Electron Tubes for the SD Submarine Cable System

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Three new codes of electron tubes of the high reliability that is required for submarine cable service have been developed for use in the type SD systems. The basic philosophy was much the same as that which proved successful in designing tubes for the earlier cable systems. However, in order to meet the one-megacycle bandwidth requirement of the new system, it was necessary to extend such amplifier tube design considerations as transconductance, cathode current density and interelectrode spacing. The emphasis in this paper is on designing for reliability, since the amplifier tube is electronically quite conventional. In the field of protective devices, the new gas-filled cold cathode tubes also offer conservative and reliable applications of established design techniques.

I. INTRODUCTION

Three codes of electron tubes have been designed and developed specifically for use in the SD submarine cable system: the 455A-F, 456A, and 458A. The 455A, B, C, D, E, and F are pentode-type amplifier tubes manufactured as one type and subsequently designated for the six amplifier sockets to obtain optimum repeater performance. The 456A is a gas-filled cold cathode tube used as a power bypass device to (1) protect the heaters of the amplifier tubes, and the low-voltage components in parallel with them, from transient high-voltage surges on the cable and (2) to provide a continuous path for the cable current in case of an open heater in any of the amplifier tubes. The 458A signal path protector is a high-speed gas-filled cold cathode tube used at both the input and output of the repeater to protect the transmission path from voltage surges.

For a period of approximately two years engineers of the Western Electric Company were resident at Bell Telephone Laboratories to participate in the final development stages of the tubes. As a result of this endeavor the final tube designs and processing schedules represent the combined thinking of both the development and manufacturing organizations.

II. RELIABILITY CONSIDERATIONS

2.1 *Objectives*

Reliability requirements for electron tubes for use in submarine cable systems were formulated for the SB (flexible repeater) system[1] and have not been materially changed for the new broader-band system. Lifting cables for the purpose of changing faulty repeaters will always be an expensive operation. Revenue loss during the out-of-service period increases with bandwidth because of the additional voice channels.

The reliability objective for the tubes may be stated in several ways. Loosely, one hears "no tube failures in twenty years." Actually, the objective adopted is that the probability of system failure due to a tube failure shall not exceed 50 per cent for a twenty-year service period for a 3000-mile system. This objective corresponds to a mean time between system failures of twenty-nine years.

The amplifier tubes (455A-F) are probably limiting with respect to reliability, because they have closer interelement spacings, tight requirements on stability, and are operating continuously, as compared to the gas tubes (456A and 458A), which are on standby duty. Because of this and the large number of repeaters required for a long system, the amplifier includes two parallel strings of three tubes each with the circuit so arranged (see Fig. 5, Section 3.4.1) that the most probable kinds of tube failure will cause a system failure only if both strings are involved. Such defects would be permanent open circuits or short circuits between tube elements. There is no protection against plate shorts in the amplifier output stages, and it is also recognized that a single noisy tube could make the system unsatisfactory for commercial service.

The objective stated above corresponds to a tube failure rate of 0.08 per cent* for twenty years for defects not minimized by circuit redundancy. A failure rate of 2.4 per cent* is the corresponding value where circuit redundancy is provided. In the reliability analysis, it has been assumed that the deterioration due to decreasing thermionic emission would be negligible. This assumption is justified in Section 3.4.2, *Thermionic Life.*

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* See Appendix for details.

2.2 *Background and Prospects*

The reliability objective and the prospects for adequate stability for the 455A-F tubes for twenty years were based largely on the experience gained from the 175HQ tube used in the SB system where, to date, no tube failures have occurred during more than 80 million tube-hours of sea-bottom operation. In 1955, when development work was started on 455A-F tubes, 18 of the 175HQ tubes had been in sea-bottom service in the Havana-Key West system for about five years with no failures and no significant change in tube performance. Some 50 175HQ tubes of essentially the final design had been life-tested for lengths of time up to about sixteen years at various operating conditions. The results indicated that the transconductance would decrease less than 1 per cent per year at the operating conditions adopted for cable use. Additional life tests on 4800 tubes[1] showed that a 5000-hour aging period was sufficient to cull out substandard tubes and allow selection of those tubes most likely to meet the reliability objective. A 5000-hour aging-in and screening period was therefore adopted for the 455A-F tubes.

Since no gas tubes were used in the Havana-Key West system, no field data were available. However, considerable life testing had been done on the gas tube subsequently used in the first transatlantic system.

This background offered promise that the development of a higher transconductance vacuum tube and suitable gas tubes was feasible, with the stated reliability as a reasonable objective. However, it was evident that unproven materials, processes, and design features should be avoided where possible. Also, the basic philosophy which had been used in the fabrication and selection of 175HQ tubes was adopted for the new tubes. Every significant deviation from the "expected" by an individual or a batch is viewed with suspicion. If the cause can be found and understood, the cloud of suspicion may be removed; otherwise, the affected tubes must not be used. The methods of implementing this philosophy are described in a later section.

III. THE 455A-F AMPLIFIER TUBES

3.1 *Design Considerations*

The 455A-F electron tubes are pentodes of the indirectly heated cathode type using fine-pitch frame-type grids. With the emphasis on reliability and reliance on proved techniques, most of the design features are conventional, some perhaps even old-fashioned. Since optimizing pentode performance characteristics by geometry is an established art, the emphasis of this article is on designing for reliability.

Because of the excellent performance of the 175HQ tube it was used as the datum point for designing the new tube. The most important parameters and operating conditions for the 175HQ and the 455A-F tubes are compared in Table I. This comparison provides a basis for explaining the design considerations involved in the development of the 455A-F tubes.

3.1.1 *Cathode Temperature*

The most important operating factor affecting the thermionic life of the cathode is the cathode temperature. It was decided at the outset that, in spite of the higher current density required, the cathode temperature for the 455A-F tubes would be no higher than that of the 175HQ. Use of a special cathode alloy and improved processing and storage techniques for tube parts made this possible.

3.1.2 *Cathode Current Density and Transconductance*

The higher cathode current density of 10 ma/cm² is necessary in the 455A-F tube to achieve the higher transconductance. Life tests on 175HQ tubes which had run about fourteen years at a cathode temperature of 710°C showed no significant difference between tubes operated at 0.2 ma/cm² and those operated at 2.8 ma/cm². These and other similar results indicated that 10 ma/cm² was a reasonable operating level. The higher transconductance also requires an improved cathode alloy which develops less interface resistance than the nickel used in the 175HQ tubes.

3.1.3 *Grid-to-Cathode Spacing*

The 0.0055-inch grid-cathode spacing of the 455A-F is also necessary to achieve the higher transconductance. This is perhaps where the great-

Table I — Comparison of Parameters and Operating Conditions

	175HQ	455A-F
Cathode temperature (true)	670°C	670°C
Cathode current density	0.7 ma/cm²	10 ma/cm²
Grid-cathode spacing	0.024 in.	0.0055 in.
Maximum element voltage	51 v	45 v
Transconductance	1000 μmhos	6000 μmhos

est extrapolation from the 175HQ (0.024-inch spacing) is involved. Spacings of only 0.0025-inch are successfully employed in several telephone tubes for readily accessible land systems. For the less accessible submarine cable tubes, it was felt that the greater care in fabrication and inspection which is necessary to minimize particles can economically be justified. This would make the 0.0055-inch spacing feasible, even with the high level of reliability required.

3.1.4 *Maximum Element Voltage*

Although there was no indication that the maximum element voltage of 51 volts was high enough to affect the life of the 175HQ tube, it was found possible to operate the 455A-F at 45 volts maximum, which was considered desirable.

3.2 *Structural Features*

3.2.1 *Interelectrode Spacings and Foreign Particles*

The design of the tube was strongly influenced by the "particle problem." The reduction in grid-cathode spacing is a serious factor because of the risk of failure due to a particle of foreign matter becoming lodged in this critical area. A conducting particle can cause a short circuit or it can cause noise. A nonconducting particle can cause noise, particularly after it has been subjected for some time to the deposition of the normal vaporization products from the cathode. Noise is particularly serious, since the parallel-path redundancy feature of the amplifier circuit actually increases the risk of trouble due to noisy tubes, because there are twice as many tubes in positions followed by substantial amplification.

The tubes have been designed to minimize particle generation, are fabricated in extremely clean areas using the highest practicable degree of housekeeping measures, and employ selection criteria designed to minimize the hazards due to particle contamination.

3.2.2 *Tube Mount Assembly*

A phantom drawing of the based tube is shown in Fig. 1. The glass envelope, the ceramic base, and the braided gold-plated beryllium copper flexible leads are essentially the same as those used in the earlier cable tubes. The stem of the glass envelope is made from a molded glass dish into which are sealed eight pre-beaded two piece nickel-dumet leads

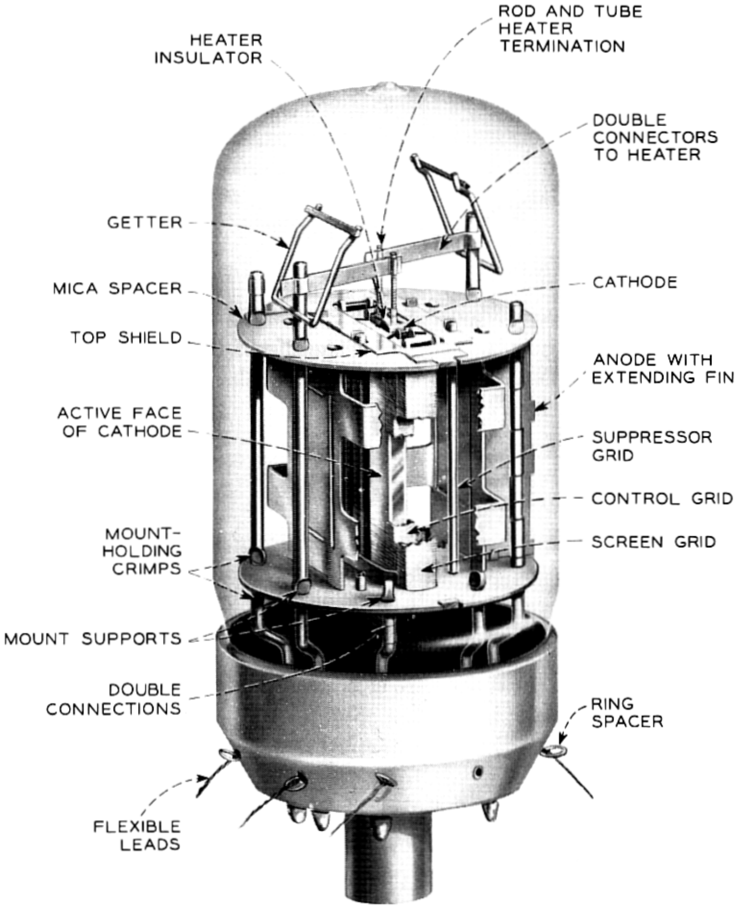

Fig. 1 — Structural details of the 455A-F electron tube.

whose inner nickel portions form the supports for the element assembly. The entire mount is supported from the stem leads. It was so designed to eliminate the mica insulator to bulb contact present in the earlier tube, with its resultant production of small mica particles.

The element "cage" assembly consists of the molybdenum anode, the oxide-coated cathode sleeve, frame-type control and screen grids, four rods that act as a suppressor grid, and two end shields. All of these are held together in proper relationship by two magnesium oxide-coated mica insulators. The "cage" assembly slides over the support leads, which are then crimped to position the cage. The coated heater and insulator assembly slides into the cathode sleeve from the top. The attachment of the heater connectors and getters completes the mount. The judicious placement of standoffs, tabs and lead crimps creates a truss-like structure that permits the tube to withstand a 500-g, 2-msec shock in any direction without damage. (This is ten times the predicted maximum shock to which the tube might be subjected in cable laying.)

In a repeater the based tube is supported on rubber cushions in a methacrylate housing as shown in Fig. 2. The flexible leads pass through the housing to form circuit connections and to provide for relative motion between the circuit and the tube. The small rings that pass through the flexible leads control the length of lead in the various regions.

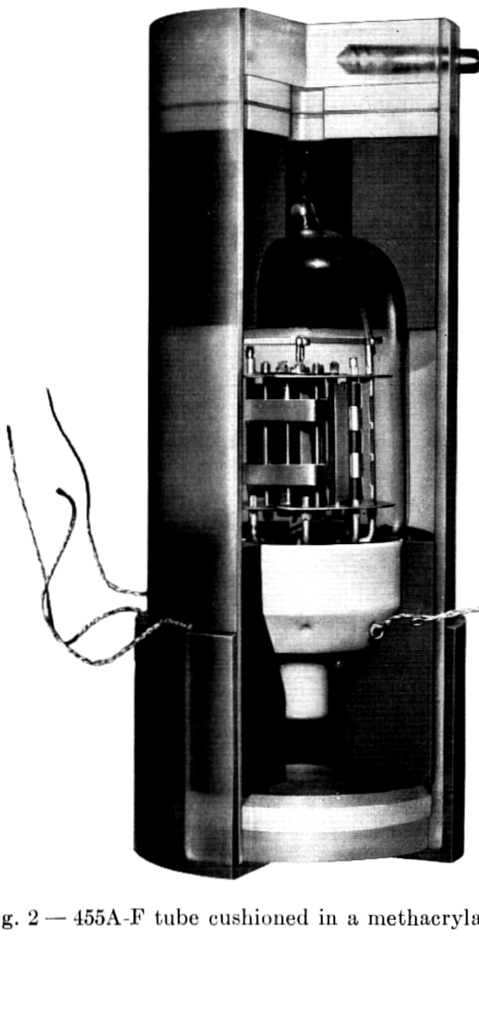

Fig. 2 — 455A-F tube cushioned in a methacrylate housing.

3.2.3 *Lead Welding and Crimping*

Again referring to the particle problem, a hazardous condition is created by splattering from the spot welds made during mount fabrication. Particles of 0.005 inch can be seen quite readily when viewed under a microscope on a flat surface. They are, however, extremely difficult to detect in a mount structure. This problem has been minimized by designing the tube so that the number of spot weld positions is roughly one-third those in the early flexible repeater tube. The tube design is such, however, that even with the reduction in the number of welds, every active tube element is redundantly connected so that should a single weld fail, the tube would still function.

Another design feature to minimize particle contamination is the use of crimped leads to support the mount structure. The older submarine cable tubes used metal eyelets crimped to the micas and welded to the stem leads as the mount supporting arrangement. Experience had shown that eyelets so used provided excellent structural support but, in a close-spaced tube, had the disadvantages of increasing the weld splash problem, generating mica particles, and catching and retaining all kinds of particulate matter and concealing it until late in the tube processing.

3.2.4 *The Anode*

The anode is a one-piece detail with a side fin. An earlier design, utilizing a two-piece plate with no side fin, optimized the interelectrode capacitances and provided sufficient mount ruggedness in the direction parallel to the grid plane, but was somewhat weak in the transverse direction. Ruggedness for tubes intended for the quiescent environment of the ocean floor may seem incongruous but is needed to protect against shocks during cable handling and laying. The anode structure, as can be seen in Fig. 1, has had all nonfunctional portions eliminated to provide the most open structure possible. This was done to permit microscopic examination of the cathode surface and the critical 0.0055-inch grid-to-cathode region to insure that no foreign matter has been entrapped.

3.2.5 *The Grids*

The control grid and screen grid are both made with fine tungsten wire wound at high tension on frames blanked and formed from sheet molybdenum (see Fig. 3). The frames are made in two sections, lapped to very precise dimensions, and paired to close tolerances. After the wires are wound on the paired frames, a single furnace operation brazes the frame

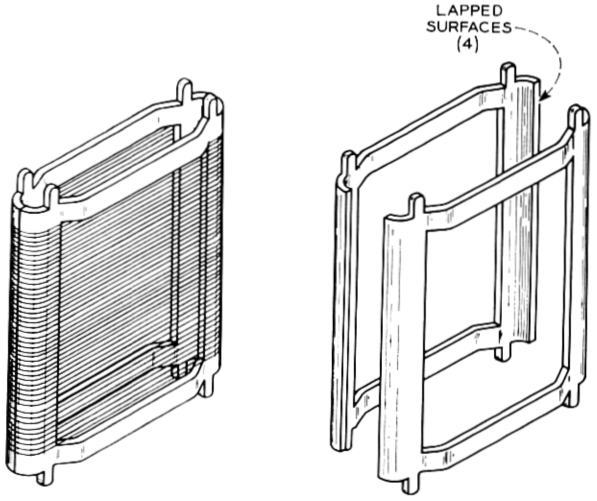

Fig. 3 — Wound grid and a pair of grid frames for the 455A-F tube.

sections together, brazes the fine wire to the frame and causes molten gold to cover the fine wire. While other types of frame grid construction were available,[2,3] this type, patterned after the original frame grid,[4] was selected because of fewer welds, lower grid mass, and the elimination of frame embrittlement.

3.2.6 *The Heater*

Heater reliability is of major concern, as this element is probably the most susceptible to catastrophic failure in that tungsten is subject to possible recrystallization and embrittlement. The heater in the 455A-F tube is a coiled tungsten wire formed into a precisely dimensioned M-shaped heater, spray coated with alumina, and slipped into a formed alumina block. Details of the heater and connectors are shown in Fig. 4. Connection to the tungsten heater is made in a manner similar to that which proved successful for the 175HQ tubes[1] with a single modification, namely, the crimping of the nickel sleeves to obtain a more intimate heater-to-connector contact. The 1090°C heater temperature is consistent with the conservative approach to design and operation.

To insure a large supply of uniform quality material, a procurement program was worked out with the supplier, the Westinghouse Electric Company. Special ingots of tungsten were made specifically for this use. The ingots were reduced to the wire form and wound onto many small spools, each one related by code marking to each other and to the original ingot. The spools were sampled in a statistical manner by making heaters and running regular and accelerated life tests on them. The accelerated tests included higher temperature operation as well as ON and OFF cycling. Use of a spool of wire was contingent upon obtaining no failures on these tests.

The insulator block shown in Fig. 4 is novel[5] and worthy of discussion. It is essentially a four-bore alumina block with the wall broken through between the two center holes, giving this opening a dumbbell shape. This permits the heater in its final M shape to be inserted into the block from one end. In addition to permitting an easier assembly operation, the dumbbell insulator makes it possible to insert a coated heater that has been fired. Use of a coated heater minimizes the transfer of tungsten to the insulator walls and insures high insulation resistance between the heater and cathode.

3.2.7 *The Cathode*

3.2.7.1 *Study of Cathode Materials.* There was evidence that impurities in commercial cathode nickel could, in time, cause performance degrada-

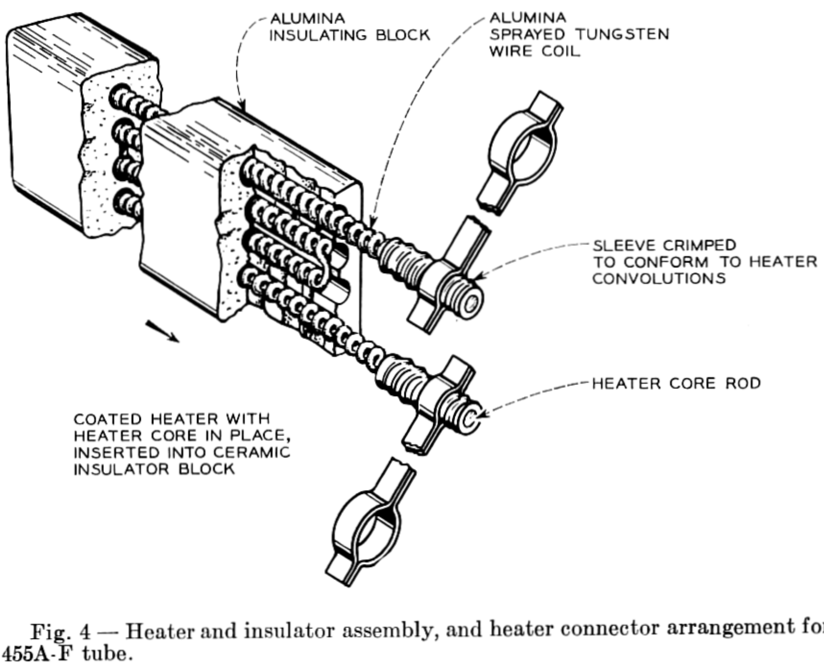

Fig. 4 — Heater and insulator assembly, and heater connector arrangement for 455A-F tube.

tion either through sublimation with consequent leakage between elements or with the development of cathode interface impedance. A survey showed that there was no source of supply for cathode nickels of the purity needed for the newer long-life high-transconductance tubes with their more stringent requirements.

Accordingly, a development program was undertaken to (1) provide special materials for the tube development work and (2) establish means for procuring production quantities in cooperation with the Western Electric Company. The first part of this program made available small billets of high-purity nickel and nickel with various additives[6] in which no single impurity exceeded 0.005 per cent by weight. Studies of the fundamental properties of these materials and a comprehensive evaluation of their suitability for use in long-life electron tubes were conducted.[7,8]

3.2.7.2 *Cathode Fabrication.* The cathodes are made of rectangular tubing with the emissive coating on the two broad surfaces. Initially they were fabricated from two channel-shaped pieces of nickel joined together by a diffusion welding process using sapphire tooling to avoid contamination of the nickel.

Approximately 700 tubes were fabricated and put on life test, using as a test vehicle a modification of the Western Electric 435A electron tube. This pentode was used because its close electrode spacing and high transconductance would accentuate the effects being studied. The tests included nine different cathode melts run at nine different operating conditions. Throughout the development program complete analytical tests were made at various points to insure the cleanliness and purity of the cathodes.

The making of cathodes from sheet material had provided ultra-pure sleeves for all of the cathode program. The fabrication method had been developed to an extent that would permit its use in production, and some 230 tubes of preliminary and refined designs for the 455 A-F amplifier tube were on life test. Since there were some undesirable aspects to the welded cathode, a program to produce seamless cathode sleeves from raw material supplied by Bell Laboratories was worked out with the Superior Tube Company of Norristown, Pennsylvania. Special measures were applied at their plant to insure that no contaminants were picked up and that each individual cathode sleeve was identified with respect to its starting billet. Analytical tests were applied to insure the purity of the material at critical points in the production. No changes could be observed from the original data. Tubes made with the new seamless cathode sleeves were put on life tests along with suitable control lots.

3.2.7.3 *Choice of Cathode Material.* As the development neared completion, a pilot production run of 300 tubes was made using the final design with all fabrication techniques and parts processing oriented toward a scaled-up production run. The life data from the cathode programs had, by this time, indicated two melts with superior characteristics for long life. These were (1) a single-additive, nickel plus 2.0 per cent tungsten, and (2) a double-additive, nickel plus 2.0 per cent tungsten plus 0.02 per cent magnesium. Because ample supplies of these two kinds of cathode materials had been stockpiled, it was possible to delay the final choice until production was ready to start, thus accumulating more evidence to support the final decision. The melt ultimately chosen for production was the double-additive, since the immediate effectiveness of the magnesium as a reducing agent permits a relatively short age-in period. The tungsten, with its slower diffusion and reaction rates, would not by itself make available tubes of adequate uniformity with 5000 hours of aging.

3.3 *Processing and Cleaning Controls*

A basic principle of reliability is that while inspections are important they are usually after-the-fact, and hence reliability must be built into the product. This is done by meticulous workmanship and by a system of multiple checking on parts and processing.

The system that was evolved recognized that it is virtually impossible at the time of tube fabrication to predict what specific information would be important when the tube is to be evaluated 5000 hours later, or if the tube is on life test, perhaps years later. Each tube was given a unique serial number, and all records were arranged so that from the serial number it would be possible to:

(a) trace every item in the tube back to its raw material lot,
(b) know who treated each part at every step in the tube fabrication,
(c) know when each part was treated, and
(d) know how each part was treated.

This was accomplished by tying together with proper records:

(a) the tube serial number,
(b) a serial number on the cathode, (duplicated on the plate)
(c) a serial number on the control grid,
(d) a serial number on the screen grid,
(e) lot numbers on each group of parts, and
(f) lot numbers on all material batches.

The record keeping consumed a large number of man-hours, even though maximum use was made of modern machine aids. This detailed information on individual tubes was essential in analyzing anomalies in test results and in rationalizing the acceptability of processes and tubes.

The cleaning procedures used in tube fabrication are of utmost importance in producing long-life, highly reliable tubes. The basic cleaning procedure adopted was that developed at Bell Laboratories.[9] This is:

(a) removal of grease by solvents,
(b) removal of physical contaminants by ultrasonic agitation,
(c) rinse in deionized water in a cascade-type cleaner,
(d) light oxidation to remove residual organic materials,
(e) reduction in hydrogen to outgas parts,
(f) testing for surface contaminants by the water wettability (atomizer) test, and
(g) storage in "atomizer clean" containers with strict limitations on duration of storage, i.e., 96 hours maximum for coated cathodes to ten days maximum for shields.

These basic processes were used wherever applicable at each step in the fabrication. Early contaminant elimination and low carryover was thus achieved. The resulting fabrication and processing procedures consisted of some 350 separate operations, a formidable number under any circumstances. However, the associated test and life data proved beyond question that a uniformly high-quality tube was being turned out on a production basis.

3.4 *Electrical Characteristics and Life*

3.4.1 *Operating Characteristics*

The arrangement of the electron tubes in the SD system repeater is shown in the simplified circuit schematic of Fig. 5. In the amplifier, stages A, B, C and D, E, F comprise the two parallel amplification paths mentioned earlier in this article. Table II lists the operating voltages and principal electrical characteristics of the 455A-F tubes for input and output conditions of amplifier operation. Grid noise is important in stages A and D, and significant in B and E, while output capability is most important in stages C and F. The typical equivalent grid noise figure is 825 ohms compared to the theoretical value of 750 ohms.

A family of plate current versus plate voltage curves for a typical tube over the approximate region of operation is shown in Fig. 6. While the curves have the general appearance of a pentode family, the sharp breaks at the knee region are more characteristic of a tetrode. Actually, the tube is a cross between the two since the suppressor grid consists of only four rods and there is considerable dependence on space charge for supprestransmission of current to the plate. The double shoulders in the curves are attributable to lack of perfect symmetry.

3.4.2 *Thermionic Life*

The thermionic performance of tubes during life is of major importance to a cable system. In the discussion of reliability, it was assumed that deterioration due to decreasing thermionic emission would be negligible. This was based largely on the performance of 175HQ tubes in SB cable systems and backed up by the life data accumulated on development models of 455A-F tubes. During the development program many tubes, representing a variety of structural features, many different cathode melts and several sets of operating conditions, chiefly cathode temperatures, were put on life test.

Curve (a) of Fig. 7 shows the life pattern for the oldest test of development model 455A-F tubes. This is for a representative group of tubes with cathodes of grade 220 nickel operating at 700°C.* Transconductance has been normalized to the median value at the 5000-hour test. Per cent of this reference transconductance is plotted versus total aging time in hours and years. Median values and ranges are shown at the various test points. The decrease in transconductance with time is attributable to the development of cathode interface impedance which, at the latest test point, had a median value of about six ohms.

Life performance of a group of tubes using cathodes with the tungsten and magnesium additives (final type) are shown in curve (b). At nearly 40,000 hours life the median transconductance exceeds the 5000-hour reference value by about one per cent. There was no measurable interface impedance in these tubes at the latest test. Again the cathode operating temperature was 700°C. Comparative tests subsequently showed 670°C to give results comparable to those at 700°. Consequently, in the interest of conservative operation, the lower temperature was selected for the final design.

Curve (c) in Fig. 7 is for tubes typical of Western Electric Company production operating at 670°C. While the total age is shorter for these tubes, it is gratifying to note that the trend is following closely the pattern set by the development tubes at comparable age.

The activity data of Fig. 8 present an indication of future trend in transconductance for the same groups shown in Fig. 7. Here are plotted the changes in transconductance (per cent ΔG_m) which accompany a 20 per cent decrease in tube heater current. It is noted that the activity picture is favorable for development and production tubes. The wider

* All cathode temperatures referred to in this paper are "true" temperatures.

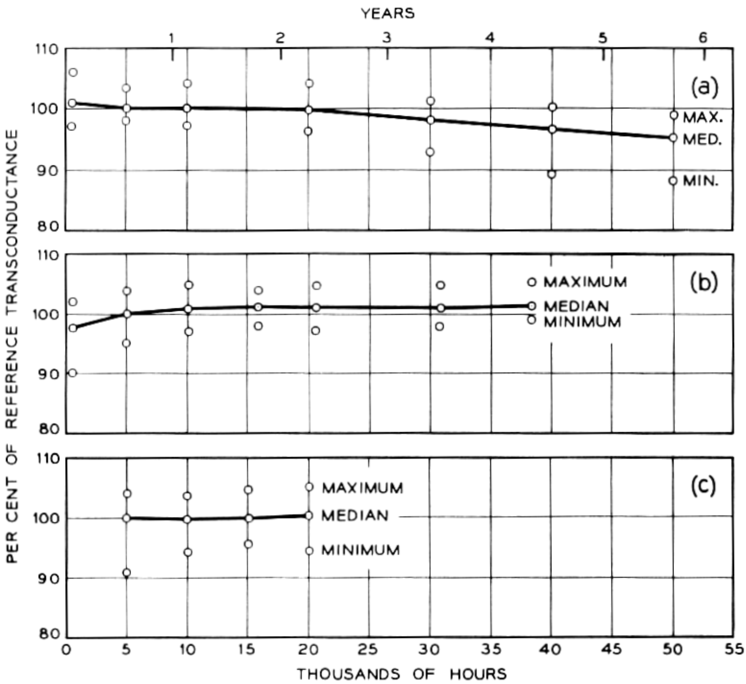

Fig. 7 — Transconductance as a function of life for 455A-F tubes.

spread for the Western Electric product is consistent with the larger sample on test. From the stability exhibited in curves (b) and (c) of Figs. 7 and 8 it appears that the extrapolation to the higher current density, the use of the special cathode alloy and operation at 670°C are all justified.

3.5 *Tube Production*

Production of tubes has been underway for nearly four years at the Allentown Works of the Western Electric Company. The philosophy of building reliability into the tubes was mentioned above, and it was pointed out that only tested and proved materials would be used. This was successful during the development and has been carried over into production. All fully certified parts and materials are given lot numbers, certain piece parts are individually numbered and each tube is given a unique serial number. To expedite the handling of product a "kit" system was adopted with six tubes in a kit. Six sets of parts and the records pertinent to them are given to an assembly operator. At the completion of the assembly, the operator passes on six tube mounts

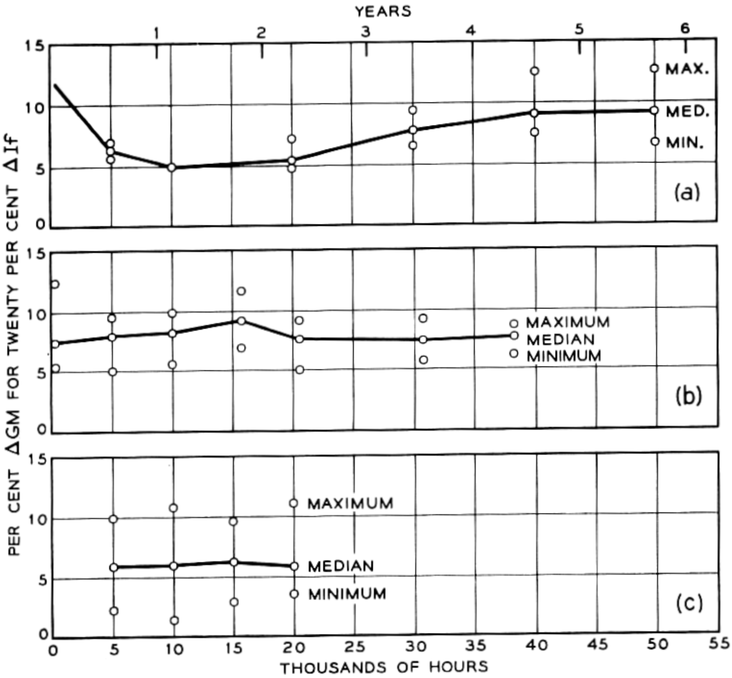

Fig. 8 — Cathode activity as a function of life for 455A-F tubes.

(assemblies) and the pertinent papers. Some operations, for example pumping, can handle two or more kits at a time. The kit system also permits examination of data for "batch effects." As the name implies, these are deviations or trends in data that can be studied in related groups of tubes as well as in individuals.

In the course of fabrication all tubes are given ten inspections, six of which include thorough searches for particles. Also, at specific times within the 5000 hours of aging the general electrical characteristics are tested five times. Supplementary tests are also made of special electrical parameters such as power output, modulation, equivalent grid noise, etc.

3.6 *Tube Selection Procedure*

3.6.1 *Review by Committee*

The selection of tubes for sea-bottom service goes beyond the mere matching of test data against limits. There are certain attributes or second-order responses of a tube to which it is difficult to assign numbers.

These attributes are assessed by the selection committee much as if the candidate were a person. Before a tube is submitted to the committee, the processing and inspection records are checked for consistency and completeness.

The selection committee reviews all of the data in detail, studying trends and minor variations occurring within the limits of acceptability. As examples: the age-in characteristics are compared to the characteristics at the 5000 hours acceptance point. The residual gas test and plate current age-in curves are reviewed. The departure of any data from the normal pattern is critically analyzed, and only those tubes which have exhibited normal behavior are accepted for sea-bottom use.

3.6.2 *Grouping for Repeater Use*

The tubes accepted for sea bottom are permanently grouped by sixes for use in an individual repeater. This grouping has no relation to the "kit" of six used for production control. The grouping takes into account the sum of the heater voltages at a fixed current, the slope of the plate current aging-in curve, and the products of the transconductances for the tubes in each of the two amplification paths (tubes A × B × C compared to tubes D × E × F). Tubes with low noise figure are assigned to input stages while tubes of high power output are used in output stages.

As a final check on the static characteristics and on the grouping of the tubes, they are given an electrical test in a circuit simulating the dc circuit of the amplifier, energized at rated cable current. Individual tube plate and screen grid currents are measured in this circuit, and then a comparison is made between tube performance in the working circuit and in the tube testing equipment. The tubes are now ready for shipment to the repeater assembly factory, where they are immediately restested in an amplifier simulating circuit identical to the one at the tube manufacturing plant. With satisfactory agreement between these two tests, the group of tubes is acceptable for assembly into a repeater.

IV. THE GAS-FILLED PROTECTIVE TUBES

4.1 *Circuit Function*

In those portions of the cable system operating at more than about 1500 volts to ground, a fault resulting in the grounding of the center conductor produces severe electrical transients. These transients propagate through several repeaters to either side of the fault before being attenuated to a safe level. If no protection were provided, damage to repeater components would be probable, and repeater failure would be possible.

Two types of gas tubes were developed to provide the desired protection. Both types are electrically symmetrical diodes, designed to conduct current in either direction, and both are of the cold cathode variety, requiring no power in the standby condition. Cutaway views of the two tubes are shown in Fig. 9.

4.2 *The 456A Power Bypass Gas Tube*

4.2.1 *Operating Requirements*

The 456A tube is bridged across the six series-connected amplifier tube heaters as shown in Fig. 5 and has two functions: (1) in the event of a fault on the cable causing an abnormal current to flow through the repeater, the tube will fire and conduct the current, preventing damage to the tube heaters and to other parallel low-voltage components; (2) if an amplifier tube heater opens, the rising voltage will fire the gas tube, holding the heater circuit voltage at a safe level. The cable voltage is then

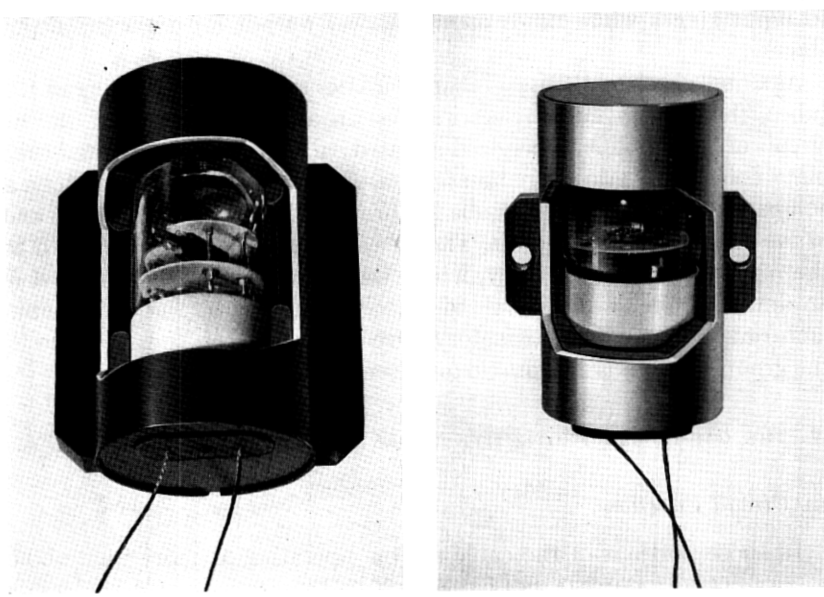

Fig. 9 — 456A (left) and 458A (right) electron tubes cushioned in aluminum housings.

turned down and the procedure carried out for energizing the heat coil, which in turn melts the fusible link to bypass the defective heater.[10] By means of a center-tap connection, only half of the amplifier tubes (ABC or DEF) will be turned off. The minimum firing voltage of the gas tube is set slightly above the voltage required by the heater circuit for this operation so that the tube does not refire. Should a heater in the second string subsequently fail, the gas tube will again fire and maintain dc continuity during trouble location tests.

For surge protection service, the tube is designed to pass a charge of 0.6 coulomb at a peak current of 75 amperes in either direction. This provides a reasonable margin for the maximum reverse surge which would occur in a near-shore repeater with a fault on the shore side, and for the maximum forward surge which would occur at the one-half voltage to ground point with a fault on the seaward side of that repeater. For a system of maximum length, the charge passed in either case is approximately 0.5 coulomb (the charge stored in a 100-mf capacitor at 5 kv). The magnitude of the peak current in the heater curcuit is less than 50 amperes under either condition and well within the capability of the tube.

The tube has a nominal breakdown voltage of 190 volts, and being located inside the power separation filters where the rate of rise of the transient voltage is relatively slow, the voltage rises only a few tens of volts above breakdown before the tube fires. Glow conduction is established within five microseconds at a tube voltage drop of about 70 volts. In less than one-half millisecond the cathode is heated sufficiently by ion bombardment to cause a transition to arc conduction, giving a tube voltage drop of about 11 volts. In this mode, as an ionically heated cathode device, the tube can conduct the large surge transient or the normal cable current as required. The power dissipation in the tube at normal cable current is approximately 5 watts. Tube life in this condition is more than 1000 hours, providing ample margin over the 100 hours estimated maximum time required to locate a cable fault. As a surge protection device the tube can conduct more than 50 maximum-energy surges without going out of firing voltage limits.

The fundamental characteristics and ratings are given in Table III.

4.2.2 *Design Details*

The detailed design of the working parts of the 456A is shown in Fig. 10. The two cathanodes are each mounted on three leads which are in turn strengthened, and made to move as a unit under shock, by means of the ceramic baffle. The baffle also prevents the arc discharge

TABLE III — 456A COLD CATHODE, GAS-FILLED ELECTRON TUBE

Maximum Ratings	
Average cathode current	450 ma
Surge cathode current	75 a
Coulombic charge	0.6 coulomb
Starts (firings)	100 max.
Surges	50 max.
Shelf life	20 years min.
Conducting life at 450 ma	100 hr min.
Ambient temperature	−10 to +50°C
Shock — 5 msec	50 g
Electrical Data	
Breakdown (firing) voltage	160 v min. 230 v max.
Breakdown time — to glow	20 μsec max.
Transition time — to arc	500 μsec max.
Sustaining voltage — glow	70 v
Sustaining voltage — arc	11 v

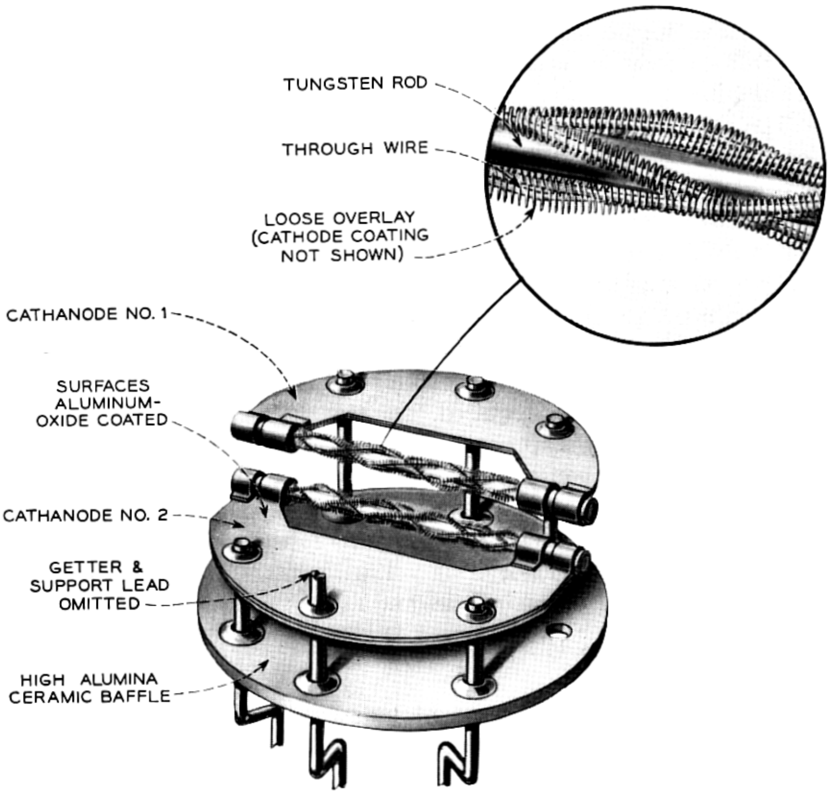

Fig. 10 — Structural features of the 456A tube.

from forming on the dumet seals. Each cathanode is formed from two identical "C" shaped molybdenum plates which clamp the active tungsten cathode.

The cathode is a composite structure made up of a 0.030-inch tungsten rod over which are braided six strands of 0.0045-inch tungsten wire, each strand carrying a loose over-winding of 0.001-inch tungsten wire. The crossed structure of braided wire and over-winding is filled with the emissive oxides of barium and strontium, providing small emission zones that have a loose thermal coupling with the rod. In establishing conduction, any one of these zones will be heated by ion bombardment, at a fraction of normal cable current, to a temperature sufficient for thermionic emission and operation as an ionically heated cathode. The zones are sufficiently short, however, that the heat energy resulting from high-current surges is conducted to the rod at the crossover points, preventing major damage to the finer wires.

The width and thickness of the molybdenum "C" plates are so proportioned that during the pumping process each part of the cathanode structure comes to the proper processing temperature simultaneously when heated by high-frequency induction. The two cathanodes are spaced approximately 0.100 inch apart and the gas filling is 18 torr of reagent-grade argon. A barium getter (not shown) is used to aid clean-up of impurity gases. The tube has a priming of one microcurie of radium bromide to insure fast breakdown in a dark environment.

4.3 *The 458A Signal Path Protective Tube*

4.3.1 *Operating Requirements*

The 458A tube is bridged across the transmission path at both the input and output of the repeater, just inside of the power separation filters (see Fig. 5). The most severe voltage surge the tube is required to handle is that caused by a short-circuit fault in the adjacent cable section. In the higher-voltage portions of the system this surge voltage may rise to a value of more than four kv in approximately one μsec. Since it is desirable to limit the voltage on many of the transmission path components to less than 1500 v, a very fast tube is required. The signal path tube is designed to fire in from 0.2 to 0.3 μsec on a 4 kv per μsec transient, limiting the surge to the transmission path to a maximum of 1200 v.

The charge shunted by the gas tube is a substantial portion of the charge stored in the high-voltage capacitors of the repeater, and may be as much as 1.5 millicoulombs. The discharge is oscillatory in nature and lasts about 10 μsec. The peak current through the tube on the first swing may be as high as 1200 a. These high currents are carried by the tube in the metallic arc mode of conduction at a tube drop in the order of 15 v.

The ability of the tube to pass such surges is tested in a circuit equivalent to that in a repeater. The size of the capacitors is doubled, however, to insure an adequate testing margin. In this test each tube is surged ten times in each direction with a total integrated charge of 4.5 millicoulombs and a peak current of 1800 a. The tube is conservatively rated to pass 50 maximum cable surges.

In use in the cable the tube is not required to carry continuous current. There is a secondary use of the tube in the power supply for equipment protection in which approximately 2 ma dc is conducted until the trouble is corrected. For this use the tube is given a 5-ma average current rating.

The fundamental ratings and characteristics are given in Table IV.

4.3.2 *Mechanical Features*

The structural details of the 458A are shown in Fig. 11. The two identical cathanodes are mounted on a high-alumina ceramic disk, one on either side, with their support tabs at 90°. The cathanodes face each other through an aperture in the support disk.

Each cathanode is a square nickel cup with integral mounting tabs. The facing surfaces are coated with a thin layer of emissive oxides of barium and strontium, activated during tube processing by means of a high-frequency discharge to develop super-emissive cold cathodes. The "nutmeg grater" shaped perforations perform two functions: (1) the

TABLE — IV — 458A COLD CATHODE, GAS-FILLED ELECTRON TUBE

Maximum ratings	
average cathode current	5 ma
surge cathode current	1500 a
coulombic charge	1.5 millicoulombs
surges	50 max.
shelf life	20 years (min.)
conducting life at 5 ma	200 hours (min.)
ambient temperature	−10 to +50°C
shock — 5 msec	50 g
Electrical data	
breakdown voltage	60 v
sustaining voltage — 5 ma	50 v
breakdown time — 500 v	5 μsec max.
breakdown time — 4 kv/μsec	0.7 μsec max.

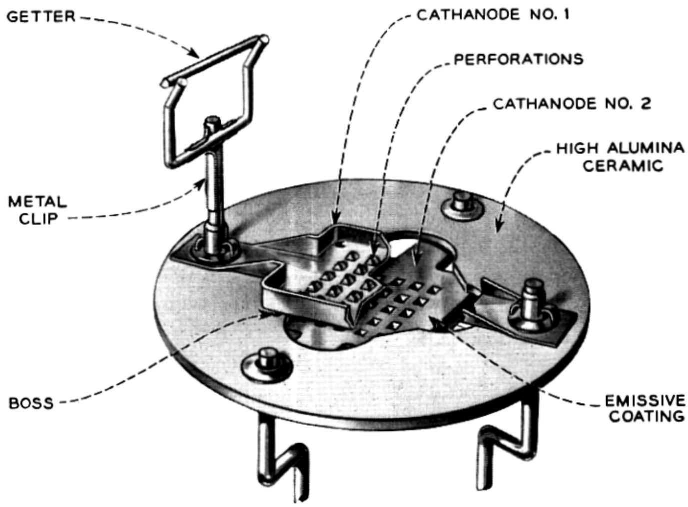

Fig. 11 — Structural features of the 458A tube.

hollow cathode effect of the small depressions increases the emission efficiency and life; (2) they allow a visual observation of the glow over the cathode surface to determine the uniformity of emission and cathode coverage. A small boss is provided at each corner of the cathanode to limit and position the contact area on the ceramic disk. This provides a leakage path of greater than 1000 megohms between the elements, even after the sputtering of the cathode material due to high-current arcs. The barium getter is the same as that used in the 456A tube.

The gas filling in the 458A tube is 1 per cent argon and 99 per cent neon at 60 torr pressure. The plane-parallel electrode geometry at a 0.030-inch spacing gives a nominal breakdown voltage of 60 v and a sustaining voltage at 5 ma of 50 v. One microcurie of radium bromide is used as a priming to insure sufficient initial ionization for high-speed operation in the absence of light.

4.4 *General Considerations*

In the design of the two gas-filled tubes the glassware, stem, bulb, and basing follow the pattern of the 455A-F amplifier tube. Both gas tubes are mounted between rubber cushions in aluminum housings (See Fig. 9). The housing for the power bypass tube has a black anodized finish and is secured to the power separation filter chassis, which it uses as a heat sink. This insures a bulb temperature of less than 130°C when carrying full cable current. The signal path tube has no heat problem and is in a bright housing. This tube and lead-out braid, however, require insulation from the housing for 6-kv operation.

In addition to the basic twenty-year standby life requirement, the tubes must also not reduce the system reliability through their own failure. Shorting of the elements has been made virtually impossible by generous spacings, rugged structural design and the multiple securement of parts. Both types can withstand some five times the shock levels expected in the present cable systems. The tubes operate on the high-pressure side of the Paschen minimum, and gas leak-in cannot reduce the firing voltages to unsafe values.

Raw material control through strict specifications, adequate testing procedures, and lot prove-in follow the pattern of the amplifier tube. Similarly, the parts production, handling, processing and cleaning, quality tests and inspections have also followed approved procedures.

The tubes are carried through a comprehensive aging and operating procedure simulating operating conditions in the cable. Elaborate testing schedules evaluate the performance at each stage in the processing, giving the detailed behavior of each tube. The tests include high-energy surge tests at or above maximum ratings and a two-hour thermal pulse at 125°C to evaluate over-all cleanliness. The tubes are checked for stability over a minimum period of three months and for operation in the dark to insure adequate radium priming. The power bypass tube is given a 30-day test in the dark at 4°C with cable voltage applied.

V. CONCLUSION

When electron tubes were first used in deep-sea repeaters for the SB systems, it was recognized that the undertaking was ambitious and perhaps even audacious. The faith exhibited in proceeding with this application of electron tubes appears well justified with more than 80 million amplifier tube hours of operation on sea-bottom with no failures. Strict attention to details of processing, fabrication, aging, testing, and selection constitute the background for this achievement. By modification and extension of this formula, it is expected that a similar record will be achieved for the electron tubes in the SD systems.

The development of the three codes of tubes for use in the SD system was a project staffed by many members of Bell Laboratories, who contributed a variety of knowledge and skills. No attempt will be made to single out individuals for special mention. It was a team effort.

APPENDIX

Discussion of Reliability

The reliability objective for the electron tubes of the SD system was stated as: "The probability of system failure due to a tube failure shall not exceed 50 per cent for a twenty-year service period for a 3000-mile system."

The probability of no system failures

$$P_{f(0)} = e^{-\lambda}$$

where λ is the expected number of tube failures for the period. For a 50 per cent probability $e^{-\lambda} = 0.5$ and $\lambda = 0.69$.

The mean time between system failures is $20/\lambda$ or twenty-nine years.

For a 3000-mile system with a twenty-mile repeater spacing there will be 150 repeaters. For defects not minimized by circuit redundancy, there are six tubes per repeater. Then, for a twenty-year period

$$\lambda = (150 \times 6 \times 20)/T$$

where T is the mean time (in years) between random failures. For $\lambda = 0.69$, $T = 26{,}100$ years.

If 0.69 failure is experienced among the 900 tubes for a twenty-year period, this corresponds to a failure rate of $0.69/900 = 0.00077$ or 0.08 per cent for the twenty years, or to 4.4×10^{-9} failure per tube per hour (4.4 fits).

For the defects which, because of redundancy, would cause failure only if both circuits were affected:

$$\lambda = 150[(3 \times 20/T)^2] = 0.69 \text{ (approximately)}$$

and

$$T = 885 \text{ years mean time between failures.}$$

Since with redundancy the required tube life is about $\frac{1}{30}$th that required without it, the corresponding failure rate would be 2.4 per cent and the number of fits 132.

This analysis has assumed that no "wear-out" mechanism is involved in the twenty-year service period. While mechanisms such as depletion of cathode coating or reducing agents are known, the rates are such that they have no significant effect in this period.

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