. Since the accuracy is not critical,

this meter is not arranged for calibration. However, the series resistors incorporate 6,000-volt components for an extra degree of reliability. The voltmeter with its series resistor is normally connected across the common cable power supply ahead of the cable current regulating point. It can, however, be switched to read the cable voltage nearer the cable termination. In the latter position, it reduces the cable current by about 1 milliamperere, causing an unbalance in cable regulation, and therefore is not normally left in this position. The cable supply voltage is also indicated by a recording voltmeter.

Other meters are provided to indicate series tube plate voltages, dc rectifier voltages, ac input voltages, series tube currents, test currents for adjusting mag-amp operating limits, and the difference in current between the positive and negative power supplies to ground. Since many of these instruments operate at high potential, a special design was used with the operating mechanism and scale depressed in the instrument case approximately 1 inch. This both eliminated possible electrostatic effects on the instrument pointers and served as a safety measure.

DC REGULATION

DC Amplifier

The direct-coupled two-stage amplifier shown in Fig. 5 is characterized by potentiometer coupling and cold-cathode gas-tube voltage stabilizers. The biases are selected high enough so that linear operation is assured even for a short circuit at the cable terminal. As is apt to be the case in a direct-coupled amplifier, cathode temperature in the low-level stage is critical. In this amplifier, a 5 per cent change in heater voltage results in a 0.5 milliamperere change in the cable current.

The required precision of current regulation in these power supplies can be expressed as representing a source impedance of not less than 100,000 ohms. To meet this requirement, the gain of the dc amplifier was made as large as practicable with the plate and screen potentials available from gas-tube regulators. Interstage network impedances are high to reduce the shunt losses, and are proportioned to provide the large biases mentioned above. Gain adjustment is provided by a variable resistance in series with the cathode of the first stage.

Shaping of the loop gain and phase characteristics to obtain margins for stable operation is accomplished by means of the RC shunt (R_1C_1) across the plate resistor for the first stage. The amplifier gain and phase characteristics without this compensation are shown in Fig. 6. These

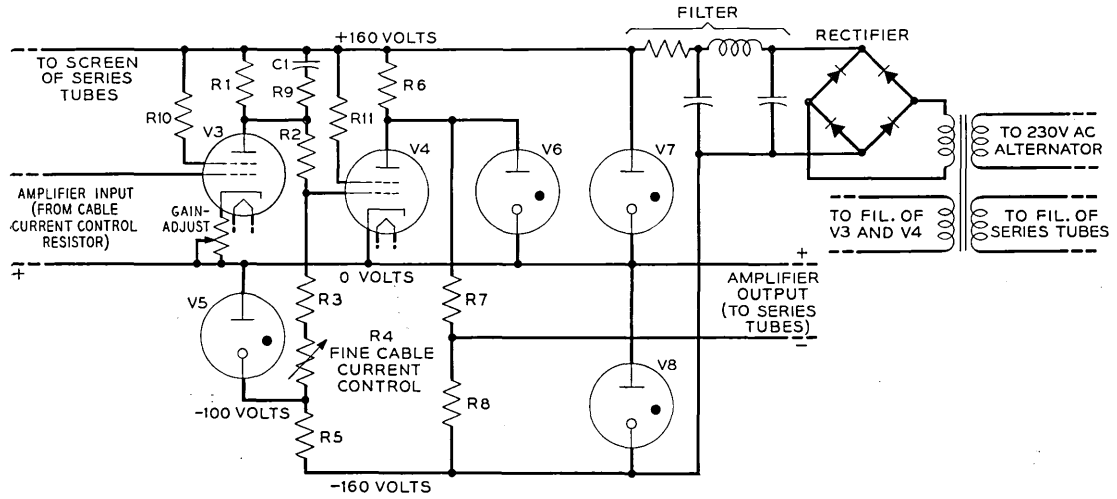


Fig. 5 — Two-stage dc amplifier.

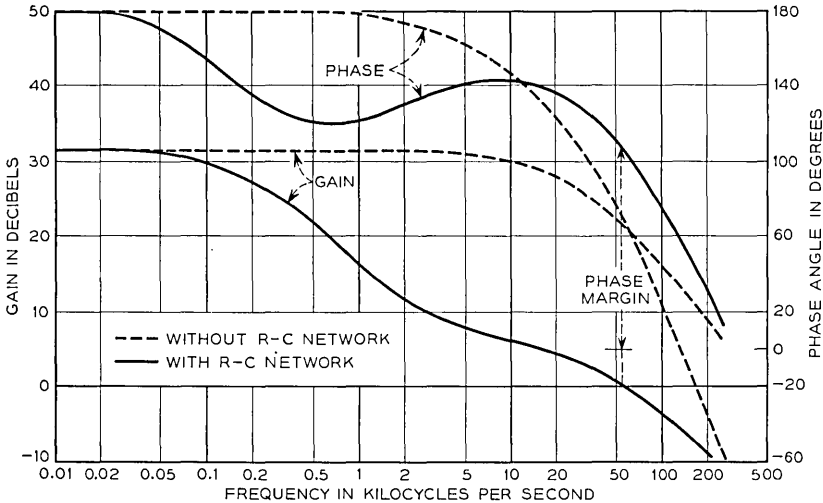


Fig. 6 — DC amplifier gain and phase, experimental model.

data were obtained by opening the feedback loop at the control grid of the first stage, applying normal dc bias plus a variable frequency ac signal to the grid of the tube, and measuring the magnitude and relative phase of the return signal.

The corresponding characteristics with the compensating network in place are also shown in Fig. 6. The compensating network effectively puts a relatively low-impedance shunt across the interstage network at the higher frequencies, resulting in a "step" in the gain characteristic. A secondary effect is the phase shift in the transition region. The calculated "corner frequencies" are 2,800 and 195 cps, respectively, chosen on the basis of the criteria (1) little effect on regulator gain at 100 or 120 cps, the most prominent rectifier ripple frequency, and (2) a gain step of something above 20 db with no appreciable contribution to the phase shift at frequencies above 30 kc. The calculated loss at 120 cps is 1.2 db with a maximum phase shift of about 60 degrees at the median frequency. These results agree quite well with the measured data plotted in Fig. 6.

As indicated in Fig. 6, the phase margin at the gain crossover frequency of 55 kc was somewhat over 100 degrees for the experimental model on which these measurements were made. The gain margin could not be measured readily but is clearly substantial. On production units, larger wire sizes and longer lead lengths resulted in lesser, but still satisfactory stability margins, as shown in Fig. 7, the phase margin being somewhat

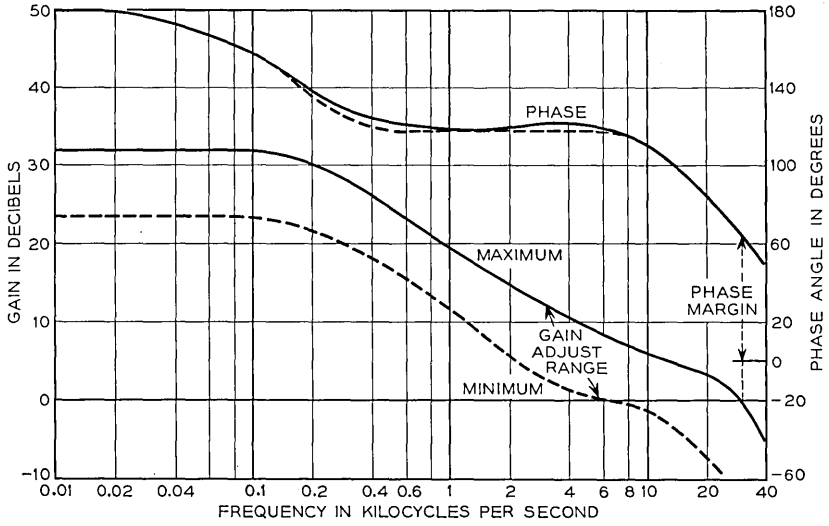


Fig. 7 — DC amplifier gain and phase, production model.

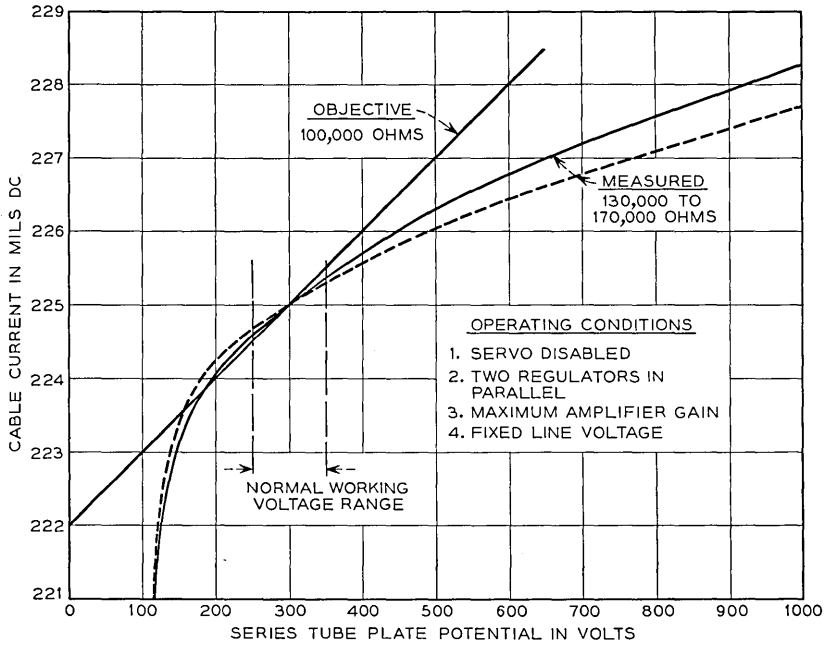


Fig. 8 — Load regulation.

over 60 degrees. Fig. 7 also shows the characteristics at the extremes of gain control, the range of control being about 8 db.

Fig. 8 shows the measured performance of the dc regulators, the servo system being disabled in order to obtain a plot of the performance of the dc amplifier and associated circuits. Twenty-two regulator units were manufactured and measured and the curves of Fig. 8 show the extreme limits observed, the differences between individual regulators being due primarily to differences between electron tubes. The measured range of source impedance, 130,000 to 170,000 ohms, allows margin for regulator tube aging above the 100,000-ohm objective.

AC Servomechanism

As noted earlier, the servo system shown in Fig. 2 is part of the current regulating scheme and holds the series tube plate potential within reasonable limits by adjusting the rectifier input voltage. In an emergency, a "turndown" feature, operated from several remote points, either manually or automatically, will reduce the autotransformer output to zero in less than two seconds. For simplicity, only the manual turndown feature is shown in Fig. 2. It operates simply by switching one end of the motor control winding from one corner of the bridge to the other, thus applying half of the input voltage to the control winding.

Manual operation of the autotransformer tap is provided to raise the cable current slowly, either initially or after a turndown. In manual operation a dynamic brake, consisting of a short circuit on the motor control winding, prevents the motor from creeping or coasting when the operator releases the handwheel, as it otherwise would since the fixed phase of the two-phase motor is always energized. The turndown feature takes precedence over the short circuit of the motor control winding, automatically, to energize the motor should the operator inadvertently cause abnormally high cable voltage or current.

One essential feature of the servo design is the dead band of the series tube plate voltage in which the servo remains stationary, even though there are small changes in the incoming signal. This band can be varied from 10 to 100 volts under control of a gain-adjust potentiometer across the control winding of the two-phase motor. Without this dead band, the servo would be constantly in operation correcting for small random variations in line voltage or earth potentials. Furthermore, since it is extremely difficult to set the current regulators at the two ends of a cable to exactly the same current, the servo dead band permits some margin of error. Otherwise the servo associated with the current regu-

lator trying to regulate for a slightly higher cable current, would drive its rectifier voltage to its stop or maximum output, unbalancing the cable voltages.

*System Stability**

A complete analysis of system stability represents an exceedingly formidable, if not impossible, task. It has been established analytically that for a linear network the two dc regulators in parallel and the system as a whole are unconditionally stable. The details of this proof are too long to be presented here but the line of reasoning with respect to the overall system is as follows. The system of Fig. 1 is symmetrical about a vertical plane through the middle of the figure. Under these conditions, the system will be stable if, and only if, the following three simpler systems† are stable:

- (a) A power supply short-circuited;
- (b) A power supply feeding an impedance equal to twice that of the half cable short-circuited; and
- (c) A power supply feeding an impedance equal to twice that of the half cable open-circuited.

The transfer function of the servomechanism was measured over the frequency range of principal interest, 0 to 1 cps, the behavior near zero frequency being determined from the asymptotic slope of the unit step response.‡ In this frequency range the dc amplifier gain is a real constant, flat gain and negligible delay as previously shown, therefore only the ac servo feedback loop characteristic has to be known to predict the stability of condition (a). The Nyquist loop for this transfer function shows that condition (a) above is satisfied. A similar examination of the Nyquist plot, including the readily computed cable impedance shows that conditions (b) and (c) above are satisfied. Thus the linear analysis indicates stable operation for the system of Fig. 1. This result was confirmed by tests of conditions (a), (b), and (c) individually and by the behavior of the system as a whole, both in the laboratory with a simulated power network for the cable and in the final installation.

One of the most obscure aspects of the power system behavior is that of equilibrium conditions after one or a series of large earth potential

* The analysis briefly summarized here was made by C. A. Desoer.

† In this discussion of simpler systems a power supply consists of only the elements shown in Fig. 2.

‡ In the course of these time-domain measurements, it was quite apparent that the ac control loop could be considered as a linear network only in an approximate sense and thus that the analytical results were primarily useful in interpretation of observed behavior of the system.

disturbances. While the system is stable in the sense that the transient due to a perturbation will disappear in a finite time once the disturbance has been withdrawn, the range of possible equilibrium positions (disregarding the overvoltage protective feature) is extremely wide — from perhaps 1,300 to 2,500 volts at the cable terminals. The upper limit of 2,500 volts is set by the maximum output available from one power plant; this also sets the lower limit of the associate power plant at the far end of the cable. This situation is illustrated diagrammatically in Fig. 9.

The behaviors of the servomechanisms at the two ends of a given cable are nearly enough alike that the repeated introduction of simulated earth potential in the laboratory was found not to disturb substantially the equilibrium point. This was true for earth potentials of either polarity up to 1,000 volts and with these potentials introduced at any point along the artificial cable. A rate of change of earth potential of 20 volts per second was adopted in these tests with the thought that such values would be realistic.

With regard to the long-term stability of the equilibrium condition described above, it is, of course, important that the controls which establish the cable current at the two ends of the same cable be adjusted for very nearly the same value. Unless this is done, the cable voltage at one end will gradually increase or decrease and the voltage at the other end will move equally in the opposite direction. This would eventually

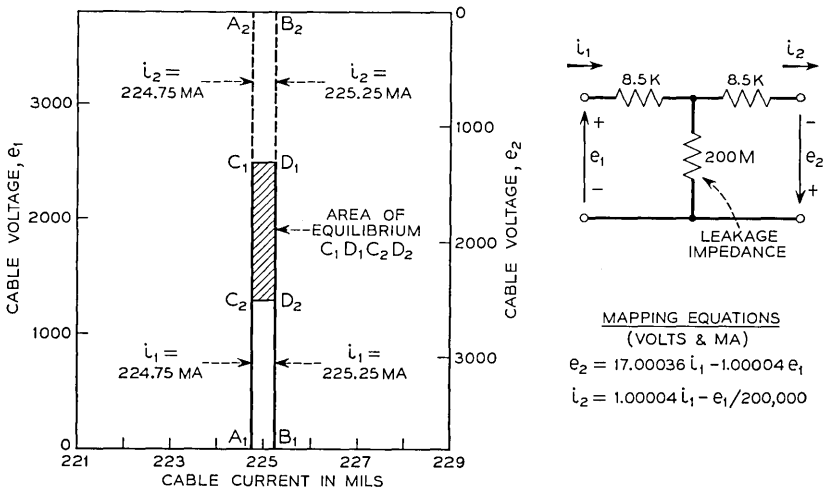


Fig. 9 — Equilibrium diagram.

bring in alarms and necessitate manual readjustment. In this connection, the voltmeters which indicate the drop through the series regulating tubes provide a very convenient magnification of any drift in cable current. The multiplying factor is the effective dc impedance of the regulated system, that is, more than 100,000 ohms. Thus 25 volts, which is an appreciable fraction of the nominal 300 volts across the series regulating tubes, is equivalent to less than 0.25 ma., which is of the order of 0.1 per cent of normal cable current. As a matter of fact, the behavior of this voltage provides the final criterion for precise adjustment of cable current to assure long-term stability.

EQUIPMENT DESIGN

Description

Fig. 10 shows the complete dc equipment for supplying one polarity of power to one cable. Similar equipment provides the opposite polarity to the other cable. The two equipments are located facing each other across a common aisle with their common control bays directly opposite. Regulator 1 on the right is normally operated in parallel with Regulator 2. Regulator 3 on the left is the spare regulator, normally off. The common bay, between Regulators 1 and 2, includes the cable

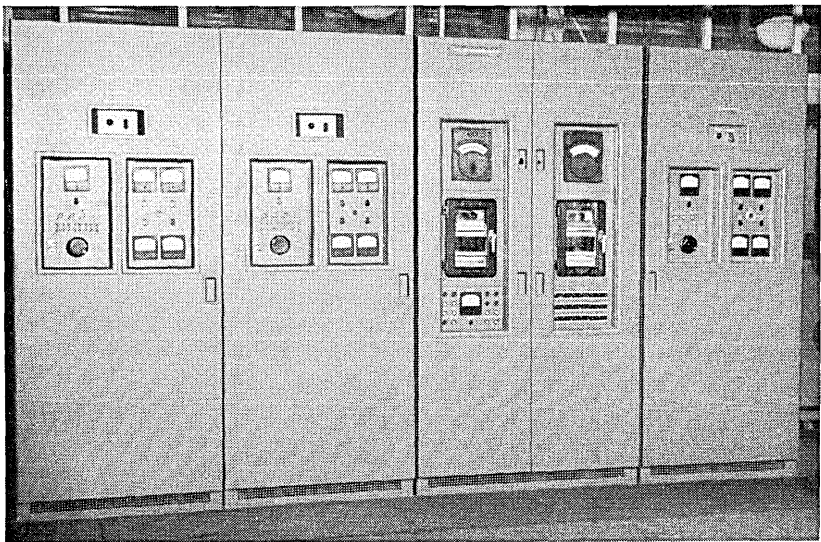


Fig. 10 — DC regulator and common control bays.

termination and power separation filter. This equipment and all the live parts of the circuit, back to the common point to which the switches in the individual regulator bays are connected, is enclosed in a high voltage compartment.

The paralleling control switches are mounted in high voltage compartments in their respective regulating bays and must remain completely enclosed, as their common cable connections are alive during cable operation. These switches have an interrupting capacity of 1 ampere at 3,000 volts, thus providing a large safety factor over the 0.245 ampere maximum load current.

Fig. 11 illustrates some of the special design features built into the equipment to facilitate maintenance. The high voltage compartment shown open at the top is locked whenever the cable is in operation and this protection feature will be described below. Pull-out drawers at the bottom contain metering shunts, a test unit for adjusting voltage and current protection limits, a voltage protection unit, a current protection unit, and an alarm unit. While only one of these compartments is to be pulled out at a time, they are arranged so as not to endanger personnel or to affect service during adjustment when open. Doors are provided on all bays to prevent accidental disturbance of adjustments and to protect against damage to controls.

Corona

The high voltage ac elements of the complete regulator bays were tested for corona with 4,000 volts ac applied, and furthermore, if corona was observed on increasing the applied rms voltage to 5,000 volts, it was required to extinguish when the voltage was reduced to 3500 volts. The maximum acceptable leakage was 20 microamperes at 4000 volts across the circuit (200 megohms). A dc corona requirement of 4000 volts was applied to the dc elements of the regulator bays and 5000 volts for the common bay, with a maximum permissible leakage of 5 microamperes. The higher corona requirements on the common bay were intended to eliminate the necessity for turning down the entire system for repair. A high standard of workmanship is required to provide such performance. There can be no sharp projections and no loose strands of wire. Solder must be applied in such a manner as to obtain a rounded smooth joint and high voltage wiring must be dressed away from exposed grounded metal, bus bars, etc., so that the outer braid (other than polyethylene) does not come in contact with metal.

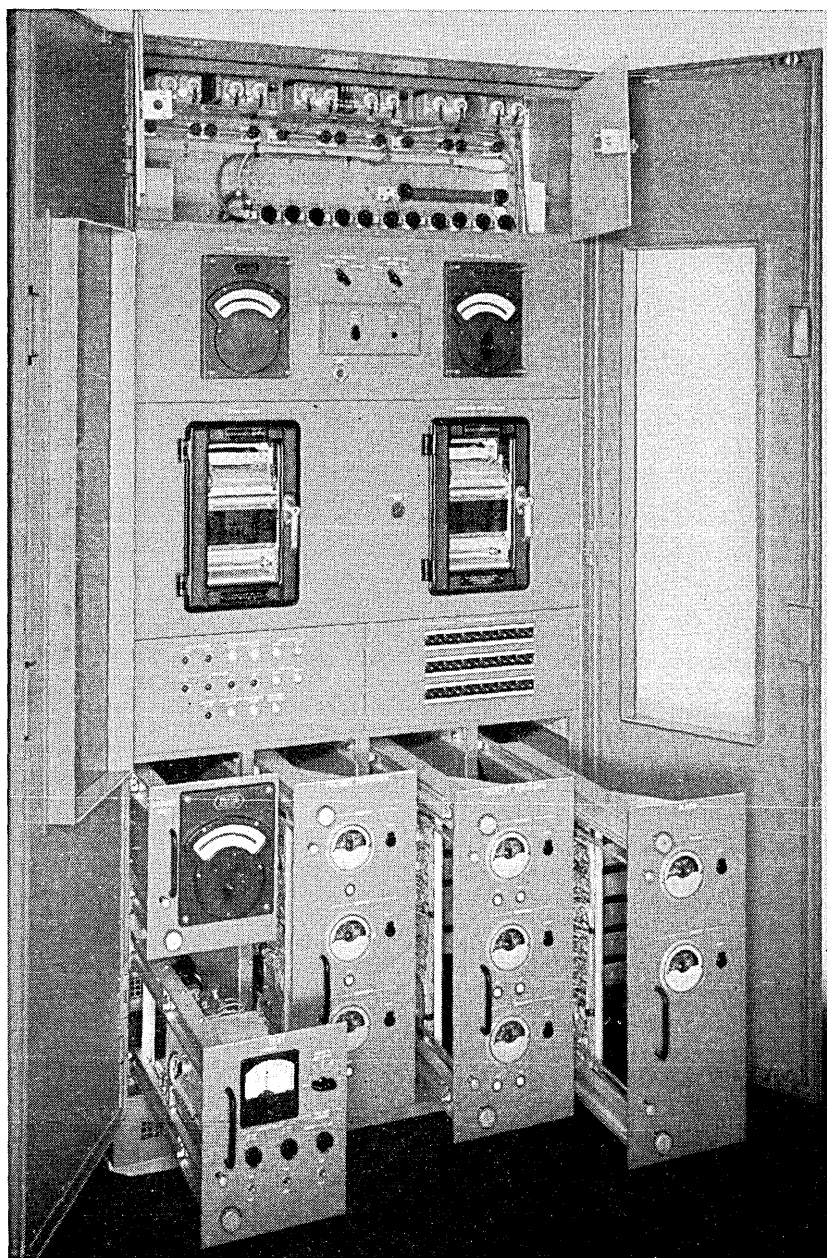


Fig. 11 — Common control bay.

Crosstalk and Outside Interference

In order to meet the severe crosstalk requirements between receiving and transmitting circuits and to guard against feeding office noise potentials into the carrier transmission system, arrangements were made so that office grounds are carefully separated from the outer conductor of the cable and from all circuit elements within the power separation filter. Pickup of external radio-frequency fields by the power separation filters was greatly reduced by completely enclosing in a copper shield the cable terminal and the power separation filter elements nearest to the terminal. The shielding itself and the cans of PSF capacitors and oil-filled coils are connected to the return tape of the cable which is insulated from office ground until it reaches sea water, thus reducing the coupling to the other cable as compared to tying both tapes together at the office or bay frame ground.

Protection of Personnel

A key locking system is provided to safeguard against any hazard to personnel from high voltages. In the common bay, the high voltage compartment can be entered only by operating a switch which shorts the cable to ground and releases a key for the compartment doors. In each regulating bay, the key system assures that the bay is disconnected from the cable and hence from the paralleling power supplies. Where access is required to the interior of any compartment, the key system insures that the ac power to the bay also be switched off.

The test compartment contains pin jacks, provided for maintenance operations which are always performed with the regulator bay connected to a low resistance load. Access to this compartment can be obtained with ac power connected to the bay. However, for such access, the key system enforces the operation of the output disconnect switch, which also transfers the bay to a low-resistance load. Moreover, a mechanical interlock with the autotransformer assures that the test voltages are reduced to safe values.

In addition to its function in protecting personnel, the key system also insures that no more than one regulating bay is disconnected at one time so that continuity of service is protected at all times by two parallel regulators.

FACTORY AND SHIP CABLE POWER

In addition to the above cable power supplies at the ocean terminals, similar dc cable current regulating equipment was designed for use at

the cable factory and abroad the cable ship *Monarch*. Well protected and closely regulated reliable power was considered essential during the cable loading and laying operations. It was necessary to have power on the cable continuously, except when splices were made, in order to detect a fault immediately, to measure transmission characteristics for equalization purposes and finally to alleviate the strain on the glassware and tungsten filaments of the repeater tubes during the difficult laying period.³

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Electron Tubes for the Transatlantic Cable System

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M. F. HOLMES†

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Electron tubes for use in repeatered underwater telephone cable systems must be capable of operating for many years with a reasonable probability of proper functioning. In the new transatlantic telephone cable system the section of the cable between Nova Scotia and Newfoundland contains repeaters developed by the British Post Office Research Station at Dollis Hill. These repeaters are built around the type 6P12 tube developed at that research station. The repeaters contained in the section of the cable system between Newfoundland and Scotland are of Bell System design and depend on the 175HQ tube developed at Bell Telephone Laboratories.

In this paper the philosophy of repeater and tube design is discussed, and the fundamental reasons for arriving at quite different tube designs are pointed out. Some of the tube development problems and the features introduced to eliminate potential difficulties are described. Electrical characteristics for the two types are presented and life test data are given. Fabrication and selection problems are outlined and reliability prospects are discussed.

INTRODUCTION

Electron tubes suitable for use in long submarine telephone cables must meet performance requirements that are quite different from those imposed by other communication systems. In the home entertainment field, for example, an average tube life of a few thousand hours is generally satisfactory. In the field of conventional land-based telephone equipment, where the replacement of a tube may require that a maintenance man travel several miles, an average life of a few years is considered reasonable. In deep-water telephone cables such as the new transatlantic system, the lifting of a cable to replace a defective repeater may cost several hundred thousand dollars and disrupt service for an extended

* Bell Telephone Laboratories. † British Post Office.

period of time. These factors suggest as an objective for submerged repeaters that the tubes should not be responsible for a system failure for many years, possibly twenty, after the laying of the cable. Such very long life requirements make necessary special design features, care in the selection and processing of materials that are used in the tubes, unusual procedures in fabrication, detailed testing and long aging of the tubes, and the application of unique methods in the final selection of individual tubes for use in the submerged repeaters.

As indicated in the foreword and discussed at length in companion papers, the British Post Office developed the section of the cable system between Clarenville, Newfoundland, and Sidney Mines, Nova Scotia. This part of the transatlantic system uses the 6P12 tube which was developed at the General Post Office (G.P.O.) Dollis Hill Research Station. The submerged portion of this system contains 84 tubes in 14 repeaters. Bell Telephone Laboratories developed the part of the system between Clarenville, Newfoundland, and Oban, Scotland. This section requires 102 repeaters, including 306 tubes, of a type known as the 175HQ. Although a common objective in the development of each of the two sections has been to obtain very long life, the tube designs are quite different.

The Bell System decided on the use of a repeater housing that could be treated as an integral part of the cable to facilitate laying in deep water. The housing is little larger than the cable and is sufficiently flexible to be passed over and around the necessary sheaves and drums. In such a housing the space for repeater components is necessarily restricted. This space restriction, combined with the general philosophy that the number of components should be held to an absolute minimum and that each component should be designed to have the simplest possible structural features, has resulted in the choice of a three-stage, three-tube repeater. In this design, each tube carries the entire responsibility for the continuity of service.

The Post Office Research Laboratories, prior to the development of the transatlantic cable system, had concentrated their efforts on shorter systems for shallow water. The placing of the repeaters on the bottom did not present the serious problems of deep-sea laying, so more liberal dimensions could be allowed for the repeater circuit. A three-stage amplifier was developed which consisted of two strings of three tubes each, parallel connected, with common feedback. The circuit was so designed that almost any kind of tube failure in one side of the amplifier caused very little degradation of circuit performance. This philosophy of having

the continuity of service depend on two essentially independent strings of tubes has been carried over to the repeater design for the Clarenville-Sidney Mines section of the transatlantic cable.

In the Post Office system containing 84 tubes in the submerged repeaters, five tube failures randomly occurring in the system will result in slightly over fifty per cent probability of a system failure; one tube failure in the 306 tubes in the Newfoundland-Scotland section of the system will result in certain system failure. It is not surprising, therefore, to find the tube designed for the Newfoundland-Scotland section of the cable to have extremely liberal spacing between tube elements in order to minimize the hazards of electrical shorts. This results in a lower transconductance than is found in the tubes designed for the Nova Scotia-Newfoundland link. Other factors in the design will be recognized as reflecting the different operating hazards involved.

Early models of the British Post Office and Bell Laboratories tubes, together with the final tubes used in the cable system, are shown in Fig. 1.

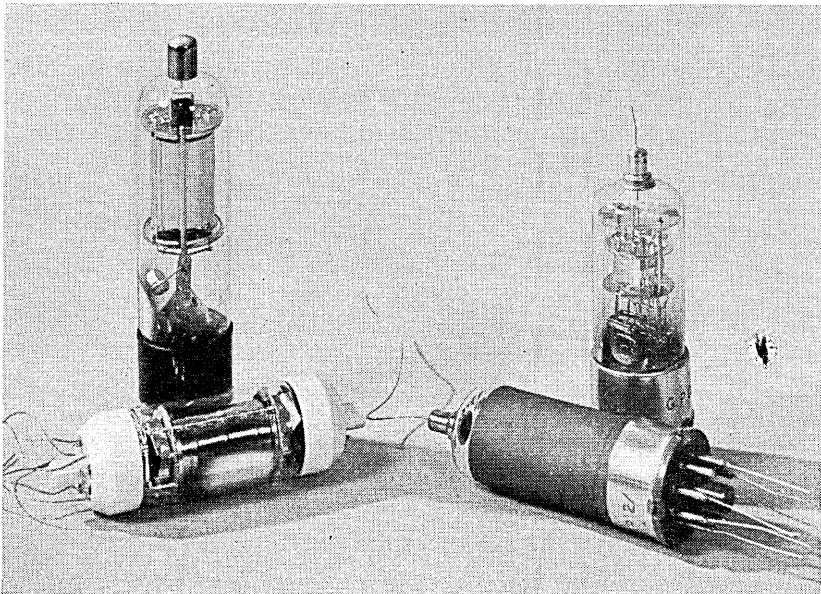


FIG. 1 — The final designs of tubes for the Nova Scotia-Newfoundland section of the cable (right) and for the Newfoundland-Scotland section (left). Early models of each type stand behind the final models.

TUBES FOR THE NEWFOUNDLAND-SCOTLAND CABLE

Early Development Considerations

In Bell Telephone Laboratories, work on tubes for use in a proposed transatlantic cable was started in 1933. This was preceded by a study of what type of tube would best fit the needs of the various proposed amplifier systems and by consideration of what might be expected to give the best life performance.

At the time this project was started, reasonably good tube life had been established for the filamentary types used in Bell System repeaters. Some groups of tubes had average lives of 50,000 or 60,000 hours (6 or 7 years). Equipotential cathode tubes were not then used extensively in the plant, and there was no long life experience with them. However, there appeared to be no basic reason why inherently shorter thermionic life should be expected using the equipotential cathode and there were several advantages in its use. One was the greater freedom in circuit design afforded by the separation of the cathode from the heater. Also there was the possibility of operating the heaters in series and using the voltage drop across the heaters for the other circuit voltages. It was felt, in addition, that the overall mechanical reliability would be greater if the cathode were stiff and rigidly supported.

The first equipotential tubes made were triodes. They were designed for use in push-pull amplifiers wherein continuity of service might be retained in case of a tube failure. This circuit was abandoned in favor of a three tube, feedback amplifier that was the forerunner of the present repeater. The pentode was favored over the triode for this amplifier for obvious reasons, and in 1936 the triode development was discontinued.

Early in the development of the tube three basic assumptions were made. These were, (a) that operation at the lowest practical cathode temperature would result in the longest thermionic life, (b) that operating plate and screen voltages should be kept low, and (c) that the cathode current density should be kept as low as practicable.

The first assumption, concerning the cathode temperature, was based on the observation of life tests on other types of tubes. While the data at the time of the decision were not conclusive, there was definite indication that too high a cathode temperature shortened thermionic life. Little was known about life performance in the temperature range below the values conventionally used.

The second assumption, concerning low screen and plate voltages, had not been supported by any experimental work available at the time of decision. Sixty volts was originally considered for the output stage; this

value was later lowered when other operating conditions were changed. Subsequent results showed that in this range the voltage effects on thermionic life were relatively negligible.

The third assumption, that low cathode current density favored longer thermionic life, affected the tube design by suggesting the use of a large coated cathode area. This implied the use of relatively high cathode power. It was decided early in the planning of the repeater that the voltage drop across the three heaters operated in series would be used to supply part or all of the operating plate and screen potentials. For a 60-volt plate and screen supply, the heater voltage could be as high as 20 volts. A quarter of an ampere was considered a reasonable cable current consistent with voltage limitations at the cable terminals. Thus 5.0 watts were available for each cathode. With this power, a coated area of 2.7 square centimeters was provided. The value of the cathode current, the cathode area, and the interelectrode spacings define the transconductance. Very liberal interelectrode spacings were provided consistent with reasonable tube performance. The original design called for a spacing of 0.040 inch between control grid and cathode. This value was later reduced to 0.024 inch, and a satisfactory design was produced which gave 1,000 micromhos or one milliamperere per volt at a cathode current drain of approximately 2.0 milliamperes. The resulting current density of approximately 0.7 milliamperere per square centimeter is in sharp contrast with values such as 50 milliamperes per square centimeter used currently in tubes designed for the more conventional communication uses. Subsequent data, discussed later, indicate that for current densities of a few milliamperes per square centimeter, the exact value is not critical in its effect on thermionic life.

Subsequent Production Programs

The development of the tube was pursued on an active basis through the years leading up to World War II. During the war development activity essentially stopped. It was only possible to keep the life tests in operation. After the war the development of the tube was completed and a small production line was set up in Bell Telephone Laboratories under the direct supervision of the tube development engineers to make and select tubes for a cable between Key West, Florida, and Havana, Cuba.

This cable turned out to be a "field trial" for the transatlantic cable which was to come later. A total of 6 submerged repeaters containing 18 tubes were laid and the cable was put in operation in June, 1950. The cable has been in operation since this date without tube failure, and

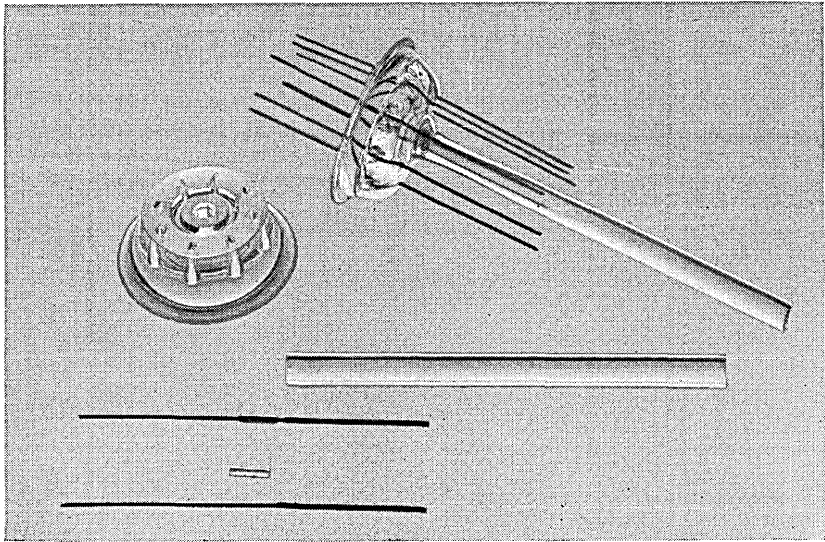


FIG. 2—Parts used in the stem and a finished stem of the 175HQ tube. The separate beading of the leads may be noted.

periodic observations of repeater performance indicate no statistically significant change in tube performance over the 6 years of operation.

Sufficient tubes were made at the same time as the Key West-Havana run to provide the necessary tubes for a future transatlantic cable. These tubes were never used principally because the tubes had been assembled with tin plated leads. Tin plating, subsequent to the laying of the Key West-Havana cable, was found to be capable of growing “whiskers”.¹

In 1953 another production setup was made, also in Bell Telephone Laboratories, for the fabrication of tubes for the Newfoundland-Scotland section of the transatlantic cable. On the completion of this job fabrication was continued to provide tubes for an Alaskan cable between Port Angeles, Washington, and Ketchikan, Alaska. After a pause of several months another run was made to provide tubes for a cable to be laid between California and the Hawaiian Islands.

Mechanical Features

The tube, shown on the left in Fig. 1, is supported in the repeater housing by two soft rubber bushings into which the projections of the two ceramic end caps fit. All leads are flexible and made of stranded beryllium copper which has been gold plated before braiding. Both for

convenience in wiring in the circuit and to hold down the control-grid to anode capacitance, the grid lead has been brought through the opposite end of the tube from the other leads.

A number of somewhat unusual constructional features appear in the tube. The stem on which the internal structure is supported consists of a molded glass dish into which seven two-piece beaded dumet leads are sealed. The parts used in a stem, and also a finished stem, are shown in Fig. 2. It is usual to embed the weld or "knot" between the dumet and nickel portions of the lead in the glass seal to provide more structural stiffness. This has not been done in this stem because it was believed that a fracture of a lead at the weld could be detected more easily if it were not supported by the seal. It might be questioned why the modern alloys and flat stem structure have not been used. It is to be remembered that one gas leak along a stem lead would disable the system, and experience built up with the older materials provides greater assurance of satisfactory seals.

The structure of the heater and cathode assembly is unique, as may be seen in Fig. 3. A heater insulator of aluminum oxide is extruded with 7 holes arranged as shown. This insulator is supported by a 0.025 inch molybdenum rod inserted in the center hole. The heater consisting of about 36 inches of 0.003 inch tungsten is wound into a helix having an outside diameter of 0.013 inch. After dip coating by well known techniques the heater is threaded through the 6 outer holes in the insulator. A suspension of aluminum oxide is then injected into the holes in the insulator so that on final firing the heater becomes completely embedded.

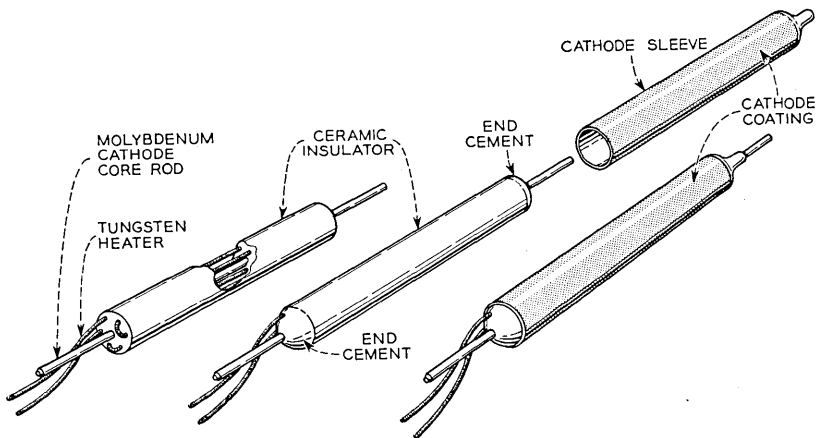


FIG. 3 — Heater, heater insulator and cathode assembly of the 175HQ tube.

The cathode sleeve, which is necked down at one end as shown in Fig. 3, is slipped over the heater assembly and welded to the central molybdenum rod which becomes the cathode lead. By this means a uniform temperature from end to end of the cathode is obtained. Under normal operating conditions the heater temperature is approximately 1100°C , which is very considerably under the temperature found in other tubes.

Connection of the heater to the leads from the stem presented a serious design problem. Crystallization of tungsten during and after welding and mechanical strains developed by thermal expansion frequently are the causes of heater breakage. This problem was successfully overcome by the means illustrated in Fig. 4. Short sections of nickel tubing are slipped over the cleaned ends of the heater coil and matching pieces of nickel wire are inserted as cores. These parts are held together by tack welds at the midpoints of the tubing. The heater stem leads are bent, flattened and formed to receive the ends of the heater, which are then fastened by welds as indicated in the drawing.

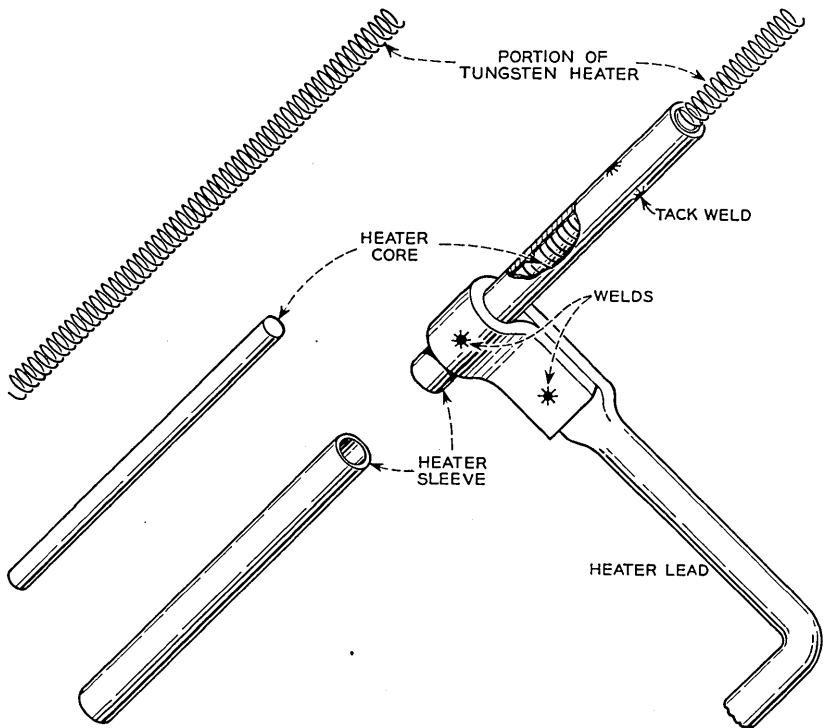


FIG. 4 — Heater tabbing arrangement of the 175HQ.

A serious attempt has been made in the design of the tube to hold the number of fastenings that depend entirely on one weld to an absolute minimum. The grids are of conventional form in which the lateral wires are swaged into notches cut in the side rods or support wires. The side rods as well as the lateral wire are molybdenum. This produces grids which are considerably stronger than those using more conventional materials.

The upper mica is designed to contact the bulb and the bulb is sized to accurate dimensions to receive and hold the mica firmly. The tube in its mounting will withstand a single 500*g* one millisecond shock without apparent changes in mechanical structure or electrical characteristics. It is estimated from preliminary laying tests that accidental or unusual handling would rarely result in shocks exceeding 100*g*.

Electrical Characteristics and Life

The average operating electrical characteristics for the 175HQ tube are given in Table I, and a family of plate-voltage versus plate-current curves for a typical tube is given in Fig. 5 for a region approximating the operating conditions.

The development of a long-life tube offers good opportunities to observe effects which are more likely to be missed where shorter lives are satisfactory. For example, some of the earliest tubes made, after 20,000 hours on the life racks, began to show a metallic deposit on the bulbs.

TABLE I — AVERAGE OPERATING ELECTRICAL CHARACTERISTICS FOR THE 175HQ TUBE

	Stages 1 & 2	Stage 3
Heater Current.....	220	217 milliamperes
Heater Voltage.....	18.2	18.4 volts
Heater Power.....	4.0	4.0 watts
Control-Grid Bias.....	-1.3	-1.4 volts
Screen Voltage.....	38	40 volts
Plate Voltage.....	32	51 volts
Screen Current.....	0.3	0.3 milliamperes
Plate Current.....	1.3	1.4 milliamperes
Transconductance.....	980	1010 micromhos
		All Stages
Capacitances (cold, with shield)		
Input Capacitance.....		9.2 $\mu\mu\text{f}$
Output Capacitance.....		15.6 $\mu\mu\text{f}$
Plate to Control-Grid Capacitance.....		0.03 $\mu\mu\text{f}$

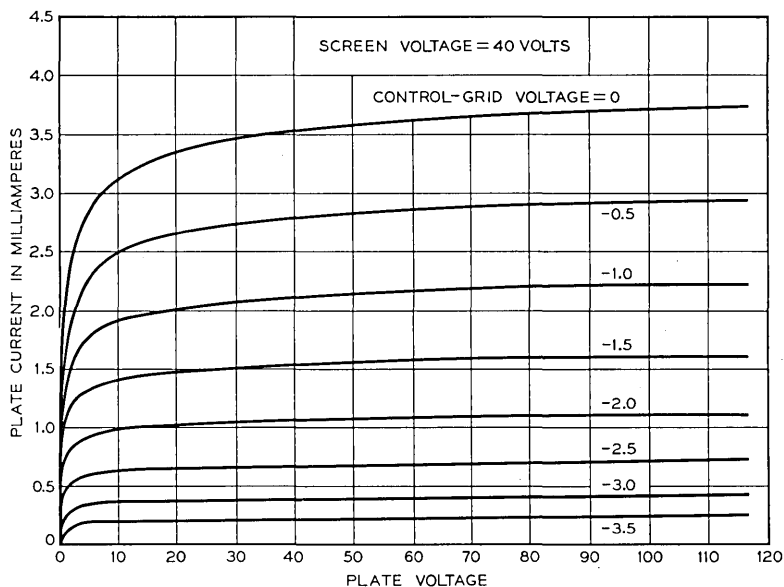


FIG. 5 — Typical plate voltage-plate current characteristics for a type 175HQ tube.

Immediate concern for the lowering of insulation resistance across mica spacers prompted an investigation. The source was traced to the use of plates made from a grade of nickel from which magnesium as a contaminant was evaporating. A change was made to molybdenum which has been used successfully since that experience.

The effect on the thermionic life of operating at different cathode current densities was of interest. Life tests were started in which the cathode current drain in one group of tubes was approximately 7.5 milliamperes (2.8 ma/cm^2) and in another group the average cathode current was 0.6 milliamperes (0.2 ma/cm^2). The results presented in Fig. 6 after 120,000 hours, or approximately 14 years, show that at the cathode temperature of approximately 710°C^* selected for the test, there is practically no current density effect in this 12 to 1 current range. The circles indicate average values, while the dots and crosses at each test point show the positions of the extreme tubes of the group.

Similar life tests set up to show the effect of operating at plate and screen voltages of 60 volts as compared to 40 volts indicate no essential differences in performance after 8 years of operation.

* All cathode temperatures referred to in this paper are "true" temperatures, not uncorrected pyrometer temperatures.

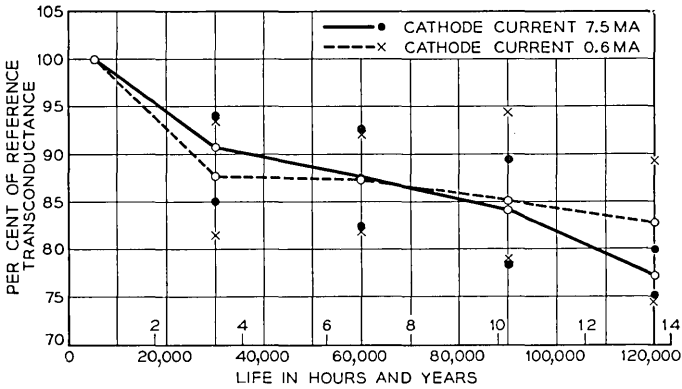


FIG. 6 — Results of life tests on eighteen 175HQ tubes operating at two different current densities.

The cathode temperature is one of the most critical operating variables affecting thermionic life. As mentioned above, the early development objective was a cathode power of 5.0 watts which corresponded to 710°C for the cathode design used at that time. The results of operating at this condition are illustrated in Fig. 7. No tubes have been lost from the test where the direct cause has been failure of emission. Several tubes were lost because of mechanical failure resulting from design defects which were subsequently corrected. It will be observed

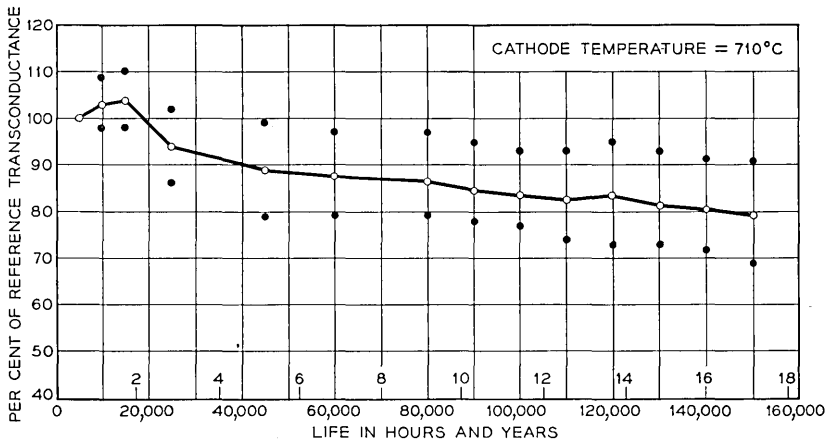


FIG. 7 — Results of life tests on sixteen 175HQ tubes operating at a cathode temperature of 710°C.

that at the end of 17 years the average transconductance is 80 per cent of its original value, and the poorest tube has dropped to 69 per cent. There is reason to believe that test set difficulties may very well account for a large part of the variation shown in the first three years.

The cathode coatings used in all experimental and final tubes for the Newfoundland-Scotland link of the transatlantic cable are the conventional double carbonate coatings. The cathode base material is an International Nickel "220" nickel. The particular melt used for the transatlantic cable is known as melt 84. A typical analysis for melt 84 nickel cathodes is given in Table II.

TABLE II — TYPICAL ANALYSIS OF INCO 220 NICKEL CATHODE MELT 84
(Analysis made prior to hydrogen firing)

Impurity	Per Cent	Impurity	Per cent
Aluminum.....	0.008	Manganese.....	0.11
Boron.....	<0.004	Silicon.....	0.033
Cobalt.....	0.46	Titanium.....	0.032
Chromium.....	<0.005	Oxygen.....	0.0001
Copper.....	0.028	Sulphur.....	0.0016
Iron.....	0.093	Carbon.....	0.058
Magnesium.....	0.046		

The relatively high carbon content (0.058 per cent) of melt 84 cathode nickel is capable of producing excessive reduction of barium in the cathode coating.^{2, 3} A treatment in wet hydrogen, prior to coating, at 925°C for 15 minutes reduces the carbon in the cathode sleeve to about 0.013 per cent.

Melt 84 was as close as was obtainable in composition to melts 60 and 63 previously used for the Key West-Havana tubes. The results of up to five years of life testing were thus available on materials of very similar composition.

One common cause of tube deterioration with life is the result of formation of an interface layer on the surface of the cathode sleeve. It is known that the rate of development of this layer depends in a complex way on the chemical composition of the nickel cathode core material. The effect of such a layer is to introduce a resistance in series with the cathode. This results in negative feedback and reduces the effective transconductance. Since the effect of a given feedback resistance in this location is proportional to transconductance, the relatively low value for the 175HQ tube tends to minimize this feedback effect. In addition, the low cathode temperature tends to reduce the rate of formation of interface resistance, and the relatively large cathode area tends to further minimize the effects. The final decision to use melt 84 was based on ac-

celerated aging tests which showed it to be superior to melts 60 and 63 from an interface standpoint.

The interface problem will be discussed further in a later section.

As the development of the tube proceeded, both the processing of the parts and the cleanliness of the mount assembly were improved and the cathode emission level increased. Life tests indicated that better thermionic life might be obtained by operating at a lower cathode temperature. Accordingly a cathode power of approximately 4.0 watts was adopted, which corresponds to a temperature of 670°C. A life test, now 45,000 hours or about 5 years old, shows the results in Fig. 8 of operating groups of tubes at three different cathode temperatures. This is a well controlled test in that the tubes for the three groups were picked from tubes having common parts and identical fabrication histories. It may be noted that the average of the 725°C lot has lost approximately 5 per cent of the initial transconductance, whereas the 4.0 watt group after about 5 years has lost essentially none of its transconductance. The 3.0

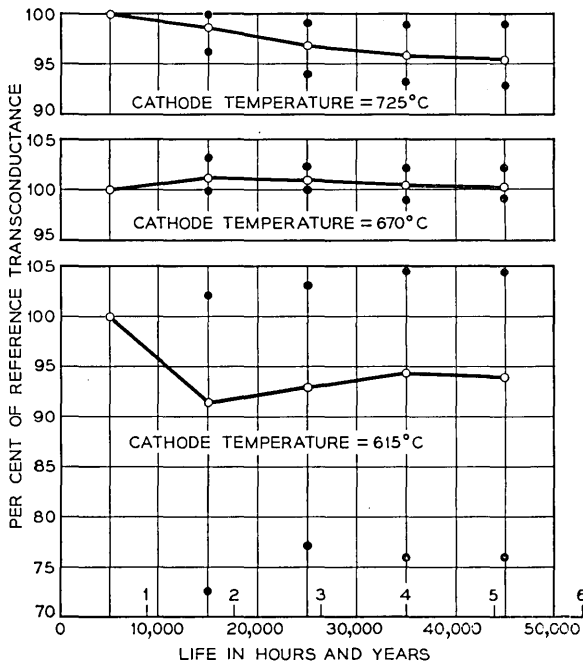


FIG. 8 — Results of operating thirty-six 175HQ tubes divided equally among three different cathode temperature conditions. For each of the curves the cathode core material used was half from melt 60 and half from melt 63. The conditions in cable operation are essentially those represented by the center curve.

watt (615°C) group shows serious instabilities in its performance. In some of the tubes the cathode temperature has not been sufficiently high to provide the required emission levels.

The design of the repeaters in the Newfoundland-Scotland section of the cable is such that reasonably satisfactory cable performance would be experienced if the transconductance in each tube dropped to 65 per cent of its original value. The life test performance data presented in Figs. 7 and 8, and other tests not shown, indicate that operation of the 175HQ tubes in the transatlantic cable at approximately 4.0 watts will assure satisfactory thermionic performance for well over 20 years.

Mention was made that cleanliness in the assembly of the mounts was a factor which affected thermionic activity. Interesting evidence supporting this view was obtained during the fabrication of tubes for the Key West-Havana cable. The quality control type of chart reproduced in Fig. 9 shows the average change in transconductance between two set values of heater current for the first 5 tubes in each group of approxi-

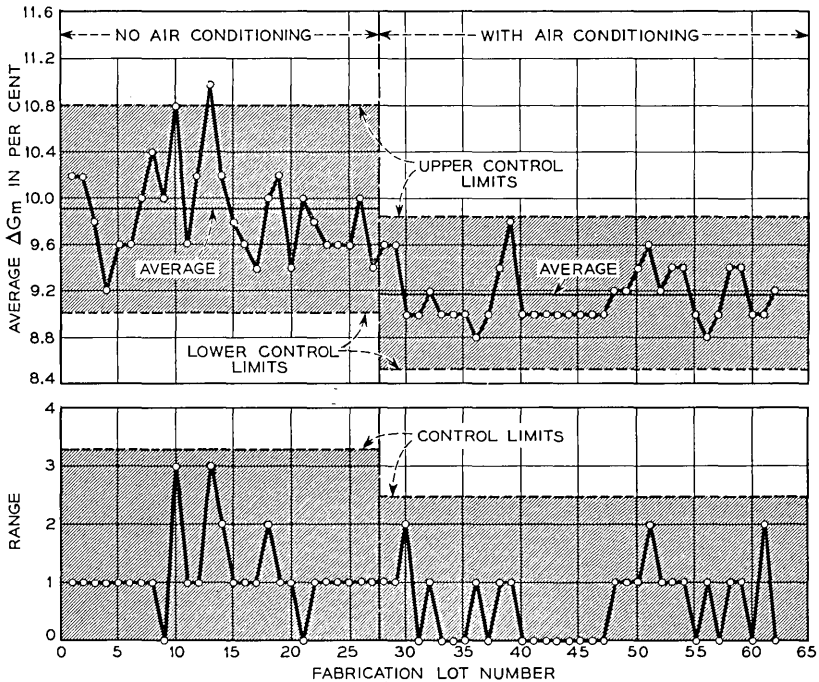


FIG. 9 — Control chart showing the effect of air cleaning on the cathode activity level. The per cent change in transconductance for normal heater current and a value 20 per cent lower is used as the measure of cathode performance.

mately 28 tubes made. The data were taken after 5,000 hours of aging. A sharp improvement in thermionic emission was noted at a point on the chart where about one half of tubes had been fabricated. An examination of the records, which are very carefully maintained, disclosed that the windows of the assembly room were sealed and air cleaning and conditioning was put in effect at the point indicated on the chart. No other changes in processing or materials occurred at this time. A second definite improvement in thermionic emission occurred when the work was moved from the location in New York City to the new and better controlled environment at Murray Hill in New Jersey.

Fabrication and Selection

All assembly operators on the 175HQ tube program wore nylon* smocks to keep down the amount of dust and lint that might otherwise leave their clothing and get into the tubes. Rayon acetate gloves were worn when handling parts as a protection against perspiration. Rubber finger cots did not prove satisfactory because they covered too little area and once contaminated they did not absorb the contaminant.

The tubes for the Newfoundland to Scotland section of the cable were made at Bell Telephone Laboratories under the extremely close engineering supervision of many of the original development engineers. All materials going into the tubes were carefully checked, and wherever possible they were tried out in tubes. Experience under accelerated aging conditions was obtained before these materials were used. For example, although during the development period all glass bulbs were used as received without any failures resulting, less than one-quarter of the bulbs bought for the actual cable job passed the inspection requirements. Each batch of heaters was sampled and results obtained on intermittent and accelerated tests before approval for use.

The fabrication of the tube was carried out with extreme care by operators especially selected for the job. If normal commercial test limits were applied to the tubes after exhaust, the yield from acceptable mounts would have been about 98 to 99 per cent. Yet only approximately one out of every seven tubes pumped was finally approved for cable use. All tubes were given 5,000 hours aging and electrical tests were made at six different times during this period. The results weighed heavily in the final selection. For example, a correlation between thermionic life and gas current had been established during the tube develop-

* Trade name for DuPont polyimide fibre.

ment period, and only tubes having control-grid currents due to gas of less than 5×10^{-11} ampere were acceptable. This corresponds to a gas pressure of approximately 2×10^{-7} mm of Hg. Very thorough mechanical inspections after the 5,000-hour aging were made to insure that there were no observable mechanical deviations that could cause trouble. The history of each group of 28 tubes, from which prospective candidates for the cable were selected, was reviewed to see if any group abnormalities were found. In case a suspected trait was seen, all tubes in the group were ruled out for cable use.

As an aid in the selection of tubes for the cable, all pertinent data were put on IBM cards. It was then possible to manipulate and present the data in many very helpful ways that would have otherwise been wholly impractical from time and manpower considerations. An over-all total of about half a million bits of information was involved.

Reliability Prospects

Questions are frequently raised concerning the probability of tube failures in the system. There are two areas into which failures naturally fall—catastrophic failures and the type of failure caused by cumulative effects such as the decay of thermionic activity, development of primary emission from the control-grid, or the build-up of conductance across mica insulators or glass stems.

The catastrophic failures might include such items as open connections caused by weld failures or fatigue of materials, short circuits caused by parts of two different electrodes coming into contact or being bridged by conducting foreign particles and gas leaks through the glass or along stem leads. Fortunately these failure rates have been lowered to a point where there are no sound statistical data available in spite of the substantial amount of life testing that has been done. In approximately 4,800 tubes made to date, there have been four failures that were not anticipated by the inspections made. All four of these failures were of different types and occurred either at or before 5,000 hours of life. All four were of types more apt to occur during the early hours of aging and handling.

Of the cumulative types of failure, life testing has indicated no apparent problem with either the growth of insulation conductance or primary emission from the grids. As indicated earlier in the paper, thermionic life results are such that there is reason to be optimistic that no failures will occur in 20 years.

TUBES FOR THE NOVA SCOTIA-NEWFOUNDLAND CABLE

*Trend of Tube Development in British Submarine Repeater Systems**Early Use of Commercial Receiving Tubes*

The development of submerged telephone repeaters in Britain has taken a somewhat different course from that followed in the United States. Off North America, deep seas are encountered as soon as the continental shelf has been passed. Consequently emphasis has been placed from the beginning on the design of repeaters for ocean depths. In Britain, separated from many countries by only shallow seas, it was natural for development to start with a repeater specially designed for shallow water. Such a repeater was laid in an Anglo-Irish cable in 1944.

The tubes used in the amplifier of this repeater were normal high transconductance commercial pentodes type SP61. These tubes were known, from life test results, to last at least for two years under conditions of continuous loading. Their performance in the first and subsequent early repeaters exceeded all expectations. So far one tube has failed, and this from envelope fracture, after a period of four years service. There remain 23 of this type on the sea bed with a service life of five or six years, and 3 tubes which have survived ten years.

All these SP61 tubes were part of a single batch made in 1942 and their performance set a high standard. It was, however, found that subsequent batches did not attain the same standard set by the 1942 batch. In 1946, therefore, the British Post Office was faced with the fact that future development of the shallow water system of submerged repeaters was dependent on the production of a tube type which could take the place of the 1942 batch of SP61 tubes. This situation led to the formation of a team at Dollis Hill whose terms of reference were, specifically, to produce the replacement tube and, generally, to study the problems presented by the use of tubes in submerged repeaters. Apart from changes in the specific requirements, these terms of reference have remained unchanged from that day to this.

Replacement by the G.P.O. 6P10 Type

Coincident with the rapid exhausting of stocks of satisfactory SP61 tubes for submerged telephone systems, there arose the need for a tube type for a submerged telegraph repeater. This latter requirement was complicated by the fact that the telegraph cable was subject to severe overall voltage restrictions which precluded the 630 ma heater current required for the 4 watt cathode of the SP61. In order to avoid production

of one tube type for telephone systems and another for telegraph, it was decided that the replacement for the SP61 should have a 2 watt cathode with a 300 ma heater.

During the years 1944 and 1945 a very successful miniature high slope pentode, the CV138, was produced for the armed services. The electrical characteristics of this tube were superior to those of the SP61 and, in addition, it used a 2 watt cathode. It was therefore decided to base the replacement tubes, electrically, on the CV138, whilst, at the same time, retaining freedom to amend the mechanical features in any way which might seem to favor the specific requirements of submerged repeater usage, in particular, maintenance of the level of transconductance unchanged for long periods. Consequently three major mechanical changes were made at the outset of the project. The miniature bulb of the CV138 was replaced by one of normal size (approximately 1 inch diameter and $2\frac{1}{2}$ inches long). This was done to reduce the glass temperature and so reduce gas evolution. At the same time a normal press and drop seal were substituted for the button base and ring seal of the CV138, as it was felt that, with the techniques available, the former would be more reliable than the latter. With the use of a normal press there immediately followed a top cap control grid connection, so producing a double-ended tube in place of the single-ended CV138.

These three modifications and a number of major changes to improve welding and assembly techniques led to the G.P.O. type known as the 6P10 [A pentode (P) with a 6.3-volt heater (6) of design mark 10]. The 6P10 replaced the SP61 in the 18 shallow water repeaters laid in various cables after 1951. There are, therefore, 54 tubes type 6P10 in service on the sea bed with periods of continuous loading ranging from two to four years. There has been one failure due to a fractured cathode tape, and one other repeater was withdrawn from service to investigate a high-frequency oscillation associated with a tube. The oscillation cleared, however, before the cause could be identified.

The first eighteen 6P10 type tubes used in repeaters had conventional nickel cathode cores. Appreciation of the problem of interface resistance led to the use of platinum as a core material for the following 36 tubes. The steps leading to this radical change of technique will be described later.

Development of the 6P12 for Long Haul Systems

Although submerged repeater development started naturally in Britain with shallow-water systems, it was inevitable that attention should

ultimately turn towards trans-ocean cables. The tube requirements for such long haul systems differ from those for short haul shallow-water schemes in that operation at a lower anode voltage is essential. A new tube to replace the 6P10 was therefore unavoidable.

By the time emphasis started to shift in Britain from shallow-water to deep-sea systems some considerable experience had been gained at Dollis Hill on the production techniques required to fit a 6P10 type tube having a platinum cathode core for submerged repeater usage. When it became apparent that a new tube had to be designed for the first long haul system, it was resolved to retain as much as possible of the 6P10 structure in order to take full advantage of familiar techniques. The 6P10 was therefore redesigned for 60-volt operation simply by a major adjustment to the screen grid position and minor alterations elsewhere. The new tube became known as the 6P12 and was used in seven repeaters installed in the Aberdeen-Bergen cable. This scheme was regarded as a proving trial for the Newfoundland-Nova Scotia section of the transatlantic project.

It has always been appreciated that the use of high transconductance tubes using closely-spaced electrodes will involve a higher liability to mechanical failure by internal short circuits. Practical experience in shallow-water schemes, where repeater recovery is a comparatively cheap and simple operation, has shown however that such risks seem to be outweighed by the economic advantage accruing from a tube capable of wider frequency coverage. In point of fact a failure by internal short circuit has not yet materialized on any shallow-water system.

This background of experience explains the British choice of a high transconductance tube for deep-sea systems, but the greater liability to mechanical failure is acknowledged by use of parallel amplifiers. Confidence in this policy has been increased by the successful operation of the Aberdeen-Bergen system.

Problems of Development of the 6P12 Tube

The main preoccupation of the thermionics group at Dollis Hill since 1946 has been a study of the electrical life processes of high transconductance receiving tubes. This effort has led to a conviction that all changes of electrical performance have their origin in chemical or electro-chemical actions occurring in the tube on a micro- or milli-micro scale of magnitude. The form of change of most importance to the repeater engineer is decay of transconductance and this will be considered in brief detail as typical of the development effort put into the 6P12 tube.

Transconductance decay in common tubes results from two separate

and distinct chemical actions occurring in the oxide cathode itself. Both actions are side issues in no way essential to the basic functioning of the cathode and it seems probable that both can be eliminated if sufficient understanding of their nature is available. The first action is the growth of a resistive interface layer between the oxide matrix and its supporting nickel core, discussed briefly in an earlier section. This effect is assumed to be due to silicon contamination of the nickel core metal.



The resistance of the layer of barium orthosilicate rises as it loses its barium activator and approaches the intrinsic state. The effect of the interface resistance is to bring negative feedback to bear on the tube with resulting loss of transconductance. The second deleterious action is loss of electron emission from the oxide cathode by direct destruction of its essential excess barium metal by oxidizing action of residual gases. Such gases result from an imperfect processing technology.

These two problems have been approached in the 6P12 tube in a somewhat novel manner. The conventional nickel core is replaced by platinum of such high purity (99.999 per cent) that the possibility of appreciable interface growth from impurities can be disregarded. The only factor to be considered is the appearance of high resistive products of a possible interaction between platinum and the alkaline earth oxides. Batch tests over a period of 30,000 hours have failed to show any sign whatever of such an action occurring and workers at Dollis Hill now regard the pure platinum-cored tube as free from the interface resistance phenomenon.

The problem of avoiding gas deactivation of the cathode is a more difficult one and so far has been reduced in magnitude rather than eliminated. It is now appreciated that the dangerous condition arises from "gas generators" left in the tube and not from a true form of residual gas pressure left after seal-off from the pump. These gas generators are solid components of the tube which give off a continual stream of gas over a prolonged period of time. The gas evolution rates are usually so small that they cannot be detected by reverse grid current measurement but they tend to integrate gas by absorption on the cathode and to destroy its activity. The gas generators are usually of finite magnitude and, depending mainly on diffusion phenomena, evolve gas at a rate which falls in roughly exponential fashion with time. The probability of transconductance failure is therefore highest in early life and tends to lessen with time as the generators move to exhaustion.

One particularly useful feature of the platinum-cored cathode is its freedom from core oxidation during gas attack and this leaves the tube

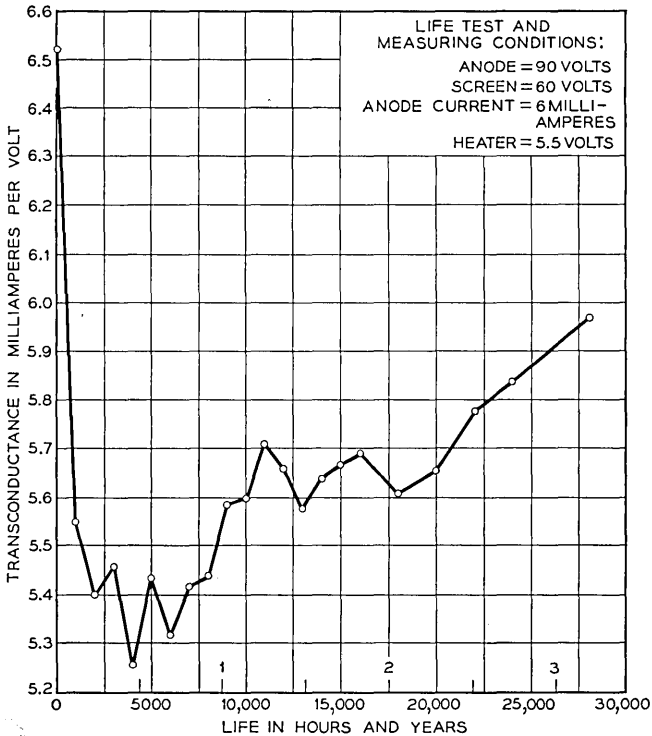


Fig. 10 — Behaviour of a group of 50 tubes deliberately left with a “gas generator” (tube type 6P12).

free to recover from transconductance failure when the gas attack has passed. In Fig. 10 is shown the behaviour of a group of 50 tubes which have been deliberately left in possession of a component capable of generating carbon-monoxide over a prolonged period of time. The curve shows the characteristic recovery of a platinum-cored oxide-cathode with the gradual passing of what is thought to be a typical gas attack.

One problem that has attracted much attention at Dollis Hill is the actual manner in which a platinum-cored cathode recovers from a gas attack. The mechanism must involve the dissociation of a small fraction of the oxide cathode itself with the retention of barium metal in the oxide lattice and the evolution of oxygen. That such an essential mechanism does in fact exist has been proved by the slow accumulation of barium metal in the platinum core. This accumulation takes the form of a distinctive alloy of barium and platinum and only occurs when the cathode

is passing current. The barium regenerative process seems therefore to be electrolytic in nature and, depending only on current flow and a stock of oxide, would appear to be virtually inexhaustible.

These few remarks are perhaps sufficient to give some idea of the lines on which the British research effort has run during the past decade. More detailed descriptions have already been presented elsewhere.^{4, 5, 6, 7}

Electrical and Mechanical Characteristics

Electrical Characteristics

The main electrical characteristics of the 6P12 are shown in Figs. 11 and 12. The heater voltage used for both sets of curves is 5.5 volts, the same value as that used in the British amplifier.

Fig. 11 shows the change of transconductance with anode current, with screen voltage as parameter. An anode voltage of 40 volts and a suppressor voltage of zero correspond with the static operating conditions in the first two stages of both the Aberdeen-Bergen and the British

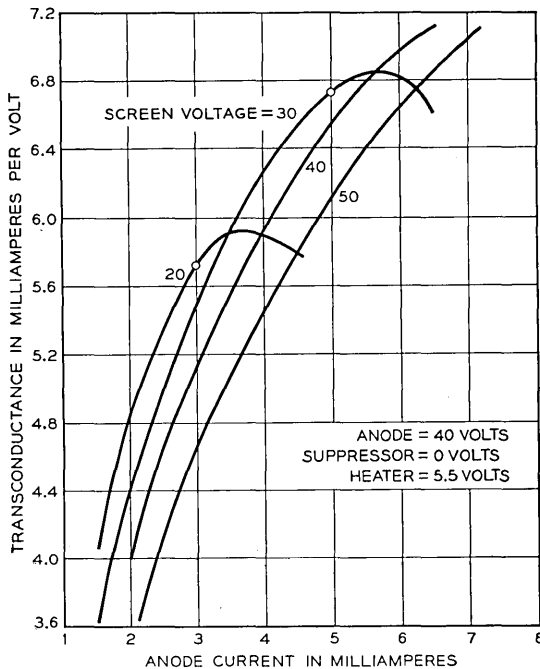


Fig. 11 — Typical transconductance-anode current characteristics for a type 6P12 tube (No. 457/6).

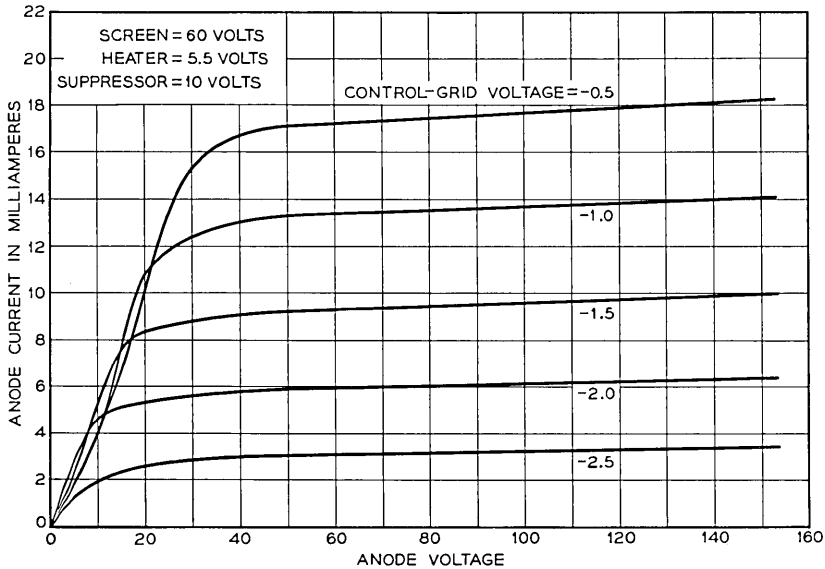


FIG. 12 — Typical anode voltage-anode current characteristics for a type 6P12 tube (No. 457/6).

transatlantic telephone (T.A.T.) amplifiers. The screen voltage and anode current of the first two stages of the British T.A.T. amplifier were chosen to be 40 volts and 3 ma respectively.

Fig. 12 shows the normal anode voltage-anode current characteristics for conditions corresponding to the output stage of the amplifier (static operating point, anode voltage = 90, screen voltage = 60, anode current = 6 ma). A final electrical characteristic worthy of comment is the level of reverse grid current. For all specimens tested at the time of selection, after about 4,000 hours life test, the level is very low, about 100 micromicroamperes per milliampere of anode current.

Life Performance

The life performance of the 6P12 is still a matter for conjecture. The only concrete evidence available is the behaviour of a group of 92 tubes which were placed on life test some three years ago. The change of the average transconductance of this group (with anode current constant at 6 ma) is shown in Fig. 13. It may be clearly appreciated that there is no definite trend over the past year which permits any firm prediction of life expectancy. Examination of other tube characteristics is equally unproductive from the point of view of prediction of failure.

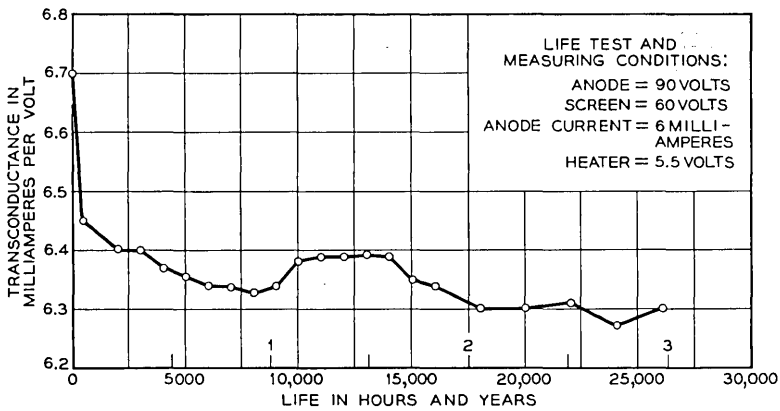


Fig. 13 — Behaviour of a group of 92 type 6P12 tubes over a period of three years.

In the early stages of the test there were eight mechanical failures. The cause in all instances was identified and corrected in subsequent production before the start of the T.A.T. project.

Mechanical Characteristics

The chief mechanical characteristics of the 6P12 have been mentioned before in that they are, as explained, very similar to those of the 6P10. A photograph of the interior of the tube is shown in Fig. 14.

Tube Selection Techniques

Not all the tubes, found after production to be potentially suitable for the British T.A.T. amplifier, remained equally suitable after the life test period of about 4,000 hours. A brief account of how the best were selected is given below.

The fact that every tube had to pass conventional static specification limits needs little emphasis here. This test was, however, supplemented by three additional types of specification. First, every tube was tested in a functional circuit, simulating that stage of the amplifier for which the tube was ultimately intended. Here measurements were made of shot noise (appropriate to first stage usage) and harmonic generation (appropriate to the output stage) in addition to the usual measurements of transconductance, anode impedance and working point.

Second, all tubes were subject to intensive visual scrutiny in which some 80 specific constructional details were checked for possible faulty assembly.

Third, the life characteristics of transconductance, total emission and working point were examined over the test period of about 4,000 hours for unsatisfactory trends. Although this type of specification is more difficult to define precisely, its application is probably more rigorous and exacting than any of the previous specifications.

Only if a tube passed the conventional test and the three supplementary tests was it considered adequate for inclusion in a repeater.

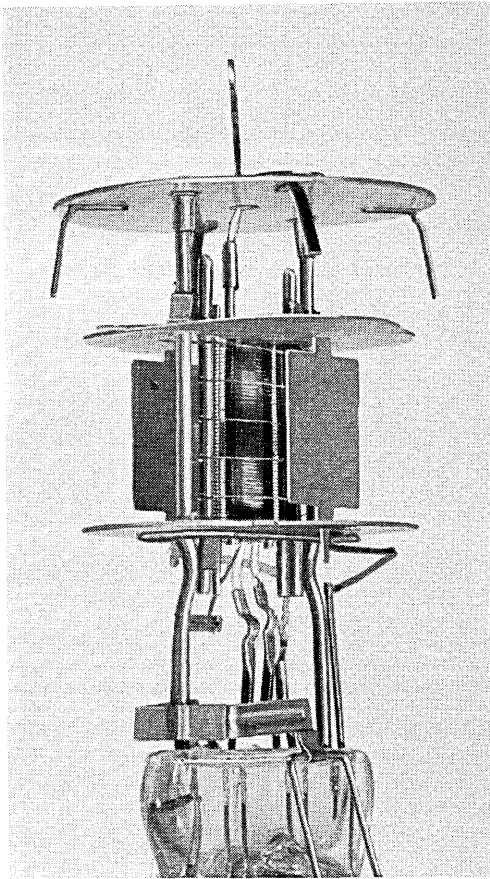


FIG. 14 — View of interior of a 6P12 type tube.

CONCLUSION

The laying of the present repeatered transatlantic cable represents by far the most ambitious use to date of long life, unattended electron tubes. On this project alone there are 390 tubes operating on the ocean bottom. If to this number are added the ocean bottom tubes from earlier shorter systems, those used in the Alaskan cable completed a few months ago, and those to be used in the California-Hawaiian cable to be laid in 1957, the total number on the ocean bottom will be about one thousand. The capital investment dependent on the satisfactory performance of these tubes is probably about one hundred million dollars — strong evidence of faith in the ability to produce reliable and trustworthy tubes.

It is of interest to note that the two groups working on the tubes on opposite sides of the Atlantic had no intimate knowledge of each other's work until after the tube designs had been well established. As a result of subsequent discussions, it has been surprising and gratifying to find how similarly the two groups look at the problems of reliability of tubes for submarine cables.

The authors would be completely remiss if they did not mention the contributions of others in the work just described. These projects would have been impossible if it were not for the enthusiastic, cooperative and careful efforts of many people working in varied fields. Over the years chemists, physicists, electrical and mechanical engineers, laboratory aides, shop supervisors and operators all have made essential contributions to the projects. It would be impractical and unfair to attempt to single out for mention the work of specific individuals whose contributions are outstanding. There are too many.

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Cable Design and Manufacture for the Transatlantic Submarine Cable System

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The transatlantic cable project required that two repeatered cables be laid in the deep-water crossing between Newfoundland and Scotland, and one across the shallower waters of Cabot Strait. The same structure was adopted for the cables laid in the two locations.

This paper discusses the considerations leading to design of the cable and describes the method of manufacture, the means and equipment for control of cable quality, the process and final inspection procedures, the electrical characteristics of the cable, and factors relating to mechanical and electrical reliability of the final product.

DESCRIPTION OF CABLE

General features of the cable structure adopted for the transatlantic cable project¹ are illustrated in Fig. 1. The cable consists of two basic parts: (1) the coaxial, or the electrical transmission path, and (2) the armor or outer protection and strength members.

The coaxial is made up of three parts: (1) the central conductor, (2) the insulation, and (3) the outer or return conductor. The central conductor is composed of a copper center wire surrounded by three helically applied copper tapes. The insulation is a polyethylene compound which is extruded tightly over the central conductor. The insulated central conductor is called the cable core. The outer or return conductor is composed of six copper tapes applied helically over the insulation.

The protection and strength components shown in Fig. 1 for the type D deep water cable are provided by a teredo tape of thin copper applied over the outer coaxial conductor, a fabric tape binding, a layer of jute rove for armor bedding, the textile covered armor wires and finally, two layers of jute yarn flooded with an asphaltum-tar compound. This cable is characterized by the extra tensile strength of its armor wires and by the extra precautions taken to minimize corrosion of these wires.

* Bell Telephone Laboratories.

At the shallow water shore ends, the armor types are characterized by the use of mild steel wires which are increased in diameter in steps as the landing is approached. These types are designated A and B and will be described in greater detail later.

The transmission loss of this cable structure at the top operating frequency of 164 kc is 1.6 db per nautical mile and is 0.6 db per nautical mile at 20 kc, which is the lower end of the frequency band. The high frequency impedance of the cable is about 54 ohms.

BASIS OF DESIGN

A coaxial structure was first used for telephone and telegraph service in a submarine installation in 1921, between Key West and Havana, Cuba. Three coaxial cables with continuous magnetic loading and no submerged repeaters were laid. One telephone circuit and two telegraph circuits were provided in each cable for each direction of transmission.

In 1950, a pair of submarine coaxial cables,² which included flexible submerged repeaters, was laid between Key West and Havana, Cuba. Each cable furnished 24 voice circuits. One cable served as the "go" and the other as the "return" for the telephone conversations. The transatlantic telephone cable design is similar to this cable except that the nominal diameter of the insulation is 0.620" instead of 0.460". An outstanding difference between the transatlantic and Key West-Havana systems is cable length — about 2,000 nautical miles as compared with 125. This difference influenced significantly the permissible electrical and mechanical tolerances applying to the cable structure.

The installation of some 1,200 miles of cable with island based repeaters for a communication and data transmission system for the U. S. Air Force, between Florida and Puerto Rico,³ followed the 1950 submarine cable system. The design of this cable is identical with that of the transatlantic cable, except for differences in the permissible dimensional tolerances on the components of the electrical transmission path. Data obtained on the electrical performance of the Air Force cable provided the transmission characteristic to which the repeaters for the transatlantic project were designed.

The design of this cable installation was the result of many years of cable development effort, which was guided by the successes and failures of the earlier submarine telegraph cables. The 1950 Key West-Havana and the Air Force cables differed from the earlier structures in one important respect, namely, the lay of the major components. A series of fundamental design studies during the 1930's and 1940's and extensive field tests in the Bahamas in 1948 demonstrated that having

the same direction of lay of the major components of a cable was very important in minimizing kinking and knuckling. In addition, other laboratory tests pointed the direction for the adoption of new materials and techniques in the manufacture of these cables. These and subsequent improvements in materials and manufacturing techniques were included in the transatlantic cable design.

Since the electrical characteristics of a cable have a direct bearing on the overall system design and performance, considerable emphasis was placed on this phase of the design of the transatlantic cable. The size of

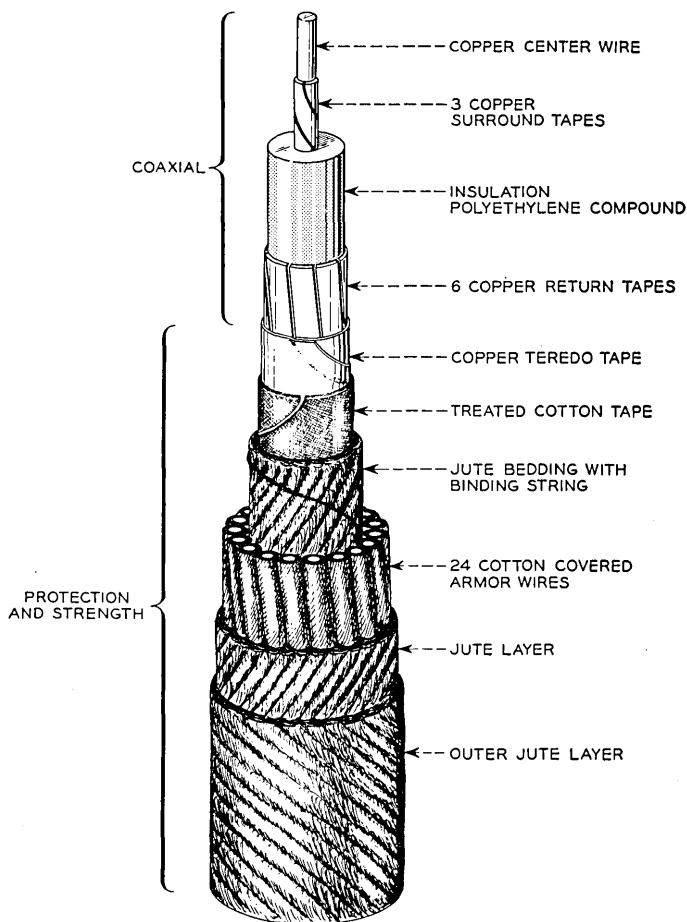


Fig. 1—Structural features of the deep water type of cable.

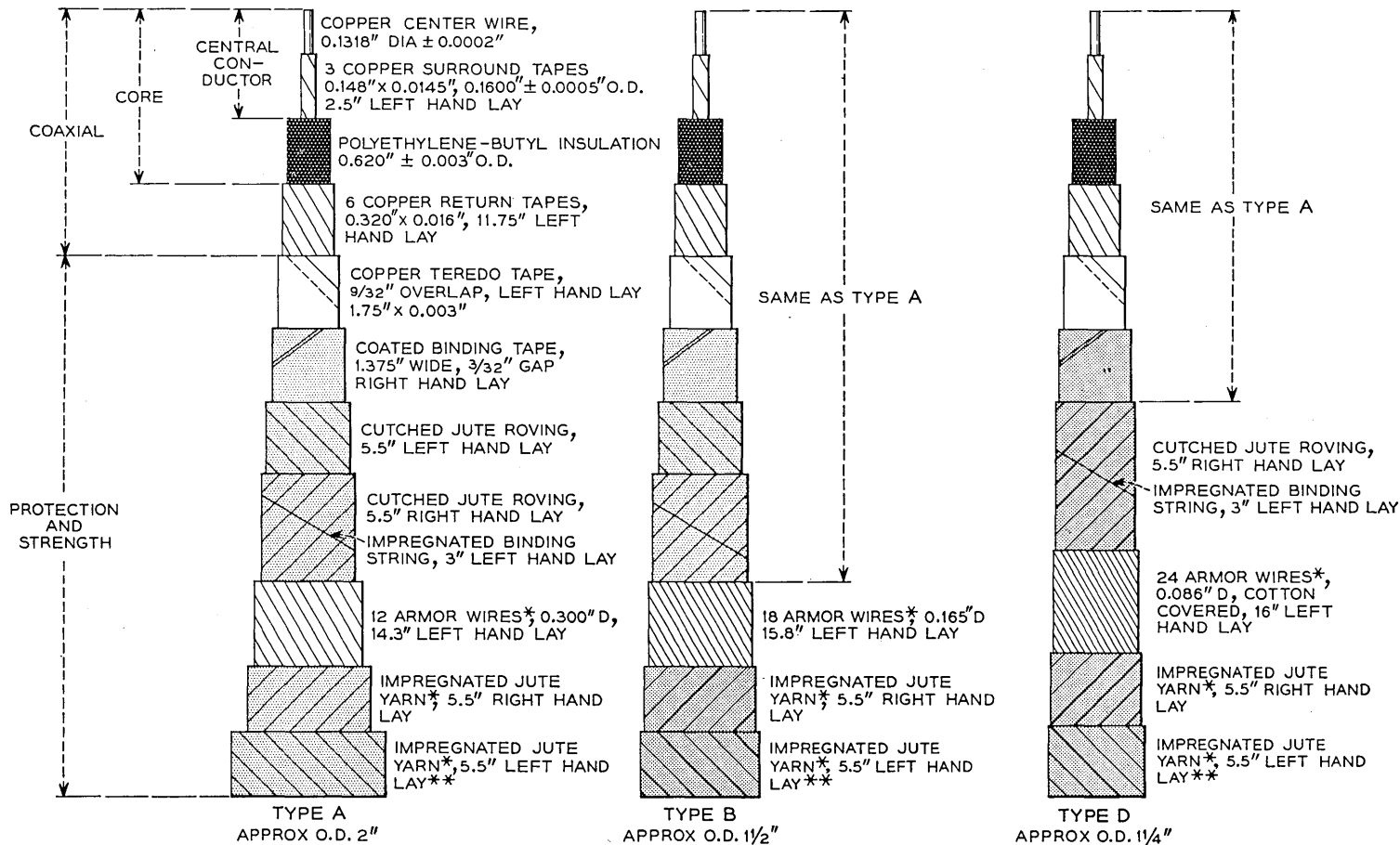


Fig. 2 — Design details of the types of transatlantic telephone cable for different depths of water.

central conductor and core used in the Air Force cable resulted in low unit attenuation and low dc resistance. These advantages resulted in the adoption of this size of cable. However, the outside diameter of the core and the diameter of the central conductor of the coaxial do not fulfill the requirements generally described as optimum for minimum attenuation. Mathematical analysis shows that there is a preferred diameter ratio which results in minimum transmission loss. For the 0.620" core diameter employed in the Air Force cable, the central conductor diameter chosen was smaller than the ideal central conductor required to satisfy the preferred diameter ratio. The diameter chosen retained the central conductor size which the Key West-Havana and Air Force cables proved to be satisfactory from a manufacturing standpoint. The choice was also compatible with the dc resistance requirement for transmission of power over the cable to each of the repeaters.

While production of the cable was proceeding, cable manufactured to the transatlantic specification was tested near Gibraltar in March, 1955. These tests provided a final evaluation of the mechanical and electrical characteristics of this cable before the actual laying of the transatlantic link.

DETAILS OF STRUCTURAL DESIGN OF CABLE

The structural features of the coaxial and of types A, B and D armor are summarized in Fig. 2.

A composite central conductor was chosen to provide a conductive bridge across a possible break in any one of its elements, due to a hidden defect, such as an inclusion of foreign material in the copper. The dimensions of the components of the central conductor were precisely controlled, and a light draw through a precision die was used to compact and size the assembly.

Use of high molecular weight polyethylene (grade 0.3) for core insulation is a major departure from the materials used in early submarine telephone and telegraph cables. The development of synthetic polymers such as polyethylene had led to the replacement of gutta percha as cable insulation, since polyethylene possesses better dielectric properties and mechanical characteristics and is lighter in weight.

Ordinary low molecular weight polyethylene is subject to environmental cracking, especially in the presence of soaps, detergents and certain oils. High molecular weight material is much less subject to cracking, and by adding 5 per cent butyl rubber, further improvement in crack resistance is obtained.

Six copper tapes applied helically over the core comprised the return

conductor and thus completed the coaxial structure. The dimensions of these tapes were precisely controlled. The helical structure was chosen to impart flexibility to the coaxial.

Insulation of some of the early submarine telegraph cables suffered from attack by marine borers such as the teredo, pholads and limnoria. To protect against such attack, a thin metallic tape was placed over the insulation in the early submarine cables. The necessity for such protection for the transatlantic cables, especially in deep water, may be questioned, but the moderate cost of this protection was considered cheap insurance against trouble. The copper teredo tape was applied directly over the return conductor, as a helical serving with overlapped edges to completely seal the coaxial from attack by all but the smallest marine organisms.

A cotton tape treated with rubber and asphaltum-tar compound was applied over the teredo tape to impart mechanical stability to the coaxial during manufacture. A small gap between adjacent turns of the helix was specified to permit ready access of water to the return tape structure and to the surface of the core. The use of a gap was based on laboratory tests which showed that transmission loss was dependent to a modest extent on thorough wetting of the exterior of the coaxial. Since transmission loss measurements are made on repeater sections of cable shortly after manufacture to determine whether any length adjustments are required, it was essential that the wetting action be as rapid as possible.

The design of the protection and strength components of the cable was modified according to the depth of the water in which the cable was to be laid. To prevent damage to the coaxial by any cutting action of the armor wires during manufacture and laying, a resilient cushion of jute roving was placed between the armor wires and coaxial. For type-D cable, a single layer of jute was used; for types A and B cable, the bedding was made up of two layers of jute. To protect this jute from micro-biological attack, a cutting treatment was employed. The traditional

TABLE I

Type	Armor Wire			Application
	Number of Wires	Diameter in Inches	Material	
A	12	0.300	Mild Steel	Up to 350 fath.
B	18	0.165	Mild Steel	350 to 700 fath.
D	24	0.086	High Strength Steel	Greater than 700 fath.

cutching process consists of treating the jute with a vegetable compound called catechu or cutch.

Armor wires were applied over the bedding jute. The use of heavy or intermediate weight near shore has been established by experience with ocean cable. This type of armor is generally employed where the cable may be exposed to wave action, bottom currents, rocks, icebergs, ship's anchors and fishing trawlers. A lighter weight structure having higher tensile armor wires is needed in deep water. Table I shows the essential differences between the armor types employed in the transatlantic cable and the approximate range of depths in application.

In addition to the above armor types, a shore length of 0.6 nautical mile was provided with an insulated lead sheath under Type A armor to facilitate preferred grounding arrangements and to provide signal to noise improvement.

Where the tensile strength of the armor wires is most important, as in the type D design, each of the wires was protected against corrosion by a zinc galvanize plus a knitted cotton serving or helically applied tape, the whole assembly being thoroughly saturated with an asphaltum-tar compound. The effectiveness of such protection is clearly apparent when early submarine cables, which used this protection, are recovered and examined. For the heavier armor types, the protection was similar to that of type D, except that the textile serving was replaced by a dip treatment to coat each wire with an asphaltic compound.

As the armor wires were applied to each type of cable additional protection was obtained by flooding the cable with a special asphaltum-tar compound and then applying two layers of jute yarn over the wires. The jute yarn was impregnated with an asphaltum-tar compound before application to the cable and then flooded with another asphaltum-tar compound after application. Formulation of cable flooding materials required the use of compounds having a relatively high coefficient of friction to avoid slippage of the cable on the ship's drum during laying.

To assure satisfactory handling characteristics during the laying operation, all of the metallic elements of the cable were applied with a left-hand direction of lay and the lengths of lay (except for the teredo tape) were chosen so that approximately the same helical length of material was used per unit length of cable. Since the teredo tape was relatively soft and ductile compared to that of the other metallic components, it was not necessary to equate its helical length to that of the other components. Width and lay of the teredo tape were selected to give a smooth, tight covering.

The choice of direction and length of lay of the jute layers was based

on experience with cable in factory handling and laying trials. Experience, particularly with the direction of lay, has shown that improper choice of lays for the two outer layers of jute may result in a cable that is difficult to coil satisfactorily in factory and ship storage tanks. The combination of lays selected for the cable components provided good performance in all the handling operations, including the final laying across the Atlantic.

MANUFACTURE OF THE CABLE

Before considering the manufacture of the cable, it should be understood that the repeater gain characteristic was designed to compensate for the loss characteristic of the cable. Therefore, once this loss characteristic was established, it was essential that all cable manufactured conform with this characteristic.

To obtain the required high degree of conformance, close control had to be kept over all stages of manufacture and over the raw materials. Controls to guide the manufacture of the cable were set up with two broad objectives:

1. To produce a structure capable of meeting stringent transmission requirements.
2. To assure that the manufactured cable could be laid successfully and would not be materially affected by the ocean bottom environment for the expected life of the cable system.

Attainment of a final product capable of meeting the stringent transmission requirements is described in a later section of this paper. Process and raw material controls in manufacture were provided by an inspection team which checked the quality of the various raw materials and the functioning of the several processes during the manufacturing operations. This type of inspection coverage is somewhat unique with submarine cable. It assures the desired final quality by permitting each error or accident to be investigated and corrected on an individual basis.

Cable for the transatlantic crossing was manufactured in America by the Simplex Wire and Cable Company and in England by Submarine Cables, Limited. Differences in machinery and equipment in the plants of the two manufacturers necessitated minor differences in the sequence of the operations and in the processes. The sequence of operations in assembly of the cable was as follows:

Step No.	Operation
1	Stranding of central conductor
2	Extrusion of insulation
3	Runover examination, repair where necessary

- 4 Panning and testing of core
- 5 Jointing of core
- 6 Application of return tapes, teredo tape, fabric tape, jute bedding and binding string
- 7 Application of armor wire and outer jute layers
- 8 Storage in tanks, testing
- 9 Splicing in repeaters, testing

The only important difference in the sequence of the manufacturing operations at the two plants was the use of separate operations for steps 6 and 7 at Submarine Cables and the combination of these operations in one machine at Simplex.

Other minor differences in process methods related to raw materials. For example, the American supplier purchased polyethylene already compounded with butyl rubber and antioxidant in granule form, ready for use. The British supplier purchased polyethylene, butyl rubber and antioxidant separately, and performed the compounding in the cable factory.

STRANDING OF CENTRAL CONDUCTOR

The central conductor was stranded on a machine which included a revolving carriage with suitable arbors for the three surround tapes. It was equipped with brakes designed to assure equal pay-off tension among the tapes and with detectors to automatically stop the strander in case of a tape break. Each tape was guided through contoured forming rolls to shape the tape to the center wire.

The joints between successive reels of wire and tape used in fabrication of the central conductor were butt brazed. The brazes were staggered to avoid more than one braze in a given cross-section of the conductor. The quality of the brazes in these components was controlled by a qualification technique described below in the section on core jointing.

The strand was drawn through several forming dies to size the finished diameter of the central conductor accurately. No lubrication was used because the removal of the resultant residues, which could contaminate the polyethylene insulation, was difficult. The taper in the central conductor diameter due to the die wear was controlled by appropriate replacement of tungsten carbide dies, where used, or by the use of a diamond die where the rate of die wear is less than 1 or 2 micro-inches per mile.

The stranding area in both plants was enclosed and pressurized to guard against dirt and dust settling on the central conductor. A high standard of cleanliness was maintained for parts of the machine which touched the conductor or its components. Undue wear of the guide faces

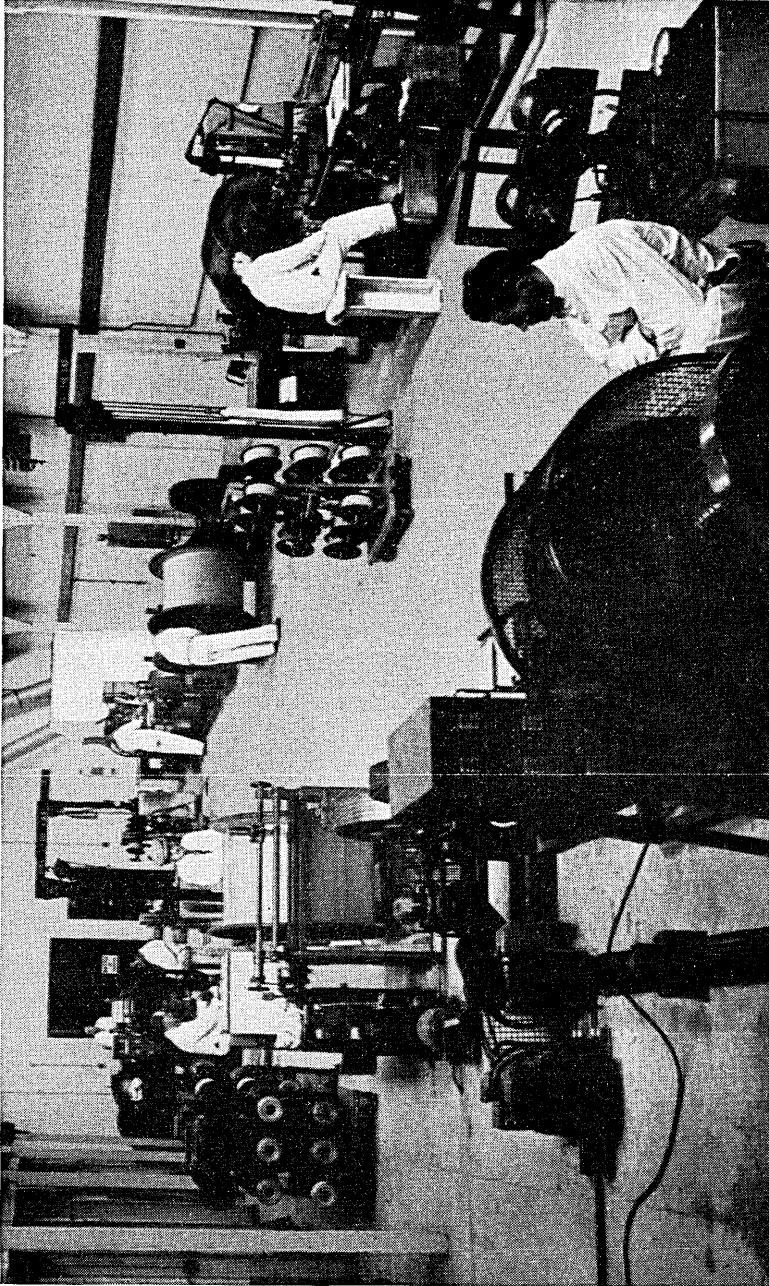


Fig. 3. — View of typical manufacturing area for stranding of central conductor.

or capstan sheaves was cause for replacement of the sheaves and adjustment of the machine. A photograph of the stranding area is shown in Fig. 3.

EXTRUSION OF INSULATION

To avoid possible contamination of the polyethylene insulating compound in the extruder-hopper loading area, a pressurized enclosure prevented entry of air-borne dust and dirt, and the containers of polyethylene compound were cleaned with a vacuum cleaner before being brought into the hopper area. A fine screen pack placed in the extruder reduced the possibility of contamination in the core.

In passing through the extruder, the central conductor was payed-off of a large reel with controlled tension, into the pay-out capstan, through an induction heater, through a vacuum chamber, and thence into the cross-head of the extruder. The induction unit heated the central conductor and provided means for controlling the shrinkback of the core insulation and the adhesion of the conductor to the insulation. Shrinkback is a measure of the contained stresses in the insulation.

On the output side of the extruder, the core was cooled in a long sectionalized trough containing progressively cooler water from the input to the output end. The annealing of the polyethylene in the cooling trough also served to hold the shrinkback of the core to a low value. The extrusion shop is shown in Fig. 4.

An important addition to the extrusion operation consisted of the use of an improved servo system to control the extruder automatically to attain constant capacitance per unit-length of coaxial. The system used is described in a subsequent section.

RUNOVER EXAMINATION

Following extrusion, the core was subjected to continuous visual and tactual examination in a rereeling operation called "runover". The purpose of the runover operation was the detection of inclusions of foreign material in the dielectric and the presence of abnormally large or small core diameters. Core not meeting specification requirements was cut out or repaired.

In addition to visual inspection of the cable, examination of short lengths of core was made at regular intervals with a shielded source of light arranged to illuminate the interior of the dielectric material. Provision of this internal illumination facilitated detection of particles of foreign material well beneath the surface of the core. Strip chart records

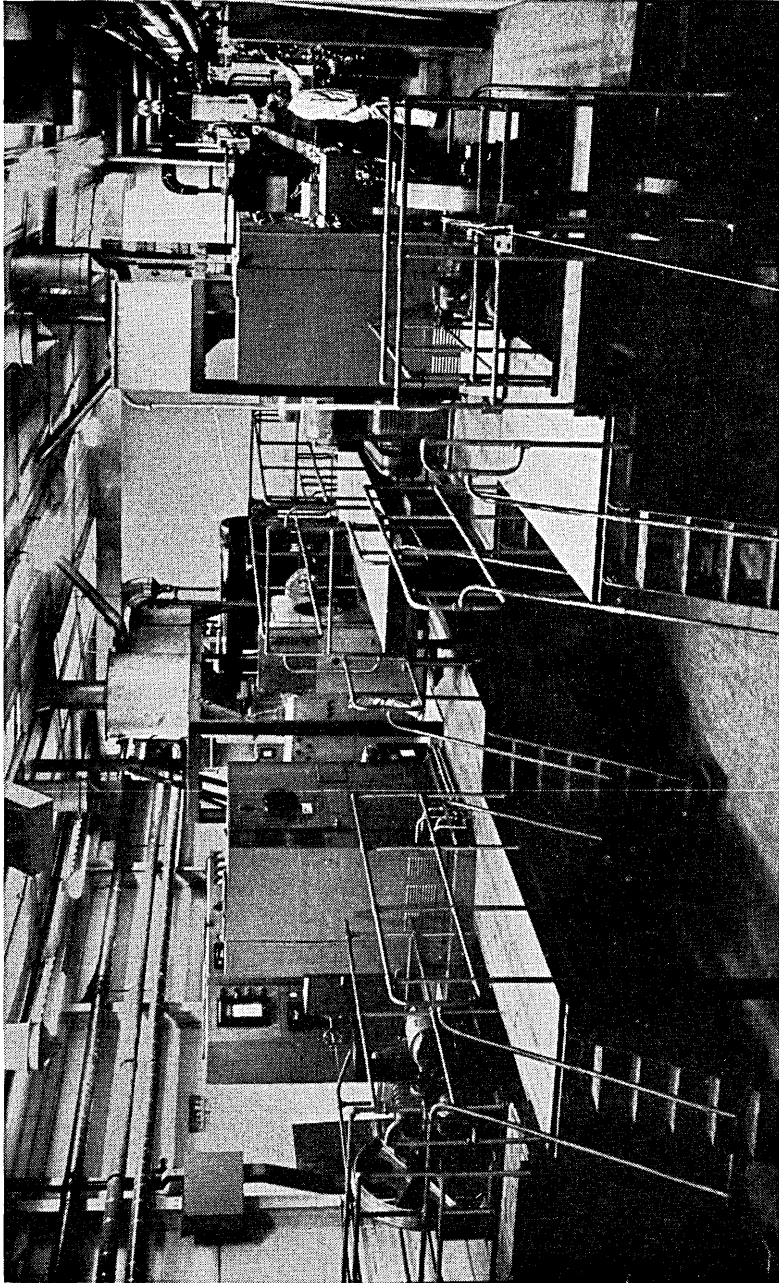


Fig. 4 — View of typical manufacturing area for extrusion of core insulation.

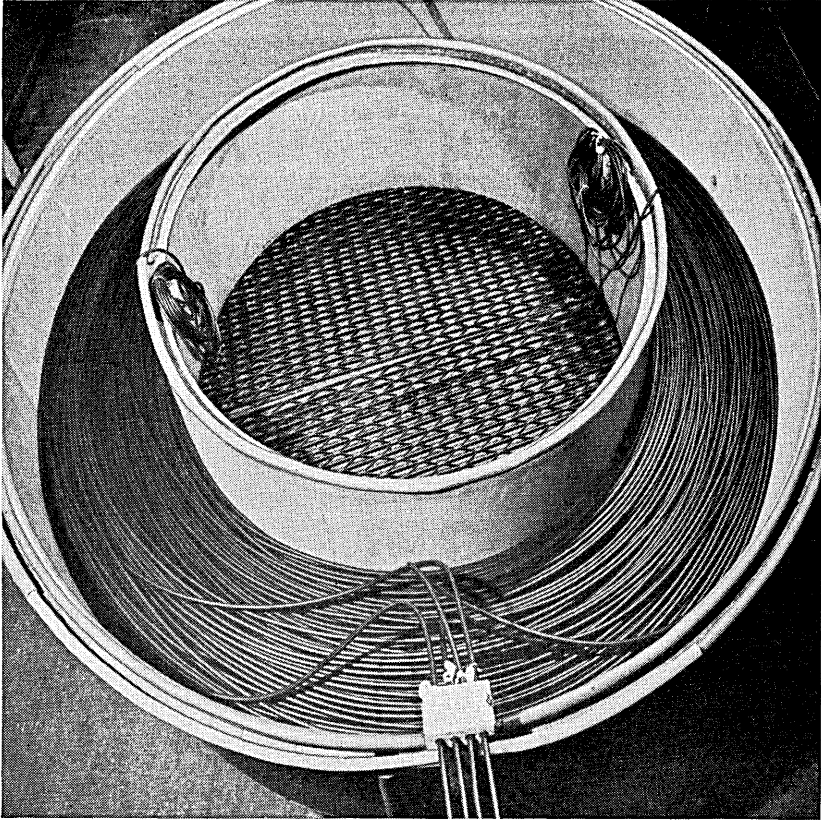


Fig. 5 — Special-water tank or pan for tests on immersed cable core.

of the unit-length capacitance of the core obtained during extrusion were used as a guide in searching out regions of uncertainty.

PANNING AND TESTING

After runover, the core was coiled in tanks of water, as shown in Fig. 5. Precautions were taken to remove the air dissolved in the water and thus prevent the formation of bubbles on the surface of the core. The water was also temperature controlled and circulated to maintain uniform temperature throughout the tank. Thermocouples placed at different levels in the tank determined when the temperature was uniform. Measurements of dc conductor resistance, ac capacitance, insulation re-

sistance, and dielectric strength were then made. These measurements are discussed in detail in a later section of this paper.

JOINTING OF CORE LENGTHS

The cable core was manufactured in lengths much shorter than a repeater section, which necessitated connecting the individual core lengths together. Jointing techniques consisted of brazing the central conductor with a vee-notch type of junction and of molding in a short section of the polyethylene insulation. After silver-soldering the vee-joint, a safety wire consisting of four fine gauge tinned copper wires was bridged across the junction in an open helix and soft soldered at the ends. Extreme care was taken to remove any excess rosin and to eliminate any sharp points on the ends of the safety wires. The safety wire is intended to maintain continuity of the electrical path in case the braze should fail.

Visual examination of brazes in the actual cable was the only means available for their final inspection. To assure a high degree of quality on these brazes, a system was devised for checking the performance of the operator and the brazing machine initially and at frequent intervals through the use of sample brazes in each of the components, which were tested to destruction. To control the uniformity of brazes, the brazing of the copper wire and tapes was made as automatic as possible by the use of controlled pressure on the components, appropriate sized wafers of silver solder, and an automatically timed heat cycle. The tests on the brazes used to qualify operators and machinery indicated that a high degree of braze performance was achieved.

Pressure and temperature were carefully controlled during the molding of the insulation over the conductor. Periodic checks similar to those described for brazes were made on operator and molding-machine to maintain a satisfactory level of performance. In addition, each molded joint placed in the actual cable was X-rayed and subjected to a high voltage test while immersed in water.

APPLICATION OF RETURN TAPES AND ARMOR WIRES

After the core lengths were joined together, they were pulled through the return taping and armoring operations. The machine for applying return tapes was designed specifically for the purpose and was similar in characteristics to the corresponding portion of the strander for the central conductor. Controlled pay-off tension, automatic breakage detectors, precision guides, and contoured forming rolls to shape the tape, were incorporated in the construction.

The return tape, teredo tape, and fabric tape were applied from taping heads, and the bedding jute and binding string were applied from serving heads in a tandem operation. Another set of tandem operations included the application of armor wires, outer jute layers and the appropriate asphaltum-tar flooding compounds. In the American suppliers plant, both sets of tandem operations were combined into one continuous production line. In the British plant, these operations were divided into two separate production lines. A view of the armoring machine area is shown in Fig. 6. Following the application of the flooding compounds, whiting is applied either at the take-up capstan on the armoring line or in the storage tanks as the cable is coiled.

To avoid core damage, the flow of hot flooding compound was stopped when the cable in the armoring line was stopped. One of the major sources of such stoppages was the reloading of the various applying heads.

STORAGE AND TESTING

In a continuous haul-off operation, the cable was conveyed from the armoring machine to the tank house for storage. The cable was coiled in spiral layers, called flakes. Each flake started at the outside rim of the tank and worked toward the central cone. Several 37-nautical mile repeater sections were stored in each tank.

Water was circulated through the cable tanks to establish uniform temperature conditions throughout the mass of cable. When thermocouples located at appropriate points in the tank indicated that the cable temperature was uniform, measurements were made of attenuation, internal impedance irregularities and terminal impedances, dc resistance, dc capacitance, insulation resistance, and dielectric strength.

To facilitate these tests without interrupting production, successive repeater section lengths were placed in alternate tanks. By this procedure, a group of four or five sequential repeater section lengths, called an "ocean block", was stored in two tanks. The ends of each repeater section were brought out of the tank to a splicing location. After all tests were completed and the specification requirements met, the repeaters were spliced in. Testing of the ocean block for transmission performance completed the manufacturing operations.

RAW MATERIALS

Stringent requirements were placed on all raw materials used in the manufacture of the transatlantic cable. Detailed specifications covered

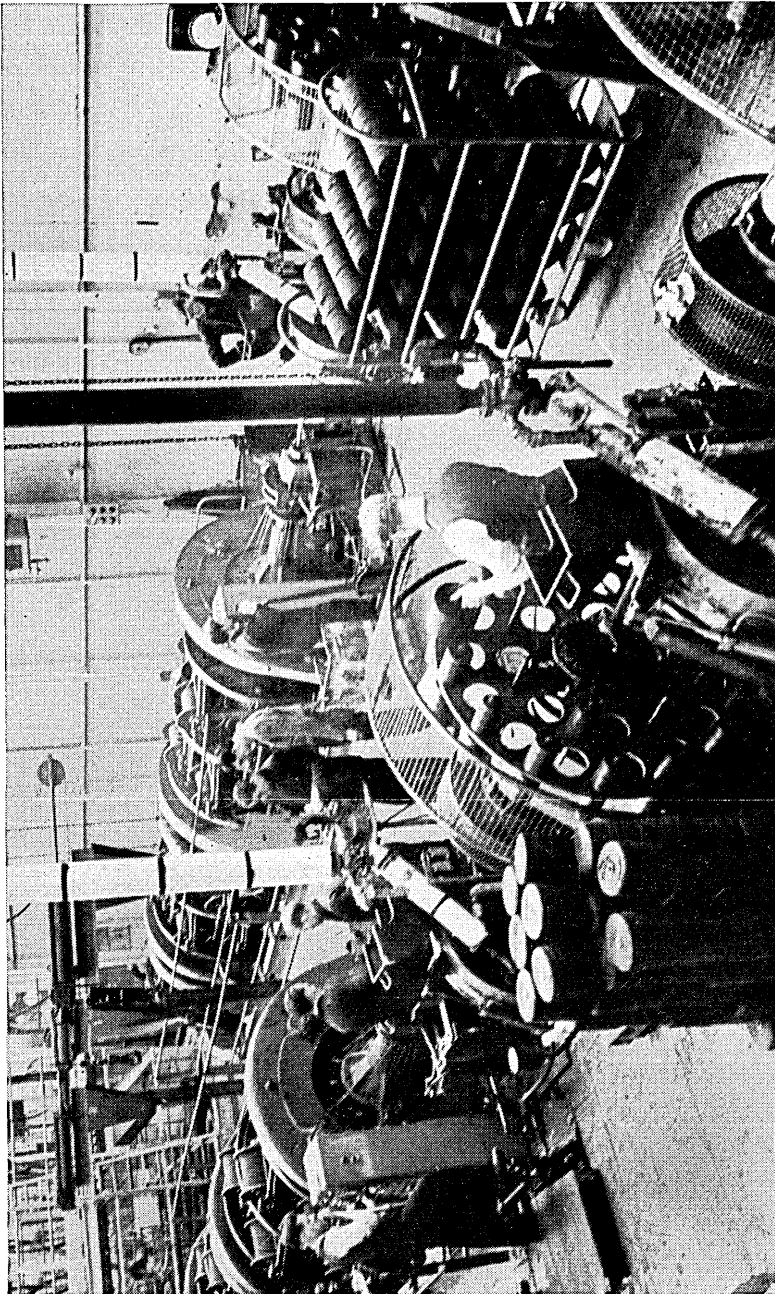


Fig. 6 — View of shop for application of cable armor.

the basic requirements and the methods of controlling their quality on a sampling inspection procedure. The requirements for the materials were established to insure that their use would not jeopardize the life of the cable. Since cable life is critically related to the integrity of the insulation, all materials had to be scrutinized for their tendency to cause environmental cracking. These tests were necessarily made on an accelerated basis. Since no correlation exists at present between accelerated tests and long term (20 year) life tests, only conservative design selections can be justified.

Close tolerances such as ± 0.0002 inch for the diameter of the solid center wire in the central conductor were specified for all copper components of the coaxial. In addition, these components had to be free from slag or other inclusions, and the wire drawing and rolling of the tape had to be controlled to assure smooth surfaces, edges of prescribed shape, and freedom from filamentary imperfections. Compounds used in drawing and rolling operations were selected to minimize the possibility of contaminating or causing cracking of the polyethylene. Residual quantities of compound on the wire or tapes were removed prior to annealing, which was controlled to prevent the formation of oxides and to assure clean and bright copper.

The dielectric constant range of the polyethylene-butyl compound was limited to 2.25 to 2.29. These limits were determined by the limited accuracy of the measuring equipment available at the time. Restrictions covered the allowable amount of contamination since its presence in other than minute quantities might reduce the dielectric strength or degrade the power factor of the compound.

In addition, the melt index (a factor related to molecular weight) of the final insulating compound composed of polyethylene resin, butyl rubber, and antioxidant, was held to 0.15 to 0.50. The melt index of ordinary polyethylene used for insulation generally, is 2.0 or higher. Choice of the low index assured the maximum resistance to environmental cracking.

The cutting and fixing processes used in the manufacture of bedding jute were adjusted to limit the alkalinity of the jute because of the adverse effect of alkaline materials on polyethylene compound. Oils used in the spinning of the jute were selected to obtain types which were not strong cracking agents for polyethylene, and the quantities used were reduced to the workable minimum. The presence of such impurities as bark and roots was restricted to provide the desired fiber strength. The impregnation of the jute was controlled to ensure adequate distribution

of the coal tar throughout the fibers without having an excess that would make the jute difficult to handle during the armoring process.

The size, composition, and processing of the armor wires were also placed under close control. Purity, tensile strength, and twist requirements were designed to ensure that the wire could be applied to the cable, and welded, and that it could withstand the expected tensions during laying and pickup. Strength considerations made it mandatory that inclusions of slag or piping of the wire be eliminated. Piping is an unusual condition encountered during rolling or drawing which results in a hollow shell of steel which may be filled with slag.

CONTROL OF TRANSMISSION CHARACTERISTICS

From a broad point of view, the attainment of a final product capable of meeting the stringent transmission requirements was achieved by the following basic steps.

1. Precision control of the dimensions of the copper conductors, including the diameter of the fabricated central conductor.
2. Automatic control of the insulating process to maintain a constant capacitance, thus compensating for deviations in central conductor diameter and dielectric constant of the insulation.
3. Factory process control, by means of a running average of the measured attenuation characteristic of current production, to guide the adjustment of suitable parameters when necessary.

As indicated in the sections above on the method of manufacture and the control of raw materials, precautions were taken to obtain a central conductor that had predictable electrical performance, and a controlled taper in overall diameter along its length. The need for such effort is explained by consideration of the factors that determine the attenuation of a coaxial structure.

The attenuation, α , of the cable is directly proportional to the ac resistance, R , and inversely proportional to the characteristic impedance, Z_0 , as a satisfactory approximation. That is,

$$\alpha = \frac{aR}{Z_0} db/nm$$

where "a" is a coefficient depending on the units. It is thus clear that control of α may be attained by control of R and Z_0 . Since the resistance is a function largely of the diameter of the central conductor, and since it is held to close tolerances, the constancy of impedance completes the requirement for attenuation control.

The characteristic impedance of a transmission line is determined by:

$$Z_0 = b \sqrt{\epsilon} \log \frac{D}{d} \text{ ohms}$$

where ϵ is the dielectric constant of the insulating material, D is the inside diameter of the outer conductor, d is the diameter of the inner conductor, and b is a numerical coefficient. If the dielectric constant of the insulating material (polyethylene) does not vary, control of characteristic impedance reduces to control of capacitance. This follows from the fact that the capacitance, C , is related to the D/d ratio as follows:

$$\frac{D}{d} = \text{antilog} \frac{k\epsilon}{C}$$

where k is a numerical coefficient.

Precision control of capacitance during the insulating process is achieved by a double-loop linear servo system, as shown in a simplified block diagram, Fig. 7. The two loops consist, respectively, of one capable of introducing relatively fast capacitance corrections of only modest accuracy and of one capable of highly precise capacitance control on a relatively long time basis. The servo system controls the capstan payout

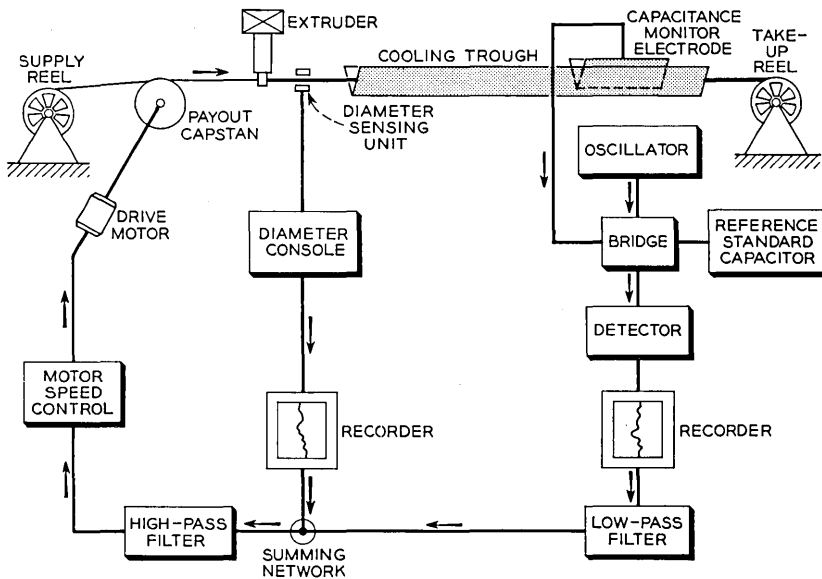


Fig. 7 — Simplified block diagram of capacitance monitor servocontrol system.

speed of the central conductor feeding into the extruder applying the core insulation, as shown in the block diagram. Since the extruder delivers insulating material at a constant rate, an increase in central conductor speed results in a thinner than normal wall of insulation and thus causes an increase in capacitance.

The sensing element for the control loop consists of a capacitance monitor. This is a device capable of measuring the unit length coaxial capacitance of the cable core continuously as it moves through the water in the trough. Since the capacitance of a polyethylene insulated core is temperature sensitive, the monitoring electrode must be located at a point in the cooling trough where the temperature of the core is stable and known to a degree commensurate with the overall accuracy objectives. The distance from the extruder to the electrode corresponds to about 10 minutes of cooling time; hence, a servo system based on this loop would be necessarily slow, due to the 10-minute delay in detecting a drift in capacitance.

Analysis shows that fast capacitance information of only moderate accuracy may be used in combination with the slow loop to speed up the response of the overall system to a satisfactory degree, without sacrifice of precision of the slow loop. The sensing element used for the fast loop consisted of a light-ray diameter gauge, which measures the diameter (changes in diameter are the approximate inverse of the capacitance) of the hot core close to the extruder. The slow and fast data are combined to control the extruder, as shown in the block diagram.

The servo constants were chosen to minimize the deviations in unit length capacitance occurring in core lengths corresponding to less than $\frac{1}{4}$ wave length of the top operating frequency. Stated in other words, the objective for choice of servo loop constants was to assure equality in the capacitance of all $\frac{1}{4}$ wave sections of core. Echo measurements indicated that a highly satisfactory degree of control was achieved. Overall servo system performance was such that the standard deviation of the capacitance of the core lengths manufactured for the two crossings was ± 0.1 per cent. The capacitance monitor electrode and the servo console is illustrated in Fig. 8.

ADJUSTMENT OF CONCENTRICITY

Means for setup and adjustment of the extrusion process to achieve relatively accurate centering of the conductor in its sheath of insulation was provided by a device called a concentricity gauge. This device operates on the principle that two small, plane electrodes on opposite

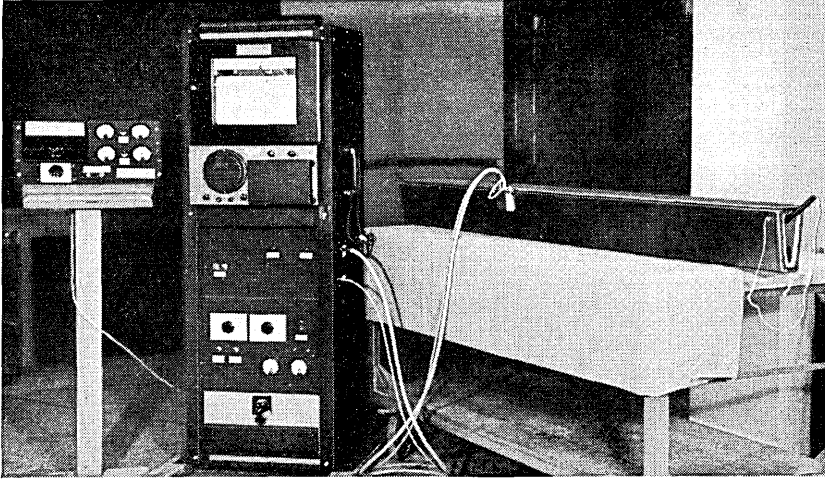


Fig. 8 — Photograph of capacitance monitor electrode and servo-controller console in laboratory setup.

sides of the core will have different direct capacitances to the central conductor, when the conductor is not properly centered.

A simplified block diagram of the concentricity gauge is shown in Fig. 9. Data obtained with two sets of electrodes displaced 90° were recorded on a strip chart recorder, with the output of the two sets of electrodes being displayed alternately. A satisfactory degree of centering was moderately easy to maintain.

ELECTRICAL MEASUREMENTS

To assist in achieving the goal of matching the cable and the repeater characteristics with a minimum of deviations, electrical measurements were made throughout the process and close tolerances were placed on the electrical parameters in each stage of production. Measurements on the repeater section lengths of cable were used as a final check to determine the extent to which all of the controls had been successful. The primary standards used were calibrated by the Bureau of Standards in the United States or the National Physical Laboratories in England. These precision standards were used to calibrate the bridges frequently.

The dc resistance of the central conductor was measured under constant temperature conditions with a precision type of Wheatstone bridge. The permissible range of resistance was 2.514 and 2.573 ohms

per nautical mile at 75°F. In practice, the spread of resistance values was well within these limits.

The 20-cycle core capacitance was also measured under constant-temperature conditions. For this measurement, the two ends of the central conductor were connected together and the measurements made between the central conductor and ground, which was provided by the water. A capacitance-conductance bridge was used for this purpose. The capacitance limits set initially were from 0.1726 to 0.1740 microfarads per mile at 75°F. Analysis of the core measurements indicates that at each factory the range of capacitance was held more closely than indicated, which illustrates the benefits of servo control to the insulating process.

The dc insulation resistance of the core was also measured by applying 500 volts for one minute. A minimum insulation resistance requirement of 100,000 megohm-miles at 75°F was established, but any lengths that had less than 500,000 megohm-miles were scrutinized for possible sources of trouble and were subject to rejection. As a general rule, insulation resistances considerably in excess of 500,000 megohm-miles were obtained.

The core was tested also at a voltage of 90,000 volts dc for a period of one minute. This test was designed to catch any gross faults in the

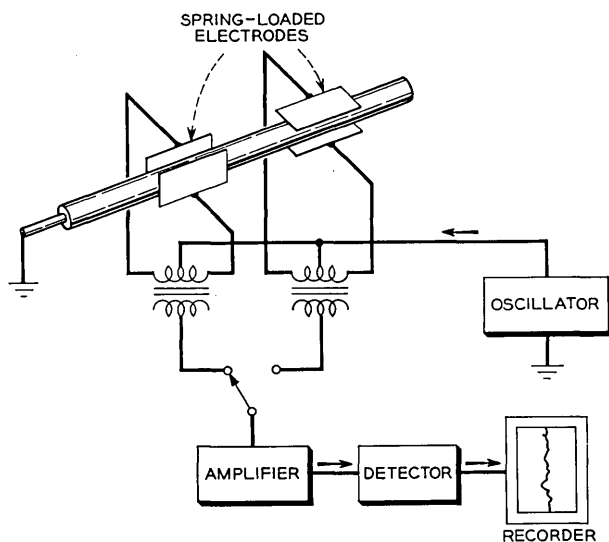


Fig. 9 — Simplified block diagram of concentricity gauge for continuous measurement of centering of central conductor.

core caused by foreign particles which escaped detection by the other mechanical and electrical tests made on the core.

As discussed under the section on jointing, the core lengths were assembled and joined together to form a repeater section of cable. In general, an effort was made to produce the core for a repeater section of cable on a particular strander, extruder, and armoring line, and to join the lengths together in the order of manufacture. Practical difficulties such as the fact that the outputs of two stranders were required to supply one extruder made it impossible to achieve this objective in all cases.

Capacitance deviations from the desired nominal resulted from a variety of causes, such as inaccurate control of the temperature of the water in the core cooling troughs and improper adjustment of the control apparatus. To minimize the reflection which would result from joining together two lengths of core of widely different capacitances, cores were not joined together if their measured ac capacitances differed by more than 0.3 per cent. When such capacitance differences did exist, the core length involved was removed from its normal sequence and placed in a position near the middle of the repeater section.

Because the taping and armoring processes were combined in one

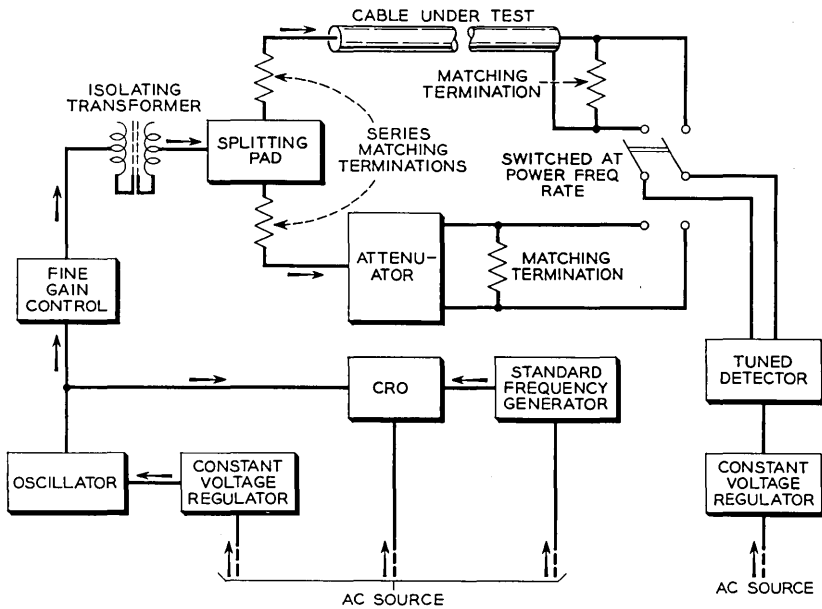


Fig. 10 — Simplified block diagram of cable attenuation measuring set.

production line in the American factory, no other electrical measurements could be made on the components of the cable until it was completely armored. In the British factory, tests for information purposes only were made on the cable in the coaxial stage. These tests included measurements of attenuation, internal impedance irregularities, and terminal impedances. They served as a means of evaluating the changes in the electrical performance during armoring.

The insulation resistance requirement after armoring and storage under water for at least 24 hours was 100,000 megohm-miles. The cable had to withstand 50,000 volts for a period of one minute without failure.

ATTENUATION MEASUREMENTS

As an aid in achieving the desired uniformity of product, new measuring equipment of improved accuracy was provided. A block schematic of this equipment is shown in Fig. 10. The requirements for this equipment were that it should be capable of measuring a 37 to 44 mile section of cable with an absolute accuracy of 0.04 db and a precision of 0.01 db in the frequency range from 1 to 250 kc.

The attenuation of the cable was measured at 10 kc intervals from 10 kc to 210 kc and measured values were corrected to 37°F, using the changes in attenuation owing to temperature, shown in Fig. 11. By comparing the corrected values with the design characteristic shown in Fig. 12, the deviations were determined. Both the attenuation charac-

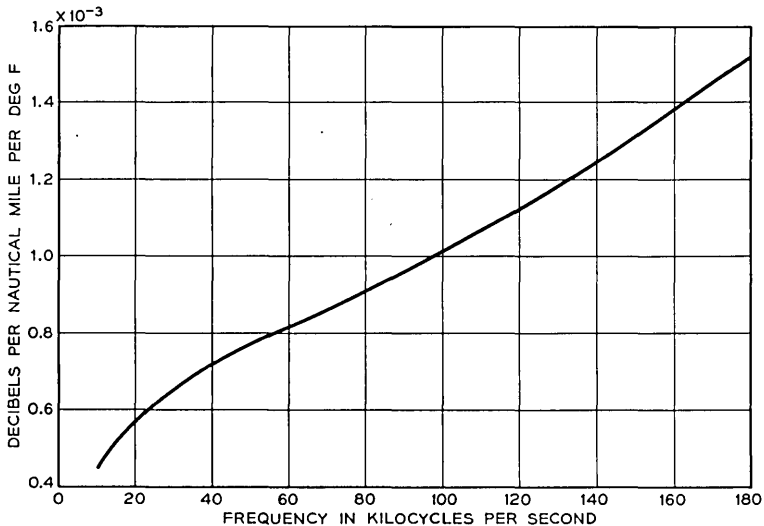


Fig. 11 — Change in cable attenuation due to temperature as a function of frequency.

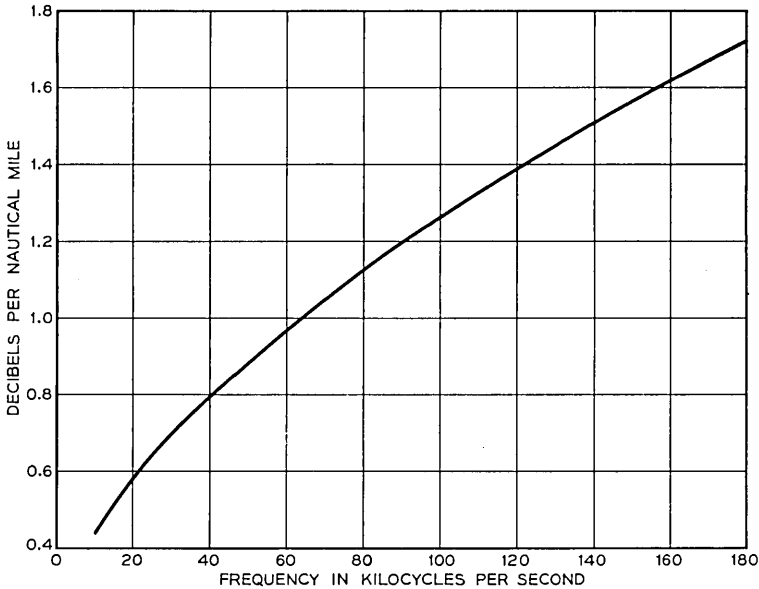


Fig. 12 — Design characteristic of cable attenuation as a function of frequency for 37°F and atmospheric pressure.

teristic and the changes in attenuation owing to temperature were derived from factory measurements of attenuation made on the Florida-Puerto Rico cable.

By comparing the running average and spread of these deviations with the design requirements, it was possible to assess the performance of the cable and, if required, to make any necessary adjustments in parameters for subsequent sections. In addition, these deviations were used to determine the length adjustment required for each repeater section to keep the sum of the deviations at each frequency in any one ocean block to a minimum. Typical average attenuation deviation characteristics are shown in Fig. 13.

TEMPERATURE AND PRESSURE COEFFICIENTS

Measurements of primary constants were made on 20-foot lengths of cable and core placed in a temperature and pressure controlled tank. These measurements were used to compute the temperature coefficients of attenuation in order to check the values derived from measurements made on the Florida-Puerto Rico cable section. Additional attenuation measurements were made on several repeater section lengths of cable over a range of temperature from approximately 40° to 70°F, to establish further the magnitude of the changes in attenuation with tempera-

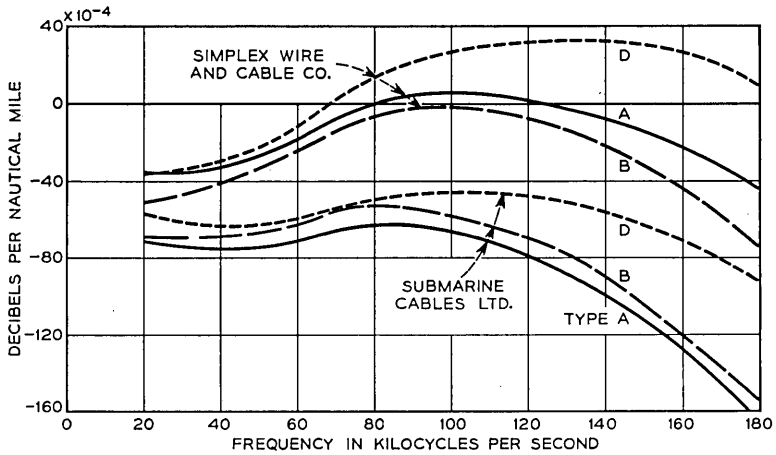


Fig. 13 — Deviation of measured cable attenuation from design characteristic as a function of frequency. Typical average values for Types A, B, and D for 37°F and atmospheric pressure.

ture. The measurements indicated that the derived temperature coefficients were accurate to within ± 10 percent.

Measurements also were made to determine the effect of pressure on the primary constants of the cable. These measurements indicated that capacitance was the only parameter affected by pressure. The capacitance increased linearly 0.1 percent for each 500 pounds per square inch of applied pressure. Since the attenuation, α , is inversely proportional to the impedance, it is evident that if C is the only parameter affected by pressure, α will also be affected by pressure to an amount equal to approximately one half the pressure effect on C . The pressure coefficient of α was therefore established as 0.05 percent per 500 pounds per square inch of pressure.

LAVING EFFECT

Analysis of the Florida-Puerto Rico cable data indicated that the measured ocean bottom attenuation was less than the attenuation predicted from factory measurements. The differences were large enough to warrant study and indicated that the measurements were in doubt or sea bottom conditions were not known accurately or that some unexplained phenomenon was taking place.

In March of 1955, approximately 22 miles of cable of the transatlantic design were laid in 300 fathoms of water off the coast of Spain in the Bay of Cadiz, and another equivalent length was laid in 2,300 fathoms off Casablanca. Precise measurements of attenuation were made in both cases, and it was established that a difference did in fact exist

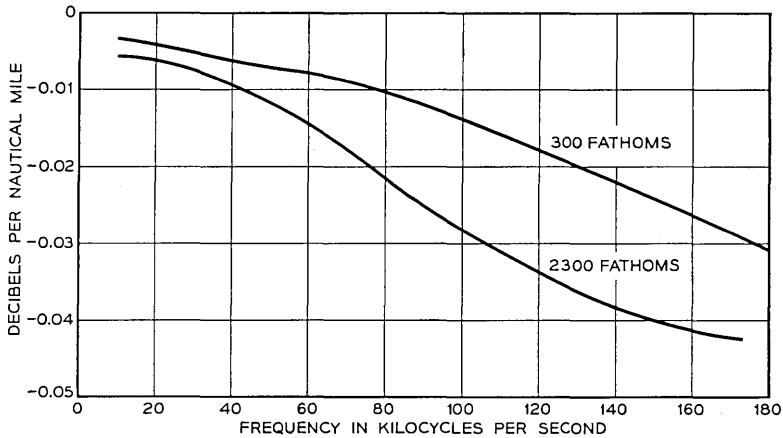


Fig. 14 — Laying effect or deviation of measured attenuation from predicted attenuation as a function of frequency, as observed in Gibraltar trials.

between measured values of attenuation at the ocean bottom and values predicted from factory measurements. It was further established that the difference in 2,300 fathoms was about twice that in 300 fathoms. The measured differences are shown in Fig. 14.

It was established during these trials that the difference increased slightly with time. Measurements made on the cable in 300 fathoms immediately, 18 hours, 48 hours, and 86 hours after laying indicated that measurable changes in attenuation were taking place. However, the change between 48 and 86 hours was so small that it was concluded only very small changes would occur in a moderate interval of time. The tests also indicated that the attenuation of the two lengths of cable decreased somewhat during loading of the cable ship.

The total difference between the attenuation at the ocean bottom and the values predicted from factory measurements, taking the temperature and pressure coefficients into account, was designated "laying effect". Various theories, such as the consolidation of the central conductor, consolidation of return structure, and changes in the dielectric material have been advanced to explain these differences. Each of these has been under study, but at the time of writing this paper, no conclusive explanation has been established.

The shape of the "laying effect" versus frequency characteristic was such that the adjustment of repeater section lengths in conjunction with several fixed equalizers, which had approximately 4 db loss at 160 kc and 0.6 db loss at 100 kc, would provide a good system characteristic. The matter of equalization is covered in greater detail in the article⁴ on the overall system. The magnitude of the laying effect observed during the laying of the two transatlantic cables substantiated the trial results.

PULSE ECHO MEASUREMENTS

Process controls, such as the use of a capacitance monitor and the jointing of the core in manufacturing sequence provided the means for controlling the magnitude of reflections due to impedance mis-matches. However, to insure that the final product met these requirements, measurements of terminal impedance and internal irregularities were made using pulse equipment.

A block schematic of the circuit of the echo set is shown in Fig. 15. For the submarine cable tests, a 1.5-microsecond raised cosine pulse

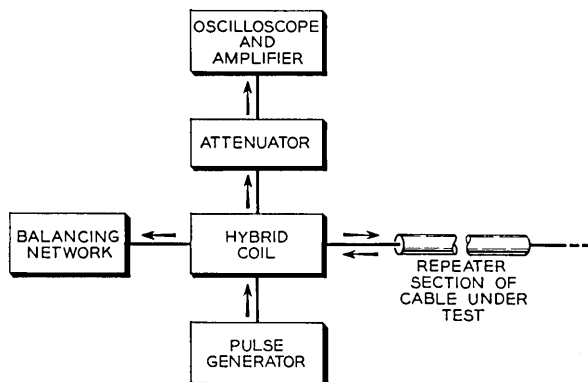


Fig. 15—Simplified block diagram of pulse echo set for measurement of terminal impedance and internal impedance irregularities.

was used, and the impedance of the balancing network was calibrated at 165 kc. The 165-kc impedance of the repeater sections was maintained well within a range of 54.8 ± 1 ohm. The internal irregularities at the point of irregularity were maintained at least 50 db below the magnitude of the measuring pulse. The requirement was 45 db.

ACKNOWLEDGMENTS

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System Design for the Newfoundland–Nova Scotia Link

By R. J. HALSEY* and J. F. BAMPTON*

(Manuscript received September 14, 1956)

The design and engineering of the section of the transatlantic cable system between Newfoundland and Nova Scotia were the responsibility of the British Post Office. The transmission objectives for this link having been agreed in relation to the overall objectives, the paper shows how these were translated into system and equipment design and demonstrates how the objectives were realized.

INTRODUCTION

Under the terms of the Agreement,¹ it was the responsibility of the British Post Office to design and engineer the section of the transatlantic cable system between Newfoundland and Nova Scotia. In common with other parts of the system, all specifications were to be agreed between the Post Office and the American Telephone and Telegraph Company, but as both the British and the American types of submerged repeater had been carefully studied and generally approved by the other party prior to the agreement, the basic pattern of the system was clear from the beginning.

The service and transmission objectives for the overall connections London–New York and London–Montreal were agreed² in early joint technical discussions in New York and Montreal and the agreed total impairments were divided appropriately between the various sections. In this way, the transmission objectives for the Newfoundland–Nova Scotia link were established.

ROUTE

The choice of Clarenville as the junction point of the two submarine sections of the transatlantic system was determined primarily in relation

* British Post Office.

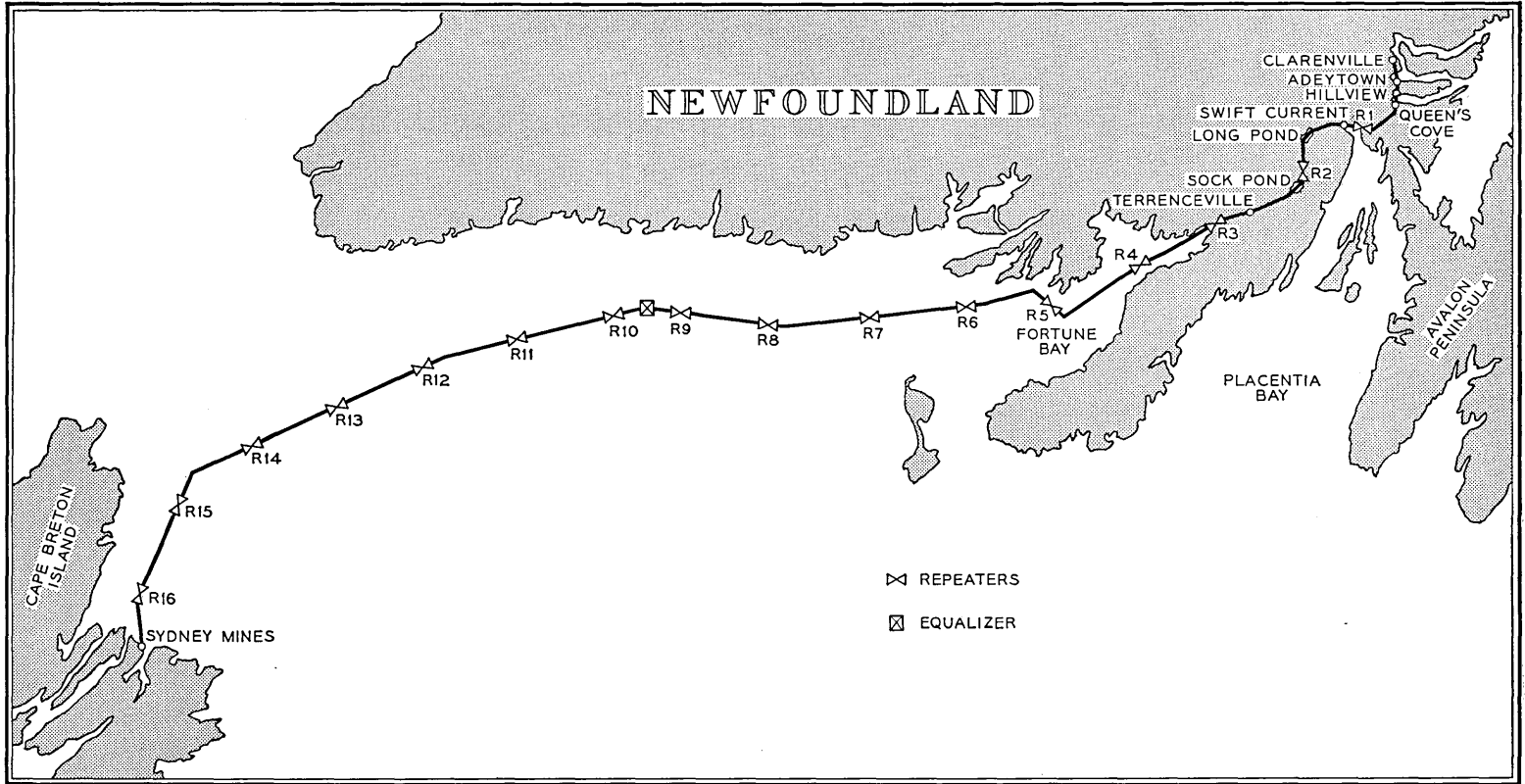


Fig. 1 — Map of route.

to the Atlantic crossing and the desire to follow a transatlantic route to the north of existing telegraph cables.³ There were a number of possibilities for the route between Clarenville and the east coast of Cape Breton Island, the most easterly point which could be reached reliably by the radio-relay system through the Maritime Provinces of Canada. One possibility, which had been considered earlier, was to cross Newfoundland by a radio-relay system and to employ a submarine-cable link across Cabot Strait only. The final decision to build a cable system between Clarenville and Sydney Mines raised a number of problems in respect of the route to be followed, concerned primarily with potential hazards to the cable brought about by:

- (a) The existence of very extensive trawling grounds on the Newfoundland Banks.
- (b) The location of considerable numbers of telegraph cables in the vicinity.
- (c) Grounding icebergs.

The route finally selected after thorough on-the-spot investigations^{3, 4, 5} (Fig. 1) is satisfactory in respect of all these hazards, involving no cable crossings and being inshore of the main fishing grounds. The straight-line diagram of the route is shown in Fig. 2; the total cable length is 326 nautical miles, of which 54.8 nautical miles are between Clarenville and Terrenceville, Newfoundland, where the cable finally enters the sea. The maximum depth of water involved is about 260 fathoms.

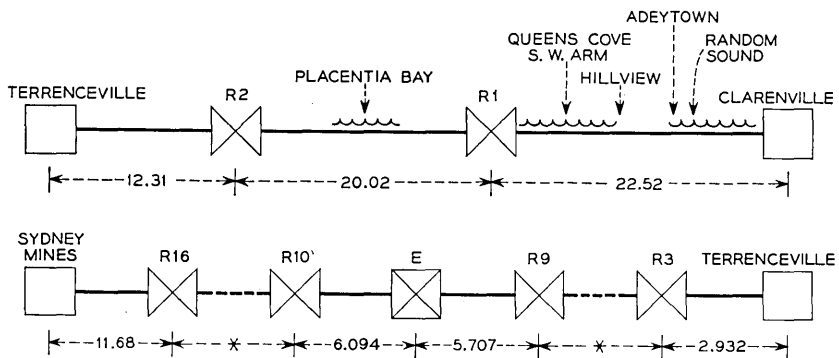


Fig. 2 — Straight-line diagram of route. R. Repeater. E. Equalizer. All distances are in nautical miles.

* Repeater spacing R3-R9 and R10-R16, 20.4 n.m.

CABLE

Choice of Design

Since 1930, when the Key West-Havana No. 4 cable was constructed,⁶ it has been usual to extrude the insulation of coaxial submarine cables to a diameter of about 0.62 inch, and most of the cables in the waters around the British Isles are of this size. The experience of the British Post Office with submerged repeaters⁷ in its home waters, dating from 1944, when the first repeater was laid between Anglesey and the Isle of Man,⁸ has therefore been mainly with 0.62 inch cables, first with paraggutta as a dielectric and later with polyethylene. Most of these cables were originally operated without repeaters, and the 60-circuit both-way repeaters which are now installed on the routes were designed to match their characteristics.

In planning a new system, the size of cable will be determined by one of the following considerations:

- (i) Minimum annual charges for the desired number of circuits.
- (ii) Terminal voltage required to feed the requisite number of repeaters.
- (iii) Maximum number of repeaters or minimum repeater spacing which is considered permissible.
- (iv) Maximum (or minimum) size of cable which can be safely handled by the laying gear in the cable ship.

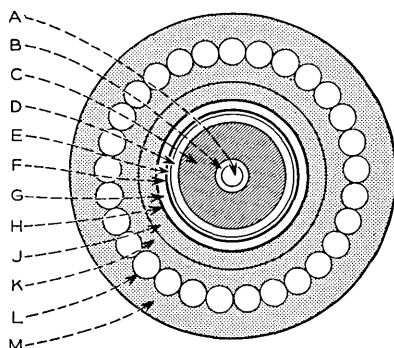


Fig. 3 — Cross-section of cable across Newfoundland showing make-up. A. Centre conductor, 0.1318-inch in diameter copper. B. Three 0.0145-inch copper surround tapes. C. Polyethylene to 0.620-inch diameter. D. Six 0.016-inch copper return tapes. E. 0.003-inch overlapped copper tereedo tape. F. Impregnated cotton tape. G. Five iron screen tapes. H. Impregnated cotton tape overlapped. J. Polyethylene sheath to 1.02-inch diameter. K. Inner serving of tanned jute yarn. L. Armour wire 29 x 0.128-inch diameter. M. Outer serving of tarred jute yarn.

When the 36-circuit system between Aberdeen, Scotland, and Bergen, Norway, was planned in 1952, the route length (300 nautical miles) greatly exceeded that of any other submarine telephone system, and it was decided to use a core diameter of 0.935 inch, first, to keep the number of repeaters as low as seven, and second, because the system was intended as a prototype of a possible Atlantic cable. The cable dielectric is polyethylene (Grade 2) with 5 per cent polyisobutylene.

For the Clarenville-Sydney Mines link it proved possible to design for minimum annual charges. With increasing experience and confidence in submerged repeaters, it was no longer considered necessary to restrict the number of repeaters as for Aberdeen-Bergen, and the terminal voltage requirements were reasonable. At the current prices of cable and repeaters in Great Britain the optimum core diameter for 60 both-way circuits is about 0.55 inch, but the increased charge incurred by using 0.62-inch cable is less than 5 per cent (0.62-inch core is optimum for 120 both-way circuits). In order to facilitate manufacture and the provision of spare cable, it was therefore logical to adopt the same design as that proposed for the Atlantic crossing and described elsewhere.^{3, 9}

After investigating various possible types of cable for the overland section in Newfoundland, it was decided to use a design essentially the same as the main cable but with additional screening against external interference.⁴ As far as the outer conductor and its copper binding tape, the construction (Fig. 3) is identical with that of the main cable except that the compounded cotton tape is overlapped. Outside this are five layers of soft-iron tapes each 0.006-inch thick, the innermost being longitudinal and the others having alternate right- and left-hand lays at 45° to the axis of the cable. After another layer of compounded cotton tape there is extruded a polyethylene sheath 0.080 inch thick, and the whole is jute served and wire armoured. As a check on the efficiency of the screening, the maximum sheath-transfer impedance at 20 and 100 kc was specified as 0.005 ohm per 1,000 yards.

It was thus possible to treat the entire link from Clarenville to Sydney Mines as a uniform whole, using the same type of repeater on land as in the sea. A small hut at Terrenceville contains passive networks only.

Attenuation Characteristics

When the system was designed, precision measurements of cable attenuation were not available. The design of the Oban-Clarenville link was based on laboratory measurements on earlier 0.62-inch cable of a

similar type, but the available data applied only to frequencies up to about 180 kc, whereas the Clarenville-Sydney Mines link was to operate at frequencies up to 552 kc; extensive extrapolation was therefore involved. As soon as the first production lengths of cable became available in February, 1955, laying trials were carried out off Gibraltar, and it was found that there were serious changes of attenuation on laying, over and above those directly attributable to temperature and pressure effects, and that the assumed characteristics were inaccurate. Although the attenuation in the factory tanks had been in reasonable agreement with that of the earlier cable, there were changes on transfer to the ship's tanks and again on laying, amounting in all to a reduction of about 1.5 per cent at 180 kc. This would have been comparatively unimportant had the discrepancy been of 'cable shape', i.e., the same fraction of the cable attenuation at all frequencies and therefore exactly compensated by a length adjustment of the repeater sections. As this was not so, and as the cable-equalizing networks in the repeaters were settled by this time, it was clear that precise information must be obtained in order that suitable additional equalizers could be provided for insertion in the cable on laying. There are a number of factors which can lead to small changes of attenuation on laying, but most of these tend to increase the losses. The primary reason for the observed changes appears to be contact variations between the various elements of the inner and outer conductors, i.e. the wire and three helical tapes forming the centre conductor and the six helical tapes forming the return conductor. These contact resistances tend to change with handling, and as a result of a slight degree of 'bird caging' when coiled, it seems that the attenuation decreases as the coiling radius increases, and vice versa. Also, the effect of sea pressure is to consolidate the conductors and thereby further reduce the attenuation — an effect which appears to continue on a diminishing basis for a long time after laying.

To obtain reliable data for the Clarenville-Sydney Mines link, 10 nautical miles of cable with A-type armour was laid at about the mean depth of the system (120 fathoms), off the Isle of Skye. The attenuations, coiled and laid, are shown in Fig. 4, due allowance having been made for temperature and pressure. The ordinates — attenuation versus frequency — are such that the value should be approximately constant at high frequencies.

In making a final determination of the cutting lengths for the repeater sections, it was assumed that the factory measurements of attenuation would be reduced by 1.42 per cent at 552 kc on laying, that the temperature coefficient of attenuation would be $+0.16$ per cent

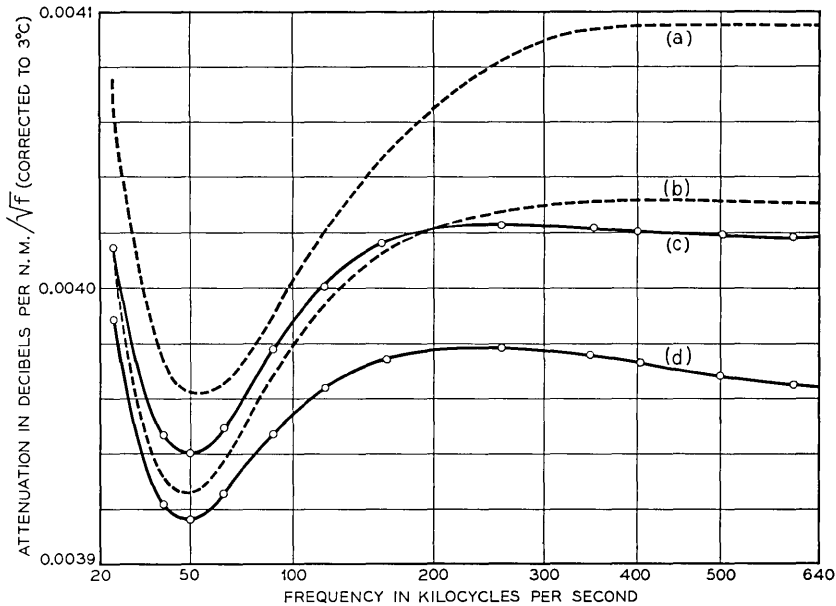


Fig. 4 — Cable attenuation characteristics — Skye trials. (a) Characteristic originally assumed. (b) Characteristic measured in factory tank (flooded). (c) Characteristic measured in ship's tank (flooded). (d) Characteristic measured after laying.

per deg C and that the true pressure coefficient of attenuation was negligible at the depths involved.

DESCRIPTION OF SYSTEM

Circuit Provision and Frequency Allocation

It was originally thought that a design similar to that of the Aberdeen-Bergen system would be suitable for the Clarenville-Sydney Mines route in that it would provide more circuits (36) than the long section across the Atlantic. This potential excess capacity, which was required for circuits between Newfoundland and the Canadian mainland, disappeared when it was found that 36 circuits could, in fact, be provided over the longer link. The Aberdeen-Bergen design was therefore modified to provide a complete supergroup of 60 circuits, the same capacity as the earlier British projects.⁷ The system thus requires broad-band transmission of 240 kc in each direction.

In the earlier British projects the frequency bands transmitted are 24–264 and 312–552 kc, but for the present purpose the lower band is

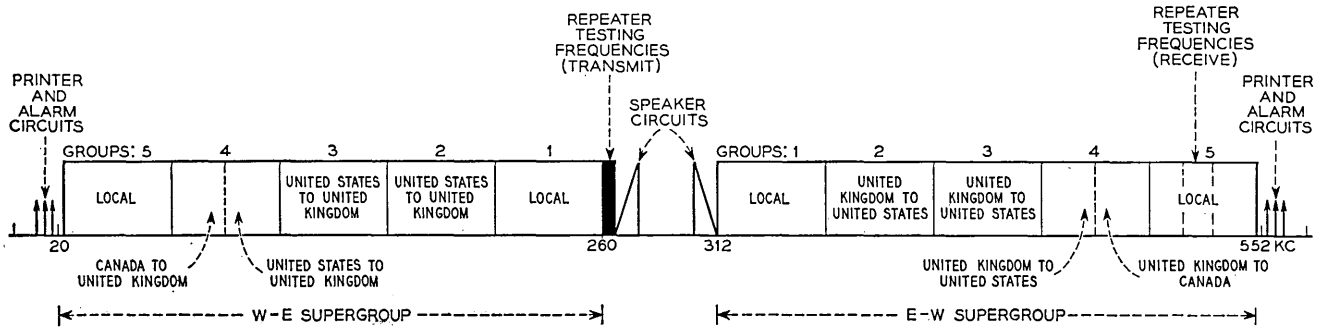


Fig. 5 — Frequency allocation.

dropped by 4 kc to 20–260 kc, so that the lowest frequency is the same as on the Atlantic cables. This enables common frequency-generating equipment to be used at Clarenville for the two links and minimizes crosstalk problems. The main transmission bands and the allocation of the five 12-circuit groups are shown in Fig. 5, together with the ancillary channels; the facilities provided are discussed later.

Submerged Repeaters

The submerged repeaters employed are fully described elsewhere,¹⁰ and it will suffice to note here that they are rigid units, approximately cylindrical in shape, 9 feet long and 10½ inch maximum diameter. They are capable of withstanding the full laying pressure in deep water, although this of little importance in the present application.

They are arranged for both-way transmission through a common amplifier which has two forward paths in parallel, with a single feedback path. The two halves of the amplifier are so arranged that practically any component can fail in one, without affecting the other.

Power-Feeding Arrangements

The submerged repeaters are energized by constant-current dc supplies between the center conductor and ground, the power units at the two ends being in series aiding and the repeater power circuits being in series with the center conductor, i.e., without earth connections, as in Fig. 6. This is the only arrangement by which it is possible to control the supply accurately at every repeater, the insulation resistance of cable and repeaters being sufficiently great that the current in the center conductor is virtually the same at all points. The constant-current feature of the supply ensures that repeaters cannot be overrun in the event of an earth fault on the system.

On the Oban-Clarenville link the anode voltage is derived from the drop across the electron tube heaters. This results in the heaters being at a positive potential with respect to the cathodes, a condition which tends to break down the heater-cathode insulation.¹¹ In the American electron tubes this insulation is very robust and the risk is considered to be negligible, but in the current British electron tubes, which have a much higher performance, the arrangement is undesirable. In view of the much smaller number of repeaters it was possible to derive the heater and anode supplies as in Fig. 6 and thus to reverse the sense of the heater-cathode voltage and also to provide an anode voltage of 90, against 55 in the longer link.

With this arrangement the link requires a total supply voltage of about 2,300. The power-feeding equipment¹² at each terminal station is designed to feed a constant current of 316 ma at this voltage, and it is permissible to energize the system from one end only, if necessary. The repeater capacitors — the limiting factors in respect of line voltage — are rated very conservatively at 2,500 volts, so that a single-ended supply of 2,300 volts, with the possibility of superimposed ground-potential differences, is near the desirable maximum. The two terminal power units are therefore designed to operate in series and to share the voltage.

With access to the cable provided at Terrenceville it is possible to operate the power system on the following bases:

- (a) No ground at Terrenceville, power from both ends on a master-and-slave basis (to ensure that the constant-current units do not build up an excessive voltage); this is the normal arrangement.
- (b) No ground at Terrenceville, power from one end only.
- (c) Ground at Terrenceville, with the Clarenville and Sydney Mines

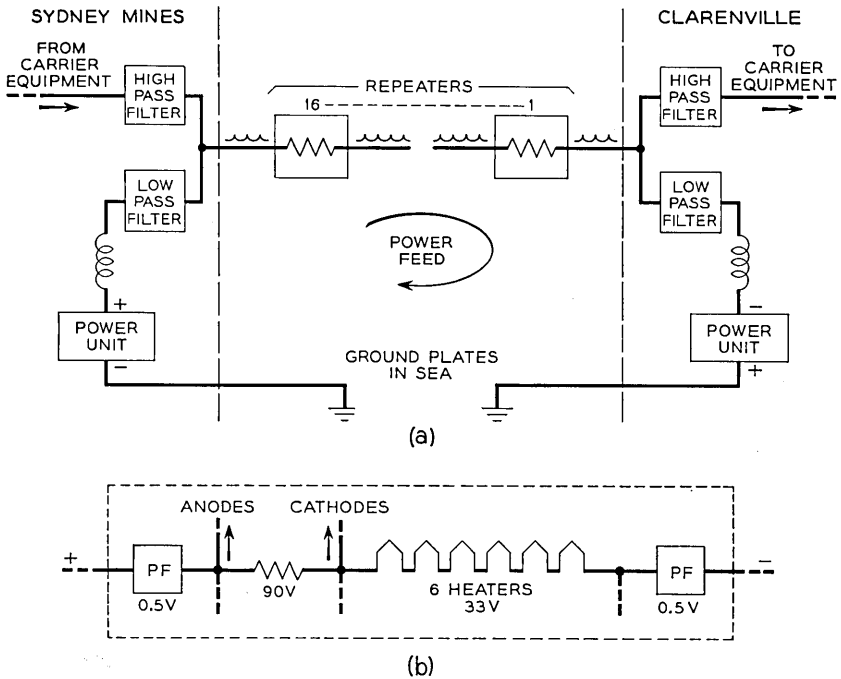


Fig. 6 — Power-feeding arrangements. (a) General schematic. (b) Repeater power circuit. P.F. — Power filter.

power units energizing the land and sea cables respectively; this arrangement has been particularly useful during the installation period.

The presence of high voltages on the cable constitutes a potential danger to personnel, hence special precautions are taken in the design of the equipment in which the cable terminates and in which high voltages exist or may exist.

The ground connections for the power circuits at the two ends are via special ground cables and ground plates located about half a mile from the main cable, and metering arrangements are provided to check that the current does in fact take this path. These measures ensure that the current returning via the cable armour is never sufficient to cause serious corrosion.

Arrangement of Terminal Equipment

Fig. 7 show the arrangement of the terminal equipment. In accordance with an early agreement defining precisely the various sections of the project, the link is considered to terminate at the group distribution frames at Clarenville and Sydney Mines, i.e. at the 60–108 kc inter-connection points.

In addition to the cable-terminating and power-feeding equipments (A and B), the following are provided at the terminals:

(a) Submarine-cable terminal equipment (C) consisting of repeaters to amplify the signals transmitted to and received from the cable, equalizers and frequency-translating equipment to convert the line frequencies to basic supergroup frequencies (312–552 kc).

(b) Group-translating (group-bank) equipment (D) to convert the basic supergroup to five separate basic groups (60–108 kc) and vice versa.

(c) Equipment for the location of cable and repeater faults (E and F).

(d) Speaker and printer circuit equipments (G and H) to provide two reduced-bandwidth telephone circuits, two telegraph circuits and one alarm circuit for maintenance purposes. It is clear that such circuits should be substantially independent of the main transmission equipment.

Two principles were agreed very early in the planning; first, that the engineering of the various links should be integrated as far as possible, and second, that the items of equipment at each station should be provided by the party best in the position to do so. In consequence:

(i) Items of standard equipment were provided by the A.T. and T. Co. at Clarenville and Sydney Mines (and by the Post Office at Oban), thus simplifying maintenance and repair problems.

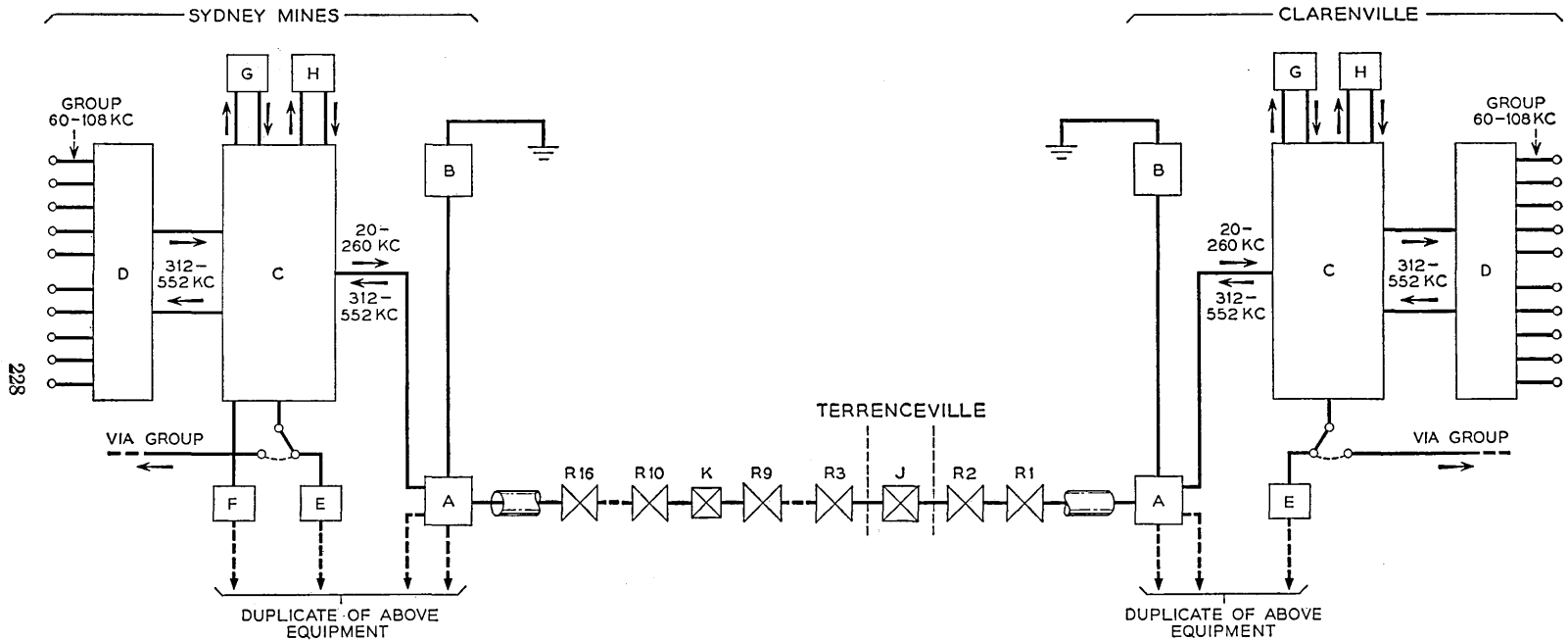


Fig. 7 — Arrangement of terminal equipment and repeaters. A. Cable-terminating equipment. B. Power-feeding equipment (dc). C. Submarine-cable terminal equipment. D. Group-translating equipment. E. Pulse test equipment. F. Loop-gain test equipment. G. Speaker circuit equipment. H. Printer circuit equipment. J. Intermediate cable-terminating equipment, including equalizers. K. Submerged equalizer. R. Submerged repeater.

(ii) Basic power plant and the carrier supplies for supergroup and group translation were provided by the A.T. and T. Co. for both terminal equipments at Clarenville.

(iii) Terminal equipment special to the Clarenville-Sydney Mines link was provided by the Post Office.

In view of the importance of the link, the power-feeding and transmission equipment are completely duplicated.

The submarine-cable terminal equipment is arranged to transmit the basic supergroup, directly over the cable in the east-to-west direction. In the west-to-east direction the supergroup is translated to the range 20–260 kc, using a 572 kc carrier.

DESIGN OF TRANSMISSION SYSTEM

Performance Requirements

The agreed transmission objects for the Clarenville-Sydney Mines link were as follows:

Variation of Transmission Loss.

The variation in the transmission loss of each group should have a standard deviation not greater than 0.5 db; this implies that the variation from nominal should not exceed 1.3 db for more than 1 per cent of the time.

Attenuation/Frequency Characteristics.

Only the overall characteristics of the individual circuits were precisely specified, the limits being the C.C.I.F. limits for a 2,500-km circuit and the target one-half of this. With this objective in view, the group characteristics in each link must clearly be as uniform as is practicable.

Circuit Noise.

The total noise contributed by the link to each channel in the busy hour (i.e., including intermodulation noise) should have an r.m.s. value not exceeding +28 dba* (corresponding to -56 dbm) at a point of zero relative level.

* This refers to the reading on a Bell System 2B noise meter (FIA weighting network); the noise level (dba) is relative to a 1 kc tone at -85 dbm. In Europe, noise is measured on a C.C.I.F. Psophometer (1951 weighting network), which is calibrated in millivolts across 600 ohms; this is commonly converted to picowatts (pw). The white noise equivalence of the two instruments is given by $\text{dba} = 10 \log_{10} \text{pw} - 6 = \text{dbm} + 84$; the agreed limit of +28 dba is therefore equivalent to 2513 pw (1.23 mv or -56 dbm). The corresponding C.C.I.F. requirement at 4.0 pw/km would be 2,400 pw, this value not to be exceeded for more than 1 per cent of the time.

Crosstalk.

The minimum equal-level crosstalk attenuation should be 61 db for all sources of potentially intelligible crosstalk; this was accepted as a target for both near- and distant-end crosstalk. Although go-to-return crosstalk is not important for telephony (it appears as sidetone) and a limit of 40 db is satisfactory even for voice-frequency telegraphy, it assumes great importance for both-way music transmission; also, it was desired to be non-restrictive of future usage.

Assessment of Requirements

The design of the high-frequency path to meet the agreed requirements involves consideration of:

(a) Noise, including fluctuation (resistance and tube) noise and intermodulation.

(b) Wide-band frequency characteristics, including the effects of the directional filters at the terminal and in the repeaters.

(c) Variations of (a) and (b) in respect of temperature and aging.

The noise requirement is by far the most important factor in the design of the line system.

The choice of route and cable having been made, the total loss was known and it was necessary to determine the minimum number of repeaters to compensate for this loss and to meet the noise requirement with adequate margin for inaccurate estimates of cable attenuation after laying, temperature variations, aging and repairs. An attempt to achieve the necessary gain with too few repeaters would result in excessive noise.

Design of the amplifiers in the British repeaters is such that, with both forward paths in operation, the overload point is about +24 dbm, and with a loading of 60 channels in each direction, this permits planning levels of about -4 dbm at the amplifier output after allowing reasonable margins for errors and variations.¹⁰ Previous experience shows that, at such output levels, intermodulation noise can be neglected and the full noise allowance allotted to fluctuation noise. The effect of tube noise is to increase the weighted value of resistance noise by about 1 db to -137.5 dbm, or -53.5 dba, at the input to the amplifier in each repeater.

At the highest transmitted frequency the equalizers, power filters and directional equipment introduce losses of about 1 db and 4 db at the

input and output of the amplifier respectively; these losses must, effectively, be added to the loss in the cable.

Two other pieces of information are necessary before the repeater system can be planned — the permissible transmitting and receiving levels at the shore stations. The transmitting equipment provided at Clarenville can be operated at channel levels up to +20dbm, and it is logical to allow the same receiving level at the shore end as at intermediate repeaters.

On the above basis it is possible to construct a curve (Fig. 8) relating the total circuit noise to the number of intermediate repeaters, and it is seen that the minimum number is 15, each of which must have an overall gain of 59 db (amplifier gain, 64 db) at 552 kc. The actual provision is 16 repeaters, each having a gain of 60 db at 552 kc, the additional gain being absorbed in fixed and adjustable networks at points along the route, as indicated in the following section.

Level Diagram

The actual level diagram (planning levels are shown in Fig. 9) differs somewhat from that which can be deduced directly from the preceding because of the following considerations:

- (a) The location of the first repeater from Clarenville (i.e., on land)

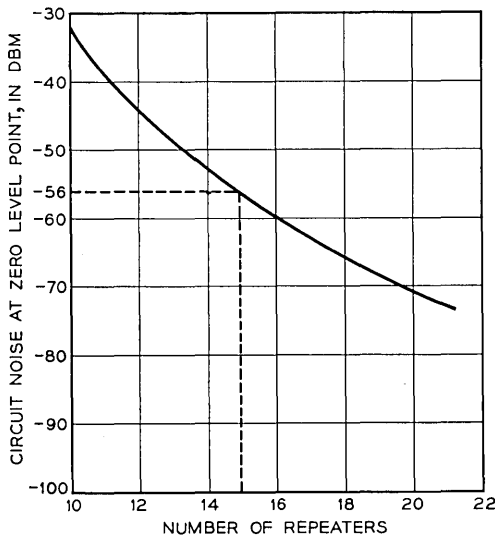


Fig. 8 — Variation of circuit noise with number of repeaters.

was dictated by topography and the desire to locate both it and the second repeater in ponds; thus the transmitting level at Clarenville is substantially lower than the permissible maximum.

(b) There are equalizing networks at Terrenceville and facilities for their adjustment to compensate for temperature variations.

(c) Because of the difference between the actual cable attenuation and that for which the repeaters were planned (see section on *Attenuation Characteristics*) it was necessary to include an equalizer unit in the sea, midway between Terrenceville and Sydney Mines. Loss equivalent to 9 nautical miles of cable was also introduced at this point to ensure that repeater No. 16 would be sufficiently far from the shore at Sydney Mines.

(d) Cable simulators are included in the cable-terminating equipment at Sydney Mines to build out this section to a standard repeater section; the actual cable length was, of course, unknown until the cable was complete.

Taking into account the existence of the intermediate networks, the repeater spacing is such that when both land and submarine cable sections are at mean temperature the compensation is as accurate as possible. In general the highest frequency is of greatest importance in this respect. Since the low-frequency channels experience less attenuation than the high-frequency channels, it is permissible to transmit them at a somewhat lower level, thereby increasing the load capacity of the amplifiers which is available to the high-frequency channels.

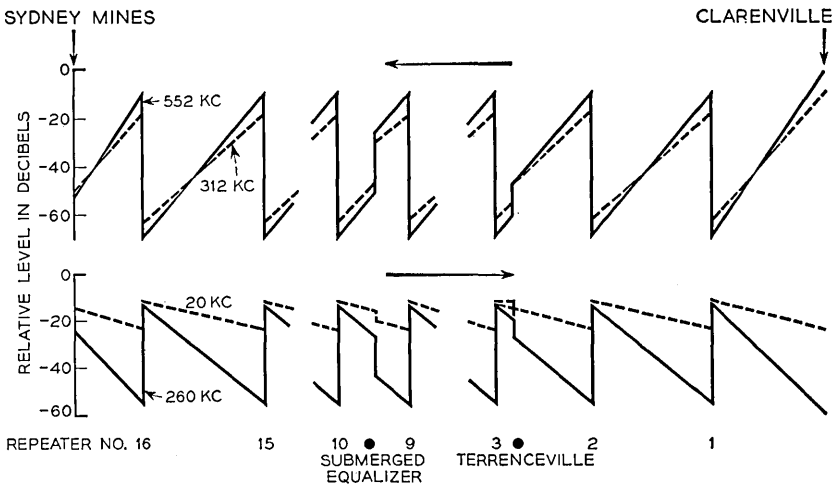


Fig. 9 — System level diagram.

Temperature Effects and their Compensation

The effect of temperature changes is likely to be somewhat complex. The land-and-sea cable sections are expected to behave in different ways in this respect, but data on the manner of variation are not very precise. The submarine cable crosses Cabot Strait, where melting icebergs drifting down from Labrador as late as June can be expected to keep the sea-bottom temperature low until well into the summer; temperatures just below 0° C were, in fact, recorded when the cable was laid in May. On land, the cable is buried 3 feet deep in bog and rock, and traverses many ponds; some data on temperatures under similar conditions in other parts of the world were available.

For planning purposes it was clear that the assumptions made would have to be somewhat pessimistic, and the assumed ranges of temperature, with the corresponding changes of attenuation at 552 kc, were:

Sea section	2.3 ± 3° C;	±4 db
Land section	7.5 ± 10° C;	±3 db

A possible method of circuit adjustment for temperature changes is to increase the gains equally at the sending and receiving terminals as the temperature rises and to reduce them equally as it falls. Under such conditions the effect of temperature variations on resistance noise is not very important; the levels at repeaters near the center of the route remain substantially constant, and the increase in noise from the repeaters whose operating levels are reduced is partly compensated by the reduction in noise from those whose levels are increased. The effect of the level changes on repeater loading is, however, more important as it is undesirable that any repeater in the link should overload, and additional measures which can be readily adopted to avoid serious changes in repeater levels are clearly desirable.

The estimated change of attenuation of the land sections is seen to be roughly equal to that of the submarine section, so that, from the point of view of temperature changes, Terrenceville is near the electrical center of the link. It was thus both desirable and convenient to provide adjustment at this point: Fig. 10 illustrates the advantage of seasonal changes in equalizer setting at Terrenceville, showing the way the output levels of repeaters are likely to vary along the route. The system of temperature compensation adopted therefore involves adjustable networks at both ends of the system and at Terrenceville. All the networks are cable simulators; hence the process of temperature compensation consists, effectively, in adding 'cable' when the temperature falls and removing it when the temperature rises.

At Terrenceville, the networks permit adjustments equivalent to ± 1 nautical mile of cable (3 db at 552 kc), but at Clareville and Sydney Mines adjustments equivalent to 0.5 db at 552 kc are provided. It should therefore always be possible to maintain the overall loss of the system within ± 0.25 db, and the level at any repeater should never change by more than ± 2 db.

System Pilots

The use of pilot tones applied at constant level at the input of a system with indicating or alarm meters at the receiving end is standard on land systems on both sides of the Atlantic, although the philosophies underlying the methods of use differ. On the submarine cables round the British Isles, with or without submerged repeaters, pilot tones are used

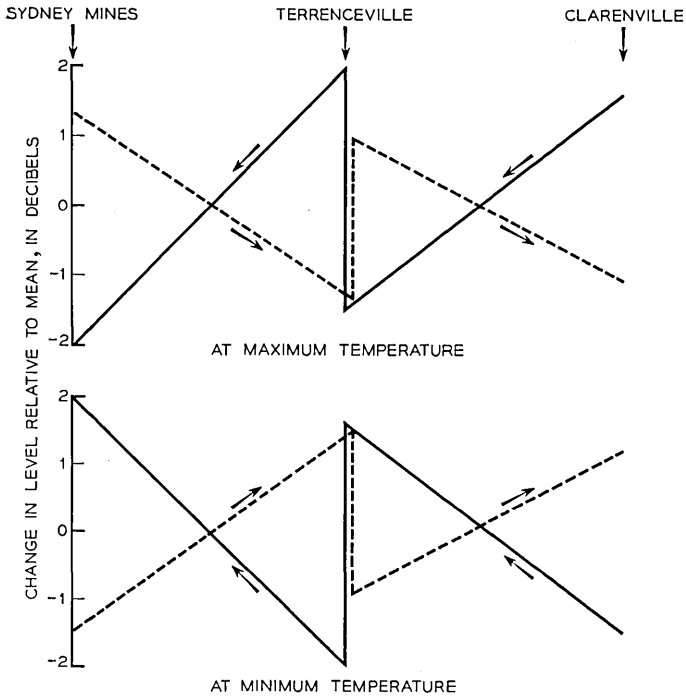


Fig. 10 — Deviation from mean of transmission levels with optimum adjustments of equalizers at Sydney Mines, Terrenceville and Clareville.

----- W-E at 260 kc.
 ——— E-W at 552 kc.

Maximum deviation in the two directions occurs at the above frequencies.

to indicate the attenuation of the transmission path; these pilots are normally located just outside the main transmission bands in each direction. In the Clarenville-Sydney Mines system the frequency bands just outside the main transmission bands are occupied by telephone speaker and teleprinter circuits and by monitoring frequencies associated with the repeaters (see Fig. 5); this prevents the use of out-of-band pilots.

Fortunately, the standard Bell System group equipment is designed to apply 92-kc pilots to each group and to measure the corresponding received level. Although these are essentially group pilots, being applied and measured at points in the 60–108-kc band, it was decided that they could reasonably replace the out-of-band pilots. These pilots are blocked at each end of the system and therefore function as section pilots only.

Normal Post Office practice, both on land and submarine systems, is to use recording level meters to provide a continuous and permanent record of the pilot levels. In the present system such recording meters are used on the 92-kc pilots of two groups in each direction of transmission.

In addition to the section pilots the system carries the 84.080-kc end-to-end pilots in each of the three transatlantic groups.

MAINTENANCE FACILITIES

Speaker and Printer Circuits

It was part of the planning of the transatlantic system that two low-grade telephone (speaker) and two telegraph (printer) circuits should be provided over the submarine cables, outside the main transmission bands, and that the speaker circuits in particular should be reasonably independent of the main terminal equipment. One speaker circuit is required for local communication between the terminals of each section, the other to form part of an omnibus circuit connecting the principal stations on the route including Montreal. The arrangement for teleprinter communication was that one channel should be an overall all-station omnibus printer, the other being a direct London-New York printer.

Independent frequency-translating equipment is provided to connect the speaker and printer bands (each 4 kc) to the line. The carrier frequencies required for the speaker are provided by independent oven-controlled crystal oscillators, but for the printer the independent generation of high-stability 572-kc carriers was not considered to be justified and the main station supplies are used.

Two half-bandwidth telephone circuits are provided in the 4 kc speaker

bands by the use of standard A.T. and T. band-splitting equipment (EB banks). Signalling and telephone equipment are provided to give the required omnibus facilities on one circuit and local-calling facilities on the other. The arrangement of the speaker and printer equipment at Sydney Mines is shown in Fig. 11.

In the telegraph band a third channel transmits an alarm to the remote terminal when the 92-kc pilots incoming from that terminal fail simultaneously.

Fault Location

The speedy and accurate location of faults in repeatered cables is of very great importance, owing to the number of circuits involved and the difficulty and cost of repairs. The standard dc methods which have been applied in the past to long telegraph cables are, of course, available. The application of these methods is, however, recognized as being rather more

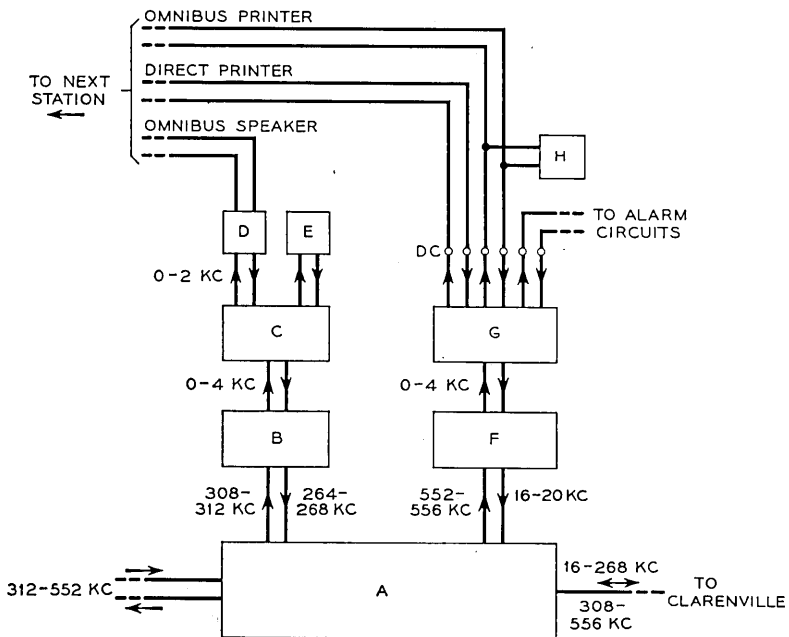


Fig. 11 — Arrangement of speaker and printer equipment at Sydney Mines. A. Submarine cable terminal equipment. B. Speaker circuit equipment. C. Emergency-band bank equipment. D. Omnibus speaker telephone. E. Local speaker telephone. F. Printer circuit equipment. G. Three-channel telegraph equipment. H. Printer.

in the nature of an art than a science and usually requires an intimate knowledge of the behaviour and peculiarities of the particular cable concerned. While the problem appears at first sight to be simple it is complicated by:

(a) The presence of ground-potential differences along the cable, sometimes amounting to hundreds of volts; these vary with time.

(b) Electrolytic e.m.f. generated when the center conductor is exposed to sea water.

(c) Absorption effects in the dielectric of the cable.

When repeaters are added the position is further complicated by:

(d) The lumped resistance of the repeaters, which is current-dependent and exceeds the cable resistance.

(e) The lumped capacitance of the repeaters with an absorption characteristic which differs from that of the cable.

It is a great advantage of both-way transmission over one cable that, by introducing some form of frequency changer at each repeater, signals outgoing in one direction can be looped back to the sending terminal. There have been a number of developments based on this principle, and in the Clarenville-Sydney Mines link two methods are available for use. Of these, the so-called 'loop-gain' method uses steady tones and depends on selective frequency measurements to discriminate between repeaters; the second is a pulse method in which repeaters are identified on the basis of loop transmission time.

The use of these methods under fault conditions depends on the possibility of keeping the repeaters energized. Work is in progress to develop methods of fault location which are of general application and do not depend on the activity of the repeaters, but these are outside the scope of the present paper.

Loop-Gain Method.

In the loop-gain method, the frequency changer in the repeater takes the form of a frequency doubler and each repeater is identified uniquely by one of a group of frequencies spaced at 120 cycles and located immediately above the lower main transmission band in the frequency range 260-264 kc. Since the frequency changing is in an upward sense, the measuring terminal is Sydney Mines, which transmits the lower band. On the Clarenville side of the directional filters in each repeater is connected, via series resistors, a crystal filter accepting the test frequency appropriate to the repeater [see Fig. 12(a)]; this frequency is doubled, filtered and returned to the repeater at the same point at which

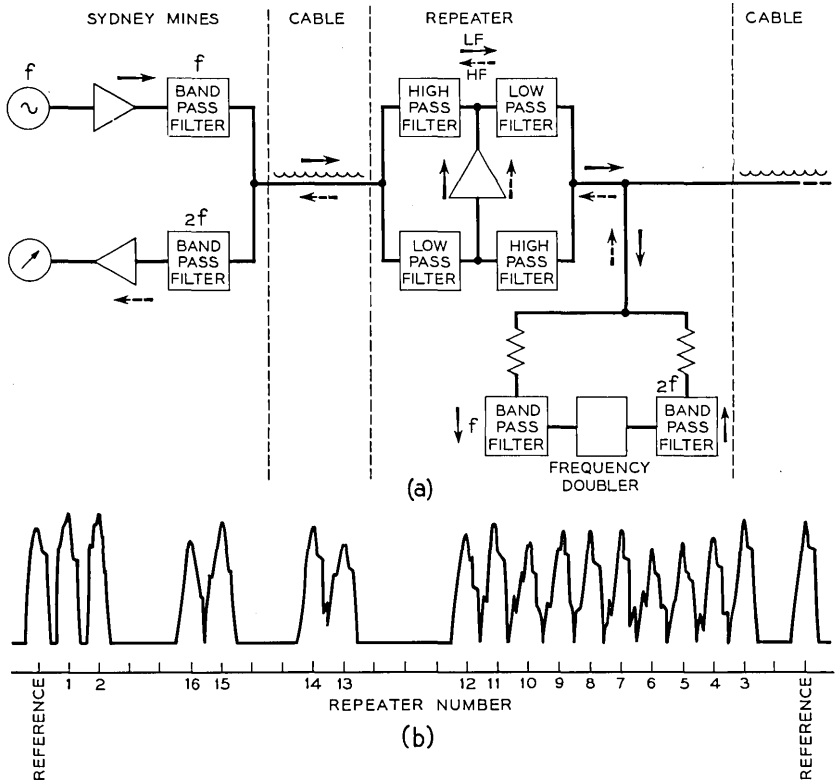


Fig. 12 — Fault location — loop-gain method. (a) Block schematic. Frequency f is in the band 260–264 kc. (b) Diagram of display.

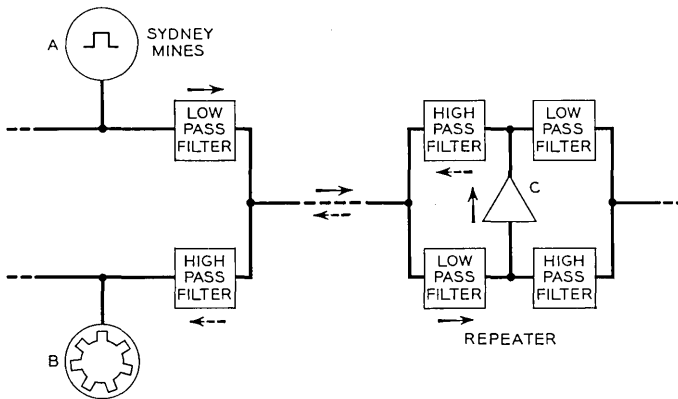


Fig. 13 — Fault location: pulse method. A. Pulse generator. B. Display of received pulses. C. Point of intermodulation (output of amplifier).

the original frequency is selected. From this point it passes via the high-pass directional filters through the amplifier and back to Sydney Mines, where the level is measured on a transmission measuring set. Information obtained in this way on each repeater can be compared at any time with that obtained when the system was installed and any gain variations localized. The test equipment provided has the additional facility of an automatic sweep of the test frequency at 4 cycles and a display of the returned-signal levels on a cathode-ray tube as in Fig. 12(b).

Although the transmitted signals lie outside the band of the W-E supergroup, the received signals, 520–528 kc, lie within the band of the E-W supergroup, and two channels must be removed from traffic to carry out the tests; these channels are in a “local” group.

Pulse Method.

As applied to the present system, the pulse method utilizes the overload characteristic of the amplifier to effect the frequency change in the repeater. At Sydney Mines a continuous train of single-frequency pulses is applied in the lower transmission band, such that either the second or third harmonic is returned in the upper band, as in Fig. 13; at Clarenville two-frequency pulses are applied in the upper band such that either a second- or third-order difference product is returned in the lower band. The pulse length is 0.15 millisecond, and the frequencies used are given in Table I. At Sydney Mines the signals can be sent and received either on the line itself or via the group equipment; in the latter case only one group need be taken out of service. At Clarenville line measurements only are provided for.

The primary display is on a cathode-ray tube with a circular time-base, and any one returned pulse can be accurately compared with the reference pulse on a second tube with a linear time-base. The pulse selected for such measurement is automatically blacked out on the primary display.

TABLE I

Station	Send to line		Product	Receive
	f_1	f_2		
	kc	kc		kc/s
Sydney Mines	216	—	$2f_1$	432
	144	—	$3f_1$	432
Clarenville	530	380	$f_1 - f_2$	150
	530	340	$2f_2 - f_1$	150

Usefulness of the Loop-Gain and Pulse Methods.

Both methods require that all the repeaters between the testing terminal and the fault can be energized. If the fault is in the cable there is a very high probability that the center conductor will be exposed to the sea, in which case the power circuit can be maintained on one side of the fault at least, although it may be somewhat noisy. Because the system is short, it is permissible to energize the link fully from one end only. The condition can never arise — as it can in the Oban-Clarenville link — that the line current is limited by the maximum permissible terminal voltage.

The loop-gain test is concerned with the amplifiers in their linear regime and gives no indication of the overload point; for this the pulse test must be used. On the other hand, the pulse test does not permit accurate measurement of levels, since the pulse level reaching a particular repeater may be restricted by the overload of an earlier repeater in the chain. The pulse test is particularly useful in providing a check that both sides of each amplifier are in operation and in locating a fault of this type.

Each method depends for its operation on non-linearity at a point within each repeater and can only identify a fault as lying between two such consecutive points in the link. It is therefore desirable that these points should be as close as possible to the terminals of the repeater in order to ensure that the faulty unit can be identified. In this respect the loop-gain test has the advantage over the pulse test.

EXECUTION OF WORK

Problems due to the remoteness of the site were overcome without undue difficulty with the co-operation of the other parties concerned in the project, but the present paper would be incomplete without a brief reference to the cable- and repeater-laying operations in Newfoundland and at sea.

The terrain and conditions in Newfoundland were quite unlike those with which the British Post Office normally has to contend, involving trenching and cabling through bog, rock and ponds in country of which no detailed survey or maps were available. Maps were constructed from aerial survey, and alternative routes were explored on foot before a final choice was made. As much use as possible was made of water sections in the sea, river estuary and ponds; some 22 miles were accounted for in this way, leaving about 41 miles to be trenched by machine or blasted. A contractor was engaged for this purpose and to lay the cable in the trench, but all jointing was done by the Post Office. The standards of conductor and core jointing were the same as those in the cable factories

and on ship, portable injection-moulding machines and X-ray equipment being specially designed for handling over the bog. A single pair cable was also laid in the main cable trench to provide speaker facilities between Clarenville and Terrenceville (which has no public telephone), with intermediate positions for use of the lineman. As a measure of protection against lightning strikes, two bare copper wires were buried about 12 inches apart and 6 inches above the cable. Both the constructional work in Newfoundland⁴ and the laying operation at sea⁵ have been described elsewhere.

TEST RESULTS

In the interval between the completion of the link in May, 1956, and its incorporation in the transatlantic system, tests were carried out to establish its performance and day-to-day variations; an assessment of the annual variations has, of course, been impossible at this date.

Variation of Transmission Loss

Close observation of the transmission loss of the 92 kc pilots on Groups 1 and 5 leads to the following tentative conclusions:

(a) Over periods of 1 hour the variations are not measurable, i.e., less than ± 0.05 db.

(b) Over periods of 24 hours there are no systematic changes; apparently random changes of about 0.1 db are probably attributable to the measuring equipment.

(c) Over a period of eight weeks (July and August, 1956) there was a systematic increase in loss of about 0.3 db. By means of the loop-gain equipment it has been possible to deduce that most of this change has occurred in the land section.

The results indicate that the submarine cable link has better day-to-day stability than the best testing equipment which it has been possible to provide. Many more data will clearly be necessary before the annual variations can be definitely established, but the present indications are that these will be less than those assumed in the design of the link.

Attenuation/Frequency Characteristics

The frequency characteristics of the supergroup in the two directions of transmission are shown in Fig. 14. It will be seen that in no transatlantic groups does the deviation from mean exceed ± 0.35 db.

Circuit Noise

Table II shows the noise level on Channels 1 and 12 of each of the five groups measured without traffic on the system.

To assess the magnitude of intermodulation noise, all channels in one direction were loaded simultaneously with white noise and measurements taken on each channel in the opposite direction. From the talker volume data assumed in the design of the system, the expected mean talker power is -11.1 dbm at a point of zero relative level, with an activity of 25 per cent. For an equivalent system loading, therefore, the level of white noise applied to each channel under the above test conditions should be -14.1 dbm. Since this loading gave no sensible increase in the circuit noise, the test levels were raised until a reasonable increase in the noise level was obtained. In order to raise the channel noise to the specified maximum of 28 dba it was necessary to raise the channel levels to about -1 dbm and -4 dbm in the lower and upper bands respectively. These levels, some 13 db and 10 db above the assumed maximum loading of the system, give noise levels at least 26 db and 20 db above normal, and it is seen that adequate margins exist for variations and deterioration of the link.

Closely allied to the problem of intermodulation is the overload characteristic of the system. Table III shows the measured overload point of the link expressed as an equivalent level at the output of the amplifier in the repeater nearest to the transmitting terminal. It also shows the margin between the channel level at that point and the overload point of the system; according to Holbrook and Dixon¹³ the minimum requirement in this respect is 18 db.

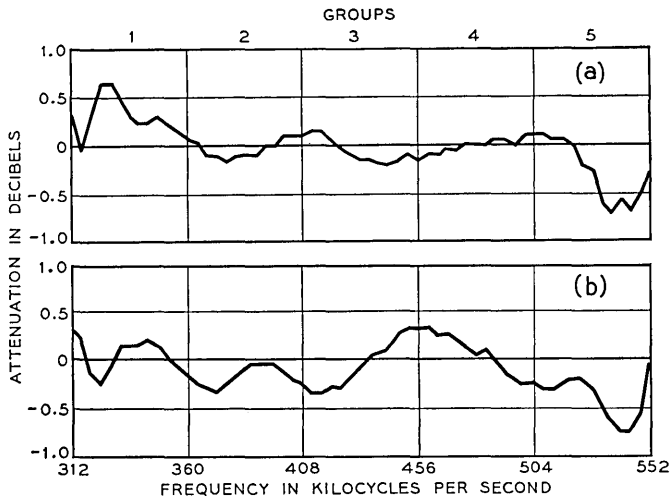


Fig. 14 — Attenuation versus frequency characteristics of supergroup. (a) Sydney Mines—Clarenville. (b) Clarenville—Sydney Mines.

TABLE II

Group	Channel	Noise level	
		Sydney Mines	Clarenville
		dba	dba
1	1	25.0	24.5
1	12	24.5	23.2
2	1	24.0	22.5
2	12	23.5	22.0
3	1	24.0	20.5
3	12	25.0	17.5
4	1	24.5	17.5
4	12	24.5	16.5
5	1	24.5	17.5
5	12	27.0	18.0

These results justify the assumption made in the design of the link, that intermodulation noise is negligible.

Crosstalk

The crosstalk requirements are met in all respects.

CONCLUSIONS

The submarine-cable link between Clarenville, Newfoundland, and Sydney Mines, Nova Scotia, was completed in May, 1956, and provides five carrier telephone groups, each capable of carrying twelve high-grade telephone circuits or their equivalent. The transmission objectives have been met in every respect.

Three 12-circuit groups are connected to the three groups across the Atlantic between Scotland and Newfoundland; the other two groups are available to provide 24 circuits between Newfoundland and the mainland of Canada.

TABLE III

Frequency	Equivalent at amplifier in first repeater		
	Channel level	Overload	Margin
kc	db	db	db
552	-2	+20	22
312	-4	+24	28
260	-5	+25	30
20	-5	+25	30

ACKNOWLEDGMENTS

It has been the authors' privilege to present an integrated account of the work of many of their colleagues in the Post Office and in industry. Post Office staff have been responsible for designs and for inspection and testing at home and in the field, as well as the laying of the submarine-cable system by H.M.T.S. *Monarch*. In Great Britain, Submarine Cables, Ltd., and the Southern United Telephone Co., Ltd., provided the submarine and overland cables respectively, while Standard Telephones and Cables, Ltd., supplied and contributed much to the design of the submerged repeaters and terminal equipment. On site, the assistance rendered by the Ordnance Survey of Great Britain, the Canadian Comstock Co., Ltd., who laid the cable across Newfoundland, the Northern Electric Co., Ltd., who carried out the terminal equipment installations, and by the other partners in the project, the American Telephone and Telegraph Co. Inc., the Canadian Overseas Telecommunication Corporation and the Eastern Telephone and Telegraph Co., has been invaluable. The permission of the Engineer-in-Chief of the Post Office to make use of the information contained in the paper is gratefully acknowledged.

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Repeater Design for the Newfoundland-Nova Scotia Link

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The Newfoundland-Nova Scotia cable required the provision of 16 submerged repeaters each transmitting 60 circuits in the bands 20–260 kc from Newfoundland to Nova Scotia and 312–552 kc in the opposite direction. The paper deals with the design and production of these repeaters. Each repeater has a gain of 60 db at 552 kc, and the amplifier consists of two forward amplifying paths with a common feedback network. Reliability is of paramount importance, and production was carried out in an air-conditioned building with meticulous attention to cleanliness and to very rigid manufacturing and testing specifications. The electrical unit is contained in a rigid pressure housing 9 feet long and 10 inches in diameter with the sea cables connected to an armor clamp and a cable gland at each end. A submerged equalizer was provided near the middle of the sea crossing.

INTRODUCTION

The British Post Office has engineered many shallow-water submerged-repeater systems,¹ and there has been a progressive improvement in design techniques and in the reliability of components which has been reflected in a growing confidence in the ability to provide long-distance systems having an economic life. The seven-repeater scheme from Scotland to Norway laid in 1954 introduced for the first time repeaters which would withstand the deepest ocean pressure together with an electrical circuit which embodied improved safety and fault-localizing devices. Also, since a repeater is only as reliable as its weakest component, much greater attention and control was directed at this stage to the design, manufacture and inspection of all components, both electrical and mechanical. This repeater design was, in fact, envisaged as a prototype for a future transatlantic project.

* British Post Office.

In the finalized plans² for the Newfoundland-Nova Scotia cable it was required to carry 60 circuits, so that some redesign of the 36-circuit 'prototype' repeater became essential. It was accepted, however, as a guiding principle throughout the redesign that there should be no departure from previous practice without serious consideration and adequate justification. It was obviously not an occasion to experiment with new ideas.

Post Office and Bell Telephone Laboratories experiences were pooled for the project, and the whole technical resources of both organizations were freely available at all times for consultative purposes. Detailed manufacturing and testing specifications were exchanged and approved, and each party was free to inspect the other's production methods. This mutual interchange was undoubtedly highly beneficial, and in the British case it resulted in a still more rigorous control of manufacturing and inspection methods.

PLANNING

General

Preliminary design calculations indicated that it should be possible to increase the circuit-carrying capacity of the Anglo-Norwegian prototype repeater from 36 to 60 circuits, and tests on a model confirmed that, with band frequencies of 20-264 and 312-552 kc, a 60.0 db gain at 552 kc could be realized with satisfactory margins against noise, distortion and overload. This gain fixed the repeater spacing at about 20.0 nautical miles so that on the selected route two repeaters would be required on the land section between Clarenville and Terrenceville and 14 in the Terrenceville-Sydney Mines sea section. It was noted that the land repeaters might have to work with an ambient temperature 12°C higher than in the sea repeaters.

Each repeater would need to be energized with a direct current of 316 ma at 124 volts so that the total route voltage would be about 2,300 volts. This voltage would be quite acceptable to the repeaters, but for normal operation it was proposed² to feed from both terminals simultaneously, thereby halving the maximum voltage to ground.³

The precise localization of any faulty or aging repeater would be of paramount importance. It was decided to retain the two supervisory methods which on the prototype had worked satisfactorily in this respect. These consisted of a pulse-distortion equipment requiring no additional components in the repeater and a loop-gain monitoring set involving a special unit in the repeater and the allocation of a 4-kc band (260-264 kc) for its operation.

Manufacture and testing of the electrical units was again to be carried out by a contractor in a temperature- and humidity-controlled production building, and in order to enable manufacture to start as early as possible, arrangements were made for the contractor to co-operate with the Post Office at an early design stage so that engineering could follow fast on the heels of the design. The outer housing and method of brazing-in the bulkheads had all proved entirely satisfactory on the prototype, and therefore these operations could proceed according to previous production. The Post Office assumed responsibility for the production and testing of the glands, since no contractor had experience of this work.

Forward planning in early 1954 scheduled the first electrical unit to be completed in June, 1955, with units following at 5-day intervals. This target was, in fact, delayed until August, 1955, but all 16 working repeaters were available fully tested before the commencement of the alying operation in May, 1956.

Distortion Monitoring Equipment

The pulsed-carried supervisory method as used on previous systems¹ is employed primarily for measuring the distortion on repeaters. Under normal operating conditions the distortion level may be only just noticeable above the noise, but should appreciable distortion occur, e.g., failure of one amplifying path in a repeater, it could be readily located, since the pulse amplitude from the faulty repeater would increase by about 12 db for second-harmonic distortion and about 18 db for third-order distortion.

Loop-Gain Monitoring Equipment

For the loop-gain monitoring equipment¹ the repeaters have to be designed to incorporate a second-harmonic generator operating at a frequency unique to each repeater at 120-cycle spacing in the 260–264-kc band. The second harmonics return to Sydney Mines in the 520–528-kc band, and these two channels must be taken out of service during the measurement.

Levels and Equalization

Controlling Factors.

In practice, deviations from an ideal system wherein all repeaters match the cable and operate at all times at the same levels require the repeaters to be designed with specific margins against overload and intermodulation to meet an agreed maximum noise figure for the system

under all working conditions.² Factors involved in assessing these margins and in planning the equalization and level diagram for the system are as follows:

(a) *Temperature.* — The final assumed sea-bottom temperature was 2.3°C, with a maximum annual variation of $\pm 3^\circ\text{C}$. The maximum change in attenuation might therefore be ± 4 db at 552 kc. The land section change would be ± 3 db at 552 kc due to a possible $\pm 10^\circ\text{C}$ change on a mean of 7.5°C. The effect of these seasonal changes would be reduced by the provision of manually adjusted equalization at Clarenville, Terrenceville and Sydney Mines.

The repeaters show a small change in gain (less than 0.05 db) during the warming-up period after energization, but the effect of ambient-temperature change is negligible.

(b) *Repeater spacing.* — The repeater-section cable lengths were to be cut in the cable factory such that the expected attenuation at 552 kc when laid at the presumed mean annual temperature of the location should be 60.0 db. An anticipated decrease in attenuation of 1.42 per cent at 552 kc was assumed when laid. The assumed mean annual temperature of sections of the route varied between 1.7 and 4.0°C. Temperature corrections employed an attenuation coefficient at 552 kc of +0.16 per cent per degree centigrade. It was expected that the total error at 552 kc after laying seven repeaters would not exceed 1.5 db, and this could be largely corrected as explained in (c).

(c) *Cable Characteristics.* — The cable equalization built into the repeater was based on a cable attenuation characteristic which was later discovered to be appreciably different from the laid characteristic. Cutting the cable as described in (b) overcomes this difficulty at 552 kc, where the signal/noise ratio is at a minimum. The new shape of the characteristic, however, indicated that at about 100 kc the error would reach 7 db on the complete route. To reduce this deviation it was decided to introduce a submerged equalizer in the middle of the sea section to correct for half this error and to insert in each of the four-wire paths of the transmit and receive equipments equalization for one-quarter of this error. There is an appreciable signal/noise margin in hand at this frequency, so that the system would not be degraded below noise specification by these equalizer networks.

It was also decided that the splice at the equalizer which would connect the halves of the link together should not be completed until after the laying operation had commenced. An excess length of cable was provided on the equalizer tail, and this could be cut at a position indicated by measurements taken during the laying of the first half-section so that

the equalization at the 552-kc point could be largely corrected for laying and temperature-coefficient errors. It is not, in practice, easy to separate these two factors.

(d) *Repeater characteristic.* — The repeater was designed to equalize the original cable-attenuation characteristic to ± 0.2 db, as this was possible with a reasonable number of components. This variation appeared as a roll in the gain/frequency characteristic, which was expected to be systematic and would therefore lead to a ± 3 db roll in the overall response. It was proposed that equalization for this should be provided at the receive terminal. Manufacturing tolerances were expected to be small and random.

(e) *Repeater interaction.* — At the lower frequencies where the loss of a repeater section is comparatively small, a roll in the overall frequency response will arise due to changes in the interaction loss between repeaters. The design aimed at providing a loop loss greater than 50 db which would reduce rolls to less than ± 0.03 db per repeater section and therefore to about 0.5 db at 20 kc with systematic addition on the whole route.

Planning of Levels

From a critical examination of all these variables it was concluded that the repeater should be designed to have an overload margin of 4 db above the nominal mean annual temperature condition. It was also desirable for the system to be able to operate within its noise allowance if one path of a twin amplifier failed. Tests on a model amplifier gave overload values of +24 dbm and +19 dbm for two- and one-path operation, respectively, so that with a single-tone overload requirement of 18 dbm⁴ at a zero-level point, the maximum channel level at the amplifier output would be -3 dbr for a single amplifying path.

Thermal-noise considerations (i.e. resistance plus tube noise) fixed the minimum channel level at the repeater input at -69 dbr in order to meet the allowable system noise limit of +28 dba at a zero-level point. At 552 kc the amplifier gain is 65 db, so that the minimum level at the amplifier output is -4 dbr. A system slope of ± 4 db due to temperature variations, corrected by similar networks at the transmit and receive terminal, would, however, degrade the noise by 0.5 db. Intermodulation noise was estimated⁵ on an average busy-hour basis, and it was concluded that the increase in noise at 552 kc from this source was negligible — less than 1 db, even with several repeaters in which the amplifier had failed on one path. At lower frequencies the contribution from intermodulation noise is greater, and at 20 kc it exceeds resistance noise.

However, at 20 kc the total noise is some 8 db below the specification limit, and therefore again several amplifiers could fail on one path before the noise exceeded the specification limit. Actually it was discovered that the predominant source of third-order intermodulation on the repeater was in the nickel-iron/ceramic seals on high-voltage capacitors and followed a square law with input levels.

From a more detailed examination of the factors briefly mentioned above it was decided that the initial line-up should be based on a nominal flat -3.5 dbr point at the amplifier output and the final working levels decided upon as the results of tests on the completed link.

With equal loading on the grid of the output tube at all frequencies the worst signal/noise ratio exists at 552 kc; some pre-emphasis of the transmit signal should therefore prove to be beneficial. In fact, after completing the tests on the link it was decided to improve the margin on noise by raising the level at 552 kc by 2 db, thus giving a sloping level response at the amplifier output in the high-frequency band. To maintain the same total power loading, the low-frequency band levels were decreased by 1 db, still retaining a flat response.

Laying

It was proposed to use laying methods with continuous testing similar to those employed successfully on the Anglo-Norwegian project. The complete link with a temporary splice at the equalizer would be assembled and tested on board H.M.T.S. *Monarch* and laying would proceed from Terrenceville to Sydney Mines in the high-frequency direction of transmission. A detailed description of the actual laying operation is given elsewhere.⁶ After completion of tests on the submarine section the land section to Clarenville would be connected with appropriate equalization at Terrenceville.

DESIGN OF ELECTRICAL UNIT OF SUBMERGED REPEATER

General

The equipment is contained in a hermetically sealed brass cylinder (filled with dry nitrogen) $7\frac{3}{4}$ inches in diameter and 50 inches long, which is bolted at one end to one of the bulkheads of the housing. A flexible coaxial cable emerges through an O-ring seal at each end, and these are ultimately jointed to the cable glands. The various units forming the complete electrical unit are mounted within a framework of Perspex (polymethylmethacrylate) bars which forms the main insulation of the

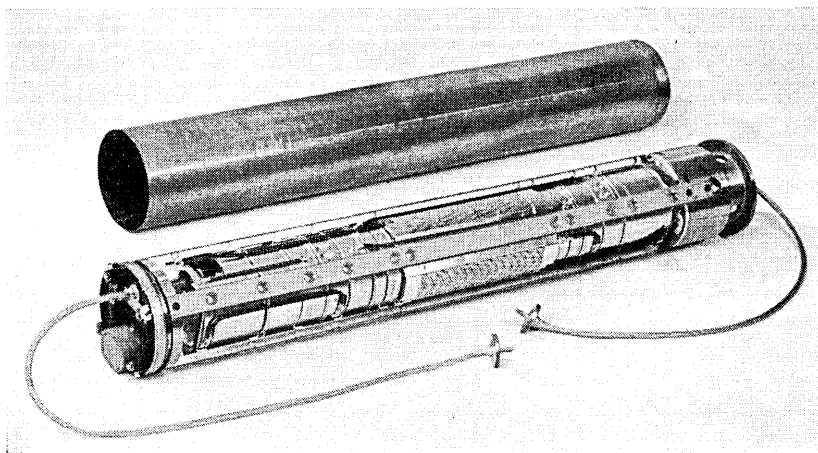


Fig. 1 — Internal unit.

repeater, and these units may operate at 3 kv dc to the grounded brass cylinder. Fig. 1 shows the construction.

A schematic of the electrical circuit is given in Fig. 2. The direct current for energizing the repeater is separated from the carrier transmission signals by the A- and B-end power separating filters, and passes through the amplifier tube heaters and a chain of resistors developing 90-volt high-voltage supply for the amplifier. The carrier-frequency signals pass through the same amplifier via directional filters. Equalization is provided in the amplifier feedback circuit (about 20 db) and in the equalizers and the bridge networks which combine the directional filters. The main purpose of the bridges, however, is to reduce the severe harmonic requirement on the directional filters due to having high- and low-level signals present at the repeater terminals. The whole carrier circuit is designed on a nominal impedance of 55 ohms. Attached to the B-end of the repeater is the loop-gain supervisory unit and also, via a high-voltage fuse, a moisture-detector unit used primarily during the high-pressure test to confirm that the housing is free from leaks. The latter comprises a series-resonant circuit at about 1.3 mc, in which the inductance is varied by the gas pressure on an aneroid capsule mounted in the space between the electrical unit and the housing. The presence of moisture in this cavity increases the gas pressure owing to the release of hydrogen by the reaction of water vapor with metallic calcium held in a special container. At a later stage the fuse is blown to disconnect this circuit.

The circuit design of the repeater introduces multiple shunt paths

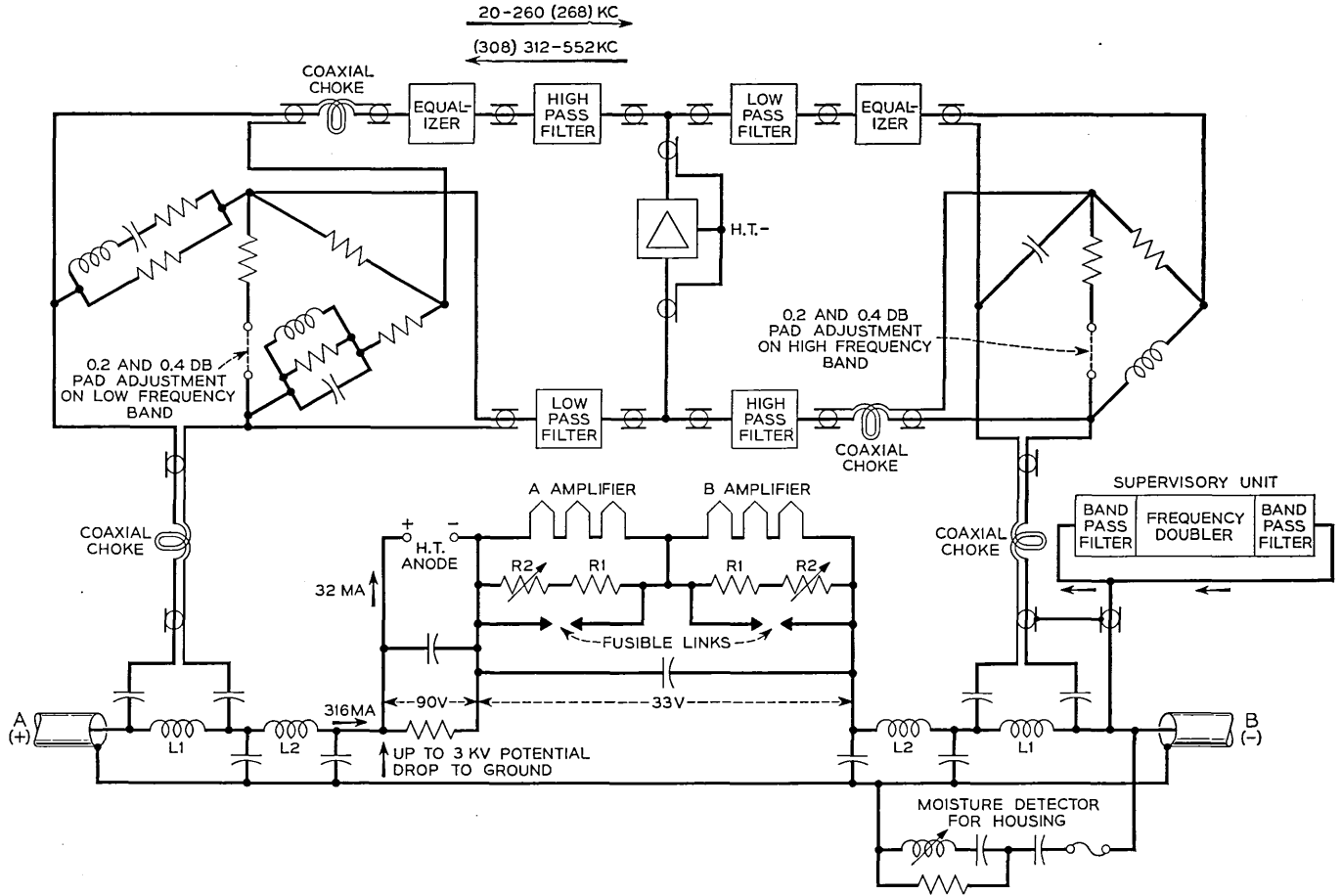


Fig. 2 — Schematic of submerged repeater.

across the amplifier, and care has to be taken to ensure that there is adequate attenuation in each path. In general, the design is such that the combination will give a loop loss of at least 40 db in the working band (to reduce rolls in the gain characteristic) and 20 db at all frequencies (as a guard against instability), even when one repeater terminal is open- or short-circuited to simulate a faulty cable.

Unit Details

Power Filter.

The power filters are, in effect, a series pair of high- and low-pass filters (see Fig. 2). The shunt capacitors may have to withstand 3 kv, and clearances on the input cable and some wiring have to be adequate for this voltage. The inductors have to carry the line current of 316 ma dc, and the intermodulation must be extremely low (see section on inductors below).

Directional Filter.

The directional filters are a conventional Zobel high-pass and low-pass filter pair with a susceptance-nulling network. Silvered-mica capacitors and carbonyl-iron dust-cored inductors are used. The bridges combining the 'go' and 'return' filters reduce the distortion due to the ferromagnetic material to an acceptable level.

Bridge and Equalizer.

A simple non-resonant bridge is used at the B-end of the repeater, but the A-end bridge is a resonant type and provides a substantial degree of equalization (see Fig. 2).

The equalizers are of conventional form. Trimming capacitors (selected on test) were provided for critical capacitances in order to utilize standard tolerances on all capacitors. A pad of 0.2 db and 0.4 db is provided on each equalizer unit so that the repeater low-frequency or high-frequency path can be independently trimmed to give the best match to the target response for the repeater.

The components in the above circuit were small air-cored inductors, silvered-mica capacitors, and wire-wound resistors, except for a few high-resistance ones, which were of the carbon-rod type. Included in this unit are coaxial chokes whose purpose is to separate parts of the circuit to avoid the effect of multiple grounding. They are merely inductors wound with coaxial wire on 2-mil permalloy C tape ring cores.

Supervisory Unit.

The supervisory unit comprises a frequency-selection crystal filter of about 100-cycle bandwidth in the range 260–264 kc fed from the low-frequency output end of the repeater via a series resistor. This filter feeds a full-wave germanium point-contact crystal-rectifier bridge which acts as a frequency doubler. The second harmonic in the band 520–528 kc is filtered out by a coil-capacitor band-pass filter, and fed back through a resistor to the same point in the repeater. The two series resistors minimize the bridging loss of the unit on the repeater and ensure that a faulty supervisory component has negligible effect on the normal working of the repeater.

DC Path.

The dc path includes a resistor providing the 90-volt supply and the heater chain of six electron tubes (see Fig. 2). The voltage drop across the heater chain is not utilized for the amplifier high-voltage supply, as the heaters would then be at a positive potential with respect to the cathodes, thereby increasing the risk of breakdown of heater-cathode insulation. There would also be a complication in maintaining the constant heater current, particularly should the high-voltage supply current fail in one path of the amplifier. The normal amplifier high-voltage supply current is 32 ma.

It is essential to maintain a dc path through the repeater even under fault conditions in order that fault-location methods can be applied. Special care has therefore been taken to provide parallel paths capable of withstanding the full line current. For example, the high-voltage resistor actually consists of a parallel-series combination of ten resistors, and the whole assembly is supported on Sintox (a sintered alumina) blocks which maintain a good insulation at 3 kv dc, even at high temperatures.

Electron tube operation for consistent long life indicates the necessity to maintain a specific constant cathode temperature, and to achieve this, electron tubes are grouped according to heater characteristics into six heater-current groups between 259 and 274 ma and stabilized to ± 1 per cent. The appropriate heater-shunt resistor is applied so that the tube operates correctly with 316-ma line current, but for convenience the shunt is taken across each set of three tubes, all in one heater group, forming one amplifier path. R1 is fixed (300 ohms) and R2 is selected to suit the tubes. R1 is the resistance winding of a special short-circuiting fuse; when energized by the full line current should a heater become

open-circuited, it causes a permanent direct short-circuit across the heater chain. The line voltage will be temporarily increased by about 95 volts while the fuse operates (1 min) and will then drop to 12 volts below normal.

Amplifier.

The amplifier circuit is shown in Fig. 3. It consists of two 3-stage amplifiers connected in parallel between common input and output transformers with a single feedback network. This circuit arrangement allows one amplifier path to fail without appreciably affecting the gain of the complete amplifier (less than 0.1 db for all faults except those on the grid of V1 and the anode of V3, but the overload point is reduced by about 5 db and distortion at a given output level is increased (about 12 db for second harmonics). Care has been taken to ensure that the open- or short-circuiting of a component in one amplifier path will not affect the performance, life or stability of the remaining path, and this involves the duplication of certain components.

Mixed feedback is employed to produce the required output impedance; the current feedback is obtained from the resistor feeding the high-voltage supply to the output transformer, and the voltage feedback is developed across a two-turn winding on the output transformer, which also serves as a screen. The output of the feedback network is fed in series with the input signal to the grid of V1. The gain response of the amplifier is chiefly controlled by the series-arm components in the feedback network, which resonate at 600 kc.

The input transformer is built out as a filter and steps up in impedance from 55 ohms to 17,000 ohms. Protective impedances minimize the effect of a short-circuit on the grid of one of the first-stage tubes. The anode load of the first stage resonates at 600 kc, and is roughly the inverse of the feedback network so as to give constant feedback loop gain over the working frequency band. The output tube has about 5.5 db of feedback from its cathode resistor, and the pair of output tubes feed the output transformer, which steps down from 5,000 to 55 ohms.

Specially designed long-life tubes are used.⁷ The first two stages are operated at about 40 volts on the screens and anodes; each anode current is 3 ma, giving a mutual conductance of 5.1 ma/v. The output stage is operated at 60 volts on the screen, +15 volts on the suppressor grid to sharpen the knee of the V_a/I_a characteristic, and nearly the full high-voltage supply of 90 volts on the anode; the anode current is 6 ma, giving a mutual conductance of 6.6 ma/v. The tube dynamic impedance is approximately 300,000 ohms. To obtain an anode current nearest to the

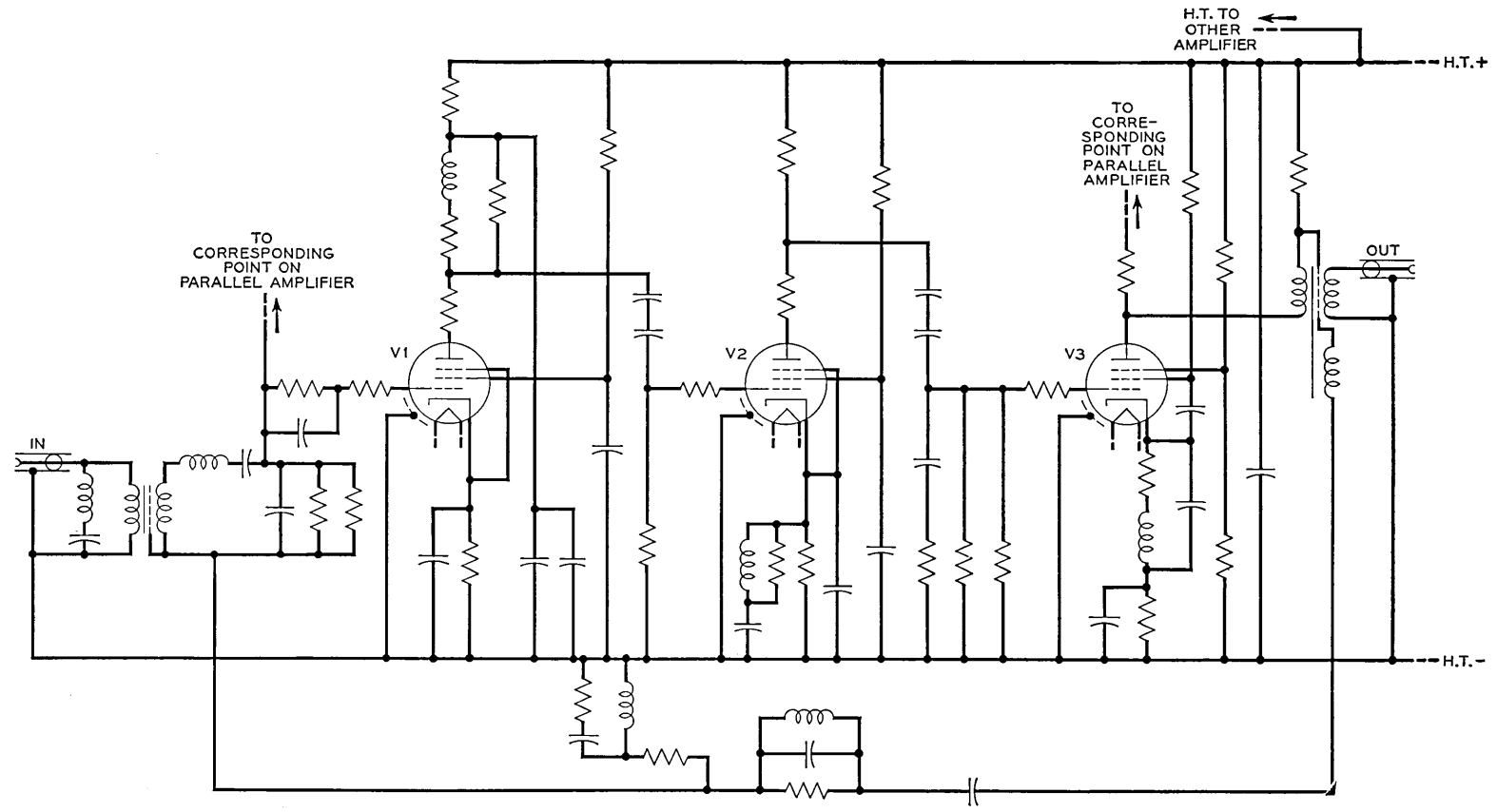


Fig. 3 — Amplifier circuit.

design value (and for which the tubes are aged), one of two values of bias resistance can be selected for V1 and V2, and one of three values of bias resistance for V3.

All capacitors subject to the high-voltage supply voltage are of the oil-filled paper type, and the others are of the silvered-mica type. Inductors are air-cored spools which are multi-sectioned when used in high-impedance circuits. All resistors are of the solid carbon-rod type, except for the input-transformer termination, which consists of two high-stability cracked-carbon resistors, and those in the feedback network, which are wire wound.

The input and output transformers employ 2-mil permalloy C laminations, and the latter core is gapped on account of the polarizing current. A narrow Perspex spool fits the center limb, and conventional layer windings are used; the screen is a sandwich made of copper foil with adhesive polythene tape.

3.3 *Mechanical Design Details*

The arrangement can be seen from Fig. 1. At the A-end is a cast-brass pot containing the resistors providing the amplifier high-voltage supply, and as this is bolted directly on to the housing bulkhead, the heat generated is readily conducted away. The remainder of the units are in cylindrical cans mounted in the insulating framework formed by four Perspex bars. These are sprayed with copper on both faces to guarantee the dc potential on these surfaces and eliminate the risk of ionization at working voltages. The cans are not hermetically sealed but are dried out with the repeater when it is finally sealed and filled with dry nitrogen. Perforated covers on the amplifier allow air circulation to reduce the ambient temperature.

Fig. 4 shows a typical can assembly, and Figs. 5 and 6 the construction of the amplifier. It will be seen that the latter is a double-shelved structure with tubes alternating in direction, and an amplifier path is located on each side of the chassis; the input and output transformers are at opposite ends, and the feedback network is contained in a hermetically sealed can in the center of the unit.

All cans are finished with a gold flash which is inert and gives a clean appearance stimulating a high standard of workmanship. Tin plating was formerly used, but it has been shown that tin tends to grow metallic whiskers.⁸ Unfortunately certain capacitor cans had to be tin plated, and extra precautions consisting of wide clearances or protective shields have had to be taken. The risks from growth on soldered surfaces is not

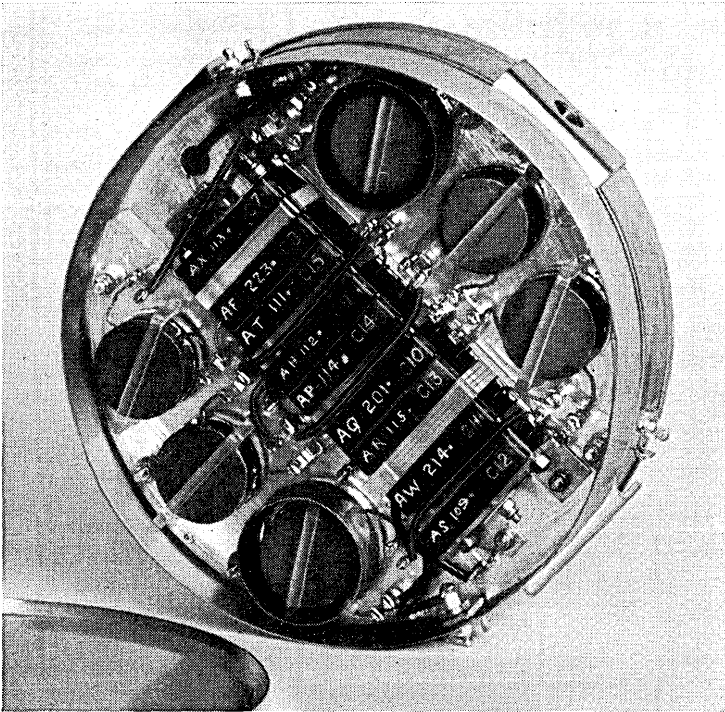


Fig. 4 — Directional filter unit. High-pass filter with low-pass filter can on rear.

thought to be great, as all solders used have less tin content than the eutectic alloy. All connecting wires are gold plated instead of the usual tin plating.

The insulating sub-panels in units are usually made of Perspex, but where the items are subjected to high temperatures (e.g., resistance box), Sintox, a sintered alumina ceramic, or Micalox is used.

Polytetrafluoroethylene (p.t.f.e.) is another insulant used, and p.t.f.e.-covered wire threaded through copper tube forms the coaxial interconnecting leads between the can units.

Careful attention is paid to the mounting of components. Small resistors, etc., are supported by soldering to tags which are the appropriate distances apart, and multi-limb tags are employed to minimize the number of soldered joints. Where it is essential to solder more than one wire per limb on a tag, they must be soldered at the same time.

Larger components are clamped. Electron tubes are mounted in a holder so as to facilitate preliminary testing with 'standard electron tubes,' and they have a sprung nylon retainer; the final electrical connection is made by soldering on to an extension of the wire leading through the pins.

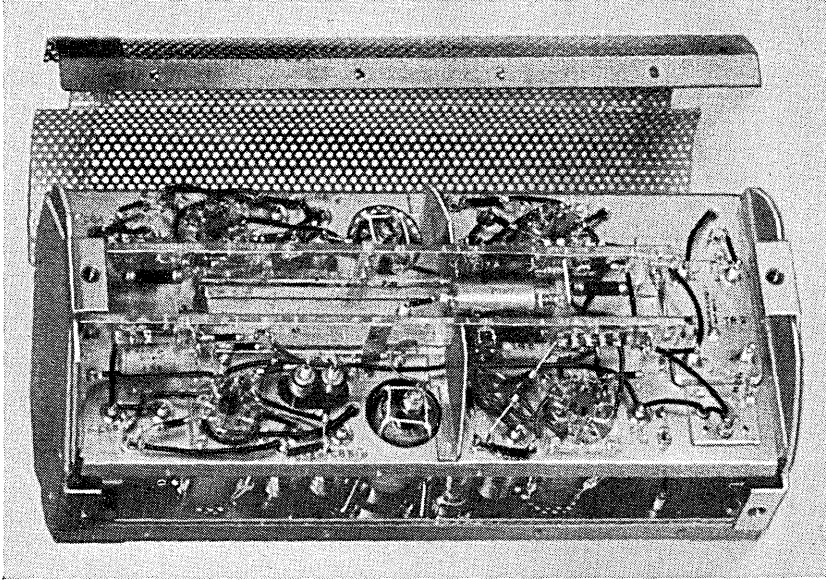


Fig. 5 — Amplifier.

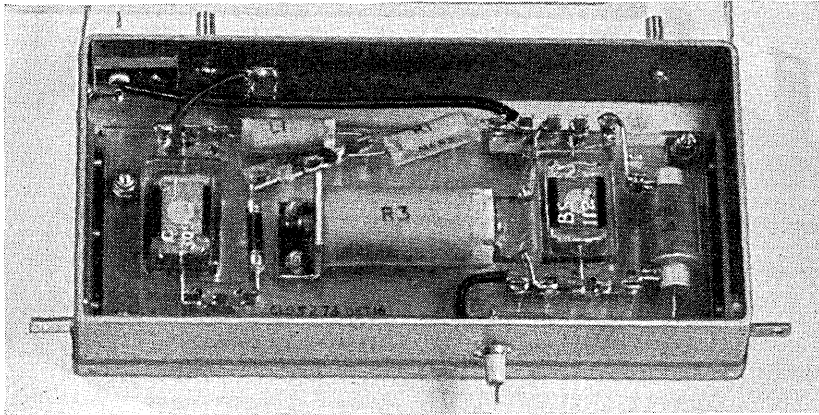


Fig. 6 — Feedback unit of amplifier.

DESIGN OF INTERNAL UNIT OF SUBMERGED EQUALIZER

The submerged equalizer corrects for the difference between the assumed design cable characteristic and the subsequently determined laid characteristic for equal attenuation lengths at 552 kc. It also absorbs the loss of 9 nautical miles of cable and has an attenuation of 26.0 db at 552 kc.

The construction is identical with the submerged repeater except for the replacement of all can assemblies, other than the power filters, by the equalizer cans. Fig. 7 is a schematic of the unit.

ELECTRICAL COMPONENTS

General

The components used in the repeaters were either designed specially for submerged repeaters or were standard items with improvements. There are approximately 300 components in each repeater of which 110 are in the amplifier. Rigorous control of manufacture and meticulous inspection is imperative to ensure a consistent long-life product, and cleanliness is essential at all stages. In some cases 'belt and braces' tech-

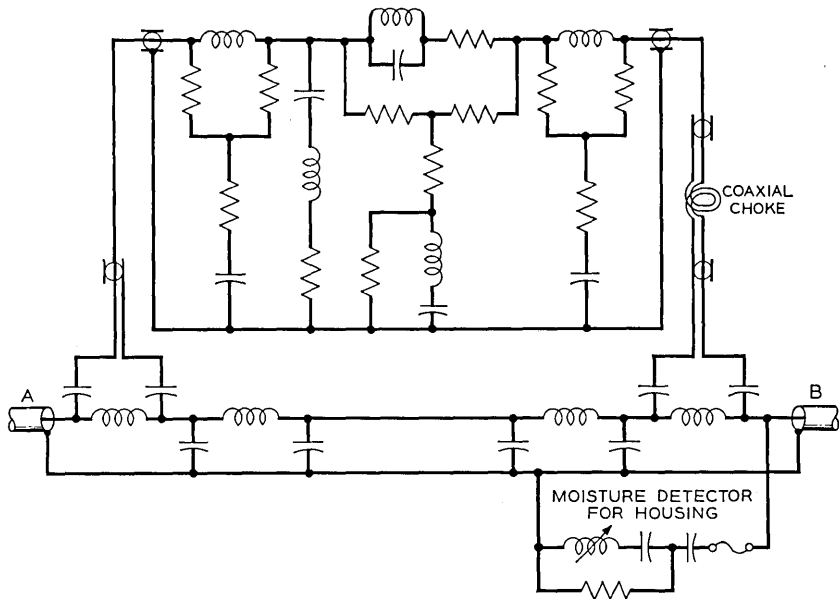


Fig. 7 — Schematic of submerged equalizer.

niques can be effectively employed, e.g., by using double connections. Over 1,500 separate soft-soldered connections are involved in the complete assembly. Much work has been done on components, but only a brief indication can be included here. A range of typical components appears in Figs. 4-6.

Resistors

Resistors fall into the following categories:

(a) Power resistors used solely for dc purposes (e.g., resistors providing the amplifier high-voltage supply). These are wire-wound vitreous-enamelled resistors on Sintox ceramic formers. Nichrome terminal leads are used, and all connections are brazed.

(b) High-frequency resistors whose tolerance is not close, and often carrying direct current but of low power (e.g., anode load resistances). A modification of a standard carbon-rod resistor is used. The ends of the rod are copper plated and the end caps and terminal leads are soldered on. The tolerance is normally ± 5 per cent, and the maximum rating permitted is about one-quarter of the commercial rating.

(c) Precise high-frequency resistors of resistance below 1,000 ohms (e.g., feedback components). Here wire-wound spool resistors are suitable, and bifilar or reverse layer windings with Lewmex enamel and silk-covered wire are used.

(d) Precise high-frequency resistors of high resistance. For terminating the input transformer a resistance of 17,000 ohms is required. Because it is not possible to make a suitable wire-wound resistor, high-stability cracked-carbon film resistors are used, but to minimize the effect of a disconnection two are used in parallel.

Inductors

The majority of inductors used in the amplifier and equalizer do not require a high Q-factor. They are wound on air-cored ceramic bobbins of four types, and the high-inductance ones are sectionalized. In general solid wire with Lewmex enamel and double-silk covering is used for the amplifier inductors, and stranded wire for the equalizer inductors.

A high Q-factor inductor is essential in the directional filters, and a carbonyl-iron pot core was used; the Q-factor is about 250 at 300 kg. Precise adjustment and stability of inductance was obtained by setting the gap between the halves of the pot core with a cement of Araldite (an epoxy resin) and titanium dioxide. A Perspex former was used.

Special inductors were required in the power filters to take the 316-ma

dc line current. A wave-wound air-cored coil was used for the carrier-path filter (L_1 in Fig. 2), and a toroid on an a.f. Permalloy dust-core ring for the low-pass filter (L_2 in Fig. 2). Solid wire, with Lewmex and double-silk covering, was used to keep the dc resistance to a minimum.

5.4 Capacitors

Capacitors are divided into three categories:

(a) Those subjected to the full line voltage which may operate at up to 3 kv.

(b) Those subjected to the amplifier high-voltage supply of 90 volts.

(c) Those which have negligible polarization (less than 10 volts), and which are often required to precise values.

Groups (a) and (b) are of the oil-filled paper type, with, respectively, four layers of 36-micron and three layers of 7-micron Kraft paper. The oil is a mineral type loaded with 18 per cent resin, and the capacitors are filled at 60°C and sealed at room temperature.

Small capacitors and those of precise value as in group (c) are silvered-mica capacitors. These are encased in an epoxy resin to give mechanical protection and a seal against moisture. Visual inspection of all mica plates is made before and after silvering, and any with cracks, inclusions, stains or any other abnormality are rejected. Mica is a very variable material and at times the percentage rejects were high, but probably many of the reasons for rejection would not have been significant as far as the life of the capacitor is concerned. However, experience has shown

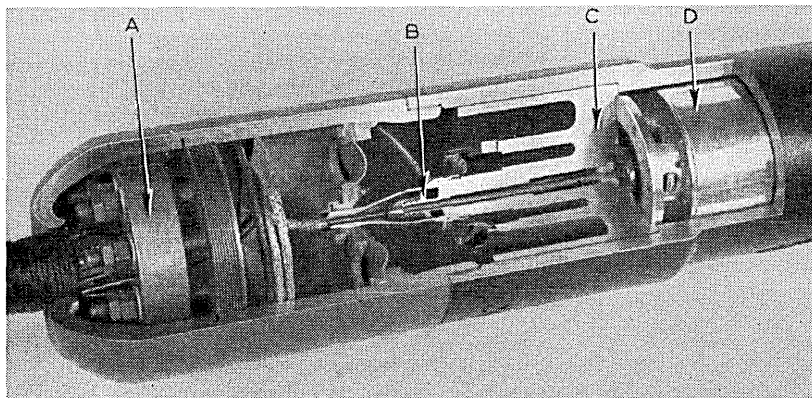


Fig. 8 — Details of housing construction. A. Armour clamp. B. Gland. C. Bulkhead. D. Part of internal unit.

that even with stringent precautions mica is not an entirely satisfactory dielectric material.

Other Components

Electron tubes form the subject of a separate paper.⁷ Of the other miscellaneous components used, one of interest is the short-circuiting fuse across the electron tube heaters. It is constructed like a normal wire-wound resistor on a Sintox tube former, but inside are two cupped copper electrodes filled with a low-melting-point eutectic alloy. If the full line current (316 ma) is passed through the winding, owing to a heater disconnection, the heat generated is sufficient to melt the alloy, which then fuses the two electrodes together. The winding is thus short-circuited, and a permanent connection is left between the electrodes.

DESIGN OF HOUSING AND GLAND

General

Although the maximum depth of water in which British rigid-type repeaters were laid did not exceed about 250 fathoms, the housings used for these repeaters were generally of a type designed for use at ocean depths, and when connected into the cable they were amply strong enough to transmit stresses up to the breaking point of any of the cables used.

The part of the housing which is sealed against water pressure consists essentially of a hollow cylinder, machined from hot-drawn steel tube, and closed at both ends by steel bulkheads carrying the cable glands through which the connections are made to the electrical unit (see Fig. 8). The latter is bolted rigidly to the inner face of the A-end bulkhead. The steel blanks used for the main cylinder and the bulkheads are tested with an ultrasonic crack detector, and after machining they are further subjected to magnetic crack-detection tests.

Each gland has a brass cover which completes the coaxial transmission path and contains a weak solid mixture of polythene and polyisobutylene (p.i.b.). Outside the brass cover is a larger chamber closed by a flexible polyvinylchloride (p.v.c.) diaphragm and containing p.i.b. — a viscous liquid — which prevents sea water coming into direct contact with the bulkhead seal and the gland assembly.

Cylindrical extension pieces, screwed on to the main casing, contain the clamps for attaching the repeater housing to the armour wires of the sea cable, and the housing is completed by dome-shaped end covers. Two external annular ridges near the centre of the housing accommodate

the special quick-release clamp used for handling the repeater during the laying operation.

Protection against corrosion is provided by shot-blasting the surface and then applying hot-sprayed zinc to a thickness of 0.010 in, followed by two coats of vinyl paint. The A-end of the repeater is finished red. The dimensions of the complete repeater are 8 feet 11 $\frac{3}{8}$ inches \times 10 $\frac{1}{2}$ inches diameter, and its weight is 1,150 lb in air.

Sealing of Housing

The bulkheads, which register on seatings designed to withstand the axial thrust due to the water pressure, are in the form of discs with extended skirts. A watertight and diffusion-proof seal is formed between the casing and the outer skirt of each bulkhead by a silver-soldering process, using carefully controlled electromagnetic induction heating to raise the jointing region to the required temperature. The diametral clearance between the cylinder and the locating surface of the bulkhead is 0.003 inch \pm 0.002 inch, the diameter of the bulkhead being reduced by 0.004 inch for an axial distance of 3 inches from the rim of the skirt to provide a recess into which the molten solder can flow.

The solder is applied as eight pre-formed No. 16 s.w.g. wire rings which are fitted into place cold and coated with a paste formed by mixing flux powder with dehydrated ethyl alcohol. The generator used for heating has a nominal output of 50 kw at a frequency of about 350 kc and is capable of raising the temperature of the jointing region to 750°C in 5 min. The temperature, as indicated by four thermocouples inserted in special holes drilled in the ends of the casing, is maintained at 750°C for a period of 45 min to allow ample time for the entrapped gas and flux pockets to float to the surface. Fig. 9 shows the arrangement for soldering in a bulkhead.

The primary object of the outer skirt is to keep the heated region far enough away from the base to prevent the temperature of the latter rising unduly. Temporary water jackets are also clamped over the gland and around the outside of the casing during the sealing operation. A subsidiary skirt on each bulkhead contains a vent hole which serves to allow displaced air to escape as the bulkheads are inserted into the casing. These vents are later used to apply a low-pressure gas-leak test to the bulkhead seals and then to flush the housing with dry nitrogen to remove any trapped moisture. The vents are finally sealed. At this stage the sealed housing is pressure-tested in water at 1 $\frac{1}{2}$ tons*/square inch for a

* These are long tons. 1 long ton = 2240 lb.

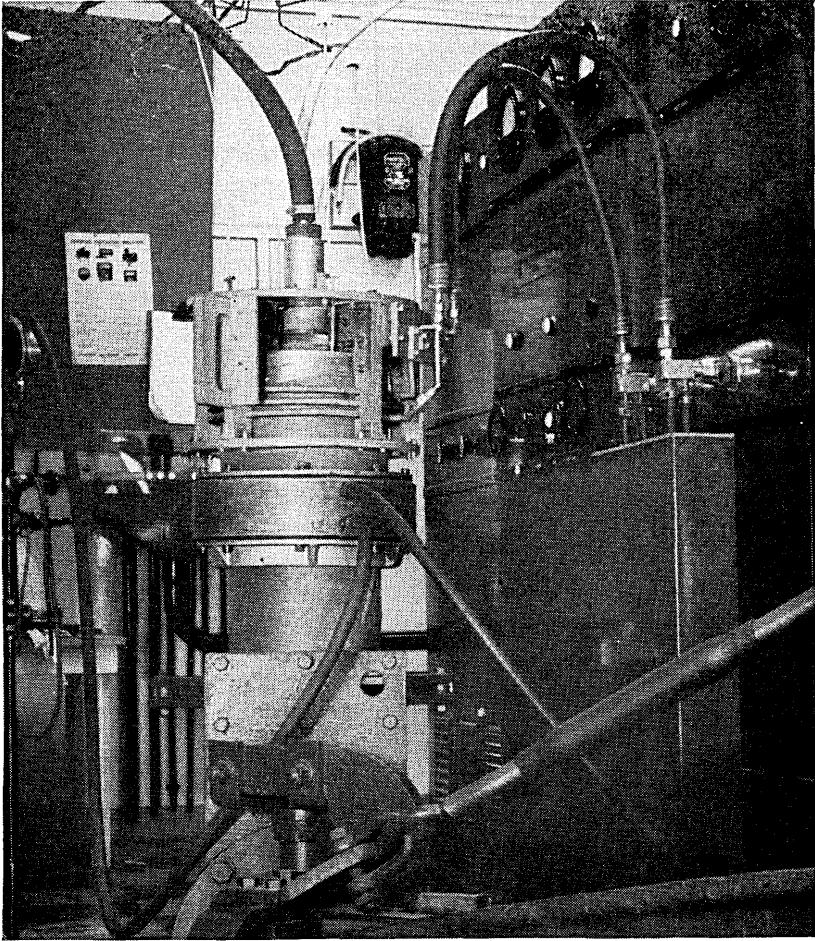


Fig. 9 — Silver-soldering of bulkhead into housing with induction heater.

period of seven days, a moisture detector, mentioned previously, being used to check that no leakage occurs.

Glands

The deep-sea gland was developed from the castellated gland which has been used successfully for a number of years in shallow-water repeaters. The basic principle of this gland is very simple and is shown in Fig. 10; the polythene-insulated cable core passes right through the

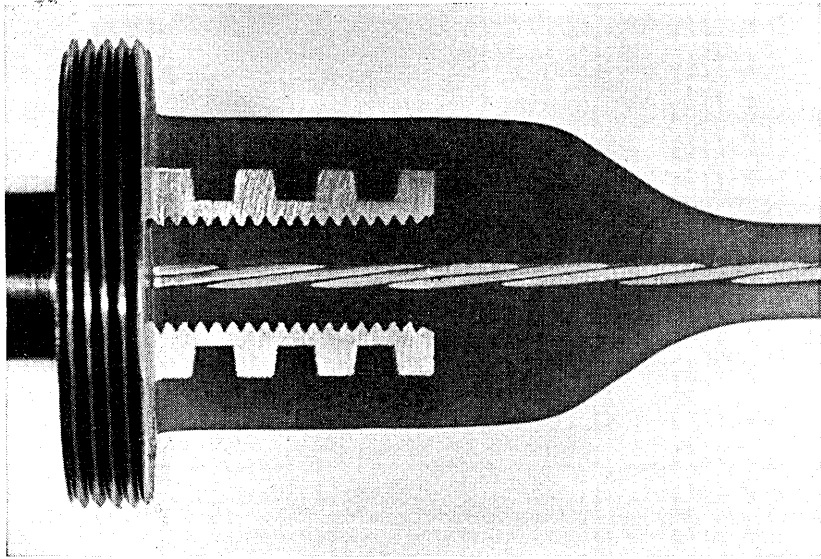


Fig. 10 — Section of high-pressure gland.

bulkhead, and the initial seal is formed by the contraction, during cooling, of polythene moulded on to the core and enclosing a steel stem, having a castellated profile, which forms part of the bulkhead. Each side of the castellation has a taper of about 7° . The application of water pressure increases the contact pressure between the polythene and the stem, thus making the gland inherently self-sealing. As an additional safeguard, the gland stem is first prepared by a lead plating and anodizing process, followed by the application of a thin film of polythene which forms a chemical bond to the plated surface. The injected polythene merges with this film, thus bonding the molded portion to the castellated stem. Tests on sample glands, using a radioactive tracer, have shown no measurable (less than 0.001 mg) water diffusion at a pressure of 5 tons*/square inch over a period of 6 months.

Intrusion of the polythene into the housing, at hydraulic pressures up to at least 6 tons*/square inch, is eliminated by the use of a small-diameter core and by the provision of a screw thread in the hole through which the core passes. During the molding operation a corresponding thread is formed on the polythene core itself. This method of construction distributes the axial force over a sufficiently wide area to prevent any appreciable creep of the polythene.

The completed gland assemblies were all subjected to a minute X-ray examination, followed by a pressure test at 5 tons*/square inch for three months. Whilst under pressure, the glands had to withstand a voltage test of 40 kv dc for 1 minute, to show no ionization effects when a voltage of 3 kv (r.m.s.) at 50 cycles was applied and to have an insulation resistance greater than 20×10^{12} ohms.

MANUFACTURE

General

The manufacture of the electrical units was carried out in accommodation specifically designed for submerged-repeater production. Temperature was controlled at 68°F and the relative humidity was less than 20 per cent in the component shops and 40 per cent in the assembly and test shops. Filtered air forced into the building maintained a slight positive pressure with respect to the outside and eliminated the ingress of dust. With the exception of the tubes and some resistors all components were manufactured in this 'diary' (Fig. 11). Operators are specially selected, and they must change into clean protective clothing in an ante-room before entering the working area, where no smoking or eating is permitted. All operators are particularly encouraged to report or reject any condition which is abnormal or in which they have not complete confidence. Rigorous inspection and testing were carried out by the contractor at all stages, and a Post Office team collaborated with 'floor' inspection and the examination and approval of test results.

The Electrical Unit

The components, after the most careful examination and testing, which in some cases included an aging test, were assembled into their cans and then subjected to a shock test before undergoing detailed electrical characteristics tests. Initial tests on the amplifier were done with a set of 'standard' electron tubes, which were later replaced by the final tubes for the complete tests. The cans were then assembled in a repeater chassis and the electrical tests required before sealing performed — this included a gain response to determine the best settings for the trimmer pads in each transmission band. After fitting and sealing the outer brass case, dry nitrogen was blown through the unit for 24 hours and the gas holes then sealed. The overall electrical characteristics were then taken, the repeater was energized for a two weeks' 'confidence trial' and the characteristics were rechecked. During the 'confidence trial' the gain was

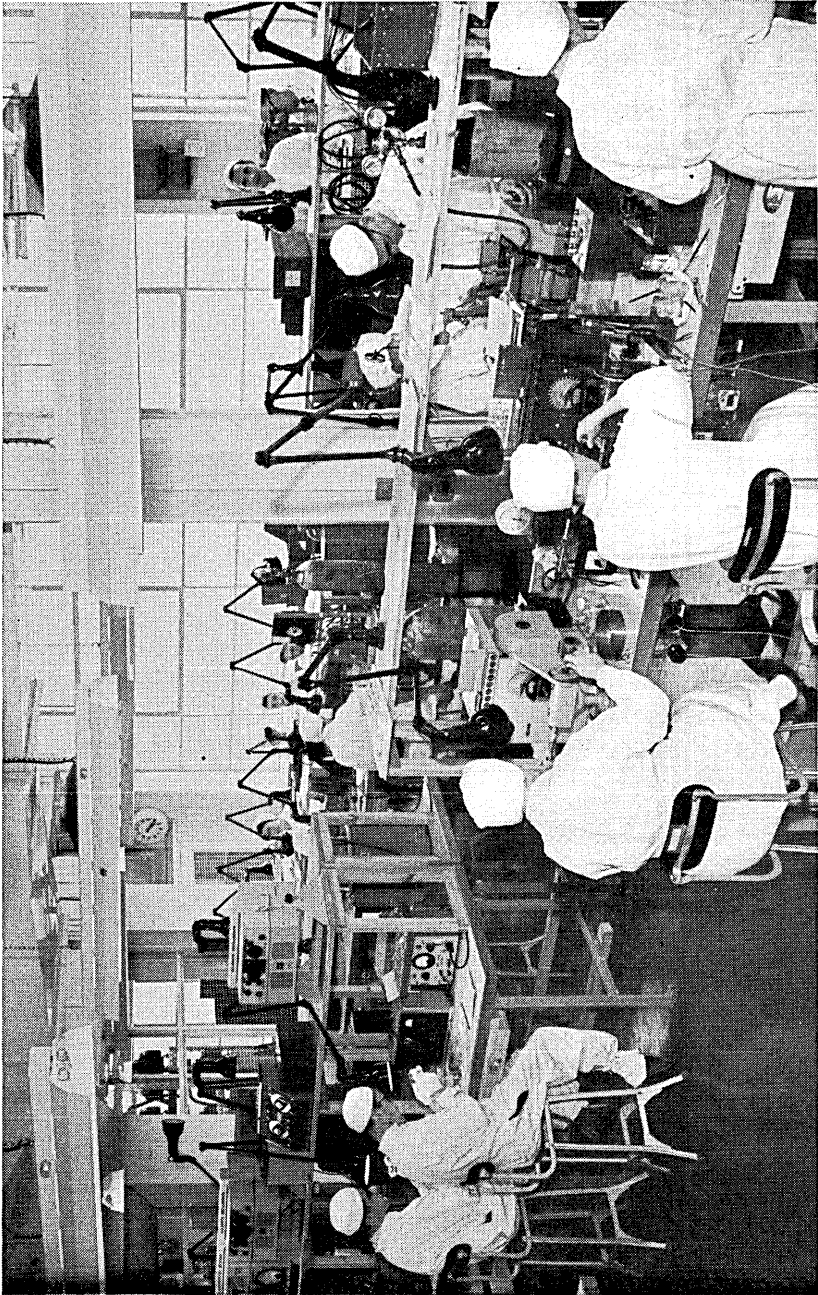


Fig. 11 — Coil production in the 'dairy'.

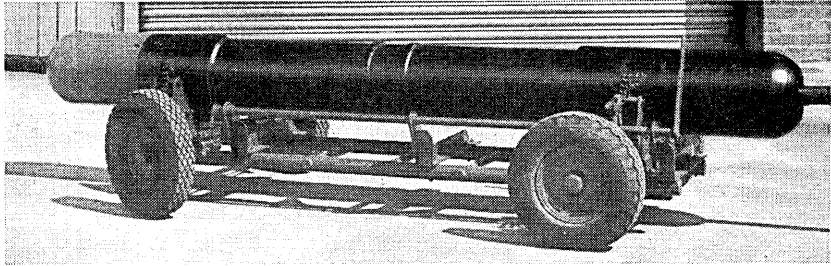


Fig. 12 — Completed repeater.

continuously monitored on a recorder (duplicated to distinguish between test equipment and repeater variations) on which changes in gain of 0.01 db were clearly indicated. On satisfactory completion of these tests the unit was ready for housing.

Assembly of Electrical Unit in Housing

The first step was to complete the molded joint between the tail cables from the A-end of the electrical unit and the low-pressure side of the appropriate bulkhead. This joint was X-rayed and proof tested at 20 kv dc for 1 minute. The electrical unit was then bolted to the bulkhead, the slack tail cable being correctly coiled into the recess provided, and the whole assembly was lowered into the housing for the first silver-soldering operation. Following this sealing the tail cable joint was made to the B-end bulkhead, which was then lowered into the housing and sealed.

A leak test was then made by applying an internal air pressure of 5 lb/square inch (gauge) and observing the surface when wetted with a solution of a suitable detergent in water. After flushing with dry nitrogen the vents were sealed and the housing was pressure tested. Finally the brass gland covers were fitted and filled with compound, the extension pieces were screwed on, the flexible diaphragms were fitted and the internal space was filled with polyisobutylene. The housing was then ready for further electrical testing.

Tests on Complete Repeater

After housing, the repeaters were submerged in a tank of water for a three-month electrical 'confidence trial.' Before and after the trial the complete characteristics were checked and the noise was monitored on both terminals; during the first and last few weeks of the trial the gain

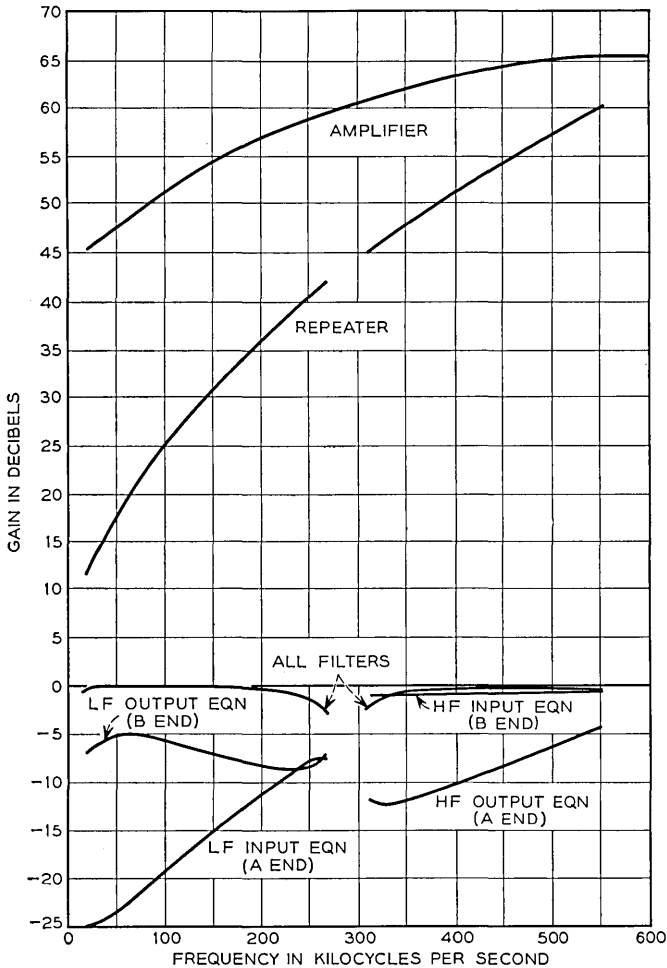


Fig. 13 — Repeater gains and losses.

was monitored on recorders in both directions. Owing to the insertion and withdrawal of repeaters in the power circuit from time to time, the repeaters were subjected to several power-switching operations and temperature cycles.

Stability of electrical characteristics, particularly gain, between the pre-housing tests and the completion of the 'confidence trial' some four months later was regarded as an important criterion of the reliability of a repeater. Unfortunately test conditions and differences between, and

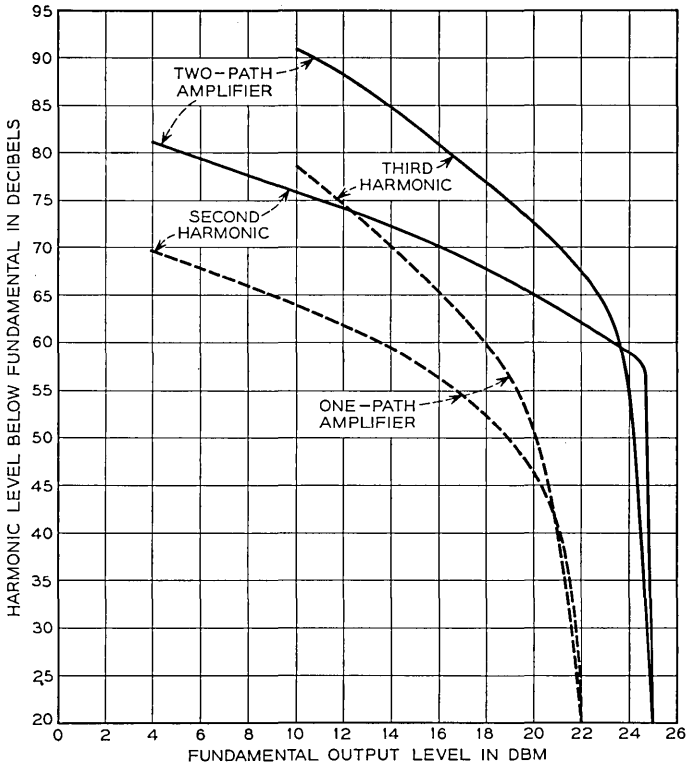


Fig. 14 — Amplifier distortion.

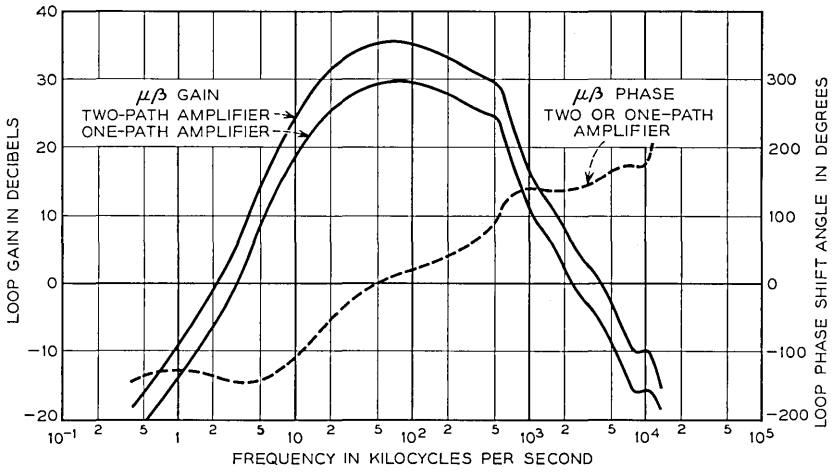


Fig. 15 — Amplifier $\mu\beta$ characteristic.

stability of, the testing equipments reduced the accuracy originally expected, but even so, changes of over 0.1 db were regarded as significant.

Connection of Repeaters to Cable

On board the cable ship the cable ends were prepared by making tapered molded joints to 0.310-inch tail cable, sliding the domed ends of the repeater up the cable and forming the armor wires round the armor clamps. The tapered joint included a castellated ferrule on the center conductor, which, operating on the principle of the main gland, acts as a barrier against the possible passage of water down the center conductor into the repeater. The final assembly operation consists of jointing the tail cables, bolting the armor clamps to the repeater housing and screwing on the domed ends. Fig. 12 shows a completed repeater connected to a cable.

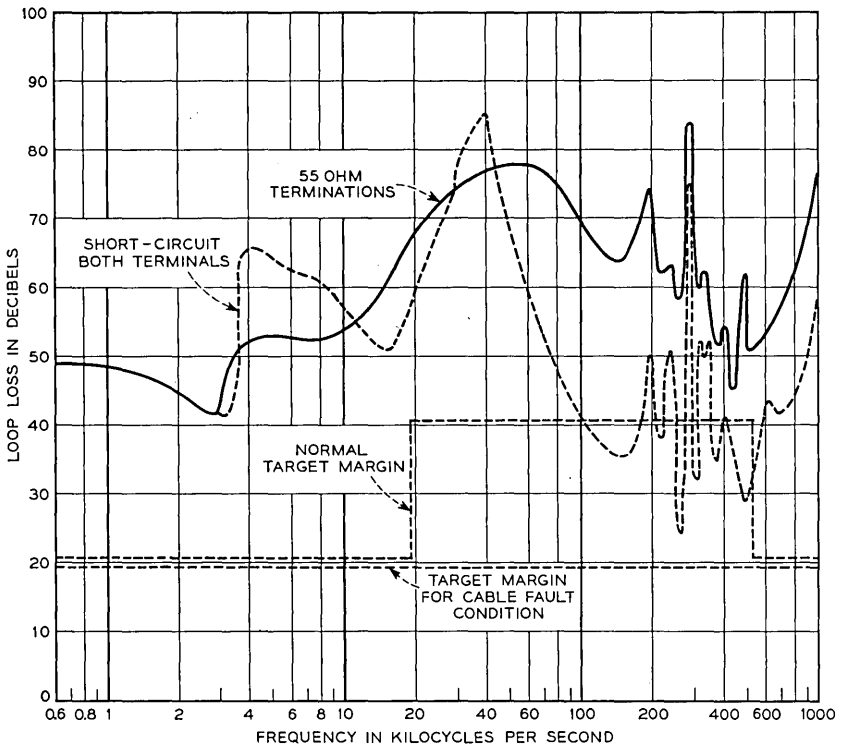


Fig. 16 — Repeater loop loss measured at amplifier input.

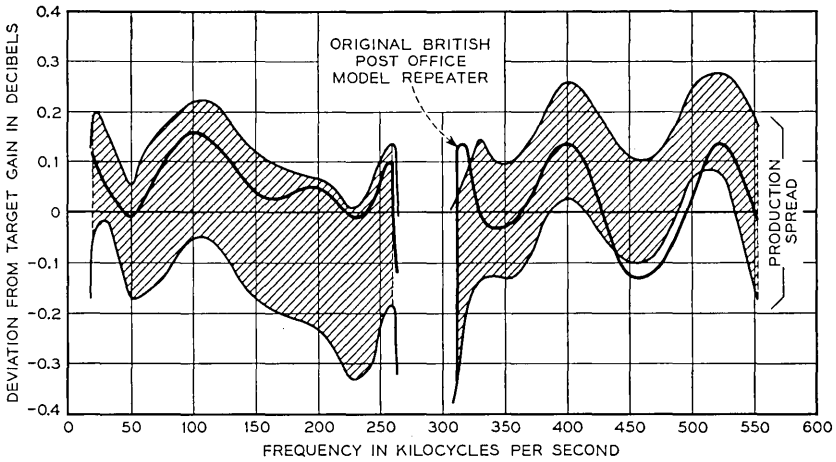


Fig. 17 — Repeater-gain response.

PERFORMANCE

The gains and losses of various sections of the repeater are shown in Fig. 13. Figs. 14 and 15 show, respectively, the harmonic distortion and the stability characteristics of the amplifier with one and two paths operating. The total shunt loss across the amplifier is shown in Fig. 16 as a margin above the amplifier gain. The curves show the result with 55-ohm terminations on the repeater and with a short-circuit on each terminal. Fig. 17 shows the production spread in gain of the 16 repeaters for the system as a deviation from the target value. The highest standard deviation (at 260 kc) was only 0.11 db. In all respects the production repeaters proved to be very consistent and satisfactory in their performance and differed little from the original laboratory-built model.

Typical electrical characteristics of a repeater and the submerged equalizer are shown in Appendices 1 and 2 respectively.

The characteristics of the completed link are described elsewhere,⁹ but it is of interest to note that the overall tests showed that the link behaved as predicted and met the noise requirement and the design margins.

ACKNOWLEDGMENTS

It will be appreciated that the design and manufacture of these repeaters has been an undertaking of teams rather than of individuals. The authors are very grateful to Standard Telephones and Cables, Ltd.,

and Submarine Cables, Ltd., for their unsparing efforts to ensure the very highest standards in the engineering, production and testing of these repeaters. Numerous firms have also co-operated in specialized fields, and the authors are very appreciative of their help. The authors also wish to acknowledge the enthusiastic assistance of their many colleagues in the Research Branch of the Post Office in the design and in the supervisory inspection during manufacture. Finally a grateful acknowledgment is made to the Engineer-in-Chief of the British Post Office for permission to publish the paper.

APPENDICES

1 PERFORMANCE OF TYPICAL SUBMERGED REPEATER

- (a) Insulation resistance..... 8000 megohms (cold).
- (b) DC resistance at 20°C.

Current, ma	DC resistance, ohms
5	343.0
20	343.2
50	344.2
100	347.9

- (c) Voltage drop at 316 ma..... 124 volts
- (d) Carrier gain (55 ohms) without moisture detector.

Frequency, kc	Gain, db	Frequency, kc	Gain db
20	11.54	308	44.52
30	13.82	312	44.87
50	17.47	320	45.56
100	25.06	330	46.29
150	30.86	350	47.75
200	35.81	400	51.19
230	38.40	450	54.20
260	40.96	500	57.31
264	41.13	552	60.01
268	40.83		

- (e) Noise level.
 - A terminal (312-552 kc)..... -59.8 dbm
 - B terminal (20-260 kc)..... -70.3 dbm
- (f) Harmonic level.
 - 170 kc fundamental level at B terminal..... +10 dbm
 - 340 kc second harmonic level at A terminal..... -60 dbm
 - 510 kc third harmonic level at A terminal..... -58 dbm

(g) Supervisory — 260.800 kc (nominal).

Fundamental level at B terminal, dbm	Second harmonic level at A terminal, dbm
-12	-26
-2	-13.8
+8	-3.6

(h) Moisture detector.

Resonant frequency with 30-ft cable tail..... 1,237 kc

(i) Impedance.

Return loss against 55 ohms

Frequency, kc	A-terminal return loss, db	B-terminal return loss, db
20	17	8
50	17	13
100	16	15
200	16	4
260	16	4
312	13	21
350	14	14
500	18	16
552	16	25

2 PERFORMANCE OF SUBMERGED EQUALIZER

- (a) Insulation resistance..... 8,000 megohms
- (b) DC resistance at 20°C..... 9.2 ohms
- (c) Voltage drop at 316 ma..... 3.0 volts
- (d) Carrier loss (55 ohms) — without moisture detector.

Frequency, kc	Loss, db	Frequency, kc	Loss, db
20	4.28	260	15.90
30	4.23	312	18.26
50	4.87	350	19.96
100	7.47	400	21.75
150	10.35	450	23.16
200	13.04	500	24.55
230	14.52	552	25.97

(e) Moisture detector.

Resonant frequency with 5-ft cable tail..... 1,387 kc

(f) Impedance

Return loss against 55 ohms

Frequency, kc	A-terminal return loss, db	B-terminal return loss, db
20	35	31
50	19	19
100	25	25
260	34	27
552	30	23

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Power-Feed System for the Newfoundland-Nova Scotia Link

By J. F. P. THOMAS* and R. KELLY†

(Manuscript received September 22, 1956)

Design engineers now have available the results of many years of operating experience with submerged-repeater systems supplied from electronic, electromagnetic and rotary-machine power equipments. To meet the very high standards of reliability required for the transatlantic telephone system, a scheme has been evolved that is a combination of new developments and the best features of previous methods. Electronic-electromagnetic equipment forms the basis of an automatic no-break system requiring very little routine maintenance.

INTRODUCTION

The operating power for the submerged repeaters of the Clarenville-Sydney Mines link is derived from a constant current supplied over the central conductor from power equipments located at the two terminal stations. In order to protect the electron tubes in the repeaters the current must be closely maintained at the design value, irrespective of changes in the mains supply voltage or ground potential differences between the two ends of the link. Automatic tripping equipment must be provided to disconnect the cable supply should the current deviate beyond safe limits, but otherwise there must be a minimum of interruptions due to power-equipment and primary-source failures.

Earlier British Post Office schemes have been powered by electronically controlled units feeding from one end only.† Manual change-over to standby units has been provided at the end feeding power and at the distant end — a method which has satisfactorily met the economic requirements of short schemes.

* British Post Office, † Standard Telephones and Cable Ltd.

† WALKER, D. C., and THOMAS, J. F. P., The British Post Office Standard Submerged-Repeater System for Shallow-Water Cables (with special reference to the England-Netherlands System), *Proc. I.E.E.*, **101**, Part I, p. 190, Feb., 1954.

For the Clarendville-Sydney Mines link a new and more reliable design of equipment has been developed. An automatic no-break system provides an uninterrupted supply to repeaters unless equipments at both ends of the link simultaneously fail to deliver power.

The main improvement in the reliability of the equipment is the replacement of all high-power electron tubes by electromagnetic components. The automatic no-break system takes advantage of the fact that the rating of the repeater isolating capacitors has been chosen to permit single-end feeding. Normally the link is fed from both ends, but in the event of one equipment failing to deliver power the link is powered from the other end without interruption to the cable supply. If the failure is due to a power-equipment fault, double-end feeding can rapidly be re-established by manual switching to the standby. During an ac-supply failure, single-end feeding must be maintained until the supply is restored. In view of the very reliable no-break ac supply provided at both stations, the possibility of a simultaneous ac supply failure at both ends of the link is extremely remote.

The power equipments at each end of the link must be capable of supplying the whole of the power to the cable should one end fail, which requires that each should be capable of operating as a constant-current generator. If two constant-current generators are connected in series, unless precautions are taken, an unstable combination will result and the unit supplying the higher current will drive the other unit 'off load.' Manual adjustment could be provided to equalize the currents fed from the two ends, but a different solution has been developed in which one of the units is a constant-current master and controls the line current, while the other unit is a slave whose voltage/current characteristic in the normal operating range is such that its current is always equal to that of the master unit. If the slave unit fails, the master will take over the supply; if the master unit fails, the slave unit will take over the supply and automatically assume the role of a master unit. The first unit switched on to an unenergized link operates as a master generator and the other unit, on being switched on, automatically operates as a slave. Other than ensuring that the link is safe for energizing, there is no need for any cooperation between the two ends when putting the equipment into service.

DETAILS OF METHOD EMPLOYED

The Master-Slave System of Operations

The output-current/output-voltage characteristics for the equipments are shown in Fig. 1, and are the same for both regular and alternate

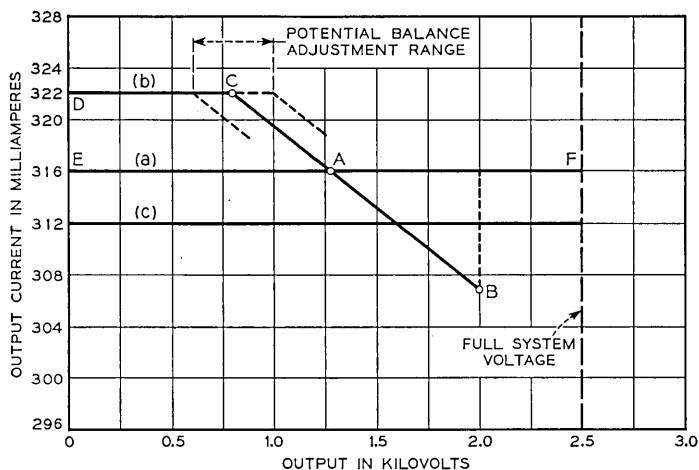


Fig. 1 — Output-current versus output-voltage characteristics. (a) Master. (b) Slave. (c) Master versus master shut-down.

equipments at both ends of the link. Any equipment can operate with any of the characteristics (a), (b) or (c).

Normally the choice between characteristics (a) and (b) is made automatically by the equipment. If the output voltage does not reach 80 per cent of the full link voltage (approximately 2 kv), the unit will have the slave characteristic (b) (DCAB). If the output voltage reaches or exceeds 2 kv, the unit automatically switches to the master characteristic (a) (EAF). Once having switched to the master characteristic the equipment does not automatically change back to the slave characteristic even if the output voltage falls below 2 kv.

When the link is energized, the first equipment switched to line will come on as a slave unit; its output voltage will then pass 2 kv and it will automatically be switched to the master characteristics and the complete link will be energized from one end. The second unit switched to line will come on as a slave unit, and having a higher output current, will drive down the output voltage of the master unit at the other end until the current of the slave unit has become equal to that of the master (DCA in Fig. 1). The output voltage of this equipment will not exceed 2 kv and it will not switch to master. The cross-over point of the two characteristics, A, will determine the potential fed from each end, and this can be adjusted as indicated by the dotted lines near C.

In an emergency, an equipment can be taken out of service by switching off the ac supply, and the links will then be powered from the dis-

tant end only. Should the master end be switched off, the distant slave unit will switch to master characteristic as soon as its output voltage exceeds 2 kv. This abrupt disconnection of one equipment causes unnecessary voltage surges on the cable, and when an equipment is removed for normal maintenance purposes the following procedure is adopted. The slave equipment is switched to the master characteristic (an external key is provided for changing from master to slave or vice versa, but see the limitation described in the next paragraph). This leaves two master equipments feeding the cable, but any redistribution of voltage is slow since the currents are approximately equal. An external control (master/master shut-down), is then operated on the equipment to be taken out of service, changing its characteristic to that shown in Fig. 1(c). The output voltage of this unit will then be slowly reduced, and when it is zero the equipment can be switched off without causing surges on the cable.

The current deviations occurring over the slave characteristic (c) (from +2 per cent to -3 per cent) are the maximum permitted by the tube design engineers for the tubes in the submerged repeaters, and are permitted only for short periods. The circuit associated with the manual switching of the equipment to the slave characteristic is therefore made inoperative if the output voltage exceeds 2 kv, since in this range the slave characteristic is the extension of the line CAB on curve (b) and the current is outside the permitted range. The slave characteris-

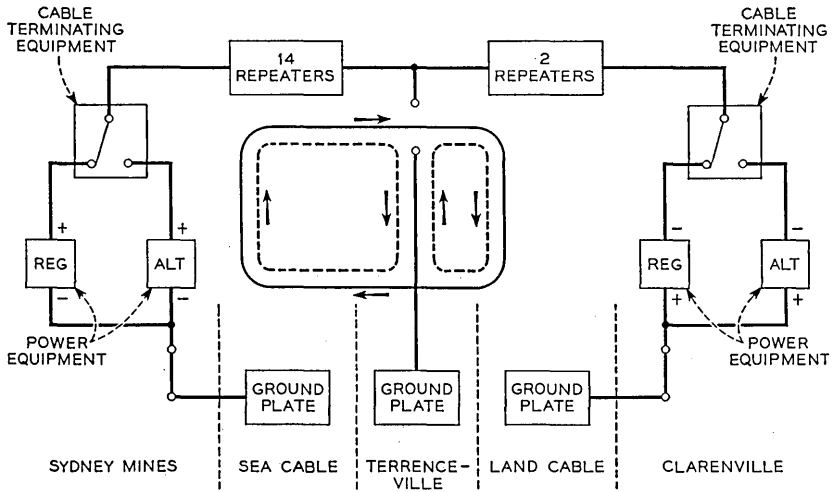


Fig. 2 — Current paths on Clarenville-Sydney Mines link.

tic over the range CAB is controlled by a voltage-sensitive circuit connected near the output of the equipment, and the stability of the characteristic against input voltage and component aging is the same as for the master characteristic. Changes in the distribution of the system potential due to supply variations and component aging are therefore small.

Overall Current and Voltage Distribution

Facilities have been provided at the junction of the land and sea cables (Terrenceville) to connect a power ground to the center conductor of the cable. Normally this ground will be disconnected, but during installation it enables the land and sea sections to be energized separately and may subsequently be of assistance in the localization of cable faults near Terrenceville.

The full line in Fig. 2 shows the current path with normal double-end feeding, while the broken lines show the current paths when a ground is connected at Terrenceville.

The full line (d) in Fig. 3 shows the voltage distribution along the link

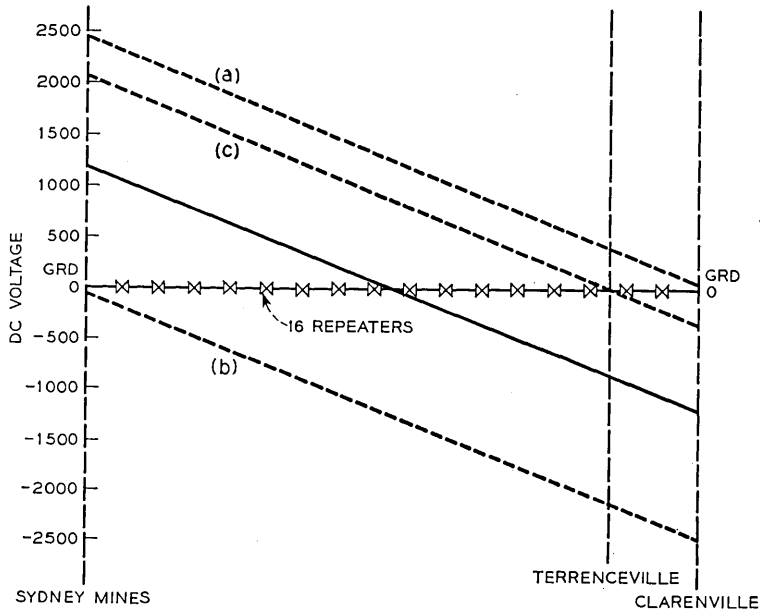


Fig. 3 — Potential distribution on Clarenville-Sydney Mines link. (a) Single-end feeding from Sydney Mines. (b) Single-end feeding from Clarenville. (c) Ground at Terrenceville; double-end feeding. (d) Normal operation; double-end feeding.

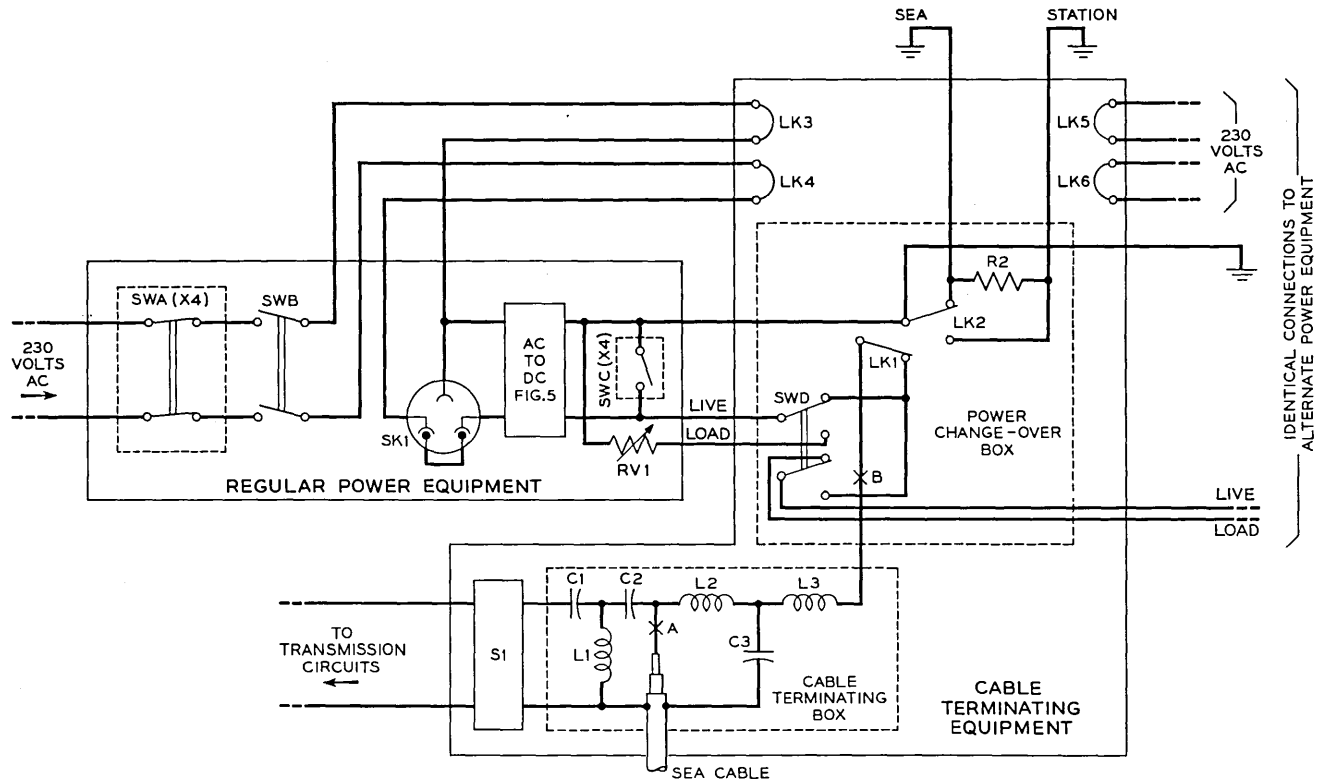


Fig. 4— Cable terminating equipment and interconnections with power equipments.

with normal double-end feeding, the broken lines (a) and (b) show the distribution with single-end feeding from Sydney Mines and Clarenville respectively and the broken line (c) shows the distribution when a power ground is connected at Terrenceville.

DETAILS OF EQUIPMENTS

Connection of the Equipment to the Cable

Each station is provided with two power equipments and one cable-terminating equipment interconnected as shown in Fig. 4. When the live side of the output of the regular equipment is connected to the cable via SWD and the link LK1, the alternate equipment output is connected to its own dummy load (equivalent of RV1) and vice versa.

The grounded sides of the regular and alternate equipments are made common and then connected via a removable link, LK2, to the sea ground. A safety resistor R2 connects the sea ground to the station ground to restrict the rise in potential to 100 volts if the sea ground becomes disconnected. During maintenance on the sea-ground circuit the link LK2 can connect the power equipment ground to the station ground.

If, for maintenance purposes, it is necessary to feed from the distant end only, the link LK1 can connect the cable to the power-equipment ground and disconnect the live side of both power equipments from the line.

Safety Interlocks

Safety interlock circuits are installed to protect the maintenance staff if the equipments are used incorrectly and are not the normal methods employed for controlling the power supplies. With double-end feeding, dangerous voltages are generated at both ends of the system, and when access is gained to any point in the equipments personnel must be protected from the local and distant power sources.

To minimize interruptions to traffic, the units of the cable-terminating equipment have been grouped under three headings (see Fig. 4), namely

(a) Transmission equipment (S1) isolated from the dc cable supply: this includes cable simulators and monitoring facilities not associated with the power supplies.

(b) Equipment associated with the dc supply that can be made safe without interrupting traffic.

(c) Equipment that can be made safe only by interrupting traffic.

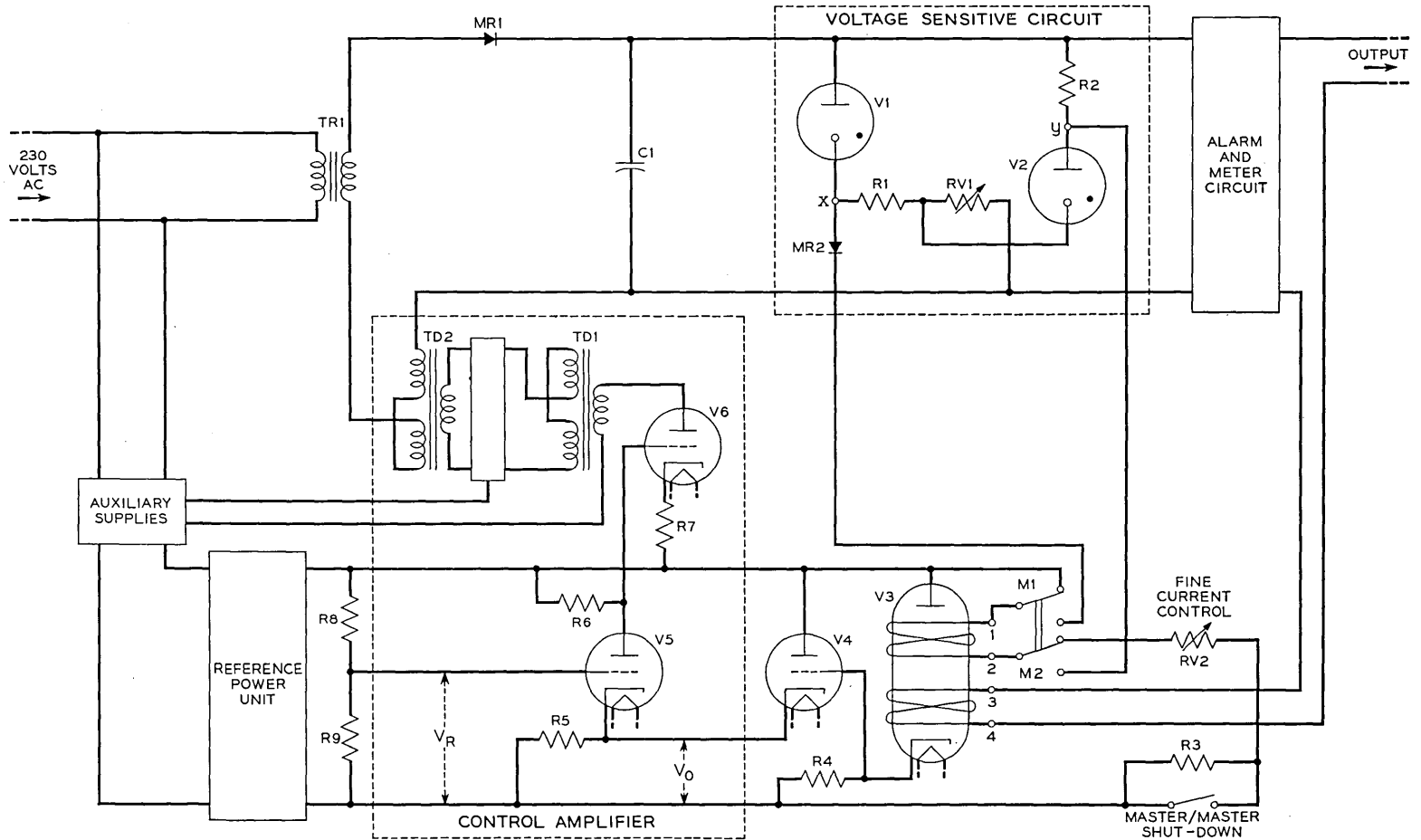


Fig. 5 — Simplified schematic of power-feeding equipment.

Group (a) is treated as normal terminal transmission equipment and is not interlocked. Groups (b) and (c), the power-change-over and cable-terminating boxes respectively, both require that the local power equipments are switched off before they can be made safe. The external panel covers over both boxes have links disconnecting the ac supplies to both of the local power equipments when the covers are removed (LK3-LK6). This will not interrupt traffic, since single-end feeding will continue from the distant station.

The doorknob switch of the power-change-over box automatically connects the live lead to ground (at the point B) when the door is opened. This will not interrupt traffic since the impedance of L2 is high at carrier frequencies. Changing over the power equipments and grounding arrangements can therefore be performed without interrupting traffic.

The doorknob switch of the cable-terminating box automatically connects the center conductor of the cable to ground (at the point A) when the door is opened. Traffic will therefore be interrupted if maintenance work is necessary within this box.

Access is gained to a power equipment by opening one or more of four doors. Each of the doorknob switches disconnects the ac supply (SWA) and short-circuits the output of the equipment (SWC).

It will be appreciated that if the correct procedure is adopted the local power equipments will be switched off by SWB after the master/master shut-down procedure (described in section on *The Master-Slave Systems of Operations*) has been carried out and not by removing the panel covers or opening the doors.

Electrical Details of Power Equipment

Control Method.

Fig. 5 is a functional simplified circuit diagram in which TR1, MR1 and C1 represent a conventional unregulated power unit.

The control circuit compares a signal proportional to the output current, V_o , with a stable reference signal, V_R , the two signals being applied to the cathode and grid, respectively, of V5; the difference between them is amplified and used to adjust the voltage fed to the rectifier circuit, MR1, to maintain the output current constant.

Ignoring at this stage the auxiliary coil 1-2 of the magnetically controlled diode V3, the output current flows through the coil 3-4 and controls the voltage across R4 and hence, via the cathode-follower V4, the potential V_o on the cathode of V5. V_R is a function of the output of a conventional electronic constant-voltage power unit (reference power

unit) using a neon tube for its reference. The grid-cathode bias of V5 controls the secondary impedance of the transducer TD2 via the amplifier V5, V6, TD1. The gain of the control amplifier and the sign and magnitude of the normal impedance of the secondary of TD2 are arranged to give a fall of approximately 0.25 per cent in the current from full system load to short-circuit.

Two advantages are obtained by employing a magnetically controlled diode for V3 instead of an electrostatically controlled tube. The control is directly proportional to the output current, and is not dependent upon the stability of a series resistor, while the control circuits are isolated from the output-circuit voltage, which simplifies maintenance of the more complex parts of the equipment.

Current Characteristics.

Without current flowing in the auxiliary coil 1-2 (on V3 in Fig. 5) the equipment has a normal constant-current characteristic, the value of which, 322 ma, is preset by adjusting the mechanical position of the coil assembly along the main axis of V3.

Two neon tubes and two resistors form the bridge V1, V2, R1 and R2, which is balanced when the voltage drop across R1 and R2 equals the constant voltage across V2 and V1, the output voltage at which this occurs being adjusted by RV1. At voltages below balance, current tries to flow from y to x and at voltages above balance it flows from x to y. The balance voltage corresponds to the voltage at which the slave-unit characteristic changes slope (C in Fig. 1). For voltages below balance the rectifier MR2 prevents current from flowing in the winding 1-2 (on V3), and in this range the constant current of 322 ma is maintained (see DC, Fig. 1). For voltages above balance, current flows in the winding 1-2 and progressively decreases the output current (CAB, Fig. 1). At 80 per cent of the full link voltage, the contacts of relay M are operated and disconnect the auxiliary coil 1-2 from the voltage-sensitive bridge and connect it across the reference supply. The current through 1-2 is then set by the fine current control (RV2) to make the output current the required 316 ma. As previously stated, relay M does not automatically switch back when the output voltage drops below 80 per cent of full link voltage; the current characteristic of a master unit is EAF in Fig. 1.

The master/master shut-down characteristic [Fig. 1, curve (c)] is obtained by short-circuiting R3, which causes the constant current to fall to 312 ma. Adjusting RV2 would be equally effective, but short-circuiting R3 does not permanently disturb the normal current setting.

Alarms.

The equipment trips and gives both aural and visual alarms for +20 per cent current, +20 per cent full link voltage and for the failure of certain auxiliary supplies that would damage the equipment.

Aural and visual alarms are provided for ± 1 per cent current and ± 3 per cent voltage and for equipment changes from slave to master characteristic or vice versa. Visual indication is given if the ac supply fails.

Reliability.

Where possible, only components of proven integrity have been used. High-power thermionic tubes have been excluded and the tube types employed have been specially selected for long life. Electrolytic capacitors have been excluded from all except one position, and in this case the component has been divided into six units in parallel, the failure of all but one of these units causing only a slight increase in the output ripple.

Particular attention has been given to the continuity of the output circuit. A failure of a power equipment for any reason other than an open-circuit in the output will not interrupt traffic, the link changing to single-end feeding from the far end. A disconnection anywhere in the dc feed path will disconnect all power from the line. Relatively short-lived components in this part of the circuit have either been duplicated in parallel or shunted by resistors capable of carrying the full line current.

Other facilities.

Each equipment has facilities for checking its overall performance. A variable-ratio transformer can be introduced at SK1 (Fig. 4) and with the 4-position dummy load referred to earlier, the regulation against alternating input voltage and output load can be measured.

Provision is made for checking all the alarms, and the current can be measured at strategic points in the control circuit either when the equipment is normal or with the loop feedback disconnected.

Separate large-size meters are provided for measuring the output voltage and current to an accuracy of ± 1 per cent. A more accurate measurement of current is obtained from potentiometric measurements made across a standard resistor connected in series with the output.

Electrical Details of Cable-Terminating Equipment

The majority of the electrical features of the cable-terminating equipment have already been considered.

Within the cable-terminating box (Fig. 4) are the power-separating filters; the high-pass filters C1, C2 and L1 passing the carrier frequencies and the low-pass filter L2 passing the direct current. The transmission equipment represented by the block S1 is for convenience mounted in the cable-terminating cubicle. The extra low-pass filter L3, C3 can be specially designed to prevent signals that are peculiar to the site (local radio stations, etc.), which are picked up in the power equipment, from being fed to the transmission circuits.

Metering facilities (not shown in Fig. 4) are provided to check the continuity of the sea-ground circuit. A separate insulated wire is connected to the sea-ground plate and the continuity is checked by measuring the voltage drop along the ground cable. Aural and visual alarms are given if the sea ground becomes disconnected.

Current and Voltage Recorders

Current and voltage recorders are provided for both the regular and the alternate equipments, the values being measured at the points where the outputs of the power equipments enter the cable-terminating equipment.

A magnetic-amplifier unit drives the current recorder, the scale deflection being from -5 per cent to $+5$ per cent of the normal line current. The voltage recorder is connected across the ground end of a resistance potentiometer, the full-scale deflection being 3 kv.

The magnetic amplifier and potentiometer units are mounted in the cable-terminating equipment, but the four recorders and their associated supplies and alarms are mounted on a separate rack.

Mechanical Details

Fig. 6 shows two power equipments and a cable-terminating equipment as installed at each terminal station. The same cubicle frameworks are used for power and cable-terminating equipments, the power equipment consisting of two cubicles bolted side by side and fitted with doors at the front and back.

The top of the cable-terminating cubicle contains the power-change-over box, the center contains the cable-terminating box, while the transmission and ground-cable test circuits are located near the bottom. The

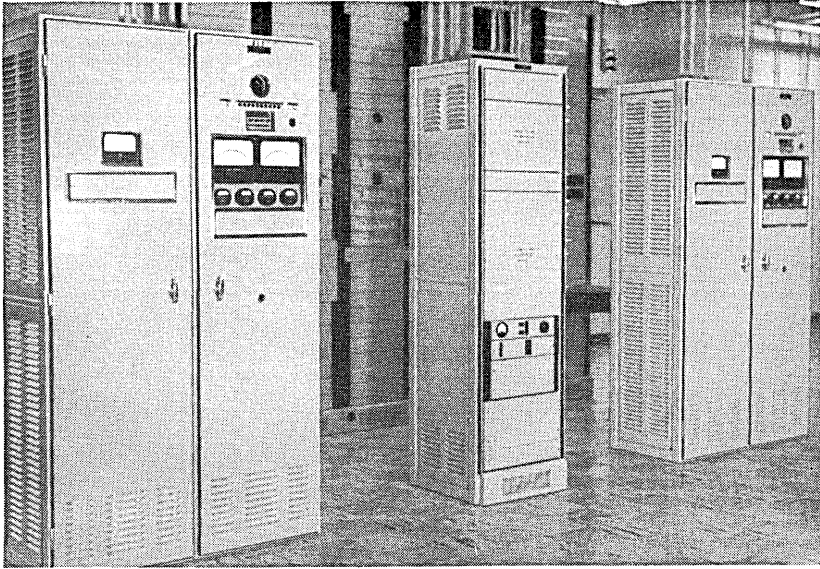


Fig. 6 — Power and cable-terminating equipments as installed at each terminal station.

main cable enters the bay at the top and passes behind the power-change-over box into the cable-terminating box. Access to the recorder units and cable simulators is from the rear.

Fig. 7 shows the front of one power equipment with the doors open. The left-hand cubicle contains the main h.v. transformer, the electronic and magnetic parts of the control circuits, the reference power unit and the auxiliary supplies. The other cubicle contains the main rectifier and smoothing circuits, and the associated meter and alarm circuits.

PERFORMANCE

Six power equipments and four cable-terminating equipments were manufactured for the link. Of these, four power equipments and two cable-terminating equipments were provided for the terminal stations and the remainder were for use on H.M.T.S. *Monarch* during the cable laying and subsequently as off-station and training spares.

After individual testing, the power equipments were checked in pairs energizing a 16-section artificial cable constructed to simulate the Clarenville-Sydney Mines link. These tests were kept running for approximately two weeks on each equipment, and the line current was monitored with

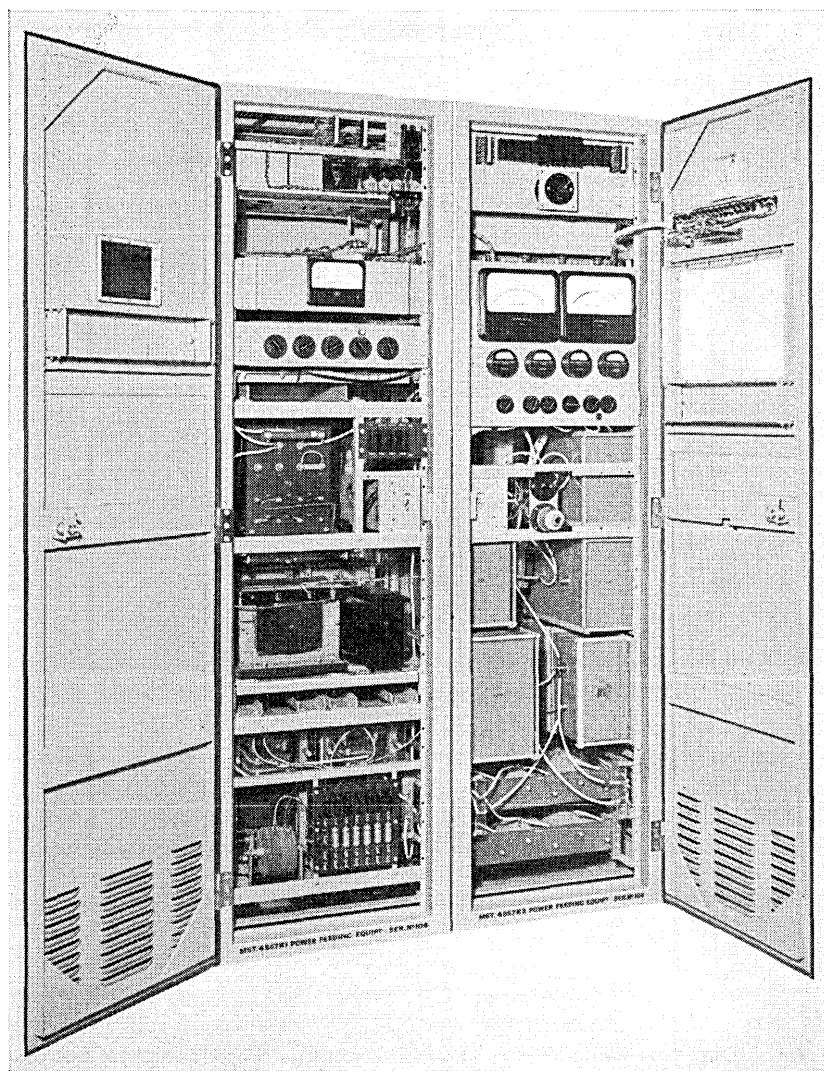


Fig. 7 — Power equipment.

expanded-scale current recorders (from -1 per cent to $+1$ per cent of the normal current).

The equipments were completed at the beginning of 1956, and have given satisfactory service both at the terminal stations and on board H.M.T.S. *Monarch*. From March to June, 1956, all four units at the

terminal stations were operating into their dummy loads and daily current and voltage readings were well within the required specifications. Since the laying of the sea section the equipments have satisfactorily operated the completed link. When the link is in service the working equipment at each end will be changed at 6-monthly periods and the change-over time will be staggered by three months each end. The equipment coming out of service will be immediately routine checked and adjusted if necessary.

The tests since installation confirm the laboratory and factory results that the regulation is better than ± 1 ma for any alternating input voltage from 195–265 volts in the frequency range 40–70 cycles for output voltages of 0 to 3 kv. The relatively long correction period of the magnetic-amplifier control circuit (about 0.5 sec) is satisfactory with the type of no-break supply installed at the stations.

Another useful by-product of double-end feeding is that, when there is a shunt fault on the system, the voltages supplied from the two terminal stations give an indication of the fault position. Many factors will control the accuracy of the location, e.g. magnitude and position of the fault, and how nearly the currents fed from the two ends are equal. Calculations, confirmed by tests made with shunt faults introduced at Terrenceville, show that any continuous shunt fault that will affect transmission (to the extent of operating the 1 db pilot alarms) will be detected to an accuracy of ± 1 per cent. The limit is set by the accuracy with which the link voltage distribution can be measured.

CONCLUSIONS

The power-feeding system described is suitable for submerged-repeater schemes that can, in an emergency, be temporarily powered from one end only. For locations within reasonable reach of a central catastrophe-spare store the equipment should be sufficiently reliable not to need duplication at both terminal stations. For future schemes this will provide a method which is economically attractive compared with the present single-ended methods and which offers numerous electrical advantages.

The routine maintenance required on the power equipment could be further reduced if the few remaining electron tubes were replaced by electromagnetic components. On schemes where short interruptions to traffic do not involve a relatively high loss of revenue it would then be unnecessary for the local staff to maintain the high-voltage equipment and the expensive no-break ac supplies could be abandoned. The latter

depends upon the probability of the primary sources at the terminal stations failing simultaneously.

ACKNOWLEDGMENTS.

The authors wish to express their thanks to many of their colleagues in the Post Office and Standard Telephones and Cables, Ltd., who have contributed to the developments described in the paper. The permission of the Engineer-in-Chief of the Post Office, and of Standard Telephones and Cables, Ltd., to make use of the information contained in the paper is also gratefully acknowledged. The equipments for the Clarendville-Sydney Mines link were manufactured by Standard Telephones and Cables, Ltd., at North Woolwich, London.

Route Selection and Cable Laying for the Transatlantic Cable System

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The repeatered submarine cables which form the backbone of the transatlantic telephone cable project were installed during the good weather periods of 1955 and 1956. This paper considers the factors entering into the selection of the routes, describes the planning and execution of the laying task and presents a few observations on the human side of the venture. It also covers briefly the routing of some 55 nautical miles of repeatered submarine type cable which were trenched in across the neck of the Burin Peninsula in Newfoundland to connect the Terrenceville submarine terminus with the cable station at Clarenville.

GENERAL

In the days of Cyrus Field, Lord Kelvin and those other foresighted and courageous entrepreneurs of the early transoceanic submarine cable era, the risks involved in selecting a route and laying such a cable must have appeared formidable beyond description. And indeed they were, for not until the third attempt was a cable successfully laid.

Today the hazards may be somewhat more predictable, our knowledge of the ocean bottom more refined and our tools improved, but only to a degree. The task still remains extremely exacting in its demands for sound engineering judgment, careful preparation, high grade seamanship, and good luck — weatherwise. For the basic methods now in use are still remarkably like those employed on *Great Eastern* and other early cable ships and the meteorological, geographical and topographical problems have changed not at all.

In the current transatlantic project — the first transoceanic telephone cable system — there are two submarine links. Between Clarenville in Newfoundland, and Oban in Scotland there lie some 1,850 nautical miles§ of North Atlantic water, most of it deep and all of it subject to

* American Telephone and Telegraph Company. † British Post Office. ‡ Bell Telephone Laboratories.

§ A nautical mile, as used herein, is 6,087 feet, 15.3 per cent longer than a statute mile.

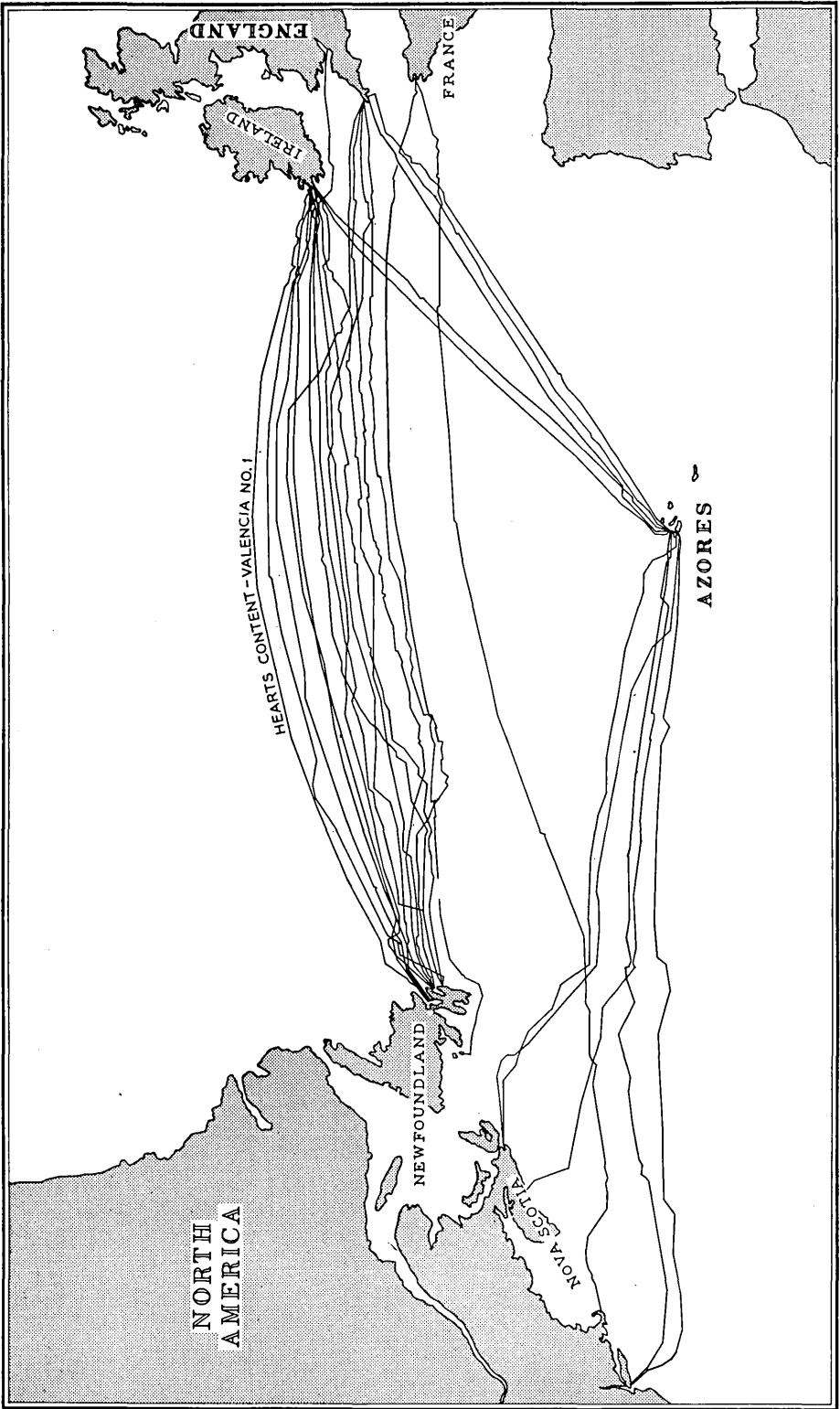


Fig. 1 — Telegraph cables in the North Atlantic.

weather of unpredictable and frequently unpleasant nature. The bridging of this required the laying of two one-way cables over carefully selected routes, using an available cable ship. And the presence in these cables of 102 flexible repeaters posed problems quite unique for such long and deep cables, as also did the need for trimming the system equalization during laying so that transmission over the completed system would fall within the prescribed limits.

From Terrenceville, Newfoundland, to Sydney Mines, Nova Scotia, a single cable, 270 nautical mile path was required through Fortune Bay and across Cabot Strait. While this water is considerably shallower, here again a relatively conventional cable laying problem was complicated by the presence of repeaters which in this section were rigid units, 14 in number.* Trimming of system equalization was also required.

These cables were laid during the spring and summer months of 1955 and 1956. And the preparation for the laying required many months of effort in fields which were for the most part quite foreign to the usual scope of land wire telephone activity. Some appreciation of the problems encountered in this phase of the venture may be gained from the following sections.

NORTH ATLANTIC LINK

Route Selection

The first successful transatlantic telegraph cable was laid across the North Atlantic in 1866. Since that date 15 direct cables have been laid and 5 cables by way of the Azores. The approximate routes of these cables are shown in Fig. 1. It is at once evident that the shortest and possibly the best routes were already occupied so that selection of routes for the two transatlantic telephone cables could be expected to present some difficulty.

Some of the more important considerations which guided the selection were (a) route length, (b) clearance for repairs, (c) trawler and anchor damage possibilities, (d) terminal locations suitable for repeater stations, with staffing in mind as well as facilities for onward routing, due consideration being given to the strategic aspects of the locations.

Route Length

Obviously, the shorter the length of a submarine route, the better. In the present instance, any system length much in excess of about 2,000

* Two additional repeaters are located in the 55 nautical-mile section which is trenched in across Newfoundland from Clarenville to Terrenceville.

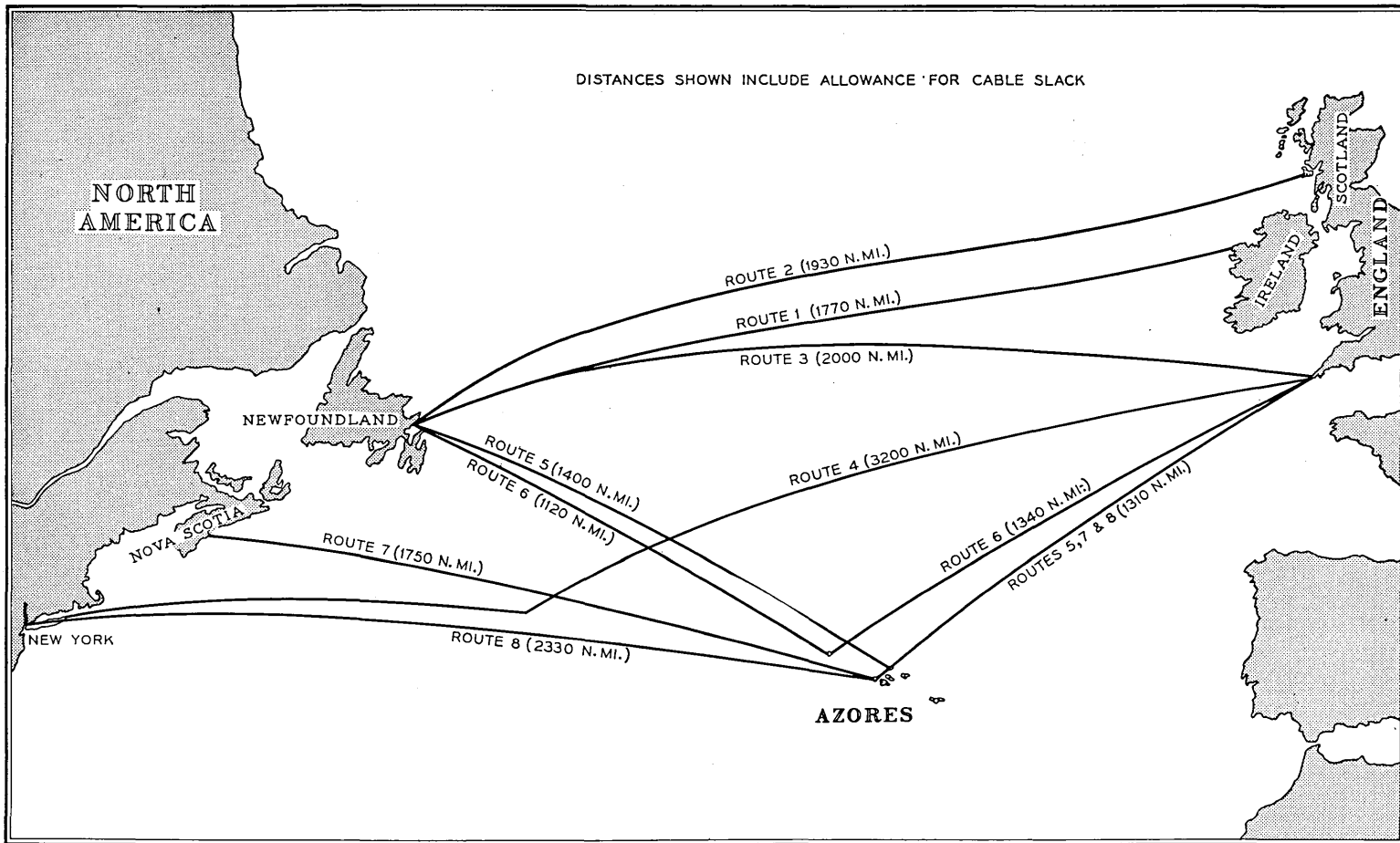


FIG. 2 — Tentative telephone cable routes.

nautical miles would have resulted in a reduction in the number of voice channels which could be derived from the facility.

On Fig. 2 are shown a number of the routes to which consideration was given in the early planning stages. The distances shown are actual cable lengths and include an allowance for the slack necessary to assure conformance of the cable to the profile of the ocean bottom.

Route 1, from Eire to Newfoundland, at 1,770 miles, is the shortest route and in point of fact was provisionally suggested in 1930 for a new cable. But the difficulty of onward transmission of traffic to London made this route unattractive.

Route 2, from Newfoundland to Scotland, compared favorably in length with *Route 1*, but its adoption was dependent upon location of a suitable landing site in Scotland.

Route 3, from Newfoundland to Cornwall, England, approximated 2,000 miles laid length and would have been very attractive had not so many existing cables terminated in southern Ireland or the southwest corner of Cornwall, which would lead to a great amount of congestion and consequent hazards to the telephone cables.

Route 4, from New York to Cornwall, was too long to be considered as its length amounted to some 3,200 miles.

Routes 5, 6, 7 and 8 were indirect via the Azores. They were attractive, as only relatively short lengths were involved and suitable sites for intermediate cable stations could have been found on one of the several islands in the Azores. But difficulties attendant upon landing rights, and staffing problems in foreign territory could be foreseen.

Clearance for Repairs

Repair of a faulty cable or repeater necessitates grappling, and in deep water this is likely to be a difficult operation. To avoid imperiling other cables while grappling for the telephone cables and, conversely, to provide assurance against accidental damage to the telephone cables from the grappling operations of others, it was considered essential that the route selected provide adequate clearance from existing cables. Suitable clearance is considered to be 15 to 20 miles in the ocean, with less permissible in the shallower waters of the continental shelves.

Trawler and Anchor Damage Possibilities

It is probable that fishing trawlers cause more interruption of submarine cables than any other outside agency. Cables laid across good fishing grounds are always liable to damage from fouling by the otter

boards of the trawlers. Final splices, either initial or as a result of repair operations, are especially vulnerable to damage because of the difficulty in avoiding slack bights at such points. It was desired, therefore, to avoid fishing grounds if at all possible.

If cables are laid in or near harbors frequented by merchant shipping, damage must be expected from vessels anchoring off shore in depths of less than 30 fathoms and proposed routes should, therefore, avoid such areas.

Cable Terminal Siting

Location of the cable terminal stations must be considered from the standpoints of suitability of shore line for bringing the cables out of the water and also from the standpoint of amenities for the staff. This latter factor is most important in keeping a permanent well-trained staff. For example, owing to staff difficulties, it was necessary to move a terminal station of one company from the west side of Conception Bay in Newfoundland to a site within easy reach of St. Johns.

A further factor in proper siting of the cable terminals is consideration for onward routing of the circuits carried by the cables.

And finally in view of the importance, generally, of submarine cable facilities, it is considered desirable to avoid cable terminal locations in or near a potential military target area and, if at all possible, consideration should be given to underground or protective construction for the terminal stations.

Preliminary Selection

The routes for the telephone cables were considered in the light of the foregoing and after preliminary discussion it was agreed that the two new cables should lie north of all existing cables, should avoid ships' anchorages and should lie on the best bottom which could be picked, clear of all known trawling areas.

In 1930, A.T. & T. Co., in conjunction with the British Post Office, gave serious consideration to the laying of a single coaxial telephone cable between Newfoundland and Frenchport, Ireland (Route 1, Fig. 2). A tentative route was plotted and the cable ship *Dominia* steamed over this taking a series of soundings. These soundings indicated that good bottom was to be found about 20 miles north of the Hearts Content — Valencia cable of 1873. This cable was the most northerly of the telegraph cables spanning the Atlantic. Study of its life history

indicated that faults clear of the continental shelf were few and far between throughout its long life.

The latest British Admiralty charts and bathymetric charts of the U. S. Hydrographic Office for the North Atlantic Ocean were scrutinized and from these and a study of all other relevant data, two routes were plotted which appeared to fulfill the necessary requirements so far as possible. However, it was agreed that if possible the selected routes should be surveyed so that minor adjustments could be made if desirable.

Landing Sites

East End — It was now necessary to find suitable landing sites having regard for the decision that the telephone cables should be routed north of all other existing cables.

On the British side it was necessary to look north of Ireland.

The North Channel, the northern entrance to the Irish Sea, divides northern Ireland from Scotland and had this channel been suitable, the telephone cables might have been run through it to a terminal station on the southwest coast of Scotland in the vicinity of Cairn Ryan. However, the tidal streams through the channel are strong, at least 4 to 5 knots at spring tides; the bottom is rocky and uneven, with overfalls, and any cable laid through it would have a very short life indeed.

It was therefore necessary to search farther north. The west coast of Scotland presents a practically continuous series of deep indentations and bald, rocky cliffs and headlands. The chain of the Hebrides Islands stretches almost uninterruptedly parallel with and at short distances from the coast. It was obviously most desirable to land the cable on the Scottish mainland, and close to rail and road communication if at all possible.

From previous cable maintenance experience it was known that Firth of Lorne which separates the island of Mull from the mainland was a quiet channel, little used by shipping or frequented by trawlers and with tidal streams which were not strong. Earlier passages of Post Office cable ships through the Firth had yielded a series of echo sounding surveys which indicated that except for a distance of about 5 or 6 miles in the vicinity of the Isles of the Sea, the bottom was fairly regular. Several small bays on the mainland side of the Firth just south of Oban appeared from seaward to be very suitable landing sites and this was confirmed by a survey party, which selected a small bay locally named Port Lathaich for the cable landing and site of the station.

The fore shore was mainly firm sand with outcroppings of rock which could be avoided easily when landing the cables. The seaward approach

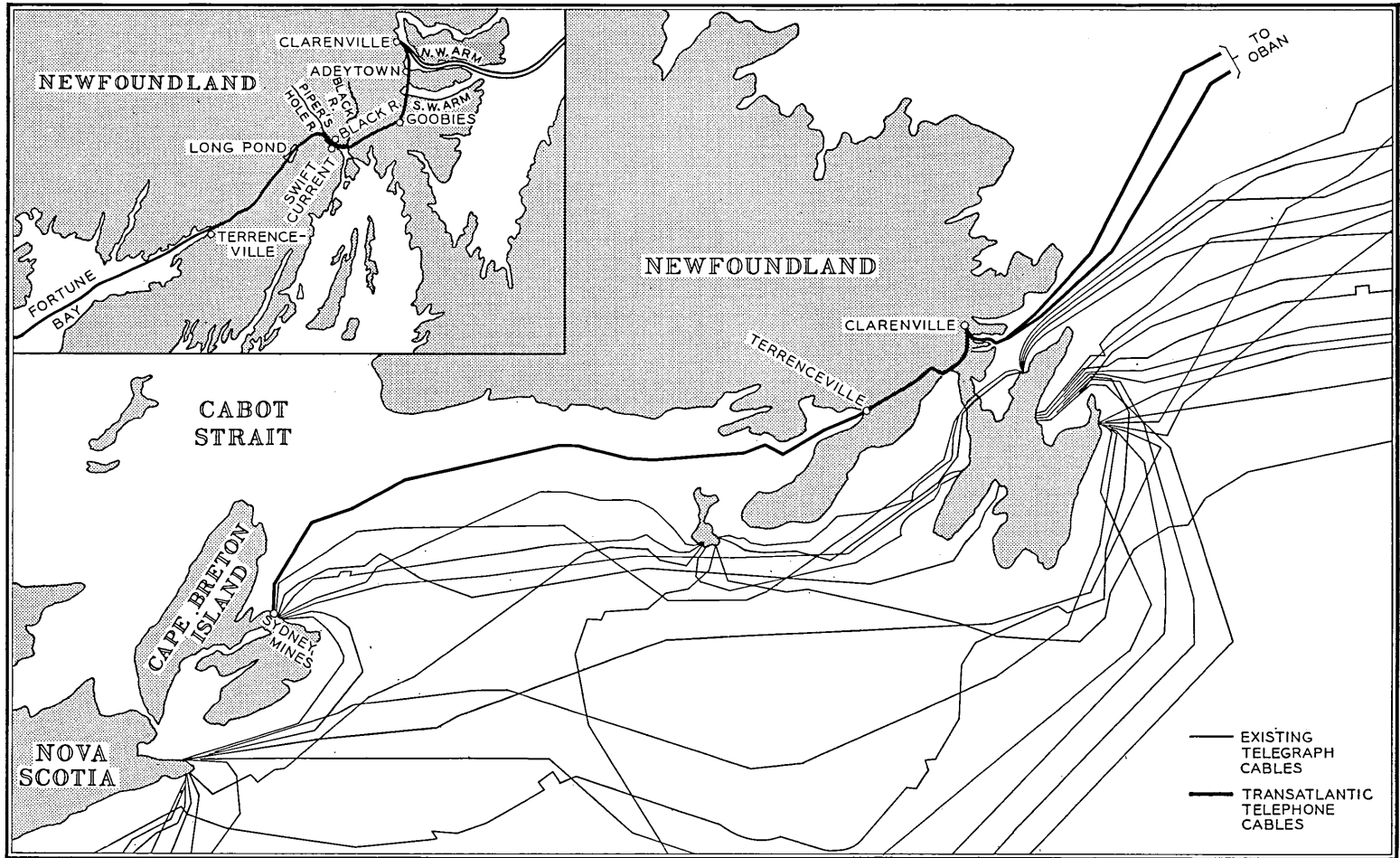


FIG. 3 — Cable landings on Newfoundland, and final route of overland section of the Clarenville-Sydney Mines cable.

was clear of danger and there was ample room to land two cables with a separation on the shore of some 30 yards.

Port Lathaich is only about 3 miles by road from Oban. Additional land cables would be necessary, however, to carry traffic to the main trunk network. From a strategic point of view, although Oban might only just be considered a target area, the cable landing was sufficiently remote to be relatively safe, especially if the cable terminal station was sited in the rocky hillside. To ascertain whether any serious chafing or corrosion would result if cables were laid over the uneven bottom in the Firth, some 8 miles of coaxial cable with E type armoring were laid over the area and recovered after 2 years. There was no evidence of any chafing or corrosion. It was therefore decided that the telephone cables should be routed through the Firth of Lorne to the cable terminal station site at Port Lathaich.

West End — The choice of a suitable cable landing in Newfoundland was more difficult to make, in view of the rugged and sparsely populated nature of the country. From Fig. 3 it will be seen that the existing telegraph cables spanning the Atlantic land either just north of St. Johns, in Conception Bay, or in Trinity Bay. North of Cape Bonavista the coast becomes more broken, and the sea approach is not good. Accordingly, there was no good alternative to routing both telephone cables into Trinity Bay, close to and northwest of the telegraph cable landing at Hearts Content on the southern shore of the bay. A survey party made an extensive examination of all likely places on the western side of the bay from Cape Bonavista in the north to Bull Arm at the southern end where, incidentally, the first successful telegraph cable was landed. Careful consideration of all of the places visited led to the agreement that Clarenville was the best site for a landing and for a cable terminal station.

Clarenville is at the head of the Northwest Arm of Random Sound. It is a junction on the main railway, and a good road to St. Johns will pass through the town in traversing its course from St. Johns to Port aux Basques. Clarenville has a growing population of some 1,600 inhabitants, with stores and repair facilities of various sorts. Good cable landing sites are available just out of town and the approach from the sea up the Northwest Arm presents no navigational difficulties. Such few small vessels as ply to Clarenville during the summer months are not likely to interfere with the cables.

Final Route Agreement

Having agreed Clarenville, Newfoundland, and Oban (Port Lathaich), Scotland, for shore terminations, it was possible to complete the routes

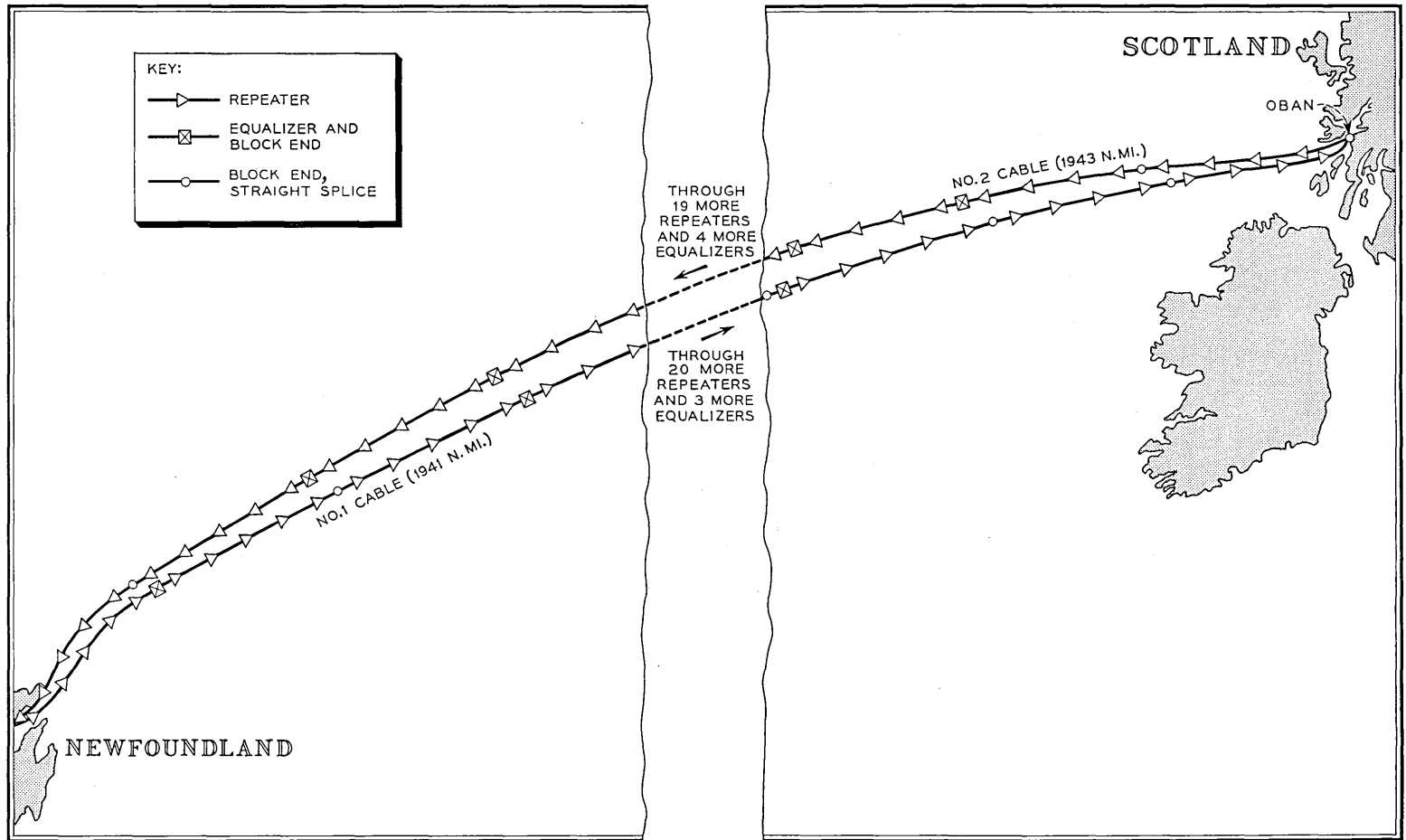


FIG. 4 — Transatlantic telephone cable routes.

for the two cables as shown in Figs. 3 and 4. The final routes are clear of existing cables and avoid crossing known trawling areas and anchorages. The cable stations are well sited with regard to staff amenities, accessibility and strategic requirements. Soundings taken during the laying of the two cables showed a very even bottom except in the Firth of Lorne and one or two places in Trinity Bay. The general profile of the route is shown on Fig. 5.

It is considered that these routes have been selected with care and meet all of the requirements of a well planned cable project. Time alone will tell how well the objectives have been met.

Cable Laying

Early Methods

In 1865 when the legendary *Great Eastern* was pressed into service to lay the first successful transoceanic telegraph cable she was fitted out with certain special cable handling gear. The need for such gear had been amply demonstrated by events which transpired during two earlier and unsuccessful attempts by *H.M.S. Agamemnon* and *U.S.S. Niagara*.

For her assignment, *Great Eastern* was fitted with three large tanks into which her cargo of cable could be coiled. She was also provided with a large drum about which the cable could be wrapped in the course of its passage from the tanks to the sea. This drum was connected to an adjustable braking mechanism which provided the drag necessary to assure that the cable pay-out rate was correct with relation to the speed of the vessel. In addition, a dynamometer was provided so that the stress in the cable would be known at all times. A large sheave fitted to the stern of the ship provided the point of departure of the cable in its journey to the sea bottom.

On Friday, July 13, 1866, *Great Eastern* steamed away from Valencia, Ireland, and 14 days later, on July 27, she arrived off Trinity Bay, Newfoundland, and completed the landing of the western shore end.

H.M.T.S. Monarch

Early in the planning for the transatlantic project it was realized that in no small measure the success of the venture would depend on availability of a vessel suitable for laying the cables. It was fortunate that one of the partners to the enterprise was also the owner and operator of the largest cable ship in all the world, and one well suited to the task at hand.

The twin-screw cable ship *Monarch*, Fig. 6, was built for H.M. Post Master General by Messrs. Swan, Hunter and Wigham Richardson, Ltd., at their Neptune Works, Walker-on-Tyne. She was completed in 1946. This ship is of the shelter deck type having principal dimensions as follows:

Length overall.....	482 feet 9 inches
Breadth moulded.....	55 feet 6 inches
Depth moulded to shelter deck.....	40 feet 0 inches
Gross tonnage.....	8,056

The ship has an overhanging bow which carries three cable sheaves, a cruiser stern with the after paying out cable sheave offset on the port quarter, a semi-balanced rudder having extra large surface, and a cellular double bottom extending from the collision to the aft peak bulkheads. Both main and shelter decks are steel and extend her complete length.

The cable is carried in four welded steel cable tanks fixed to the tank top plating. These are arranged along the ship's center line in a fore and aft direction forward of the main propelling machinery space. They are each 41 feet in diameter and have the following cubic capacities:

	Coiling Space	Gross Cubic Feet
No. 1 Tank.....	33,730	40,170
No. 2 Tank.....	31,820	38,460
No. 3 Tank.....	30,865	37,375
No. 4 Tank.....	30,230	36,300

The opening in the shelter deck above each tank is a circular hatch 8 feet in diameter.

A water tight cone of steel plates is built in the center of each tank to insure against fouling of the cable during payout. Further control

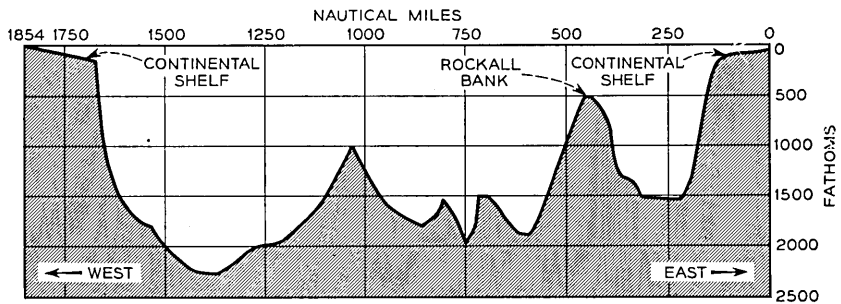


FIG. 5 — Profile of ocean depths between Clarendville and Oban.

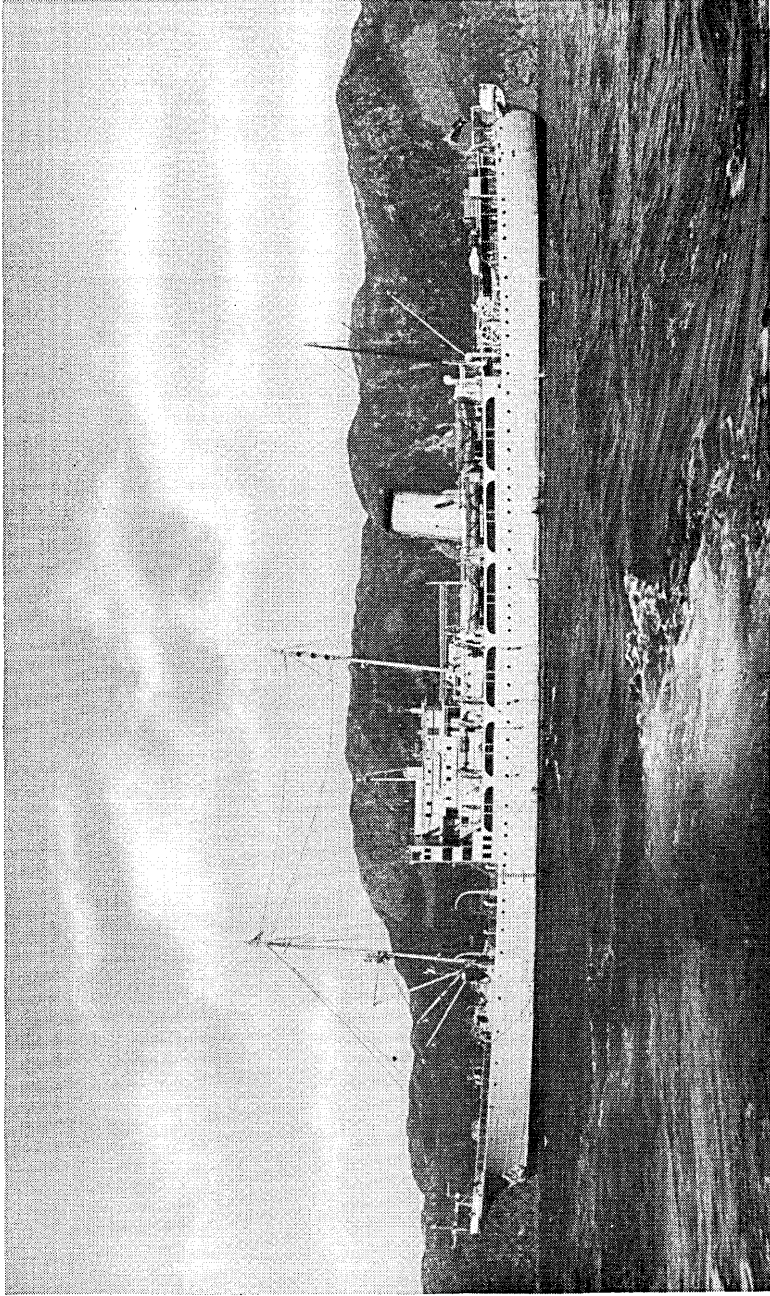


FIG. 6 — *H.M.T.S. Monarch.*

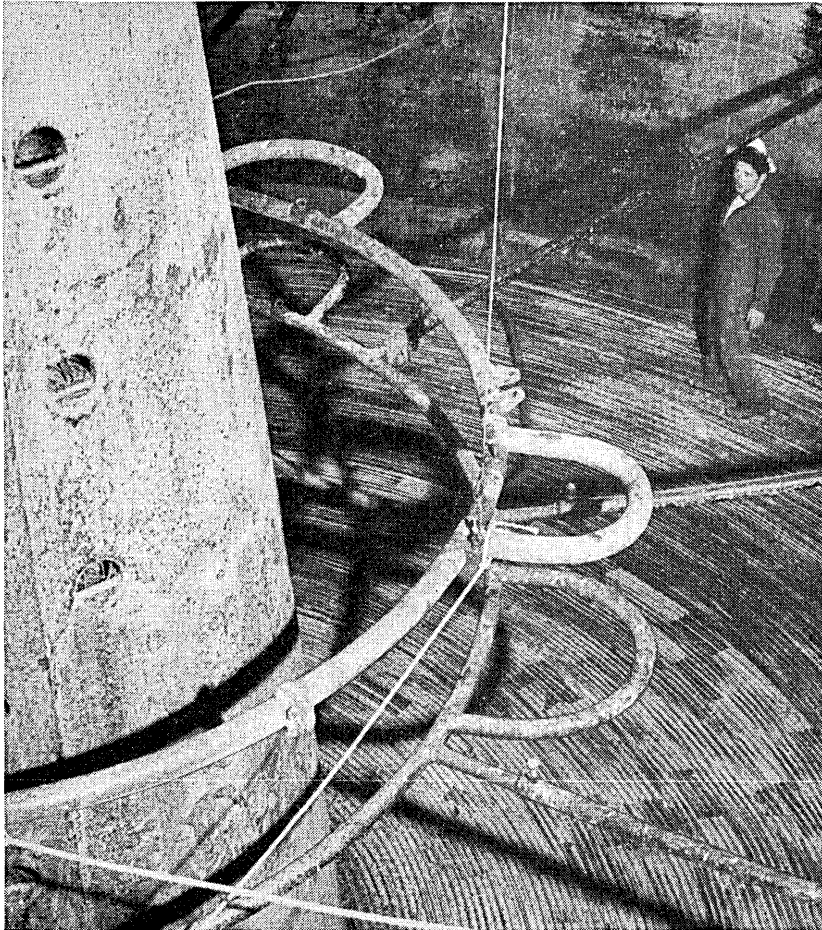


FIG. 7 — Interior of cable tank showing central core, crinoline and flake of cable.

of the cable is provided by a crinoline, Fig. 7, which is a circular spider of steel tubing normally suspended from 1 foot to 3 feet above the top layer of cable in the tank. The crinoline tends to prevent flying bights of cable and also provides a safety platform, in case of trouble, for the men who work in the cable tanks. Each crinoline may be raised and lowered by an electric motor drive.

The maximum cable carrying capacity is approximately 5,000 long tons, or almost 2,000 miles of the deep sea type of cable used on this project if no repeaters were involved.

Monarch is driven by two steam engines. The maximum propeller revolutions are estimated at 110 per minute, giving a ship's speed of about 14 knots.

Two cable engines are fitted forward, both capable of being used for picking up or paying out. These are driven by electric motors having a maximum rating of 160 hp, which will permit picking up at a rate of 0.9 nautical miles per hour with a stress of 20 tons, or at 3.5 knots with a stress of 5.3 tons. The drive system is constant current, so designed that a uniform torque may be held at the drum for any setting of the speed control. When paying out, these motors operate as generators to provide electrical braking, and auxiliary mechanical brakes are also provided.

A single cable engine is fitted aft and this is the main paying out gear. In addition to the electrical brake, the aft engine is provided with a multiple drum externally contracting band brake, manually adjustable and water cooled, and with a further auxiliary fan brake. The fan shaft is driven in such a manner that when cable is being paid out at approximately $8\frac{3}{4}$ knots the fan will revolve at 1,000 rpm and absorb 120 bhp. Adjustments in this are effected by varying the amount of opening in the fan shroud so that as little as 27 bhp may be absorbed.

Dynamometers, both fore and aft, provide for measurement of the cable tension.

Taut wire gear is furnished on the starboard quarter to provide an effective means for calculating the amount of slack paid out. With this gear, steel piano wire, anchored to the bottom, is paid out at constant tension and provides a rough measure of distance steamed over the ground.

A test room with trunks to each cable tank is provided on the shelter deck and fitted with instruments for measuring and locating faults.

Modifications for Flexible Repeaters

In the normal cable-paying-out process, the cable is drawn from the tank, carried along fairleads to the holdback gear (a mechanism for applying slight tension to the cable so that it will snub tightly around the drum), and then wrapped around the drum of the cable engine from two to four turns depending upon the weight of the cable and the depth of the water. At the drum, a fleeting knife is fitted which pushes over the turns already present to make way for the oncoming turn. From the drum the cable passes through the dynamometer and thence to the overboarding sheave.

The Bell System repeaters, manufactured by the Western Electric

Company, were designed with the objective of making them act as much like cable as possible.¹ Despite this, their presence introduced a loading and laying problem as their ability to bend without injury is limited to about $3\frac{1}{2}$ ft radius, and their structure is such that unnecessary bending may involve a hazard to their water tightness. As the majority of the sheaves and drums of the conventional laying gear are considerably smaller than 7 ft diameter, a number of modifications were required in *Monarch's* equipment to satisfy the repeaters.

For the most part, the new gear was designed by the Telegraph Construction and Maintenance Co., Ltd., to broad requirements supplied by the A.T.&T. Co. The modifications included providing the port bow sheave with a flat tread to bring its diameter to 6'10", and replacing both forward dynamometers and the aft dynamometer by a new design employing a 7-foot wheel in a pivoted "A" frame bearing on Elliott pressure type load cells. Port and starboard forward drums were replaced with the maximum diameter drums possible without a major change in the complete gear. This diameter proved to be 6'10" on the tread. The after paying out drum was replaced with one having a 7'0" diameter. The forward port and aft cable drums were equipped with

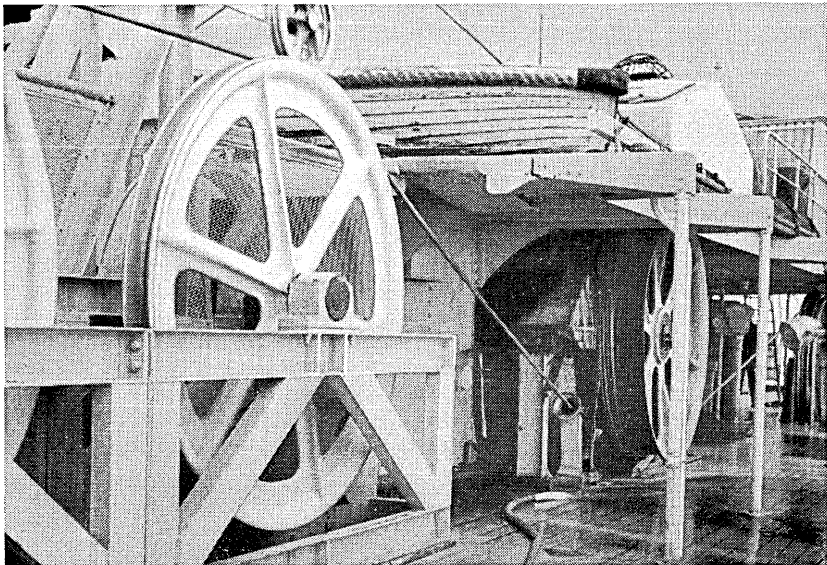


FIG. 8 — General view of modified after cable gear (one of 2 hold back sheaves, drum with fleeting knife and ironing board, and, at extreme right, dynamometer sheave).

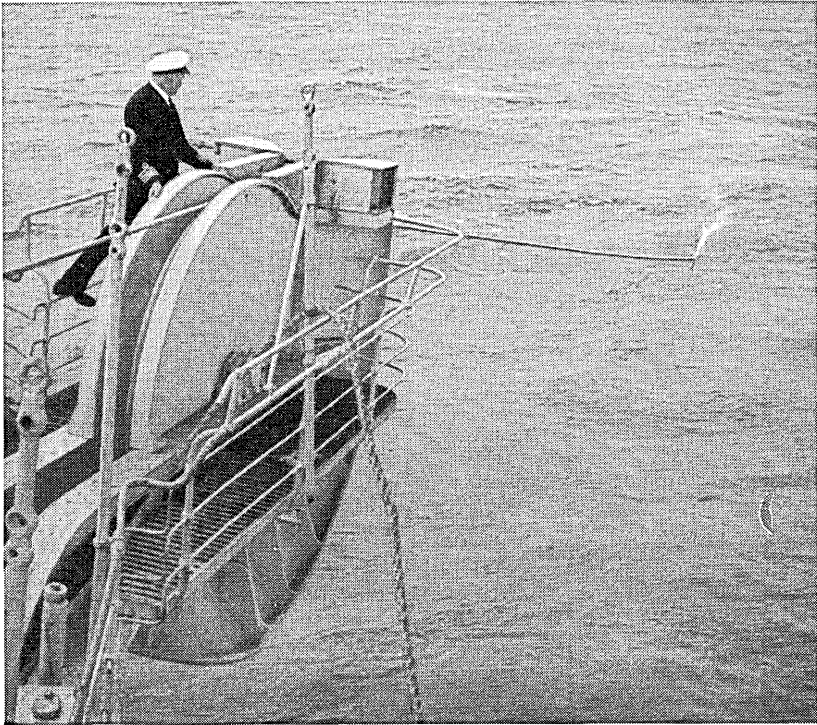


Fig. 9 — Cable payout over the stern.

ironing boards. (An ironing board is a curved shoe placed adjacent to the cable drum and spring loaded so that it will force the repeater to conform to the curvature of the drum as it goes on.)

The forward port and starboard draw-off gear sheaves were replaced with larger ones 7'0" in diameter which were made traversable. The aft hold-back gear, of the double sheave type, was also replaced with units having 7'0" sheaves.

Fig. 8 shows a general view of the modified after cable gear, and the 7-ft stern sheave may be seen in Fig. 9. A line schematic of the gear will be found on Fig. 10.

Roller type fairleads shaped into arcs of minimum $3\frac{1}{2}'$ radius were fitted at each cable tank hatch, with smaller roller guides at convenient points to assure fair lead of the cable from the tanks to the cable machinery. Electric hoisting gear was provided for the crinoline in each tank as it was necessary to raise the crinoline whenever a repeater left the tank.

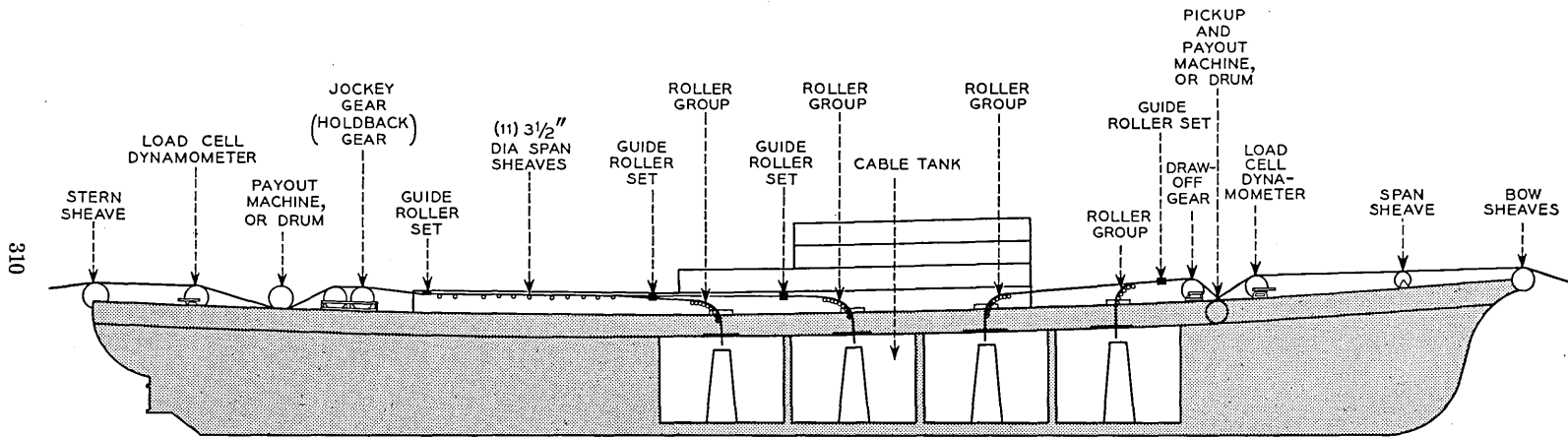


FIG. 10 — Line schematic of the cable gear on *Monarch*.

The test room was greatly enlarged and fitted with the special gear necessary for powering and measuring the system during laying.

Loading Considerations

When the ship is loaded, the cable is coiled carefully in the tanks, layer upon layer — each layer being called a “flake”. The coiling is started from the outside of the tank and progresses clockwise toward the center so that the armor is untwisted one revolution for each complete turn in the tank. When paid out in the reverse order, this twist is restored.

Handling of the repeaters during loading presents a problem because of the need to restrict their bending. After some experimental work was carried out, splints were devised to provide the needed rigidity. These consisted of two angle irons each 12 ft long and equipped at the ends with cold rolled steel rods ranging in length from $1\frac{1}{2}$ ft to 6 ft. By this device it was possible to maintain rigidity over the main central portion of the repeater, including the junction of the core tube with the end nosing, and provide limited flexibility along the outer ends of the core tubes which are less sensitive to bending. The splints were removed once the repeater reached the tank.

Repeaters are always stowed at the outside of the flake where they need be subjected to only a minimum of bending. They are protected with wood dunnage, which must be removed before the repeater is paid out.

With these modifications all repeaters and equalizers were laid successfully from either forward or aft gear at a cable speed of around three knots.

Testing and Equalization

Purpose — Once a submarine cable system has been installed, it is accessible only at the ends for adjustment to improve performance, save at great difficulty and large cost. As some irregularities cannot be corrected from the ends, it behooves the designers to discover and account for such irregularities and to correct them before the cable is finally on the ocean bed.

The laying period offers the last opportunity for accomplishing this, and indeed all too frequently, also the first. This fact, coupled with the broadband design of the link and with the presence in the system of active elements (the repeaters), necessitated a very comprehensive program of tests and measurements during laying.

The program had three specific purposes; (1) to detect immediately any fault which might develop during laying; (2) to permit the design and execution of corrective system adjustments while en route so that transmission performance of the completed link would fall within specified objectives; and (3) to gather data on system characteristics at intermediate points for eventual use in fault location or in aging studies. The need for parts (1) and (3) of the program is more or less self evident, but part (2) merits some further discussion.

In an ideal submarine cable system in an average environment, the attenuation of the cable from one repeater to the next would be offset exactly across the frequency band by the gain of the following repeater. Such a result is never achieved in practice, as the temperature and pressure environments (which affect cable attenuation) cannot be known precisely in advance, and the cable structure itself cannot be manufactured for mile after mile without variation in transmission characteristic. Additionally, the mechanics of the laying process induce minor changes in the physical structure of the cable which reflect in attenuation changes.

If such deviations from desired characteristic produced only differences from the specified system gain objective, compensation could be readily applied at the ends of the submarine link. Unfortunately, this is only partly the case. Their more important effect is the resulting misalignment of operating levels of individual repeaters from design objective.

Misalignment magnitudes must be watched carefully, for at best misalignment narrows the system latitude for seasonal temperature changes and for aging, and at worst it can result in intolerable system noise. If a repeater is preceded by too much cable the signal to noise ratio at the repeater input will be less than desired because of thermal noise. In the opposite case of too little cable, the signal level will be too high and the resulting overloading in the repeater will also affect the signal-noise adversely. Once present on the signal, the noise cannot be removed, and so the cure for excessive misalignment must be applied before the misalignment has developed. Adjustments at intermediate points along the route must therefore be contemplated.

Testing Program — The program which was evolved to meet the three objectives outlined was meticulously reviewed and practiced before the start of laying, and various forms were prepared for entering data and plotting and evaluating results. This was essential to avoid wasting effort or missing valuable data. The wisdom of this was fully apparent to all involved after experience with the close time schedules and the mental tensions which developed during the actual laying.

Staffing for testing was provided by crews of 2 or 3 trained engineers located at the transmitting cable station and on shipboard. Those on the ship served $4\frac{1}{2}$ hour watches at 9 hour intervals, which permitted a reasonable amount of rest and avoided continuous "dog watch" duty by any one crew.

Close contact between shipboard and cable station crews was essential, and was achieved by means of cable and radio order circuits (or "speakers"). Communication from shore to ship when the cable was powered made use of the standard cable order wire circuit at the cable station to apply a signal in the frequency band 16-20 kc. The signal was demodulated and amplified aboard ship by a special stripped version of this same gear. The radio order circuits employed special land antennas and equipment, and for the most part the ship's standard single sideband telephone set, although other equipment at medium frequency was sometimes used for short distances. Radio telegraph with hand keying was available for back-up when conditions were too poor for the radiophone sets.

Plans called for powering the cable at all times except when splices were being made. This was necessary for the measurement program, of course, but also provided additional assurance of safe laying of repeaters, as the glassware and tungsten heaters of the vacuum tubes are more resistant to damage when hot. Power for the first half of each crossing was provided from the cable station. Beyond this point, the required voltage would have become excessive and so the shipboard supply was inserted into the series power loop and its voltage adjusted in proportion to the amount of second half cable actually in the loop.

Monitoring against the possibility of faults was accomplished by measurement of a pilot tone at 160 kc, transmitted over the cable at all times except when data were being taken or power was turned down. Audibly alarmed limits were set on the measurement to indicate any significant deviation in transmission. In actuality, all unanticipated received alarms were found to have resulted from frequency or voltage shifts in the primary shipboard supply for the measuring equipment.

During the design of the system,² consideration of the misalignment problem had indicated the desirability of splitting the cable for each crossing into a number of sections, called ocean blocks. These contained either 4 or 5 repeaters, and were 150 to 200 miles in length. In loading the ship, the two ends of each ocean block were left accessible for connection to the test room and for splicing operations.

Measurements made in the spring of 1955 off Gibraltar had indicated an unexpected change in attenuation called "laying effect",³ which required some last minute adjustment of the repeater section lengths.

With incorporation of these changes, it was known that the factory lengths of cable between repeaters were adequate to keep misalignment within an ocean block within reasonable limits. The system could then be equalized between ocean blocks so that the signal level at the first repeater of a new block would be approximately correct, and the total system noise thus would fall within limits.

This equalization was accomplished in two ways. Excess cable of the order of $\frac{1}{2}$ to 3 miles in length was provided at the top end* of each ocean block. Based on measurements, this could be cut longer or shorter than the nominal spacing of repeaters, so that the repeater gains and cable losses would be matched at some frequency in the band. Residual deviations in other parts of the band could then be mopped up if necessary by inserting a simple equalizer, housed in a container similar to those used for the repeaters. Ten such equalization points were provided in each cable.

In practice, sending levels were adjusted at the cable station to give test tones at the grids of the output tubes of the repeaters which if the system equalization were perfect, would be flat across the frequency band, and at the proper level. These tones were measured on shipboard at the end of the ocean block being paid out. The results were plotted against mileage, with one sheet for each frequency being measured. Because of the "laying effect" and of temperature and pressure changes on the cable as it progressed to the bottom, these plots displayed a slope.

The value of loss (or gain) to be ascertained for each frequency was that which would exist when the entire ocean block was on the bottom. To obtain this, it was necessary to extrapolate the curves to the mileage point representing the end of the block in question. The extrapolation was required to avoid stopping the ship at the end of the block, and so had to anticipate the time needed for turning over and cutting the cable end at the proper point, and making one or two splices (depending on whether or not an equalizer was inserted at the point in question).

Having read the extrapolated values from the curves, these were compared with objectives for that block junction, and the deviations plotted. Transparent overlays, showing the net effect of each of several types of equalizer combined with varying amounts of cable around the nominal spacing, greatly facilitated the final decision as to cutting point and equalizer choice.

This implementation of the system undersea equalization represented a very large part of the effort required of the testing crews during laying.

Additional data gathered for fault location, aging studies and other

* First end out of the cable tank.

purposes included precise determination of repeater crystal frequencies on the bottom, gain frequency runs to show up any fine grained structure which might exist in the band, and values of line current and driving voltages.

Copper resistance and capacitance measurements proved to be of dubious value; in the first case because of the temperature/resistance characteristic of the vacuum tube heaters; in the case of capacitance, probably because of polarization effects in the castor oil capacitors used in the repeaters.

Shipboard Test Equipment — A new test room had been equipped for making the above measurements with transmitting and receiving transmission measuring sets² including the crystal test panels. These sets were provided in duplicate to forestall difficulty should one set develop trouble during the laying. The transmitting consoles were required only for use in calibrating the receiving sets, and for some measurements which were made on individual ocean blocks in the ship's tanks.

Additional gear in the test room included a cable current power supply,⁴ and a "Lookator" which is a pulse echo type of fault locator useful from a point in the cable to the adjacent repeater on either side.

Laying Sequence

H.M.T.S. Monarch is the largest cable ship afloat, with capacity for about 2,000 miles of the Type D deep sea cable in her tanks. However, because of the inherent limitation on their bending radius, the presence of flexible repeaters in the cable puts a restriction on the height to which the coil can be permitted to rise in the tanks. For repeatered Type D cable, therefore, *Monarch's* capacity is cut back to about 1,600 nautical miles.

Types A and B cable, used in shallower waters, are considerably larger and heavier than Type D and consequently, less of these can be carried.

The ideal laying program would have involved one continuous passage across the North Atlantic from cable station to cable station. However, this would have required carrying over 1,900 miles of cable including about 300 miles of Type A and something less than 50 miles of Type B. Such an amount of cable would greatly exceed the ship's capacity.

Each cable was, therefore, laid in 3 sections. The No. 1 cable (southernmost), which transmits from west to east, was laid in the following sequence: Clarenville to just beyond the mouth of Trinity Bay, a distance of 200 miles; thence about 1,250 miles to Rockall Bank (a submerged

plateau); and finally the remaining 500 miles from Rockall Bank to Oban. The No. 2 cable followed the opposite sequence, starting at Oban and proceeding in 3 sections of 500 miles, 1,250 miles, and 200 miles to the terminal at Clarenville. Shore ends, about $\frac{1}{2}$ mile long at Clarenville and 2 miles at Oban, were prepared and put in place in advance of the time when they would be needed. At each intermediate point, the cable was "buoyed off" with a mushroom anchor, connecting lines, and a surface buoy of size appropriate for the water depth.

The mileages indicated are actual cable lengths. They exceed the geographical distances between the points involved because of the slack allowance which experience has shown to be necessary to assure reasonable conformance of the cable with the contour of the ocean bed. Normally, about 5 per cent slack is considered desirable in deep water, with the allowance decreasing in steps to zero in shallow water.

All available information indicated that the most favorable weather conditions in the North Atlantic could be anticipated in the period May through August. Prior to May, ice could be expected along the western sections of the route and after August, hurricanes were likely, and later the winter storms.

The laying of the No. 1 cable was started June 28, 1955, and completed September 26. The actual laying period took in but 24 days in this interval, the remainder of the time being spent in transit and in re-loading. The No. 2 cable was started June 4, 1956, and completed August 14. About 16 of laying days were involved.

The routine aboard ship during laying consisted in passing out cable at the rate of 6 to 7 knots for a repeater section length of a little over 37 nautical miles, then slowing down to about 3 knots as the repeater passed through the cable machinery and overboard, then back to speed again. During all of this period the testing crews, both on shipboard and at the transmitting cable station, were busy measuring, recording data and planning the equalization trimming. At a point shortly after the passage of the next-to-last repeater in an ocean block, special measures were required for the equalization program. From that point until the joints associated with the connection to the following ocean block had been completed, the speed was reduced to 5 knots. The need for this arose from the following considerations.

Stopping of the ship in deep water introduces serious possibility of formation of kinks in the cable, and is to be avoided at all costs. To permit continuous laying, it was necessary to determine the amount of cable needed for equalization, measure out this cable, and complete the splices before reaching the end of the block being laid.

The addition of an equalizer at the end of the block requires two joints and armor splices. Preparing the cable ends, brazing together the center conductor and associated tapes, injection molding the polyethylene around the center conductor, replacing and overlaying the armor wires and binding the splice consumes 6 to 7 hours for a single splice, and 8 to 9 hours for two splices when overlapping of operations is practical. An allowance of 3 hours is considered necessary for remolding in event of a defective joint (disclosed by X-ray inspection). The time allowance required to complete the splicing of ocean blocks is therefore 9 to 12 hours. About $1\frac{1}{2}$ hours are needed to carry out the extrapolation, make the equalization decision and turn over cable to the cutting point. During the interval between the cable cut and the completion of the joint, the ship's speed was maintained at 5 knots so as to minimize the distance over which extrapolation of equalization data had to be extended. Even so, the final extrapolation covered the last 60 to 75 miles of each ocean block.

During the jointing intervals, system power was turned down to avoid any hazard to the members of the jointing crew. It was restored as soon as the moldings had been X-rayed and the outer or return tapes had been brazed. These activities were so timed that in almost every case the system was powered as each repeater went overboard.

CLARENVILLE-SYDNEY MINES LINK

Route Selection

Clarenville having been selected as the site of the cable terminal station on the west end of the ocean crossing, it was necessary to consider how the system was to be extended to Nova Scotia for connection with the North American continental network.

A number of alternatives were possible as described below:

Alternative 1 contemplated radio relay across Newfoundland to Port aux Basques, and thence across the Cabot Strait. However, a survey revealed that maintenance access to suitable sites would be most difficult, particularly in winter, and primary power was not obtainable.

Alternative 2 involved a poor submarine route around the Avalon Peninsula to possibly Halifax, Nova Scotia. The length of the sea cable would be about 600 nautical miles. It would be necessary to cross many working telegraph cables, (Fig. 3). Trawler damage could be expected as the cable would need to traverse known trawling areas, and during the winter months any repairs would be costly and prolonged. Also it was

not desired to lay another cable out of Trinity Bay as the route might be wanted for a second transoceanic cable at some time in the future.

Alternative 3 involved a submarine cable from Clarenville out through the North West Arm to Rantem at the head of Trinity Bay, a short land cable across the isthmus, and thence either a submarine cable direct to Sydney, Nova Scotia, or a land crossing of the Burin Peninsula at Garnish and thence by submarine cable to Sydney. This route involved three open sea sections with one or two land sections. There was rather limited space for a cable in Placentia Bay and the bottom was uneven and rocky. Existing cables laid around the Burin Peninsula have had interruptions which indicated an unsuitable bottom and fishing trawlers had been seen in the vicinity recently.

Alternative 4 also involved a cable overland, from Clarenville to Terrenceville at the head of Fortune Bay, there to join a direct submarine cable to Sydney Mines. Three short underwater sections would be involved in the Clarenville-Terrenceville link, but these could be in shallow water out of harm's way. The main submarine route from Terrenceville to Sydney Mines would be clear of other cables and would avoid trawling areas and anchorages, a not inconsiderable achievement in view of the congestion of submarine cables and the fishing activity around the southeast corner of Newfoundland. Further, a good landing site in Nova Scotia was available on property near Sydney Mines owned by Eastern Telephone and Telegraph Company.

After due consideration, *Alternative 4* was chosen as being the most satisfactory from all aspects and the final route is shown on Figure 3.

This route is considered to be most likely to have a good life history. While it would have been possible to have one continuous land cable between Clarenville and Terrenceville, the three short underwater sections saved a considerable amount of trenching without adding undue hazard to the system.

Clarenville-Terrenceville Route

It having been decided to route the Post Office single cable system overland from Clarenville to Terrenceville a number of other matters required decision. The first was the type of cable to be employed for this section. Several alternatives were considered, bearing in mind factors such as the type of terrain, access, availability of primary power, possible future expansion of capacity and, of course, interference from static and radio frequency pick-up. The advantages of using standard solid dielectric coaxial ocean cable with submarine-type repeaters were judged

to outweigh all other considerations and left only one problem, namely, shielding from interference.

Up to this time shore ends of submarine cables used by the Post Office were shielded for about a quarter of a mile from shore by a lead sheath insulated from the return tapes of the coaxial by a polyethylene barrier. Experience indicated that such shielding might not be adequate over a long distance on land. The question was resolved by the addition of iron shielding tapes and a plastic jacket to standard submarine cable. The structure is described elsewhere.⁵

Through the use of this robust, wire armored cable and two steel housed submarine repeaters, no limitations from the noise pickup angle were placed on the detailed route selection for the overland section. The first thought was to try to proceed directly across country from Clarenville to Pipers Hole River, saving at least 10 miles over a route which followed the road, and on which advantage might be taken of quite long water stretches into which the cable could be dropped. Black River Pond, for instance, is $4\frac{1}{2}$ miles long. This proposal was abandoned after surveys, because of the very rocky nature of the country and difficulty of access both for construction and any subsequent maintenance, and it was decided to follow the general course of the roads.

It was possible to avoid trenching in the rocky, precipitous cliff country from Clarenville to Adeytown by laying about 6 miles of cable in the water of Northwest Arm. Similar considerations dictated the choice of two miles of cable in the sea across Southwest Arm. Thence the route followed the road, at a distance ranging from 250 yards to more than a mile, as far as Placentia Bay, taking advantage of the larger ponds where possible to avoid trenching.

Reaching the 800 foot high ground beyond the Pipers Hole River from the north of Black River proved quite difficult. Here the road is carved out of the foot of the cliffs as far as Swift Current and the country behind is solid rock. Plans exist for a hydro-electric project involving dams in Pipers Hole River just north of the road crossing and it is naturally not desirable to bury a cable in such a locality. The river estuary itself passing by Swift Current presents only a narrow 6 foot deep navigable channel at low water but it was decided that this could be used for some 6 miles by employing a barge and a shallow draft tug for the laying.

A suitable route out of the basin up through wooded gorges to the top took about a week of very hard going to locate. Thereafter all was plain sailing taking advantage of ponds such as Long Pond (4 miles) and Sock Pond (3 miles) until the route arrived within 6 miles of Terrenceville.

Here it was reluctantly decided to bury the cable in a deep trench on the inner side of the road, as the other side falls sharply to the sea. The desire to avoid roads was due to their instability and the methods used for construction and repair. This road is dirt only, with no foundations, and in this particular section has been known to slide away into the river bed below.

The final length of cable laid was just short of 55 nautical miles.

Cabot Strait Laying

Coaxial submarine cables in which rigid repeaters are inserted cannot be laid with the existing cable laying machinery except by stopping the ship, removing the turns of cable from the drum and then passing the repeater by the drum and restoring the turns. Special equipment is also needed for launching the repeater over the bow sheaves.

Ship Modifications

The following equipment was installed on *Monarch* for the laying of cables carrying rigid repeaters.

A gantry over the bow baulks, consisting of a 22 foot steel beam projecting 6 feet beyond the sheaves, was installed for handling repeaters at the bow. This gantry was fitted with an electrically operated traveling hoist for lifting the repeaters over the bow sheaves and lowering them into the sea. A standby hand operated lifting block and traveller were provided to guard against failure of the power point.

A rubber-tired steerable steel dolly (or trolley) was developed from the chassis of a small car to transport the repeaters from the cable tank hatches to the bow sheaves. These repeaters weigh about 1200 pounds.

Storage racks were built up from steel sections provided with shaped, rubber lined wood blocks and were fitted at each cable tank hatch on the shelter deck. Each rack held 4 repeaters in double tiers. A hand operated lift was furnished for moving the repeaters from the storage racks to the dolly.

A special quick release grip was furnished for use when lifting the repeaters by the electric hoist on the bow gantry. Deflection plates were also fitted on the fore deck around dynamometers and hatches to avoid their fouling the dolly.

Launching Rigid Repeaters

The rigid repeaters were stowed in their racks in the order of their laying. The bights of the cable attached to the ends of the repeaters

were brought up the sides of the cable tanks, secured along the arms of the crinoline and up the sides of the hatch coamings to the deck, clear of the running length of cable and from where the repeater could be drawn forward along the deck on the dolly.

When the time came for a repeater to be laid, speed was reduced and the ship finally stopped head to wind. A 6x3 compound rope from the starboard cable drum was secured to the cable just abaft the bow baulks. Sufficient cable was then paid out until the tension was taken up by this rope. The turns of the running cable were then removed from the port cable drum and the resulting slack cable worked overboard by paying out the starboard drum rope which was holding the tension. When the excess cable had been cleared from the deck, the repeater on its dolly was carefully hauled along the fore deck to the traveling hoist of the overhead gantry. Cable was then drawn from the tank so that the turns could be re-formed on deck and replaced on the port cable drum. The repeater was lifted from the trolley and traversed outboard as soon as it was high enough to clear the bow baulks. It was then lowered to the water's edge and when the tension had again been taken by the cable, the quick release grip was slipped and the starboard drum rope cut. Paying out was then resumed.

Laying Program

On February 1, 1956, *Monarch*, having returned to Ocean Works, Erith, after refitting, commenced loading the various sections of cable to be used for the Terrenceville-Sydney Mines route. The sections were all carefully tested and measured in the Works before loading. The cable ends were clearly marked and dogged together by a length of rope which was not removed until the repeater had been jointed into its connecting sections of cable.

Loading of the cable and splicing in of repeaters was finished by April 10 and the system tested and checked. *Monarch* sailed for Sydney Mines on April 18 and arrived there April 30. The cable station is situated about $1\frac{1}{2}$ miles inland from the shore, with a small lake intervening. A length of Type B, insulated outer conductor, lead covered cable had previously been laid from the station across the lake to a narrow strip of land which separates it from the sea. The joint to the main cable was to be made on this strip. Two medium sized shore based motor boats were used to tow the end of the double armored section of cable from *Monarch* to the shore. During this journey the cable was supported by empty oil drums at close intervals. When the motor boats had reached

shoal water the end of the cable was secured to a landing line and two tractors took over the hauling.

When enough cable was on shore to make the joint and the splice, the barrels were cut away and *Monarch* weighed anchor and paid out this section of double armored cable on the agreed route and buoyed off the end. She then steamed over the proposed track to Terrenceville, taking soundings and sea bottom temperatures as required, and anchored off Terrenceville on May 3.

Preparations for landing the end were at once put in hand and the ship's motor launches towed the end of the cable towards the cable landing, the cable again being supported by empty oil drums. This end was jointed and spliced to a piece of cable which had been laid previously from the Terrenceville cable hut to a sand spit which juts across the head of Fortune Bay, about a mile away.

Upon completion of the splice, overall tests were made from the ship to the Terrenceville cable hut, and all being well, paying out toward the buoyed end off Sydney Mines was begun on May 4.

The first repeater went over about two hours after the start of laying and the others followed at approximately $4\frac{3}{4}$ hour intervals.

On May 7 the cable buoy on the Sydney Mines end was recovered and the end hove inward. After tests in both directions, the final joint and splice were made. This operation was completed on May 9, and on receipt of a signal that all was well, *Monarch* proceeded into harbor at Sydney to land testing equipment, a spare equalizer and other equipment.

Equalization and Testing

The cable had been loaded into the ship in repeater section lengths, so cut that when laid at estimated mean annual sea temperature, the expected attenuation would be 60.0 db at 552 kc. A correction for the change in attenuation of the cable when coiled in the factory tanks and when laid in about 100 fathoms had been determined from tests on two 10-mile lengths of cable, laid off the Island of Skye. The correction amounted to a decrease in attenuation when laid of 1.42 per cent. This was essentially an empirical result, and as the mechanism of the change was not fully understood, a possible further inaccuracy of equalization might arise.

Sea bottom temperatures along the route were obtained from information supplied by the Fisheries Research Board of Canada, but unfortunately, this information was rather meager and varied considerably with locality.

Since the cable equalization built into the repeater differed appreciably from the final determination on laid cable, it was found necessary at a comparatively late stage to introduce an undersea equalizer into the center of the sea section. This was intended to eliminate a flat peak of loss of 3.5 db, expected at about 100 kc. So that the last repeater should not lie too near the beach at Sydney Mines, a network simulating 9 miles of cable was also inserted in the undersea equalizer.

The repeaters were spliced into the cable lengths on board *Monarch* and tests were made at every stage of the buildup of the system. The equalizer was permanently jointed to the first half section of 7 repeaters and left with an excess length of tail which could be cut as desired during the laying operation to further improve the equalization. The first and second halves of the system were temporarily connected through power separation filters so that the whole system could be energized just prior to laying.

The test routine carried out included attenuation measurement at 5 frequencies in each direction of transmission, noise, pulse and loop-gain, supervisory measurements, dc and insulation resistance and capacitance. *Monarch* test room contained, therefore, two sets of terminal equipments similar to those installed at Clarendville and at Sydney Mines.

It was decided to energize the system continuously during the laying except for the few hours when power had to be removed to make the equalizer splice. This enabled a continuous order (speaker) circuit to be operated over the cable and minimized the number of energizing and warm-up periods. The only disadvantage, considered to be slight, was the necessary omission of insulation resistance and capacitance measurement during laying, except in the course of the equalizer splicing operation.

The plan was to lay from Terrenceville in the direction of the high-frequency band and to test the system to *Monarch* during the laying from this shore station. The overland section between Clarendville and Terrenceville, which contained two repeaters, was connected on with appropriate equalization after the submarine section had been satisfactorily completed and tested.

At Terrenceville, after the cable end had been taken ashore and the beach joint completed, the system was energized from *Monarch* with a dc power ground at Terrenceville for the necessary 4 hour minimum warming up period. The first set of routine measurements of the laying operation was then carried out. Thereafter, a complete set of measurements on the Terrenceville half of the system was made after every 10 miles of cable laid. An occasional check set of measurements was also made on the Sydney Mines half of the system in the tanks.

The primary object of these tests was to determine what length of cable should be inserted between the equalizer and the 8th undersea repeater to obtain the optimum system. In practice this resulted in arranging for a length of cable such that the output level of the 8th repeater at 522 kc should be equal to that at the output of the first repeater at the assumed mean annual temperature of 35.1°F.

The estimated length of cable required for this purpose was plotted after each measurement. It became evident soon after laying the 5th repeater (94.6 nautical miles of cable laid) that the linear relation obtained could be extrapolated with adequate accuracy to safely specify a length of 6.06 nautical miles of cable between the equalizer and the adjacent repeater.

This decision on length was taken, and after removing power the equalizer was accordingly jointed in, the operation being completed before it was necessary to pay out the splice. During this period capacitance and conductor and insulation resistances were checked on each half. During the laying of the second half, measurements were made as for the first half. On arrival at the buoyed shore end a final complete set of measurements was made and these suitably corrected for the shore end length, transmitted to Sydney Mines so that the first measurements from Sydney Mines to Clarenville could be checked with those obtained on the ship.

SIDELIGHTS

Weather

Weather is the big question mark in cable laying and repair activities. With few exceptions the transatlantic project was blessed with remarkably good weather. The exceptions were, however, noteworthy.

Heavy snow squalls were encountered off Terrenceville during the operation in that vicinity. At Rockall Bank on the first lay one heavy storm came up as the last repeater in the 1,200-mile section was going over, and made this launching and the subsequent buoying of the end very difficult operations. Both were accomplished successfully as a result of the superb seamanship of *Monarch's* commander, Captain J. P. F. Betson, and his officers and crew.

A second, and worse storm was encountered upon the return to Rockall. This was a manifestation of hurricane Ione, with wind velocities above 100 mph and very high seas. The ship had given up searching for the buoy (later reported drifting more than 500 miles away off the Faeroe Islands) and was grappling for the cable, when the storm hit. Fortun-

ately, the cable had not yet been found, so the ship could head into the wind and ride it out. She was driven many miles off course in the process, and the seas will be long and vividly remembered by all present. Incidentally, the cable was picked up shortly after the storm had moderated.

Generally speaking, the effect of the weather on the engineering supernumeraries on board was not severe, although *Monarch's* stock of dramamine was somewhat depleted by the end of the project.

Miscellaneous Events

At the start of the first transatlantic lay, several icebergs were encountered. One, a small one at the mouth of Random Sound, lay in the planned path of the cable and caused an involuntary, though minor, revision of the route. The others, beyond the mouth of Trinity Bay, were larger but also farther away.

Whales and grampuses got to be common sights, although much film was expended at first by the uninitiated.

An occasional bird rested on the ship far from land, obviously exhausted from its long and presumably unintended journey.

Progress Bulletins

Daily progress bulletins were radioed to headquarters of all partners during the laying.

In addition, because a telephone cable system differs considerably from submarine telegraph cables, the officers and crew were briefed by the engineering personnel as to the repeater structure, the need for equalization and the general objectives of the venture. This proved to be a very profitable move indeed, for the cooperation of all hands was everything that could be wished. As a follow up, daily performance bulletins were posted in strategic parts of the ship so that everyone no matter what his duties, could know just how the evolving system was performing with respect to objectives.

Cable Order Circuit

One way conversation from shore to ship over the cable was possible all the time the repeaters were energized. This was a source of very great satisfaction to the shipboard test crew, as it was concrete evidence that the cable was working, and working well. When power was turned down, the recourse to radio telephone provided a comparison which generally left no doubt as to the future value of the cable.

ACKNOWLEDGEMENTS

When the final splice was slipped into the water of Clarenville Harbor, on August 14, 1956, there was completed a venture quite unique in the annals of submarine cable laying. And in the laying perhaps more than in any other phase of the transatlantic project did the successful conclusion provide evidence of the friendly and harmonious relationships between the different organizations and nationalities involved, and of the close coordination of their efforts.

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R. G. GRIFFITH, graduate I.E.E., London 1924. Studied general engineering in Royal Naval Air Service and Communication Engineering in London. Mr. Griffith left England in 1924 to join All-American Cables Inc. (now American Radio and Cable Corporation) becoming Project Engineer in 1925, supervising ac telegraph transmission superimposed tests (then termed "wired wireless") on dc duplex telegraph cable between Balboa Canal zone and Fishermans Point, Cuba. He developed and supervised the introduction of the synchronous fork cable signal regenerator, which established the through cable circuits between New York and Buenos Aires via the west coast cables of South America. In 1929 Mr. Griffith was appointed Assistant Chief Engineer of Creed and Company, and in 1932 was placed in charge of development. In 1935 he joined Cable and Wireless Limited. From 1943 to 1946 he was loaned to the foreign office communication center in charge of special machine cipher development. He became Chief Engineer of Cable and Wireless London Communications center in 1946, and in May 1954 joined the Canadian Overseas Telecommunication Corporation as Chief Engineer. Mr. Griffith holds some 60 patents relating to telecommunications.

R. J. HALSEY, B.Sc. in Engineering, London University, City and Guilds College, 1926; Diploma of the Imperial College, 1926. Mr. Halsey entered the Engineering Research Branch of the British Post Office in 1927 where he was engaged on line transmission problems including, from 1938, the design of submerged repeaters and systems. In 1947 he became Head of the Line Transmission Division, and in 1952, Assistant Engineer-in-Chief concerned with all submarine cable matters; in this capacity, his primary concern has been the transatlantic submarine telephone cable. Associate of the City and Guilds of London Institute and Member of the Institution of Electrical Engineers.

WILLIAM W. HEFFNER, B.S. in Industrial Engineering, Pennsylvania State University 1929; Western Electric Company, Kearny, New Jersey, 1929-1932; Consulting work on industrial engineering in the Management Field 1932-1936; Western Electric Company 1936-. Mr. Heffner's initial work at Western was concerned with jacks, keys, and mica capacitors. In 1942, he became a Department Chief in charge of manual telephone apparatus. In 1947 he was made an Assistant Superintendent in engineering for manual apparatus. His assignments continued through 1952 in engineering for several manufacturing engineering functions, including factory engineering, manufacture of manual apparatus and equipment, metal finishing, material handling, and packing. Between 1952 and 1954 he was Assistant Superintendent in charge of the Relay Assembly Shops at Kearny, New Jersey. In 1954 he was placed in charge of operating, production control, plant operations, and maintenance at Hillside, New Jersey, where the flexible repeaters for the transatlantic submarine telephone cable were manufactured. More recently, he was placed in charge of the Fairlawn, New Jersey, shop of Western Electric, where telephone apparatus and switching equipment are being built. Mr. Heffner is a member of Sigma Tau.

M. F. HOLMES, B.Sc. in Physics 1937; British Post Office 1938-. Mr. Holmes transferred to the Engineering Department in 1942 and since 1944 has been concerned primarily with thermionics. He is now engaged in the study of factors leading to changes of tube characteristics.

JOHN S. JACK, Mountain States Telephone and Telegraph Company 1919-1930; American Telephone and Telegraph Company, Long Lines Department, 1930-. Mr. Jack was engaged in various Plant assignments in Colorado and Wyoming between 1919 and 1930. In 1930, he became Division Outside Plant Engineer for Long Lines in Denver; in 1938 he

transferred to Chicago as Division Plant Engineer, and three years later, moved to Omaha, Nebraska as District Plant Superintendent. He was transferred to the Personnel Department in New York in 1945 as General Supervisor of Wages and Working Practices. In 1949 he returned to the Plant Department as General Construction Supervisor, and in 1951 became Engineer of Outside Plant. In 1953 he was appointed Assistant General Manager—Special Projects; in this capacity he helped direct construction of the transatlantic submarine telephone cable. Mr. Jack is a licensed professional engineer in Nebraska.

M. J. KELLY, B.S., Missouri School of Mines and Metallurgy, 1914; M.S., Univ. of Kentucky, 1915; Ph.D., Univ. of Chicago, 1918; honorary degrees—D.Eng., Univ. of Missouri, 1936; D.Sc. Univ. of Kentucky, 1946; LL.D., Univ. of Pennsylvania, 1954; D.Eng., New York Univ., 1955; D.Eng., Polytechnic Institute of Brooklyn, 1955. Western Electric Company, 1918–25. Bell Telephone Laboratories, 1925–. Dr. Kelly became Director of Vacuum Tube Development in 1928; Development Director of Transmission Instruments and Electronics, 1934; Director of Research, 1936; Executive Vice President, 1944; President, 1951. He was awarded the Presidential Certificate of Merit in recognition of his contributions in World War II and now serves on several advisory boards in the Department of Defense and the Department of Commerce. Dr. Kelly is a Fellow of the American Physical Society, the Acoustical Society of America, I.R.E., and A.I.E.E. He is a Foreign Member of the Swedish Royal Academy of Sciences and a member of the National Academy of Sciences, the American Philosophical Society, Sigma Xi, Tau Beta Pi and Eta Kappa Nu. He is a Life Member of the M.I.T. Corporation and a Trustee of Stevens Institute of Technology. His honors include the Air Force Association Trophy in 1953; the Industrial Research Institute Medal in 1954; and the Christopher Columbus International Communication Prize in 1955.

R. KELLY, Associate of Royal College of Science, Ireland 1925; B.Sc. University College, Dublin 1937. After four years experience on power work for the Dublin United Tramways, he joined the power section of Standard Telephones and Cables in 1925. Following ten years of laboratory and field experience on carrier telephone and VF telegraph equipment, he took charge in 1936 of power development for transmission equipments.

HAROLD A. LAMB joined the Western Electric Company Installation Department in 1920, where he became engaged in installation and

installation engineering of telephone equipment. In 1923, he entered the Engineer of Manufacture Organization at Hawthorne, where he became concerned with relays, panel, step-by-step, and crossbar machine switching apparatus. During this time, he attended the Lewis Institute of Technology. In 1936 he was appointed a Department Chief on step-by-step apparatus. During World War II, Mr. Lamb transferred to the Passaic, New Jersey, Shops as Assistant Superintendent in the Western Electric Radio Division. Here he was engaged in engineering the manufacture of submarine radar and radar bomb sights. Returning to the Western Electric, Kearny, New Jersey, Works in 1947, he was concerned principally with central office apparatus, including the card translator, and in 1953 was placed in charge of the Hillside, New Jersey, Engineering and Inspection Organizations for building the flexible repeaters for the transatlantic submarine telephone cable. He is at present Resident Head of the Hillside Shops on flexible repeater manufacture.

ANDREW W. LEBERT, B.S. in E.E., New York Univ., 1932; Cornell-Dubilier Corporation, 1932-1936; Bell Telephone Laboratories, 1936-. For the first five years at the Laboratories, Mr. Lebert worked on transmission engineering on open wire and cable carrier systems. He then was concerned with fault location problems. During World War II, he turned to military communications on cable and open wire, and, following this period, he spent eight years on coaxial cable systems development. Since 1952 he has been connected with transatlantic telephone cable development. He is a member of I.R.E., Tau Beta Pi and Psi Upsilon.

CAPT. W. H. LEECH entered the British Post Office in 1920 as Third Officer of H.M.T.S. *Alert* and was later promoted to the old H.M.T.S. *Monarch* of which ship he became Chief Officer. Both of these ships were subsequently lost by enemy action in World War II. After a year ashore as Assistant Submarine Superintendent in 1938-39 he took command of H.M.T.S. *Aerial* and, in 1940, of H.M.T.S. *Iris*. In 1944 his ship was engaged in laying cables to the Normandy Beach head, an operation for which he was awarded the Distinguished Service Cross. In 1946 he became Submarine Superintendent, in immediate charge of the Post Office cable fleet and as such, directed the operations of H.M.T.S. *Monarch* during the laying of the transatlantic cables. He is an Officer of the Order of the British Empire (O.B.E.).

HERBERT A. LEWIS, E.E., Cornell Univ., 1926; Bell Telephone Laboratories, 1926-. Before World War II Mr. Lewis worked on the design

of equipment for manual and dial central offices, PBX's and broad-band carrier installations. During the war, he was concerned with the mechanical design of radar systems for the military. He was later responsible for transmission and equipment development for various carrier telephone systems. As project engineer for the Laboratories phases of the transatlantic telephone cable he was responsible for its transmission and equipment development. He is now Director of Outside Plant Development and is responsible for the devising and developing of new and improved methods, materials and equipment for that part of the telephone network which connects one central office with another and which ties the telephone customer's equipment into the central office. He is a senior member of I.R.E.

ARTHUR H. LINCE, B.S. in E.E., Univ. of Michigan, 1925; Bell Telephone Laboratories, 1925-. Until 1941 Mr. Lince worked on the engineering and design of dial central office equipment. During World War II he was concerned with engineering and design of radar for the armed forces. He then became involved with the development of microwave antennas, towers, waveguides and related items for microwave radio relay systems and testing equipment. He was engaged in the building of repeaters for the Havana-Key West submarine cable. Beginning in 1953, he has been in charge of the group responsible for the design of watertight enclosures for the repeaters used on the transatlantic telephone cable.

G. H. LOVELL, B.S. in E.E., Texas A & M College, 1927; M.S. in E.E., Polytechnic Institute of Brooklyn, 1943; N.Y. Edison Co., 1927-28; Bell Telephone Laboratories, 1929-. From 1929 until 1948 Mr. Lovell was concerned with the development of crystal filters for carrier systems. He then worked on the development of networks for use in broad-band amplifiers. For the transatlantic telephone cable project he worked on the amplifier networks and the equalization of the undersea system.

J. O. McNALLY, B.S. in E.E., Univ. of New Brunswick, Canada, 1924; Western Electric Company, 1924-25; Bell Telephone Laboratories, 1925-. Mr. McNally has specialized in research and development on electron tubes for Bell System communication and military uses. This included work on voice and carrier repeater tubes, electron tubes for the first commercial transatlantic radio system, and for the talking movie industry. During World War II, he had development responsibility for

many of the klystrons used in radar equipment. Later he again became concerned with the development of long-life tubes for submarine telephone cables. He has been awarded several patents on electron tube construction and operation. He is a Fellow of the I.R.E. and a member of the American Physical Society.

GEORGE W. MESZAROS, B.E.E. 1939, College of the City of New York; Bell Telephone Laboratories, 1926-. Mr. Meszaros started his Bell System career in the Systems Drafting Department. After spending a short time in several engineering groups of the System Department, he transferred to the Power Development Department in 1941. Here he has specialized in electronically controlled power equipment. Currently he is in charge of a group designing transistorized power supplies for the electronic switching system and for several military projects.

G. H. METSON, B.Sc. in Engineering, University of London 1931; M.Sc. in 1938 and Ph.D. in Applied Science and Technology, Queens University, Belfast 1941. Dr. Metson is in charge of the Thermionics Group at the Post Office Research Station and is particularly concerned with oxide coated cathodes and problems of tube life. He was responsible for the tubes used in the British submerged repeaters. Member of the Royal Institution and an Associate Member of The Institution of Electrical Engineers.

ELLIOTT T. MOTTRAM, B.S. Columbia University 1927, M.E. 1928; Western Electric Company 1922-25; Bell Telephone Laboratories, 1928-. Mr. Mottram's first assignments were in the development of disc recording and reproducing machines and equipment. Later he was concerned with sound on film recording and reproducing equipment, and with tape recording. From 1939 to 1950, he was engaged in development of airborne radio and radar equipment, electronic computer and bomb sights, and airborne homing missiles. As Director of Transmission Systems Development since 1950, he has been concerned with the development of transmission systems and equipment for military purposes, transmission test equipment, and television and wire transmission systems. In this capacity, he was responsible for technical liaison with the British Post Office on submarine cable matters and was in charge of Laboratories' activities in this field. He is a member of the A.S.M.E. and I.R.E.

SIR GORDON RADLEY, B.Sc. in Engineering, University of London 1919; Ph.D. University of London 1934. Sir Gordon's under-

graduate studies were interrupted by military service in World War I. Engineering Research Branch of the British Post Office 1920, where he was engaged initially on materials problems and later on interference, corrosion, and long distance signaling. He became Head of Research in 1939, and in 1949 was made Deputy Engineer-in-Chief. In 1951 he became Engineer-in-Chief, and in this position, was one of the principal architects of the transatlantic submarine telephone cable system. In 1954 he was made Deputy Director General, and in 1955 Director General — the permanent Head of the British Post Office. He became a Commander of the Order of the British Empire (CBE) in 1946 and was honored with a knighthood in 1954. In 1956, he became a Knight Commander of the Bath (KCB) and is President of The Institution of Electrical Engineers for the year 1956-57.

H. H. SPENCER, B.S. in M.E., Univ. of New Hampshire, 1923; Bell Telephone Laboratories, 1923-. He has been engaged primarily in the development of power supplies for broadband carrier, long distance and repeater equipment, including automatic plants for unattended operation on J, K, and L carrier systems and TD-2 microwave radio relay systems. Mr. Spencer is an Associate Member of the American Institute of Electrical Engineers.

J. F. P. THOMAS, B.Sc. London University 1942; British Post Office Research Branch, 1937-. In his early years, Mr. Thomas was engaged on investigations into contact phenomena and dust core magnetic materials. In 1948, he was transferred to the Submerged Repeater Group, where his main work has been the design and construction of power feeding equipment and pulse monitoring equipment used for fault location in submerged repeater systems. Associate Member of The Institution of Electrical Engineers.

REXFORD S. TUCKER, A.B., Harvard College, 1918; S.B., Harvard Engineering School, 1922; American Telephone and Telegraph Company, 1923-34; Bell Telephone Laboratories, 1934-. Mr. Tucker's early work was on noise and crosstalk prevention. During World War II he was engaged in classified military projects and served as co-editor of a War Department technical manual, *Electrical Communications Systems Engineering*. After the war he worked on mobile radio systems engineering and then the transatlantic telephone cable. He is an Associate Member of A.I.E.E., Senior Member of I.R.E., Charter Member of Acoustical Society of America, member of Sub-Committee No. 1 of

American Standards Association Sectional Committee C63, Harvard Engineering Society, and Phi Beta Kappa.

EDMUND A. VEAZIE, B.A. in Physics, Univ. of Oregon, 1927; Bell Telephone Laboratories, 1927-. His early assignments included the design of multi-grid tubes for use in aircraft radio receivers, police transmitters, and carrier telephone systems. During World War II he concentrated on tubes for radar and other military applications, including proximity fuses and gun directors. Since then he has been engaged principally in the design, fabrication control, testing, and selection of tubes for use in submarine telephone cable systems. He holds several patents on electron tubes and associated circuits. He is a Senior Member of I.R.E. and a member of Phi Beta Kappa.

D. C. WALKER, B.Sc. in Engineering and Diploma of the Imperial College from the City and Guilds College, University of London, 1937; British Post Office Research Branch 1938. Mr. Walker's early work was on interference and protection problems and during the war on special investigations for the services. Later engaged on development and equipment for carrier telephone systems, and since 1946 has specialized on submerged repeater systems. He is in charge of the group concerned with the design of the internal electrical unit of the rigid transatlantic telephone cable repeaters and the special terminal equipment. Associate Member of The Institution of Electrical Engineers.

V. G. WELSBY, B.Sc. London University 1934; Ph.D. London University 1946; Research Branch of the British Post Office, 1936. Dr. Welsby was at first a member of a group dealing with the design of multichannel carrier apparatus. Since 1947 he has been engaged in submerged repeater development, and during the last few years, has been in charge of the group concerned with the mechanical design of repeater housings and glands, and with the laying of rigid repeater systems. His Ph.D. degree was awarded for his work on dust-cored inductors. He is the author of a text book on inductor theory and design. Associate Member of The Institution of Electrical Engineers.

M. C. WOOLEY, B.S. in E.E., Ohio Northern Univ., 1929; Bell Telephone Laboratories, 1929-. Mr. Wooley was engaged in the development and design of inductors until 1935. Capacitor development then occupied his attention until 1949, concluding with the development and produc-

tion of capacitors for the Key West-Havana submarine cable repeaters. He then became concerned with fundamental development, primarily on materials and processes used in capacitors, including those for the transatlantic submarine telephone cable. He is currently supervising a group engaged in development and design of capacitors and resistors for submarine cable repeater applications for other systems. He is a member of Nu Theta Kappa.