Components for Submarine Telephone Cable Repeaters*

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Summary—**The first transatlantic, Alaskan, and Hawaiian Submarine Telephone Cables are provided with repeaters spaced about 37.5 miles apart. Each repeater consists of a 3-stage electron tube amplifier and contains approximately 60 components. Because of their inaccessibility for repair or replacement, it is desired that these systems operate for the order of 20 years without failure of any component. This requires a degree of reliability for both active and passive components orders of magnitude higher than are achieved in more conventional systems.**

Electron tubes and high-voltage capacitors subject to "wear out" have been the subject of intensive development and life testing for more than 15 years. These studies indicate that at the low cathode temperature and low cathode current density used in the electron tubes, satisfactory thermionic performance can be expected for more than 20 years. Likewise, tests on the high-voltage capacitors indicate that, in spite of the use of a high dielectric stress, the probability of a wear-out failure in 20 years is low.

These estimates, however, do not include the probability of catastrophic or sudden failure of the components. Since practicable test programs cannot measure the extremely low catastrophic failure rate expected of these components, it must be attained through the use of 1) reliable types, 2) close control of raw materials, 3) simple designs which are easy to make and inspect, 4) careful manufacture, and 5) thorough inspection.

This procedure is restrictive and involves close attention to all details in both design and manufacture. Consequently, unusually detailed specifications were required for raw materials, processes, and components. Complete records of all operations and inspections were kept to insure against omissions or errors. Specially selected operators were trained and required to demonstrate ability to produce satisfactorily before going on production work. Manufacture was carried out under exceptionally clean conditions. The product was inspected at each stage of manufacture so that hidden defects would not be missed. The resulting slow and painstaking manufacture disclosed many defects which would have been overlooked in normal production.

Although no numerical value can be attached to the degree of reliability attained, experience in production and service to date indicate that it is unusually high. Over 270 million component hours of service without a failure have been accumulated to date, which indicates, with 90 per cent certainty, a failure rate of less than 1 in 10,000 per year.

ALTHOUGH this is primarily the story of the components for the first transatlantic submarine telephone cable, it will be made more understandable and perhaps more interesting by a brief description of the system.

This system was a joint undertaking by the British Post Office, the Canadian Overseas Telecommunication Corporation, and the AT&T Company. The shallow water portion of approximately 300 miles between Newfoundland and Nova Scotia is of British design and manufacture. It uses a single cable for transmission in both directions. The deep sea portion of the system between Newfoundland and Scotland as well as the Alaskan and Hawaiian systems contains the components to be described. These use two cables, one for transmission in each direction. In the transatlantic system each is approximately 1940 nautical miles long and contains 51 repeaters spaced about 37.5 miles apart. The deep sea portion provides 36 voice channels in each direction in a frequency band extending from 20 to 164 kc.

The repeaters are cylindrical, $1\frac{3}{4}$ inches in diameter, and about 7 feet long exclusive of the end seals, armor bedding, and armor wires. Over the armor the total diameter of the repeater is approximately three times the diameter of deep sea cable. The repeater is flexible to the extent that it can be bent around a $3\frac{1}{2}$-foot radius. It can, therefore, be handled in the same manner as the cable in the laying operation. Flexibility is obtained by assembling the components in methyl methacrylate containers $1\frac{1}{2}$ inches in diameter and 5 inches long (Fig. 1). These are coupled together end to end with springs and enclosed in a double layer of steel rings to withstand the sea bottom pressure. These in turn are enclosed in a close fitting copper tube having a 1/32-inch wall.

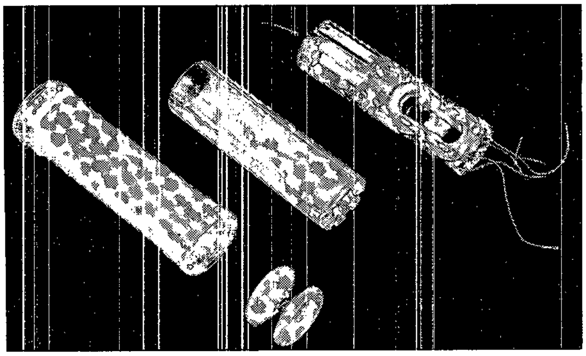

Fig. 1—Repeater network assembly. *Left to right:* outer housing, coupler, insulating sleeve, and input network with power separation filter inductor.

The plastic sections contain a single large component such as a high-voltage capacitor or electron tube, or a number of components which make up a complete network. This method of construction results in some unusual component configurations, as seen later.

The repeater consists of a 3-stage feedback amplifier coupled to the cable with transformers. The heaters for the three tubes are in series, and these in turn are in series with the central conductor of the cable. The plate and screen supply voltages are obtained from the IR drop across the three series heaters. Power for the repeaters is supplied by constant current supplies at each end of the cable. The total voltage drop through the cable and repeaters is approximately 4000 volts so that each power supply furnishes half of this. Thus the voltage to ground

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varies from 2000 at the ends to zero at the center of a cable.

A unique feature of the repeater is the method of checking performance from the shore station. A crystal in the feedback path provides a sharply tuned series resonant shunt, so that at its resonant frequency essentially all the feedback is removed from the amplifier. Under this condition the gain is proportional to the mutual conductance of the three tubes. The resonant frequency is different for each repeater, all being outside the signal band, so that by measurements from the shore ends of the gain at each of these peaks the operator can "call the roll" of repeaters and determine their performance.

The gain-frequency characteristic of the repeaters is made to match the loss of the cable between repeaters to within 0.05 db. The reasons for this close match are fairly obvious. If a systematic mismatch occurs, it will be cumulative throughout the 51 repeaters, and, if appreciable, will result in the signal level of some channels being either so high that it will overload repeaters on the receiving end or so low that it will be masked by noise. Submarine cable circuits are relatively free from externally caused noise. They are, therefore, operated at low-signal levels with a corresponding small margin between signal and noise.

The close match between repeater gain and cable loss requires that the gain range from about 20 to 60 db over the 20- to 164-kc band. This is responsible for the relatively large number of components in the input, output, and feedback circuits; it is in these circuits that the gain shaping is done.

The close tolerance on the gain, as well as the fact that a similar tolerance applies for the desired 20 or more year life of the system, places severe requirements on both the initial values and the stability of the components. Consequently, when components for this system were chosen, stability of characteristics weighed heavily in the choice. Furthermore, all of the passive components were subjected to temperature cycling between 0° and 150°F in order to stabilize them. In the case of some paper capacitors, this cycling covered a period of 30 to 40 days in order to achieve the desired degree of stability.

This leads to the question of reliability. Because of the desire to be able to lay repeaters as integral parts of the cable, space within the repeater containers was kept as small as possible. In part this discouraged the idea of designing repeaters so that there were alternate transmission paths, whereby failure in one path would not disable the whole system. Instead the philosophy was adopted of making every component—tubes, capacitors, resistors, and inductors—so reliable that there would be a reasonable chance that no failures would occur over some very long period of time, such as 20 years.

There are, in the deep sea portion of the transatlantic telephone cable system, approximately 6000 passive components for which this is the goal. If we are to be 90 per cent certain of achieving this degree of reliability, the average annual failure rate must be of the order of one in a million or less. Obviously no practical program of testing can hope to detect this small failure rate. In fact, it is estimated that tests would have to run on 6000 components for more than 400 years in order to obtain sufficient data to permit a reliable estimate of such a low failure rate.

Lacking the ability to determine from tests what the failure rate may be, the alternative is to use those types of components having a long history of reliable performance and to manufacture these to be as nearly perfect as possible. With the exception of the high-voltage paper capacitors in the submarine cable repeaters, the passive components do not "wear out." They may age or drift in value, but aside from this, it is the catastrophic or sudden failures that are most likely to occur. These may be due to poor electrical connections, broken conductors, corrosion which may result in open or short circuits, chemically unstable materials which may give off corrosive products, mechanically unstable materials which may cold flow or break, and finally, foreign material which may cause short or open circuits.

However, not all varieties of a given type of component are subject to the same defects nor to the same degree. The first step, therefore, was to select those varieties of components which would do the job at hand and at the same time be least subject to defects.

Because reliability in any complex system such as the telephone plant is always important, information on the performance of many varieties and types of components is available. From this information, those types having the best record of trouble-free service were selected as candidates for submarine cable repeater use.

This approach is both reactionary and restrictive in that it rules out a number of promising types as well as materials and processes simply because they are new. It does, however, provide a firm background on which, with extra care in design and manufacture, an extremely reliable series of components can be based. This procedure led to the use of a conservative design of electron tube, wire wound resistors, impregnated paper and silvered mica capacitors, molybdenum permalloy powder cores for those inductors requiring magnetic cores, and molybdenum permalloy tape cores in transformers. The use of ferrites for magnetic cores, carbon films in resistors, and plastic films in capacitors were all ruled out on the grounds of lack of proven long-time stability or reliability. The only exceptions to this have been certain features of the paper capacitors. These, however, have been the subject of intensive development and life tests for more than 15 years.

It is of interest to examine the requirements on the life of the electron tubes for the cable job in terms of the performance currently experienced on some of the more conventional tubes. Consider that there are two types of failure that will cause tubes to die; one of these is catastrophic failure, common to all components. Broken welds, heater failures, glass envelope failures, etc., can be put into this classification. There are also the "wear-out" types of failures. Of particular importance here is the gradual decrease of thermionic emission with life. With regard to the catastrophic failures, there are some interesting figures in Table I.

TABLE I
ELECTRON TUBE FAILURE RATES*

	Percentage Failure per 1000 Hours
6AK5 in military equipment (ave.)	10
5654 in commercial airlines	
(first 1000 hours)	0.6
(after 5000 hours)	0.1
Isolated cases in American computers	0.1 to 0.2
Objective: Transatlantic submarine cable (one failure at the end of 20 years)	0.002

* A considerable part of the data shown here has been taken or estimated from information contained in AIRINIC Research Corp. reports.

As seen here the 6AK5 tube in some military equipments under surveillance shows a catastrophic failure rate of 10 per cent per 1000 hours for the early part of life. An improvement in the 6AK5 tube, the 5654, reduced the catastrophic failure rate to 0.6 per cent per 1000 hours for the first 1000 hours in commercial airline equipment. After 5000 hours this rate drops to approximately 0.1 per cent. Some fragmentary information on computer operation in this country indicated 0.1 per cent to 0.2 per cent failures per 1000 hours for the most reliable tube. Here great care is taken in selecting, operating, and maintaining the tubes. The last line of the chart shows that if there is one failure at the end of 20 years of transatlantic cable service there will be a failure rate of 0.002 per cent or 50,000,000-tube hours per failure. Such a failure rate must include wear-out as well as catastrophic failures. This is about 50-fold better than that obtained for catastrophic failures alone in the best commercial operation now coming to attention.

Work on electron tubes for use in a proposed transatlantic cable was started in 1933. The first tubes made were triodes, but the advantages of the pentode resulted in the triode design being abandoned in 1936. Early in the development certain criteria were established for the design: 1) cathode temperature, 2) cathode current density, and 3) plate and screen voltages, all of which should be as low as practicable. Interelectrode spacings should be liberal.

The final design, Fig. 2, is conservative, with relatively large electrode spacings and a mutual conductance of 1000 micro-mhos. The cathode current density is approximately 0.7 ma/cm^2 as compared to as much as 50 ma/cm^2 in more conventional tubes.

Since each electrical connection throughout the repeater is considered a potential source of trouble, the number of such connections has been kept to a minimum. The connections to the tungsten heater are particularly susceptible to breakage due to crystallization of the tungsten and mechanical strains introduced by heating and cooling. This problem was met by a special arrangement in which the ends of the coiled heater are welded between a supporting wire core and a close fitting sleeve (Fig. 3).

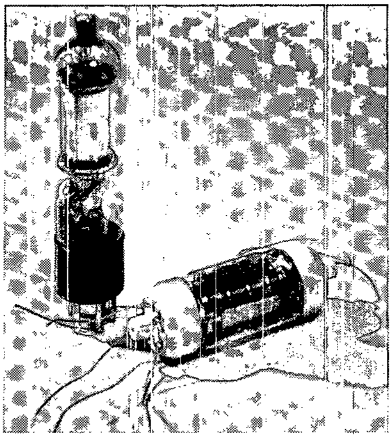

Fig. 2—Development model (*left*) and final design of tube used in flexible submarine cable repeaters.

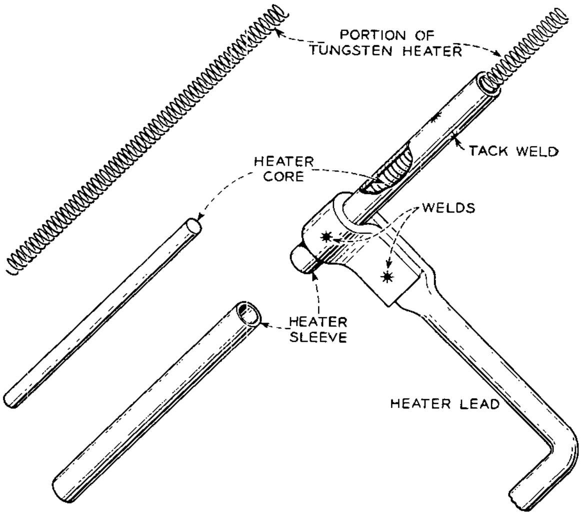

Fig. 3—Heater termination for submarine cable repeater tube.

Cathode temperature is one of the most critical operating variables affecting thermionic life. Early in the development a heater power of 5 watts, which corresponds to cathode temperature of 710°C, was chosen. Fig. 4 (a) shows the results of a life test on 16 tubes operating at this temperature. Subsequently it was found that even better life could be obtained at a cathode temperature of 670°C [Fig. 4 (b)]. Tests run for five years at this temperature show no significant change in transconductance.

The repeater design is such that reasonably satisfactory performance of the system would be expected if the transconductance of each of the tubes dropped to 65 per cent of its initial value. Consequently, on the basis of these as well as other life tests, satisfactory thermionic performance for well over 20 years seems assured.

The tubes were made at Bell Telephone Laboratories by specially selected operators working under close engineering supervision. All materials were carefully inspected and whenever possible were tried out in tubes subjected to accelerated aging tests. For example, each batch of heaters was sampled and subjected to both accelerated and intermittent tests before the batch was released for use.

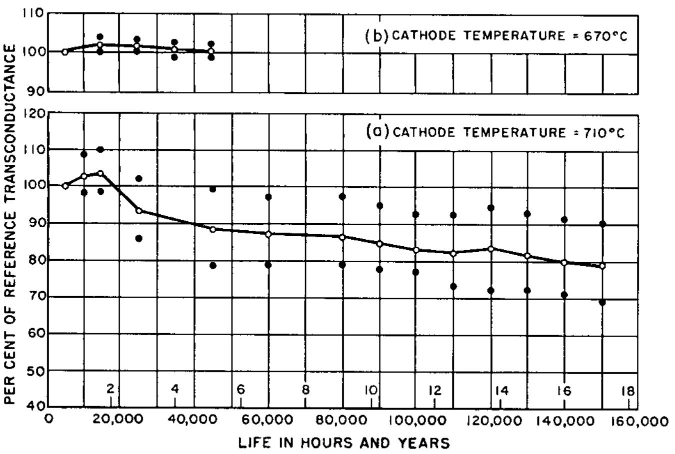

Fig. 4—Electron tube life test results. Black dots show range of data.

All tubes were subjected to a 5000-hour aging test during which electrical tests were made at frequent intervals. The performance of the tubes on this test weighed heavily in the final selection of the tubes to be used in the repeater. By normal commercial test limits the yield of tubes would have been 98 to 99 per cent. However, with the stringent inspection and selection used, only approximately one in six tubes pumped was approved for use in repeaters.

The Key West-Havana cable which was put into operation in May, 1950 contains 18 tubes very similar to those made for the transatlantic cable system. After eight years of continuous operation there has been no tube failure and the tubes show no measurable deterioration of thermionic emission over their original performance. Subsequent to the laying of the transatlantic cable, the cable system to Alaska was installed and placed in operation and the cable system from the West Coast to Hawaii is being successfully operated. In all there are approximately 800 tubes operating on the bed of the ocean and to date (September, 1958) we have had approximately 13,000,000 tube hours of operation without a failure.

CAPACITORS

The only other components of the repeater subject to "wear out" are the high-voltage capacitors which separate the dc and signal paths and provide an ac ground for the repeater. When work was started on the development of the high-voltage capacitors for a transatlantic system, the space and electrical requirement that these capacitors contain more capacitance per unit volume than most commercial designs was evident. Consequently, a fairly extensive program of life testing of various combinations of papers, foils, and impregnants was undertaken to determine the optimum combination for long life at high stress at sea bottom temperatures. In a fairly short time this program showed the superiority of liquid impregnants at low temperatures and ultimately led to the use of a castor oil impregnated-kraft paper-aluminum foil design.

Since this is the one passive component in the repeaters which does "wear out," a considerable amount of testing has been done to provide information from which a statistical estimate of the minimum life under service conditions could be made. These tests have now accumulated the equivalent of nearly 4000 capacitor years at the maximum stress used in the capacitors in the transatlantic system. From this total exposure of the life test samples, during which only one sample has failed, the range in time within which the first failure will occur in the system can be estimated. This is analogous to estimating the per cent defective in a given sample when it is known that in another sample from the same universe a certain percentage was defective. In our case the two samples did not, of course, come from the same universe. However, general experience as well as highly accelerated tests show that the life of the universe represented by the capacitors in the cable is longer than that represented by the original samples. This is due mainly to improvements in capacitor paper during the past 15 years as well as to improved control of processes and materials. Consequently, estimates of the life of the capacitors in the cable tend to be conservative. The estimate of life to the first failure is, of course, dependent upon the number of capacitors in service and their service voltage. Since the voltage varies from repeater to repeater, it is necessary to translate the total exposure of the capacitors in the cable with their respective service voltages into an equivalent exposure of a smaller number of capacitors at the maximum service voltage. This is done with the so-called "fifth-power rule" which states that the life of a paper capacitor is approximately proportional to the inverse of the fifth power of the applied voltage; *i.e.*,

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

where n ranges from 4 to 6.

From this it is calculated that in one year the 306 high-voltage capacitors in the deep sea portion of the transatlantic cable accumulate an exposure equivalent to that of 62 capacitors at the maximum voltage for the same length of time. Using this and the procedure outlined above it has been estimated, with a probability of being correct 9 times in 10, that the first failure in the transatlantic system will occur in not less than 16 nor more than 600 years.

There is the possibility of a catastrophic failure, perhaps the greatest hazard even in capacitors. Our best protection against failures of this nature is careful, unhurried construction by well-trained operators, supplemented by thorough inspection and testing. For example, high-voltage capacitor units were wound at the rate of approximately 10 per operator per day. This allows time for the operator to observe irregularities in the materials or process.

With this procedure it is surprising how many defects are found in high-quality materials. In spite of this care, some hazardous conditions might pass unobserved, so in addition to the usual dielectric strength tests all capacitors are subjected to an over-voltage test at about 150 per cent of normal ratings for periods of four to six months. This test is applied at sea bottom temperatures to paper capacitors and at room temperature to the mica capacitors which are less temperature sensitive. A total of more than 3000 capacitor years of this type of testing has been accumulated with only one failure. This attests to the care used in the production of the capacitors and also gives reason to believe that the chances of a catastrophic failure under service conditions are small.

The construction of both paper and mica capacitors followed conventional lines with some deviations in the interest of improved reliability. For example, the tension on the paper during winding was held within fairly close limits and the moisture content of the paper at the time of winding was controlled to facilitate meeting close capacitance limits and minimize the spread in the capacitance aging from capacitor to capacitor. Also, when unusually close capacitance limits had to be met, one electrode was made both narrower and shorter than the other, so that capacitance variations due to electrode misalignment were avoided. The paper capacitors all used "laid-in" or tab terminal construction and in the high-voltage type these terminals extended through the terminal plate and served as the external terminals.

Some features of the silvered mica capacitors were unusual. In the first place, all of the mica was thoroughly cleaned with acetone and distilled water before it was silvered. The purpose of this treatment was to eliminate contaminants which might result in failure or instability, but it also had the effect of reducing the ac loss of the capacitors. Contact to the silvered surfaces was made by interleaving fine silver foil between the laminations and clamping the ends of the laminations and the foil together by the terminals. As a further precaution, the foil was soldered to the terminals so that the only dry contact was from silver to silver. This covered a relatively large area. The second unusual feature of the mica capacitors is that they were simply mounted on a small slab of methacrylate by means of their terminals. This open-type construction was used for all components except oil impregnated capacitors to avoid possible damage due to operations of housing or mechanical strains resulting from the housing. However, it does make more difficult the handling of components before and during their assembly into networks. Such construction is possible because the repeater is thoroughly dried and filled with dry nitrogen before sealed. Typical paper and mica capacitors are shown in Figs. 5 and 6.

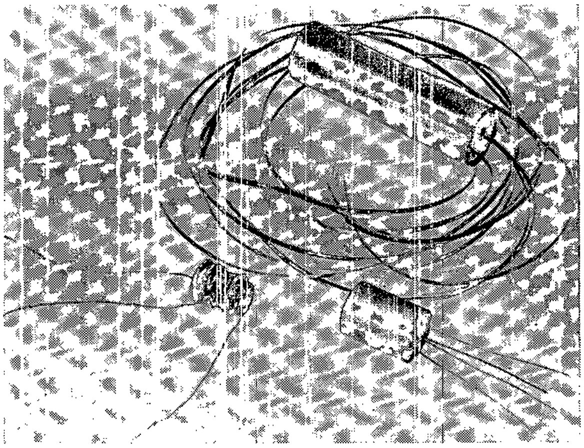

Fig. 5—Oil impregnated paper capacitors. High-voltage type is provided with long terminals to minimize soldered joints.

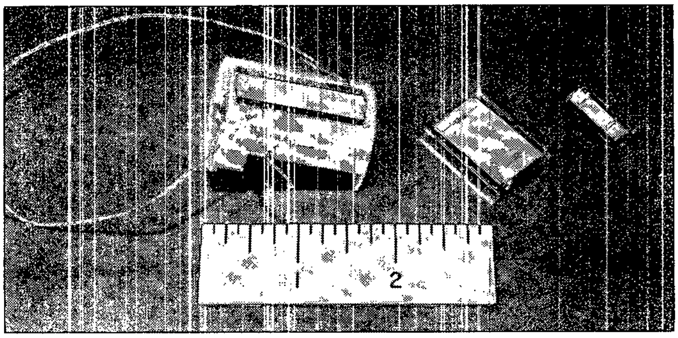

Fig. 6—Unencased silvered mica capacitors.

INDUCTORS

Because of the proximity of the steel rings which protect the amplifier from sea bottom pressure, it was necessary to use closed cores for all inductors. Consequently, they were all wound in toroidal form using either nonmagnetic or molybdenum permalloy dust cores. Some were wound with resistance wire to save the space which a separate resistor would require and also to eliminate a joint. Both inductance and resistance of such coils were controlled to close limits by providing separate adjustments. Inductance was adjusted by removing turns, and resistance, by removing wire from a "noninductive" winding. In one case, a magnetic core of larger cross section than could be fitted into the container with a conventional toroid was required. In this, two cores arranged in a figure-8 formation were threaded by the same winding (see Fig. 1). Other examples of the inductors are shown in Fig. 7.

The hazards associated with inductors are: 1) broken wire or terminal leads resulting from abnormal flexing, 2) shorted turns, and 3) mechanical instability.

Since every soldered joint is considered a potential source of trouble, the repeaters and components were designed to minimize the number of such connections. This meant that the inductors were all made without joints within the winding, and the wire of the winding was

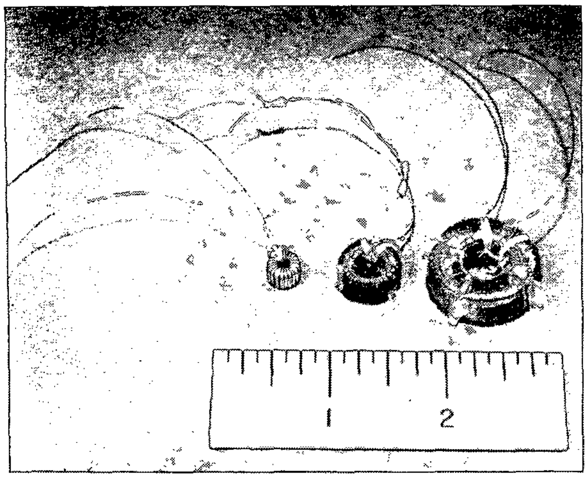

Fig. 7—Typical toroidal inductors.

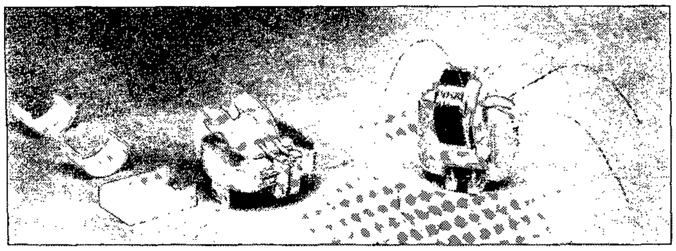

Fig. 8—The transformer and its parts.

used to connect the coil into the circuit. With this arrangement the handling associated with adjusting and testing could result in the leads being flexed nearly to the point of breakage. Two procedures were used to prevent this. Where possible, the windings were arranged so that both ends were on the outside and the initial adjustment was made so that as a last operation an additional turn or turns could be removed to provide a lead of relatively unflexed wire. When this was not feasible, special handling fixtures were used to hold the inductor or transformer and its leads in a fixed relation to each other until it was ready for use.

Shorted turns are most likely to occur in multilayer windings or from crossovers in single layer winding since these result in high pressure between turns. These hazards were minimized by carefully inspecting each layer of a winding for crossovers and by providing additional insulation between layers. Formvar enameled wire was used in most inductors, but in a few textile insulation as well as enamel was used.

Mechanical instability either in the form of cracking or flow of the core results in unstable inductance. To guard against this nonmagnetic cores were properly annealed, and all cores were carefully inspected visually for cracks. The completed coils were also subjected to repeated temperature cycles and observed for stability. This was found to be a sensitive and effective control for such defects.

TRANSFORMERS

The transformers used to couple the repeater to the cable are of conventional design, using a wound molybdenum permalloy tape core and a spool supported coil, as shown in Fig. 8. Since a considerable part of the required gain-frequency characteristic of the repeater is obtained in the input and output networks, close control of transformer parasitics such as leakage and capacitance was necessary. This was accomplished by a coil design which placed the windings in a fixed relation to each other and provided a high order of uniformity throughout the product. A precisely adjusted and stable air gap was also required. This adjustment was made by applying a test winding to the core before the regular winding. The electrical stability of the gap adjustment during mechanical stressing and temperature cycling was also measured with this test winding. In other aspects, the same factors apply to the reliability of transformers as to inductors and, likewise, the same precautions were taken to insure reliability.

RESISTORS

Although all of the resistors for the repeater are wire wound types, they are of many sizes and shapes to meet the physical and electrical requirements of the repeater. Some are simple inductive single or multiple layer windings on appropriate forms, while others are windings of mandrelated wire, *i.e.*, wire wound on a silk core and protected by a textile serving. The most critical part of their construction was the terminal connection. The wire size was limited to No. 46 gauge and larger in the interest of reliability; but since No. 46 is only $1\frac{1}{2}$ mils in diameter, it is very susceptible to electrical, chemical, and mechanical damage. Stranded lead wires were attached to the fine resistor wires by brazing. The processing of such splices was very carefully controlled so as to insure a good electrical connection and avoid flexing or overheating the resistance wire adjacent to the splice. The production of satisfactory splices was one of the most critical of all component manufacturing operations and normally required several weeks of operator training before acceptable splices could be made.

In addition to combined inductors and resistors, resistors were also included in the same container with some of the paper capacitors. This was done only for space reasons, as they have nothing in common except circuit positions. In this case the resistors were constructed of materials which would withstand capacitor drying and impregnation processes and at the same time not contaminate the capacitor. Consequently, the resistors used ceramic spools, enameled wire, and capacitor paper as interlayer insulation. These and other examples of the resistors are shown in Fig. 9.

As mentioned before, all the materials used in components had long histories of satisfactory performance,

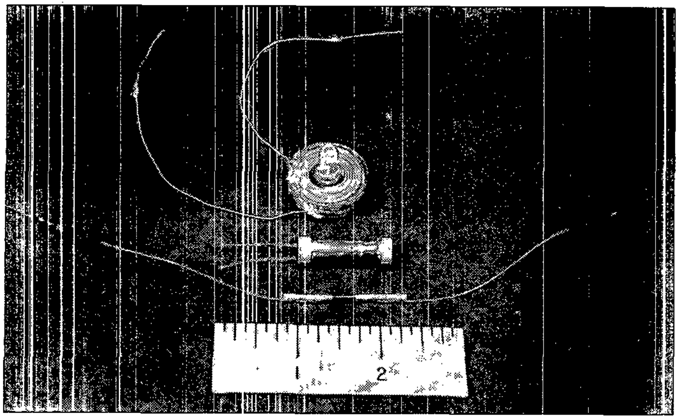

Fig. 9—Some of the various wire wound resistor structures.

but this alone was not enough. They could not be used in new ways without careful study. Most of the metal parts of components were gold-plated to improve solderability and to avoid the growth of metal whiskers. This included the lead wire used on some components. In those designs in which the resistor was included in the same container with a capacitor, these lead wires were threaded through small holes in the resistor spool. In early models phenol fiber spools were used, but for actual use in the repeaters a chemically less active material was desired for use inside the capacitors. When a ceramic was substituted for the fiber, the sharp edges around the holes acted as knives and scraped long fine slivers of the soft gold from the resistor lead wires. Such slivers were certainly undesirable additions to a capacitor in which clearances between uninsulated parts were of the order of 3/32 inch. Only by careful examination were the slivers detected originally, and they were eliminated only by rounding the edges of the holes and careful assembly of the parts.

Manufacturing Facilities

A detailed description of manufacturing facilities is beyond the scope of this paper, but it should be pointed out that cleanliness was the watchword. The Western Electric Company, which manufactured the passive components and repeaters, set up a special plant for this purpose. This plant was a separate and self-sustaining unit capable of doing all of the work associated with component and repeater manufacture except for certain mechanical operations, such as the manufacture of capacitor cans, and sampling inspection operations of an analytical nature. The whole manufacturing area was air-conditioned and the air was cleaned with both mechanical and electrostatic filters. Operators wore special clothing to minimize lint and the floors and work benches were regularly damp cleaned. Especial care was taken to avoid the accumulation of scrap materials such as small bits of fine wire, foil, filings, etc., which could stick to hands or clothing and turn up in undesirable places. The paper capacitor winding room was particularly restricted. Only winding and the assembly operations prior to impregnation were permitted in this area. The capacitor impregnation area was also separated from other areas and was maintained at a slightly negative atmospheric pressure with respect to other areas when oils or solvents were in use. All machining of metal or plastic parts was done in areas isolated from each other and from fabrication and assembly areas, and all materials were inspected and cleaned before being brought into the assembly areas. Gloves, tweezers, and vacuum pick-up tools were used extensively for handling parts and components, although the temperature and relative humidity of the manufacturing area was controlled to minimize perspiration. Exceptions were that paper capacitor and resistor winding operators were allowed to use bare fingers in the interest of greater dexterity. Washing of hands was mandatory whenever an operator returned from outside the working area and in critical areas workers were encouraged to wash more frequently.

Personnel for this plant were specially selected and were given thorough training. This training was designed not only to make the personnel skillful in their work but also to instill a sense of individual responsibility. Workers were informed of the reasons behind this instruction and, as the project progressed, were advised of its status. This feeling of personal responsibility and being an important part of the project was not insignificant in achieving a high standard of quality.

Inspection

Reference has been made several times to the critical inspection procedures used in the production of components, but it is difficult to convey in a few words an idea of the extent of this inspection. It started with a thorough examination of all of the raw materials. The specifications on these ranged from standard ASTM designations to elaborate and specialized requirements intended only for submarine cable use.

Capacitor paper, for example, was selected and inspected by a series of three life tests. The first of these was a highly accelerated routine one used by the Western Electric Company for inspection of all capacitor paper. From this test a lot of paper having outstanding leakage resistance and life characteristics was selected. A second sample from this lot was then subjected to a less highly accelerated test. Following successful completion of this test the paper was slit to the proper width, and finally each roll was sampled and life tested, using the same lot of impregnant to be used for production.

For all raw materials the sampling rate was much higher than usual; in general, a sample was taken from each piece, spool, or container. Parts for components were 100 per cent inspected, and wherever it was applicable (chiefly plated metal and ceramic parts) a water extract conductivity test was used to insure that they were free from contaminants such as plating salts or perspiration.

As the components were being made each step was inspected and approved before the next operation. Thus each layer of wire in coils, the terminal tabs in paper capacitors, the terminal splices in resistors, and the welds in electron tubes, to mention a few examples, were all subjected to individual scrutiny. In most cases this was done with the aid of low power binocular microscopes.

The silvered mica capacitors were the simplest of the components, but even in these there were five major inspections covering more than 20 specific points.

The results of each inspection and all data were recorded and initialed by the inspector. This in itself has a powerful effect, as signing a statement that a specific component is free from a certain defect is altogether different from passing along a trayful with a tag saying that they were inspected. In order to facilitate this record-keeping, each component was assigned an individual serial number. This system was extended into the inspection of raw materials, which were identified by an appropriate numbering system. Consequently, as part of the final approval for the use of a component, its history was traced to insure that all the raw materials used in it were inspected and had met their requirements and that all the specified operations and inspections on the component itself had been carried out. The lack of any part of these data caused the component to be rejected.

One might reasonably ask how much such detailed inspection contributes to improved reliability. Certainly no numerical value can be attached to it, but a list of some of the things uncovered by it, which would probably not have been found in normal manufacturing procedures, is some indication of its value:

1) Remains of insects calendered into capacitor paper,
2) Bits of steel wool embedded in textile insulated wire,
3) Pieces of nickel plating which had flaked off tweezers used in assembly and forming operations,
4) Floor sweepings in a roll of capacitor foil,
5) Damaged wire,
6) Mechanical damage from misaligned winding machines,
7) Damaged splices in resistors,
8) Winding errors found by measurement of the parasitics of each resistor,
9) Oil leaks in capacitors not disclosed by normal leak tests but revealed by extensive temperature cycling,
10) Loose solder in capacitors found by X-ray examination,
11) Inadequate impregnation of a lot of capacitors disclosed by a destructive sampling life test on each impregnation lot,
12) Cracked cores in inductors found by temperature cycling.

While some of these would not necessarily be disastrous, many of them would be capable of causing a complete failure of the system and if only one failure is prevented by the elaborate inspection, the cost of the extra care has been more than justified.

It is, of course, too early to make a prediction of the failure rate of the components, but in the existing systems there have been over 270 million component hours of service without a failure. We can say from this, with 90 per cent certainty, that the failure rate is not more than 1 in 10,000 per year, but this is still far short of our bogey of 1 in a million per year.

ACKNOWLEDGMENT

The development and production of components for the submarine cable systems were the work of many individuals. The author is indebted to all of these people for the privilege of reporting on their contributions. The material on the electron tubes was supplied by members of the Bell Laboratories responsible for them and more detailed information has been published.[1]

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[1] J. O. McNally, G. H. Metson, E. A. Veazie, and M. F. Holmes, "Electron tubes for the transatlantic cable system," *Bell Sys. Tech. J.*, vol. 36, pp. 163–188; January, 1957. See also T. F. Gleichmann, A. H. Lince, M. C. Wooley, and F. J. Braga, "Repeater design for the North Atlantic link," pp. 69–101, and H. A. Lamb and H. W. Heffner, "Repeater production for the North Atlantic link," pp. 103–138.