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L5 SYSTEM:

Physical Design

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The L5 Coaxial-Carrier Transmission System equipment was designed to provide long-term reliable service in diverse environments. The line repeaters, for instance, are housed in apparatus cases located in manholes that are subjected to flooding, whereas the main-station repeaters and terminal multiplexing equipment are located in the controlled environment of underground or aboveground buildings, often only partially attended by maintenance personnel. In addition to describing novel physical designs, this paper covers other very important considerations such as thermal design, manufacturability, incorporation of hybrid integrated-circuit technology, efficient "building-block" system growth capability, and long-term reliability.

I. INTRODUCTION

1.1 Outside plant design considerations

Proposed approaches to the physical design of L5 repeaters covered a wide array of possibilities ranging from the buried repeater concept to that of an ideal conversion. The former would capitalize on the high reliability and trouble-free performance of solid-state repeaters to gain cost advantages in outside plant for new routes, but would require initially equipping all tubes of a coaxial cable with repeaters. The latter approach would feature repeaters configured to closely resemble existing L4 system repeaters.[1] It would encourage conversions from the L4 to the L5 system and take advantage of as much existing outside plant as possible. The range of proposals also included such alternatives as limited-access enclosures, underground lockers, and single-repeater apparatus cases, all of which would have required extensive outside-plant apparatus development.

Experience with the L4 system showed that accessibility to line equipment is essential during initial installation of a system. This precluded burying L5. Perhaps, after a shakedown period, buried repeaters can be developed for new-route applications. One-mile repeater spacing and continuing improvements in reliability of solid-state devices may create a wish to bury L5 in the future. In this case, the basic repeater, the least complicated and most numerous of the L5 repeaters, is the most likely first candidate.

Clearly, the pursuit of a conversion design was the most logical initial approach to the physical design of the L5 repeaters. There will certainly be a continuing need to convert L4 routes to L5 when the demand for circuits exceeds L4 route capacity. Also, the L5 trial in mid-1970 was only realized by the use of existing plant designs where possible. In addition, by pursuing a conversion design, the development of the L5 system did not depend first on the acquisition of knowledge of a wholly new repeater environment. The existing L4 environment was usable for evaluation of the L5 repeaters during the development period. Conversely, it was also understood that pursuing a conversion design would not preclude the use of newly developed L5 outside plant in applications at the 1-mile repeater points where new manholes are required, and along new routes, if the need for new plant could be justified. Thus, the established schedules for development, trial, and commercial service for the L5 system, together with the economic advantages of reusing existing outside plant, all favored the conversion-design approach to L5 physical design.

An early plan was directed toward ideal conversion—the situation in which the L5 repeater shape would correspond closely to that of the L4 repeater, allowing easy replacement in the existing L4 apparatus case housing and chassis assembly. However, the proposed L5 system fault-location scheme requires 14 copper-wire pairs in the coaxial cable, whereas the L4 fault-location scheme requires only 5 wire pairs. This became the controlling factor in causing a change in the L4 apparatus case chassis. Once it was recognized that a chassis change was needed, the degree of change was academic, and a modified conversion plan was adopted. This plan was directed toward developing a repeater configuration that would still fit the L4 apparatus case, but required that the chassis of the apparatus case be changed to accommodate administration of the L5 fault-location pairs, to promote good heat transfer, and to simplify repeater installation. Since the L5 basic repeater dissipates some 18 watts (compared to 13.5 watts for its L4

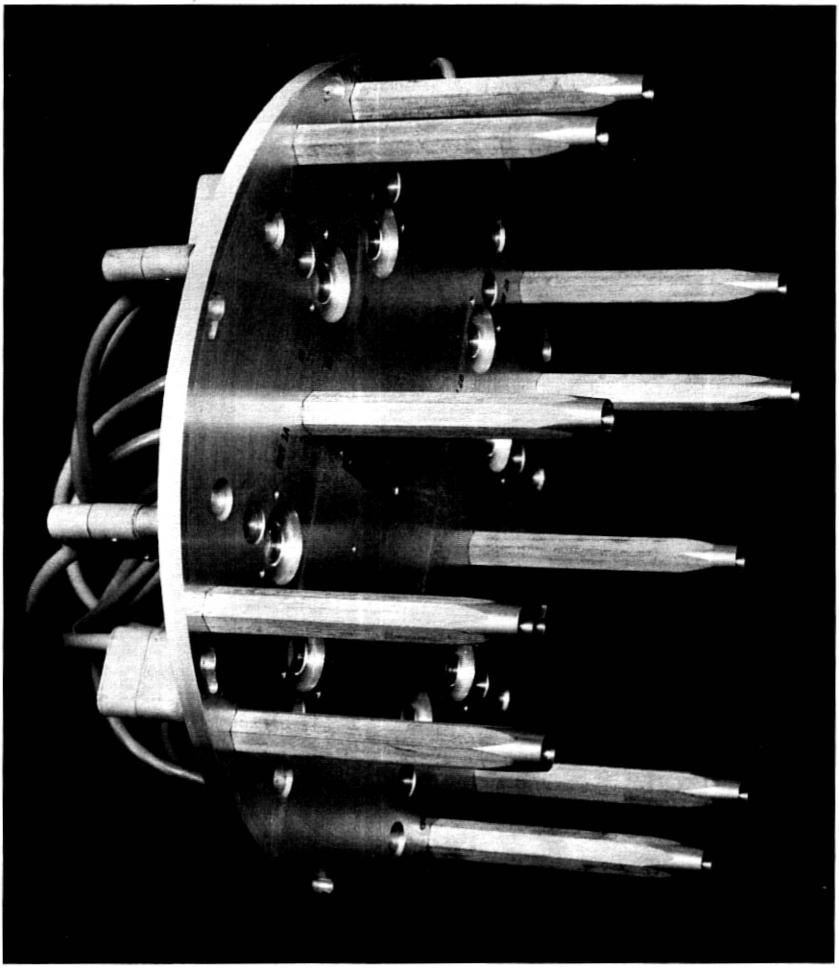


Fig. 1—Apparatus case chassis.

counterpart), it was necessary to design a more efficient thermal circuit in the L5 repeater.

Figure 1 shows the L5 apparatus case chassis, the outside-plant item required to convert an L4 apparatus case to L5. This is simply a base plate holding guide pins that line up plug-in repeaters. The guide pins serve also as retaining elements for the repeaters. Thus, the repeaters are bolted on the plate by means of the retainer guide pins, eliminating the need for the cantilevered guide and clamp arrangements used in

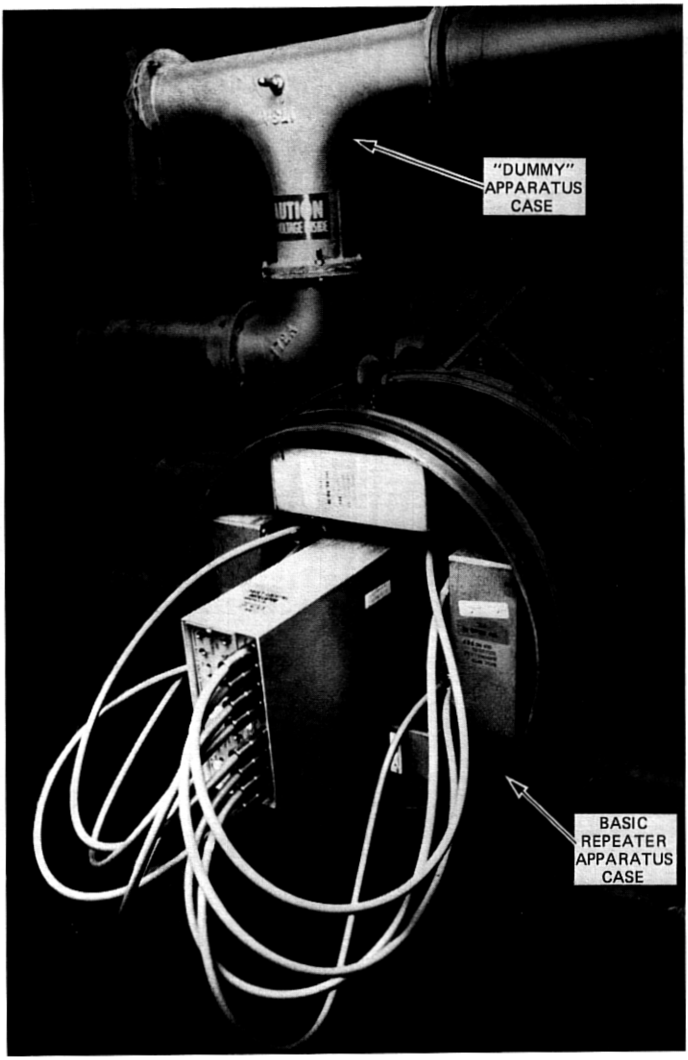


Fig. 2—Basic repeater apparatus case.

L4 (sometimes a source of problems because of the degree of precision required to insure proper mating of the plug-in units). The repeater is designed so that, when bolted in place, its leading surface is in intimate contact with the apparatus case chassis. The repeater-apparatus case chassis interface becomes an important link in the thermal path from the repeater to the manhole.

Figure 2 illustrates the L5 basic repeater apparatus case arrangement featuring four basic repeaters located on the periphery of the chassis. The center space is occupied by the non-heat-producing fault-location oscillator unit. Coaxial patch cords are used for insertion of fault-location oscillator tones at both the input and output of the repeaters via twin coaxial jacks located on the apparatus case chassis. The twin jacks serve also as repeater by-pass points in the high-voltage, series-powered L5 line to permit a power patch around a repeater, without turning power down on a line, in the event repeater replacement becomes necessary.

Apparatus cases are mounted in precast concrete manholes (6 by 12 by 6½ feet high inside the basic repeater manhole) that are not intended to be impervious to water. The apparatus cases are watertight and are filled with dry nitrogen to 9-psi cable pressure to protect against water seepage. Six apparatus cases are required in a basic repeater manhole to fully equip a 22-tube coaxial cable. Adaptors, or "dummy" apparatus cases (one of which is shown at the top of Fig. 2), are installed to permit an entire manhole to be racked and spliced initially. Apparatus cases are installed only to cover the number of tubes being equipped in order to defer expenditures until necessary.

The cross-connect apparatus case, an additional watertight apparatus case that is somewhat different in design, is also located in the manhole. It houses both the logic unit (used to turn on fault-location oscillators) and the appearances of all the coaxial cable's copper wire pairs used for support systems such as fault location, order-wire, alarm, and surveillance. A logic-unit support-shelf kit was designed to permit conversion of this type of L4 apparatus case for use on L5.

II. MANHOLE REPEATERS

2.1 Basic repeater

Figure 3 is an L5 basic repeater with covers removed. Elements of the basic repeater are the fundamental building blocks of the L5 system and appear in every repeater in the L5 equipment.[2] These basic elements, the preamplifier, the power amplifier, the low-frequency networks, and the line-build-out (LBO) network, are assembled to an inner chassis located inside a rugged die-cast aluminum outer housing. Figure 4 is a simplified repeater cross section showing the relative physical positioning of the apparatus on the inner chassis which is assembled to a flange protruding from the inner surface of the outer housing. The low-frequency networks protrude into the power separation filter (PSF) cavity through a cut-out in the flange.

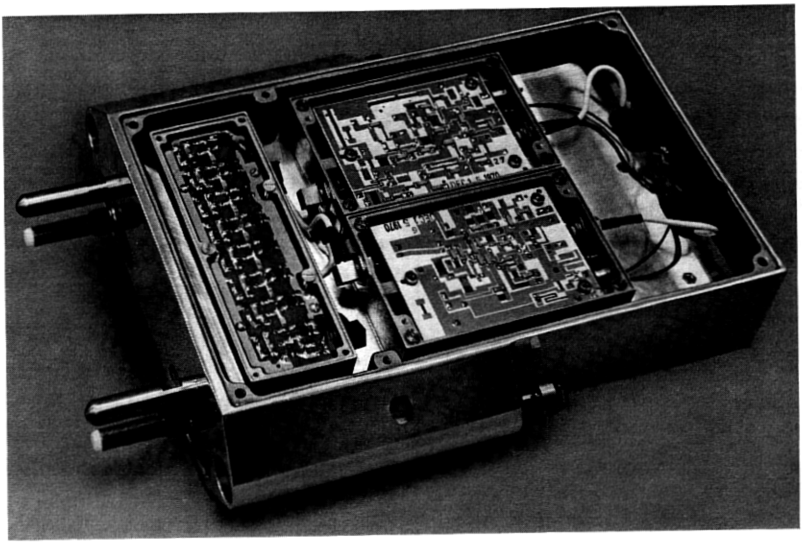


Fig. 3—Basic repeater.

Because of the series-powering arrangement for the L5 repeatered line, repeater circuit ground can be as much as ±1150 volts dc (1750 volts dc under trouble conditions) from earth or sheath ground. In Fig. 4, the cross section of the inner chassis assembly which is at circuit-ground potential is shown clear to contrast with the heavy black cross section of the outer housing, which is at earth-ground potential. Insulation between these two items is provided by a conformal coating of epoxy, 0.015-inch thick, applied to the inside cavities of the outer housing. A thin layer of epoxy sheet adhesive is used to bond the inner to the outer. The controlled-thickness epoxy interface provides the structural strength required, preserves the integrity of the insulation for the safety of personnel and the protection of precision, low-voltage electronic components, and constitutes a very low impedance to the thermal path.

The insulating and bonding techniques are the same as those developed for the L4 repeaters. As in L4, the bond joint was designed to cover a relatively large area for strength and for enhancement of thermal conduction, which is further enhanced by the massive cross sections of the repeater's structural elements. The epoxy is applied by the fluidized bed process. The process is carefully controlled to eliminate voids, thereby minimizing the likelihood of high-voltage corona "popping."

The individual apparatus units are contained in die-cast aluminum cans fastened to the inner chassis by threaded inserts integral to the inner chassis. The repeater covers are coated with epoxy on the inside to complete the continuity of the insulation of the two cavities. They are secured using one-way screws as a safety feature. In effect, "sealed" repeaters are shipped to the field. There are no field adjustments to be made on a basic repeater, and repairs, if necessary, are made at the factory. Therefore, there is never a reason to open a repeater in the field. They are sealed to avoid the exposure to high voltage that would occur if a coverless repeater were accidentally inserted into a powered apparatus case. Thus, safety features are not compromised by the use of the simplified apparatus case chassis design (Fig. 1). High voltage appears on the center conductor of the coaxial jacks that are located deep inside the apparatus case, and sealed repeaters keep the high voltage from the reach of craftspeople.

2.1.1 Hybrid-integrated circuits

The preamplifier and power amplifier are the heart of the L5 repeaters. They are thin-film hybrid integrated circuit amplifiers, and in the basic repeater they are located side by side in the center part of

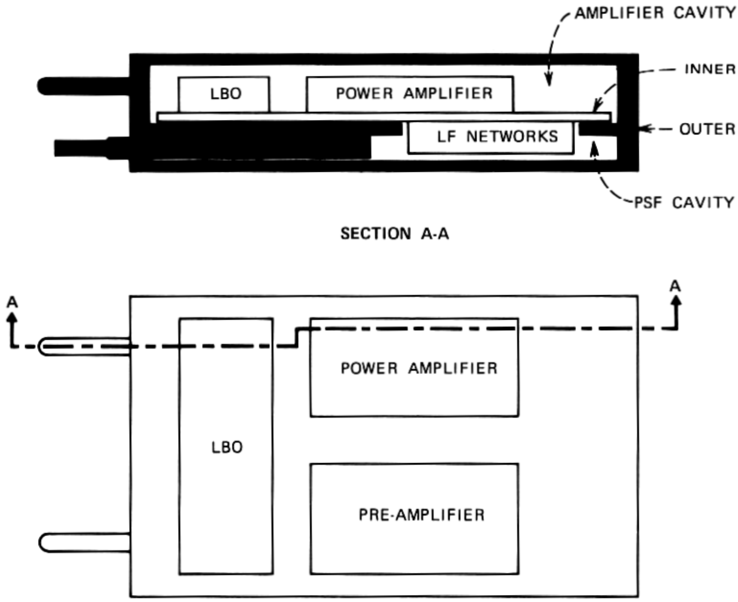


Fig. 4—Basic repeater cross section.

the repeater as shown in Fig. 3. Even though the amplifiers require many discrete components such as transformers, inductors, capacitors, and transistors, it was established very early in the L5 development that conventional printed-wiring arrangements could not be used. The precision required for L5 amplifier circuits was such that thin-film circuits were essential to the amplifiers. However, L5 required large substrates, holes in the substrate to mount discrete components, low-value precision resistors, and high-conductivity conductor paths. Each of these requirements suggested a departure from generally accepted thin-film practice. Together, they constitute a unique set of requirements and resulted in HIC's that are unique in their physical and electrical attributes.

Although most HIC's are small enough to fit many patterns on a single $3\frac{3}{4}$ by $4\frac{1}{2}$-inch ceramic mirror, the L5 HIC's are large enough ($2\frac{1}{2}$ by $3\frac{1}{2}$ inches) to allow only one per mirror. Conventional, leaded components are almost never mounted on a ceramic substrate, but this was required here. This gave rise to the need for about 50 holes per substrate. Holes complicate the manufacture of substrates and are avoided, if possible. To produce the low-value precision resistors, the resistive metal layer was deposited to a thickness of 25 ohms per square, as opposed to the conventional thickness of 50 ohms per square. This allowed longer resistors and a larger proportion of anodized-to-unanodized area. The higher percent of the area anodized results in greater long-term stability. Furthermore, thicker metal film is more stable because resistance changes are caused by surface changes, and the surface constitutes a smaller portion of a thicker metal film than of a thinner metal film. An operating temperature of less than 90°C is necessary to maintain end-of-life tolerance for the precision resistors. Power resistors, on the other hand, would stay within their required resistance tolerance at film temperatures as high as 110°C. The power resistors and the discrete transistors are virtually the only heat producers on the substrate. Therefore, the layouts were designed so that the power resistors skirted the periphery of the substrate. The transistors, however, had to be centrally located because of circuit requirements for short connecting conductor lengths. Massive heat sinks were designed to divert the transistor heat from the precision resistors and other temperature-sensitive components.

Figure 5 is the L5 power amplifier. The top view shows the two heat sinks, each housing a matched pair of transistors, surrounded by other discrete components. The bottom view, the thin-film side of the hybrid integrated-circuit amplifier, illustrates the film topology and a number

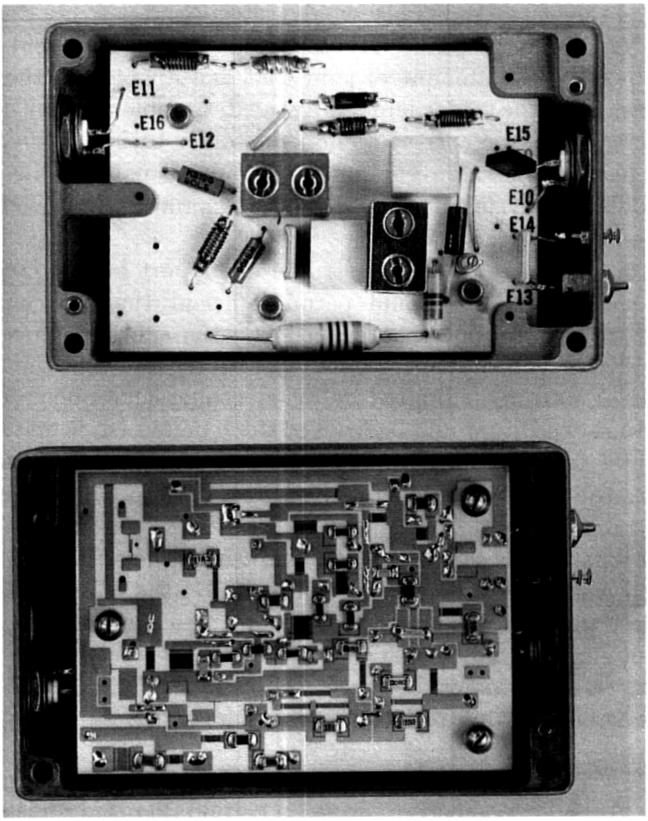


Fig. 5—Power amplifier.

of reflow-soldered barium titanate chip capacitors. A special conductor metal system was developed for L5 to produce the needed high-conductivity paths and to provide solderable pads for the chip capacitors and the leaded conventional components. The high conductivity is obtained by depositing "thick" gold. Electroplated rhodium is added to prevent the gold from dissolving in the solder. A gold flash over the rhodium protects the rhodium from oxidation, thereby retaining its solderability. By selectively etching the gold to expose a rhodium strip around the solder pads, solder "dams" are formed after the exposed rhodium strip becomes oxidized and nonsolderable when exposed to the elevated temperature of the film pre-aging process. Therefore, during the solder reflow process, when the chip components are connected into the circuit, the exposed rhodium strips confine the solder to the area they surround. This avoids wetting and possibly degrading the high conductivity paths. By precisely defining the solder area, thereby limiting the amount of gold that can dissolve in the solder, embrittlement of the solder joints is avoided. Complementary developments determined the correct amount of solder to be supplied as an integral part of the chip component terminations and the precise reflow soldering cycle, thereby assuring reproducible, reliable HIC assemblies.

It was necessary to develop a structural support for the large, thin ceramic substrates that would permit efficient thermal conduction from the transistors, but that would keep the substrate free of mechanical stress. The substrates are not perfectly flat, and the amount of bowing or warping is limited by die-screening subsequent to firing. Ideally, the substrate would be fixed at three points (to define a plane) and contact to the transistor would be by a flexible heat conductor. However, the requirements are inconsistent for providing, simultaneously, a massive heat sink for adequate heat dissipation and a flexible heat sink for stress-free mounting. Consequently, the structural support developed was to hard-mount the substrate on the massive heat sink and merely stabilize its outer periphery on three bosses of the die-cast aluminum amplifier housing. The location of the three bosses and the stabilizing screws is shown in Fig. 5, and a partial cross section of an amplifier assembled in a repeater is shown in Fig. 6.

2.1.2 Thermal path

In Fig. 6 the large substrate, in cross section, appears virtually as a beam with a fixed support in the center. The end supports (only one shown) are designated "grommet suspension." At these points, the substrate is held between two soft, rubber grommets confined in a large hole in the substrate by a shoulder screw anchored to the boss in the amplifier housing. The role of the grommets is to stabilize the nonflat substrate in whatever position it may happen to fall and have it remain there, stress-free.

The substrate's fixed support is the massive transistor heat sink, also shown in cross section in Fig. 6. The discrete transistor, located inside the heat sink, has a beryllium-oxide header hermetically sealed to a Kovar* case. Heat sinking is to the beryllium oxide, which has the higher coefficient of thermal conductivity, and thermal flow through the transistor-heat-sink interface is enhanced by the force exerted by

* Trade name of Westinghouse Electric Corporation.

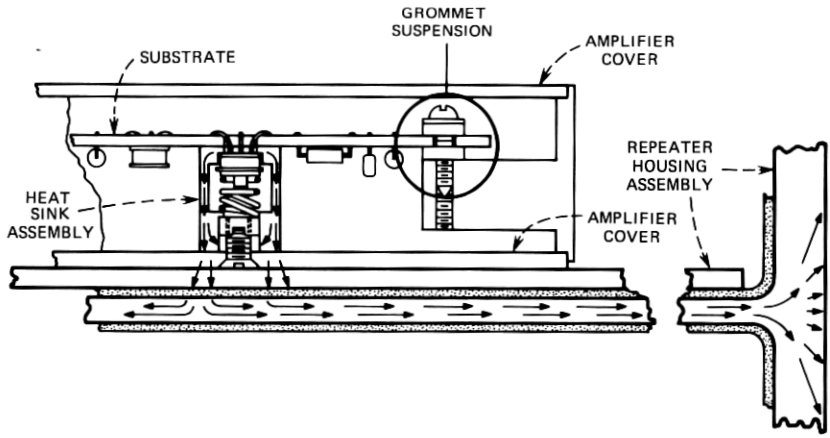


Fig. 6—Thermal path for L5 HIC amplifier.

the preloaded spring confined within the heat sink. While high, compressive pressure is applied through the transistor to the heat sink, none of it is transmitted to the delicate thin-film substrate to which the transistor is soldered. The result is a stress-free structural support for the large L5 substrates and an effective thermal circuit. As shown by the arrows in Fig. 6, heat is conducted from the transistor through the heat sink, through the amplifier cover into the inner repeater chassis, and through the thin layer of epoxy to the outer repeater housing.

2.1.3 Heat sink

Close spacing of the transistors on the substrate was required to minimize parasitic inductance and capacitance in the electrical circuit and resulted in a unique heat sink design. Spring-loading the transistor within the confines of a massive heat sink was developed for use in the L4 system amplifiers. However, the L4 scheme was not applicable to L5 because of the combination of space limitations and the application of the heat sinks to delicate, large, ceramic substrates in L5, in contrast to the rugged epoxy-glass printed wiring boards used in L4. The L5 heat sink is a precision assembly that, for good heat transfer, presents the largest possible metal cross-sectional area within the allowable limits for the transistor lead lengths and transistor spacing. The screw that preloads the spring against the transistor serves as the threaded nut for mounting the heat sink against the flat amplifier cover. To minimize thermal impedance, the heat sink's functional faces have a

32 micro-inch finish, and an indium washer is inserted at the transistor-heat-sink interface. This assures intimate contact at the thermal circuit joints.

The heat sink's cavity, large enough to accept the transistor with its flanged case, is constricted at the threaded portion because of the transistor spacing constraints. This constriction makes it necessary to have a side opening in the heat sink to load the transistor and precludes the use of conventional screw-machine methods of manufacture. Double heat sink designs are used in the preamplifier and power amplifier to maximize the amount of metal usable for heat sinking within the transistor spacing constraints. This works out well, because the transistors are used in matched pairs and can be preassembled into the heat sinks for subsequent assembly onto the substrates.

2.1.4 Individual packages

The thin-film substrates are housed in die-cast aluminum cans. These cans require a certain degree of precision to provide accurate stress-free positioning of the substrates, as shown in Fig. 6. Substrate supporting surfaces are held within tight tolerances with respect to the cover supporting surface. The bottom amplifier cover is controlled for flatness and is designed to be overflush to present maximum contact area to the repeater inner chassis for heat transfer.

Having top and bottom amplifier covers removable provides accessibility to both sides of the substrate during shop processing and also for trouble shooting, and the open die-cast frame of the amplifier housing serves as a convenient carrier and substrate protector during handling in the shop.

Connections to the substrate are made through 75-ohm miniature coaxial connectors that clearly define electrical and mechanical boundaries for the amplifiers. This substantially facilitates amplifier testing, repeater assembling, and, if needed, repair and replacement.

2.1.5 Maximum transistor junction temperature

To ensure reliable performance of silicon solid-state devices, the physical design goal was to limit the maximum junction temperature to 125°C and, in the case of the elements of the L5 repeatered line, can be expressed as

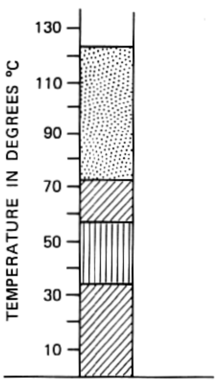
$$T_J \text{ MAX} = \Delta T_{AC} + \Delta T_R + \Delta T_T + T_M \leqq 125°\text{C}, \tag{1}$$

where

T_J = transistor junction temperature,
ΔT_{AC} = temperature rise in the repeater apparatus case,
ΔT_R = temperature rise in the repeater,
ΔT_T = temperature rise from case to junction of the transistor because of its thermal impedance,
T_M = maximum manhole ambient temperature.

For the L5 basic repeater, T_M has been calculated at 37°C for the hottest manhole in the hottest part of the country, based on an empirical expression relating manhole power dissipation, soil condition, and manhole dimensions. ΔT_T for a device is fixed for its specific power dissipation and heat sinking environment, and the design features to control ΔT_{AC} and ΔT_R were described earlier in this paper.

The maximum junction temperature for transistors in the L5 basic repeater power amplifier has been determined by tests to be 128°C, and comparative performance of L4 and L5 is shown in Fig. 7. Recalling that an L5 repeater dissipates some 18 watts in comparison to $13\frac{1}{2}$ watts for L4, it is evident that the thermal conductivity enhancement was realized as anticipated because of the apparatus case chassis design and the repeater packaging techniques developed for L5. At 128°C, maximum transistor junction temperature for L5 transistors, thermal results of L4 and L5 are equivalent and, based on L4 performance to date in the field, it appears that high-reliability performance of L5 devices is ensured.



	L4	L5
JUNCTION	124° C	128° C
TRANSISTOR	50	52
REPEATER	17	17
APPARATUS CASE	22	22
MANHOLE MAX	35	37

Fig. 7—Maximum transistor junction temperature.

2.2 Regulating repeater

The "modified-conversion" design concept as applied to the L5 regulating repeater requires that two repeaters fit in one apparatus case. The two repeaters are bolted to a newly designed apparatus case chassis, similar to that for the basic repeater illustrated in Fig. 1, in a layout that positions the fault-location oscillator unit between the two repeaters. A maximum of 11 apparatus cases are required to accommodate an L5 22-tube coaxial cable, and these cases are arranged on one wall of a precast concrete manhole 6 by 12 by 9 feet high on the inside, $2\frac{1}{2}$ feet higher than a basic repeater manhole.

The regulating repeater package is one of the most difficult of the L5 physical designs. A number of design constraints were imposed, such as field access for adjustments, addition of constituent apparatus and in-service testing, heat dissipation, high-voltage insulation, and personnel safety.

This repeater contains the same circuitry as a basic repeater with the addition of regulating circuitry, space for field insertion of two line-build-out networks and a deviation equalizer, and a low-voltage test point for in-service measurements. Like the basic repeater, a rugged, epoxy-insulated outer aluminum die-cast housing holds the captive retainer screws for bolting the repeater to the apparatus case chassis. Unlike the basic repeater which has a flat-plate inner chassis, the inner chassis of the regulating repeater is compartmented to accept individually packaged circuit sections and units that do not require their own individual shield cans (see Fig. 8). Because of the packaging density required to have two repeaters cantilevered from the apparatus case chassis in a single apparatus case, the center flange of the outer housing had to be kept to a minimum, allowing just sufficient area to ensure a good bond to the inner chassis. Therefore, compartmenting, in combination with individual apparatus housings that act as stiffeners, produces an array of ribbing on both sides of the large inner chassis and provides the rigidity required over the large cross-sectional area of this repeater, which measures $10\frac{1}{2}$ inches wide by $17\frac{1}{2}$ inches long.

2.2.1 Hybrid-integrated circuits

The regulating repeater uses five thin-film hybrid-integrated circuit (HIC) amplifiers in addition to the preamplifier and power amplifier. The five are flat-gain amplifiers, and their ceramic substrate size is more nearly conventional, measuring 0.8 inch by 2.9 inches. Actually, three designs, two of which appear twice as part of the two $\sqrt{f}$ net-

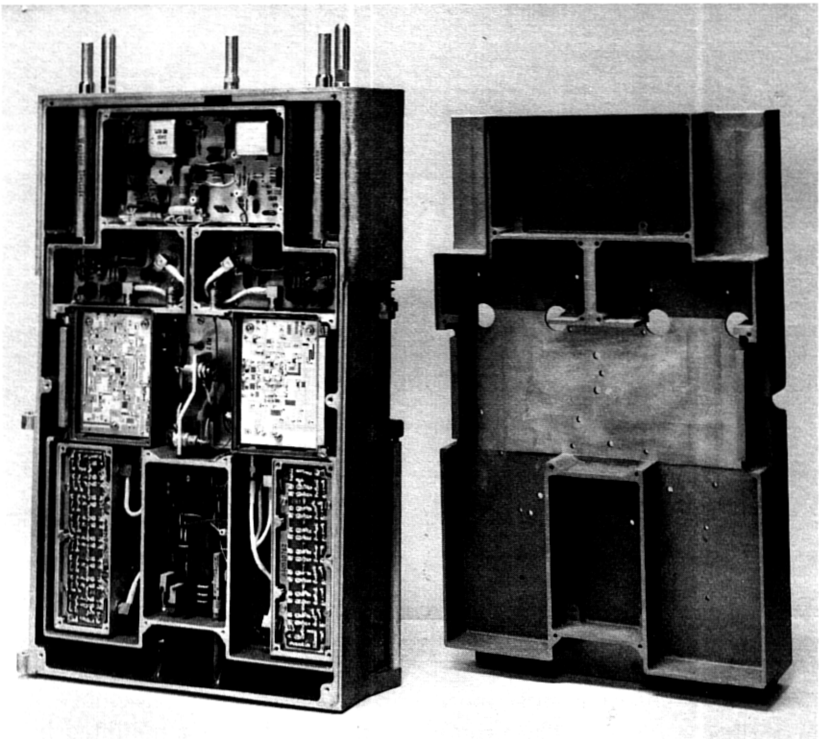


Fig. 8—Regulating repeater.

works,[3] are used in the regulating repeater. In the $\sqrt{f}$ network, the HIC's are connected as slave-boards to epoxy-glass printed-wiring network boards by means of 26-gauge leads on the HIC's. They are formed to fit into holes in the printed-wiring board and are clinched to touch land areas to which they will be subsequently soldered. The substrates are structurally supported on transistor heat sinks that enclose the discrete, heat-producing transistors and are fastened directly to the can that houses the entire network. The heat sinks are similar to those described for the preamplifier and power amplifier, except that they are the single-cavity style. Here, too, conduction is the primary mode of heat transfer. The heat from the transistors is directed away from the substrate, through the heat sink into the die-cast network housing and to the repeater framework, etc. Top and bottom network covers are removable to provide accessibility

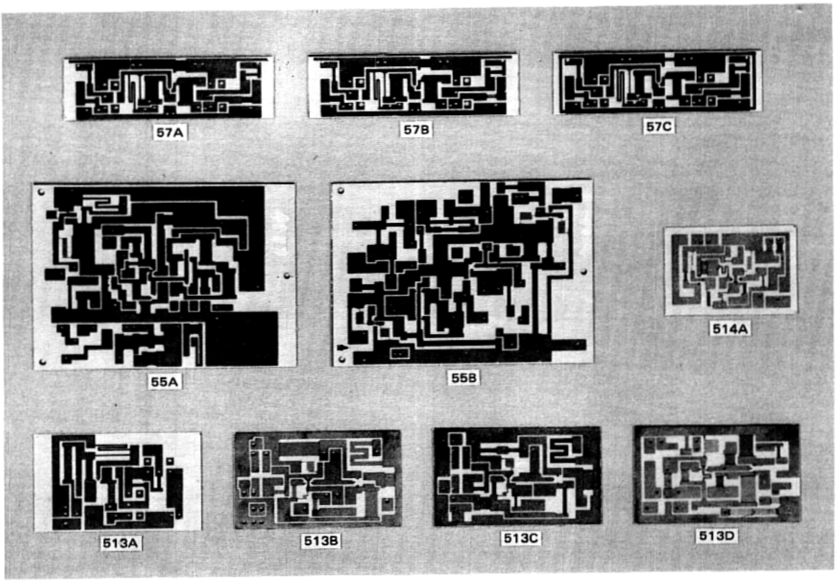


Fig. 9—FIC's used on L5.

for trouble shooting but, more important, to allow assembly in a prescribed sequence. The printed-wiring board is first mounted in its frame, then the HIC is fastened to the frame by the heat sink and finally the HIC leads are soldered to the board land areas. This assembly sequence is essential to a stress-free assembly. Figure 9 shows the collection of thin-film integrated-circuit substrates used throughout L5. The 55-types and the 57-types are the ones described earlier for use in the repeaters, while the remaining ones are used in flat-gain amplifiers for terminal equipment described later in this paper.

2.2.2 Buried thermistors

To compensate in part for changes in cable loss because of changes in cable temperature,[2] the regulating repeater requires access to ground-temperature-sensing thermistors that are buried 15 feet from the manhole at cable depth. The thermistors are contained in a cast-epoxy cable stub and, at a distance of 15 feet, are unaffected by manhole temperature. A plug-and-jack connection through the apparatus case chassis provides the thermistor connection to the repeater.

2.2.3 Safety

While the basic repeater is shipped to the field as a sealed unit, the inside of the regulating repeater must be accessible for the addition of line-build-out networks and for adjustments when the repeater is acceptance-tested in the field.[2] For this reason, the regulating repeater's two large covers are hinged as a safety feature to prevent exposure to high voltage by the accidental insertion of a coverless repeater into a live apparatus case. Manipulation of the bulky, hinged covers is awkward, at best, during manufacture and field-acceptance testing, but amounts to a relatively effective trade-off for a necessary safety precaution.

High-voltage insulation lines the cavity on the inner chassis that houses the coaxial jack used as the low-voltage access point for the repeater. Even though the jack is electrically isolated from high voltage by a transformer and is mechanically bonded to the outer housing which is at earth or sheath ground, the insulation liner is provided as a safety feature to protect personnel and equipment in the event a fault should occur.

2.3 Equalizing repeater

With equalizing repeater points located at 34-mile (maximum) intervals, or roughly midway in the 75-mile (maximum) L5 power spans, it is unlikely that, in conversion from L4 to L5, they would coincide with L4 equalizing repeater points spaced at 54-mile (maximum) intervals.[4] Therefore, the only constraint on the L5 equalizing repeater, to comply with the modified-conversion design concept for L5, is that similar apparatus cases be used for the sake of standardization.

However, L5 uses manually adjustable equalizers with less circuitry than is required for the remotely adjustable equalizer used in L4. This simplifies manhole arrangements in that the entire L5 equalizing repeater was designed to fit in a single apparatus case, in contrast with the two cases required to house the L4 equalizing repeater. For a 22-tube coaxial cable, an equalizing repeater pre-cast manhole measures 6 feet wide by 24 feet long by 8 feet high on the inside to accommodate the layout for the 22 apparatus cases required to equip the entire cable.

The equalizing repeater comprises three plug-in units—a regulating repeater, a manhole E1 equalizer (ME1), and a fault-location oscillator unit arranged in that order from left to right in the apparatus case. As with the previous repeaters, these units are bolted to the apparatus

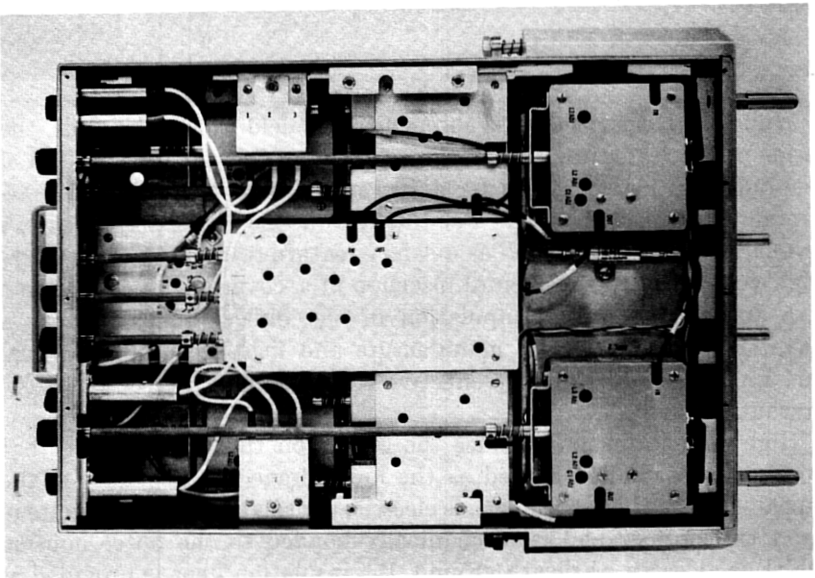


Fig. 10—Manhole E1 equalizer.

case chassis and are cantilevered inside the apparatus case. Equalizing repeater points also provide access to buried-cable-temperature-sensing thermistors.

The regulating-repeater portion of the equalizing repeater is identical to the regulating repeater described earlier except that one low-voltage test-access jack is replaced by two low-voltage jacks for connection to the ME1 equalizer.

The ME1 equalizer is a larger unit than the regulating repeater, and was designed as a fabricated unit to keep its weight down. The unit measures 12 inches wide by 17 inches long by $4\frac{1}{2}$ inches deep, and is illustrated in Fig. 10. The array of individually packaged amplifiers and Bode networks is visible. These use printed-wiring technology, are interconnected by cables terminated in miniature coaxial connectors, and are made accessible to the knobs of the ME1 faceplate by insulated shafts that permit manual control of potentiometers for equalizer adjustments. The knobs are "push-to-turn" to prevent inadvertent changes in adjustments, and universal couplings prevent lateral forces from being transmitted to the delicate potentiometer shafts. A power separation filter is contained in the lower cavity of the ME1 equalizer, and high-voltage insulation is provided by phenolic strips. This unit, like the basic repeater, need not be opened in the field and, for safety, it is sealed by having its covers secured with one-way screws. The mounting base of the ME1 is a one-piece aluminum casting that permits the precise location of the mounting holes and the coaxial plugs within the tolerances allowable for mating with the apparatus case chassis.

III. MAIN-STATION EQUIPMENT

Main stations in an L5 "backbone" route are single-story buildings containing four general categories of main-station equipment—high-frequency repeatered line, signal processing terminal, transmission surveillance, and a fourth, broad or peripheral category comprising such equipment as order wire, restoration, repeater acceptance test, and equalizer adjustment. The main-station equipment, intended for the central office environment, is bay-mounted in contrast to the rugged, cast plug-in type equipment designed for the manhole environment. The main-station equipment is generally in shelves, drawers, or panels in unequal-flange duct-type bays, on a 2-inch mounting plate modular spacing, and forming a bay-front that is flush with the bay uprights. The equipment space is 15 inches deep, the front and rear guard rails are 2 inches and $\frac{3}{8}$ inch, respectively, and the duct formed by the uprights of two adjacent bays constitutes shielded cabling space closed at the front and accessible from the wiring aisle at the rear of the bays through the opening created by the smaller flange (see Fig. 11). The space directly behind the cabling duct is available for shelf interconnections, for overflow cabling if required, and, in the case of a double bay, for additional equipment.

The deep equipment space is required because of the relatively bulky, well-shielded apparatus assemblies used throughout the system.

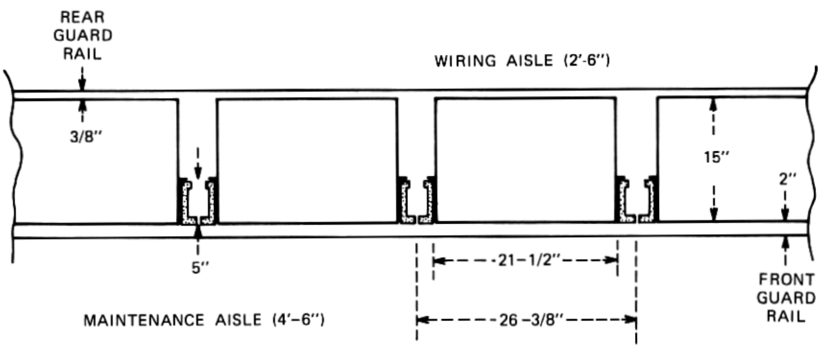


Fig. 11—Floor plan layout.

This depth, in combination with the width of the standard bay, gives rise to three-dimensional, high-density, equipment packaging which saves coveted floor space in a main station but limits accessibility of individual constituents of bay subassemblies. However, the limited accessibility is tempered by the connectorized assemblies used throughout the system to facilitate manufacture and maintenance.

Miniature coaxial connectors terminate individual pieces of apparatus (amplifiers, filters, networks, etc.) to form precise, definable boundaries for specific electrical requirements. These individual units are arranged on a shelf and interconnected by miniature coaxial cables terminated in the mating coaxial connectors. The shelf is screw-fastened to the rear flange of the bay uprights, and is itself interconnected with small Bell System coaxial plugs and jacks to the bay wiring harness for signal connections and with multicontact connectors for power and alarm connections.

In some instances, plug-in modular printed wiring board (PWB) assemblies are arranged on a shelf and interconnected by gold-plated fingers on the PWB and multicontact connectors that are part of the back-plane wiring of the shelf.

High-density packaging tends to accentuate thermal considerations, and limited accessibility coupled with high system capacity accentuate reliability considerations, both prime considerations in the design of L5 equipment.

The L5 bay height was standardized at 9 feet to accommodate power-feed main and switching power-feed main-station buildings. Terminal and terminal-main stations have higher ceilings and require bays 10 feet, 6 inches and 11 feet, 6 inches high. For these, bay extenders are added to have the 9-foot standard bay fit in 10-foot, 6-inch and 11-foot, 6-inch bay line-ups. Specific bays, intended for use only in terminal and terminal-main stations and requiring the additional space afforded by the higher ceilings, are 10-foot, 6-inch and 11-foot, 6-inch designs. The new equipment building system (NEBS) requires that future equipment be standardized on a 7-foot bay height, and a series of 7-foot bays have been designed for L5.

3.1 Main-station line equipment

3.1.1 Power separation filter cabinet

For the L5 high-frequency repeatered line, the interface between manhole repeaters and main-station equipment* is the power-separation filter (PSF) cabinet (see Fig. 12). This cabinet confines all the

* See Fig. 4 of Ref. 4.

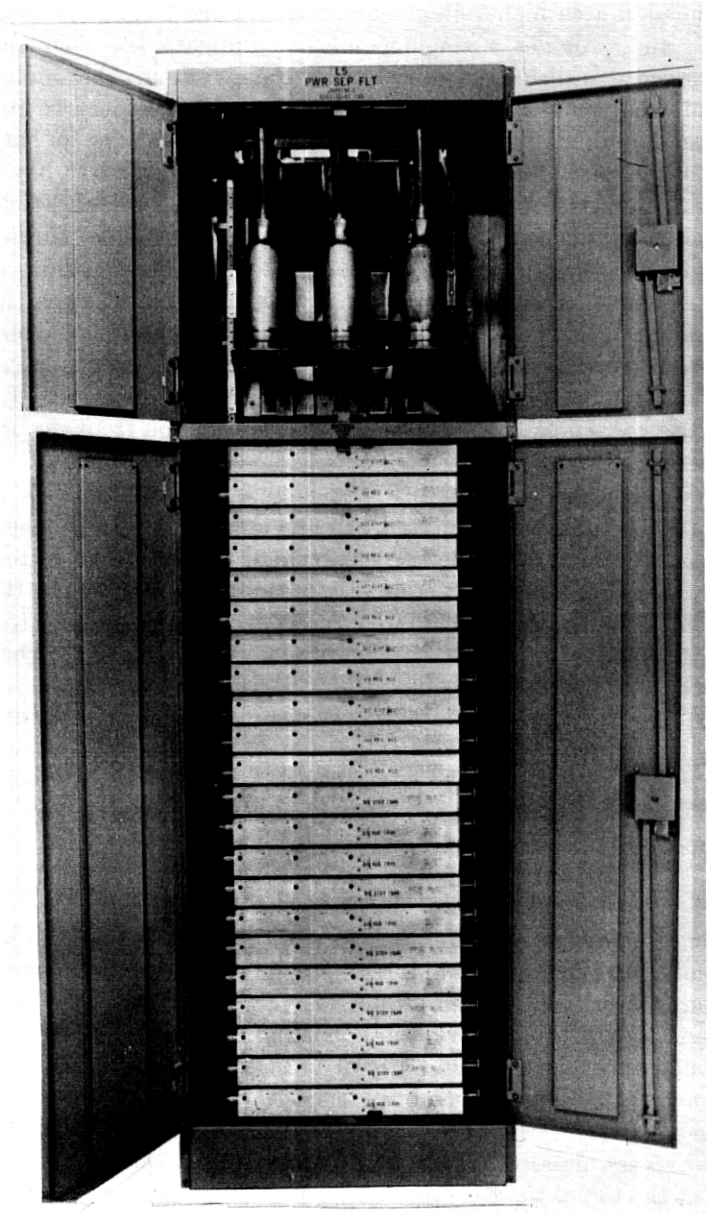


Fig. 12—Power separation filter cabinet.

transmission area high-voltage equipment in one locked enclosure for safety, and provides a single point to terminate the lead-covered, pressurized, air-dielectric cable stubs coming from the multitube, coaxial-cable splice in the station. This obviates the need to run the lead cable and the high voltage in front of the line bays, as has been done in the past. The run from the PSF cabinet to the line bays is at low voltage and uses single-unit air-dielectric and/or solid-dielectric coaxial cable, depending on the length of the connection. Initially, it was intended that the PSF cabinet be located in close proximity to the building cable entrance to minimize the run of lead cable in the station. However, placing the PSF cabinet at the recommended location at the head-end of an L5 bay line-up optimizes the interbay cabling for that line-up and, in most cases, precludes the need for the air-dielectric coaxial-cable-run portion of the connection from PSF cabinet to the line bays.

The 9-foot-high PSF cabinet can hold a maximum of 22 power separation filter shelves required to equip an entire 22-tube cable. The shelves are contained in the lower portion of the cabinet seen from the rear in Fig. 12. The cable terminals are bolted to brackets in the top portion. Connections are made by screw-type coaxial connectors for the high-voltage runs and by plug-and-jack connections for the low-voltage runs. The cabling is dressed in the ducts formed on the sides of the cabinet by the standard bay uprights (used to structure the cabinet) and the fabricated metal enclosure is assembled around the bay. Bay extenders accommodate the 9-foot cabinet in higher than 9-foot equipment line-ups. The PSF shelves are modular and can be equipped on an as-needed basis.

3.1.2 Line-protection switching system

The line-protection switching system (LPSS-3)[5] bay is the second element in an L5 line-up, and is required at each end of an L5 switching section (150 miles maximum), but not at the power-feed main stations located at the 75-mile (maximum) points. This 9-foot bay contains a preponderance of logic-type circuitry that is packaged in modular fashion on plug-in PWB assemblies arranged on fixed equipment shelves in the bay. The myriad interconnecting wires are formed into a sizable cable harness, dressed in the cable duct, and connected to a terminal strip at the top of the bay. Bay power is derived from plug-in dc-to-dc converters located and fused at the top of the bay. Status indications and controls are concentrated in a large display panel located centrally on the bay. Human-engineering design considerations predominantly influenced both the physical arrangement of this panel and the selection of the lighted indicators and keys so that the system's switching state can be clearly communicated to the craftsperson. The presence of plastic hinged protective covers on the more important controls also provide the "keying" necessary to avoid inadvertent manipulation of controls so as not to jeopardize service. Wire verification to ensure the presence of all intrabay connections is required before shipment of a bay containing the common equipment. Modular plug-in assemblies can be shipped separately on an as-required basis as the system grows.

3.1.3 Line transmit-receive bay

The line transmit-receive bays are the mainstay of the L5 line-up. One line bay is required for each transmit-receive pair of coaxials equipped in the system. This bay is essentially an equalizing repeater with manually adjustable equalizer units, E1 and E2, in both the transmit and receive sides and with the addition of a dynamic equalizer, E3, in the receive side. This, together with the elements of line-connecting, powering, and alarm equipment, comprises the line transmit-receive bay which appears at every main-station location. Four designs accommodate the 9-foot requirements at power-feed and switching power-feed main stations and the 10-foot 6-inch and 11-foot, 6-inch requirements at terminal and terminal-main stations. The difference among the four designs is the varying complexity of the elements of line connecting, ranging from the very simplest in the power-feed main-station design, where the transmit-receive bay is essentially a one-way repeater, to the more complex one-way repeater of the switching power-feed main-station design, which includes switches and switch-initiator circuitry for LPSS, to the most complex terminal and terminal-main station designs where elements of line connecting also include blocking, adding, dropping, and branching circuitry for the signal-processing features. This hierarchy of line bay designs is illustrated in Fig. 13, with shading used to contrast the variable element within the otherwise repetitive structures. Note that the only difference between the two "terminal or terminal-main" designs is that the 11-foot, 6-inch bay has room for one additional line-branching unit.

The main-station transmitting and receiving repeaters together equate to a regulating repeater used in manholes. The transmit and receive elements have been split and repackaged in an equipment shelf for bay-mounting (Fig. 14). Similarly, the main-station manually adjustable equalizer (E1) contains the same elements as its plug-in unit, manhole counterpart (Fig. 10), re-packaged in a fixed shelf for

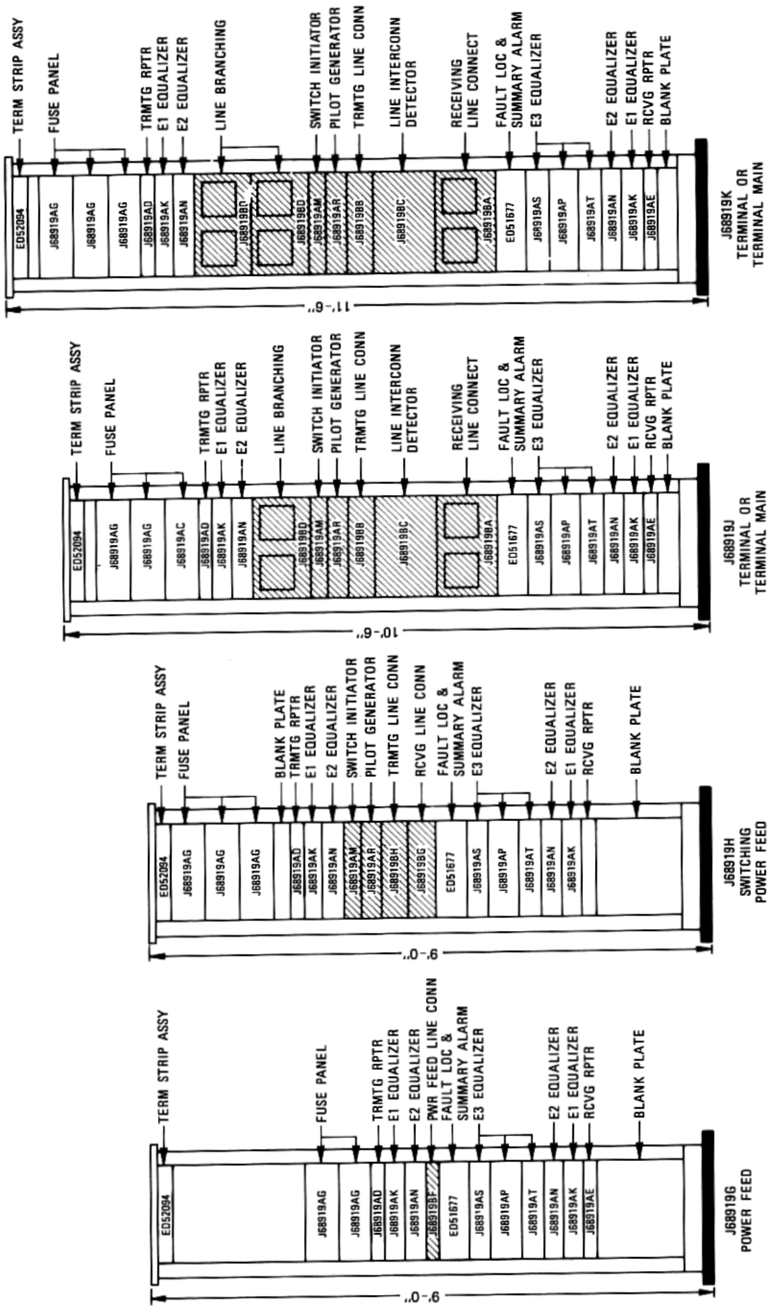


Fig. 13—Line transmit-receive bays.

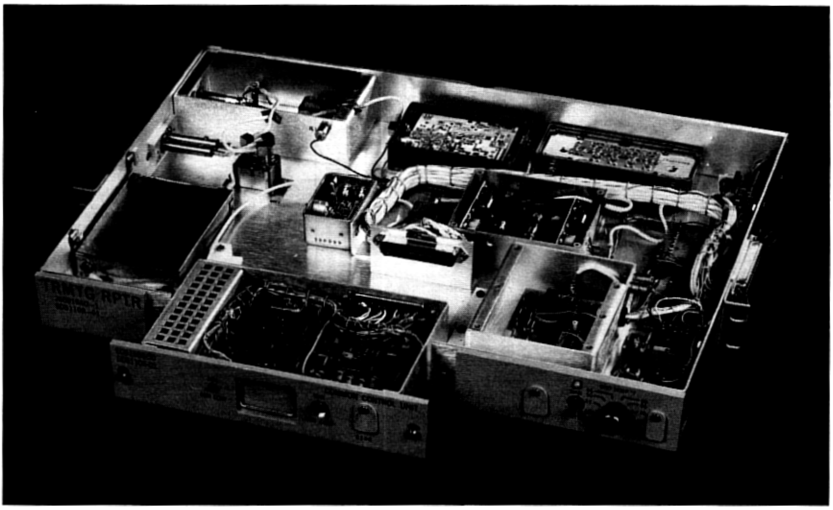


Fig. 14—Main-station transmitting repeater.

bay-mounting (see Fig. 15); and this unit, expanded to include additional networks and amplifiers required for additional bump shapes, yields the design of E2 (see Fig. 16).

Two line bays are shown at the right in Fig. 17 as they appear at a terminal or terminal-main station in an L5 five-bay line-up that constitutes the equipment required to provide service on the first working

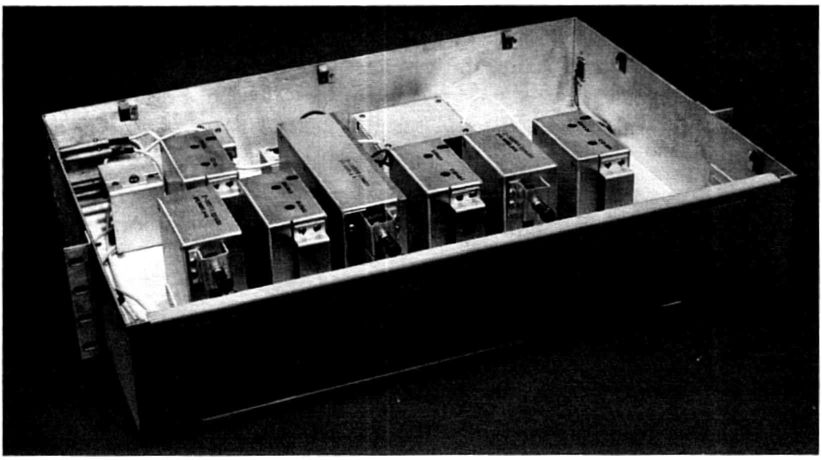


Fig. 15—Main-station E1 equalizer.

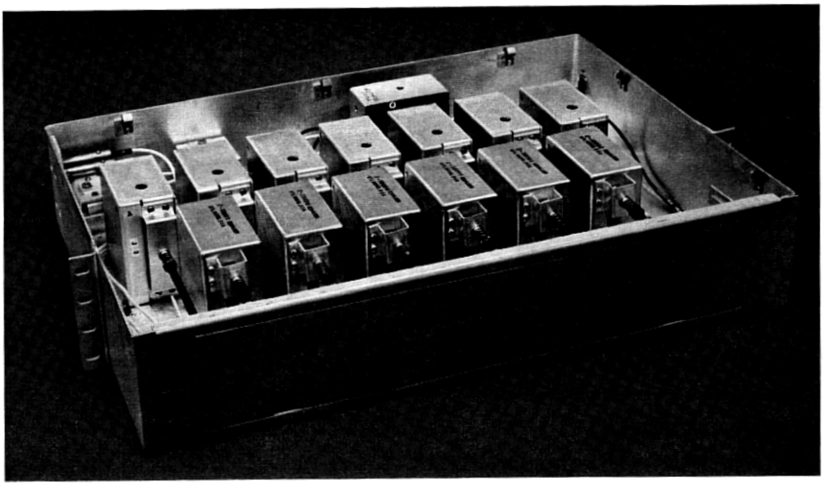


Fig. 16—Main-station E2 equalizer.

pair of tubes, with the first line bay being the protection bay and the second the first regular bay.

3.2 Terminal equipment

3.2.1 Jumbogroup multiplex bay

The final step of multiplexing required to stack jumbogroup (JG) signals for transmission over the L5 coaxial line is accomplished by the jumbogroup multiplex[6] (JMX). The JMX is a completely solid-state multiplex that utilizes thin-film hybrid-integrated circuit (HIC) elements contained in modular plug-in assemblies. The JMX equipment is mounted on a unitized bay framework shown in Fig. 18, 11 feet, 6 inches high by 52 inches wide by 15 inches deep. A complete bay accommodates a maximum of three transmitting and receiving jumbogroups. Jumbogroup multiplex designs are also available in 10-foot 6-inch, 9-foot, and 7-foot bay heights to meet the needs of telephone offices with lower ceilings.

The JMX is a completely shop-assembled, shop-wired, and shop-tested bay. It contains transmission, shaping, regulating, patching, logic, alarm, carrier supply, and dc-to-dc converter equipment and, since 3600 voice circuits could be affected by a service interruption, automatic protection switching is also provided for each jumbogroup.

Jumbogroup multiplex bays are generally located in the maintenance aisle of a central office or main station where a minimum aisle spacing of 4 feet, 6 inches is required to permit the use of rolling test consoles without restricting the operating personnel. Since this area is a center of office activity, a good appearance, without significantly increasing the cost, was considered a design objective.

The bay cabling consisting mainly of office-type coaxial cable is carefully segregated, primarily to minimize crosstalk and secondarily to facilitate installation and shop wiring. Transmitting cables are contained in the left-hand cable duct and receiving in the right-hand duct,

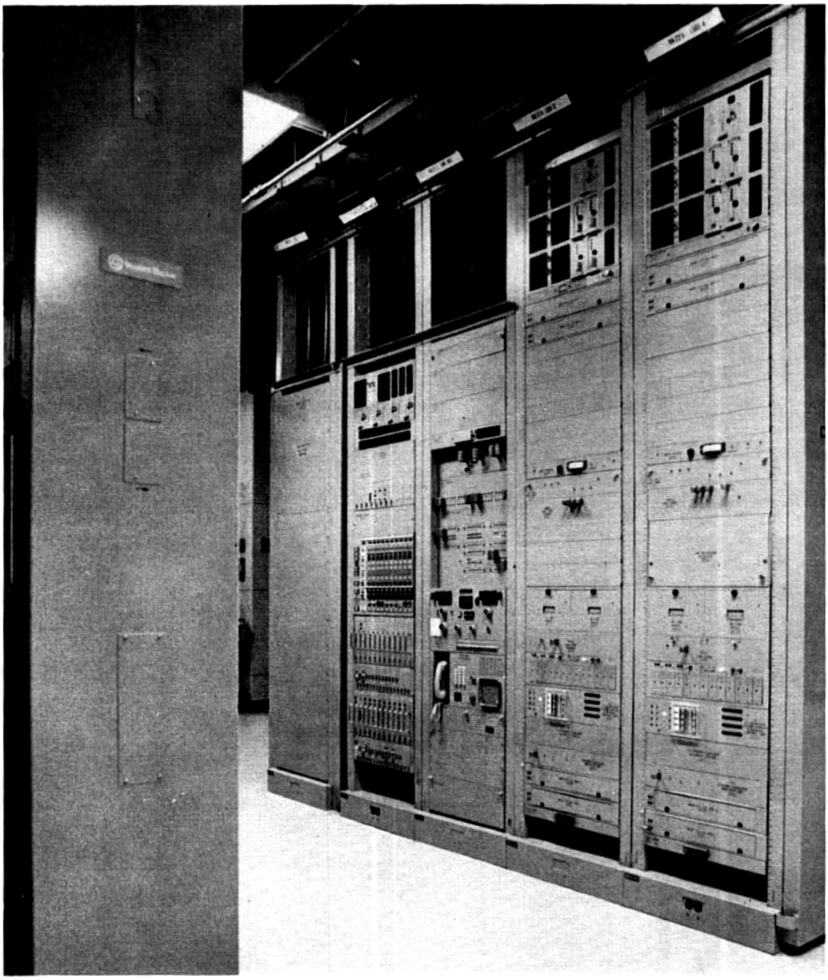


Fig. 17—L5 bay line-up.

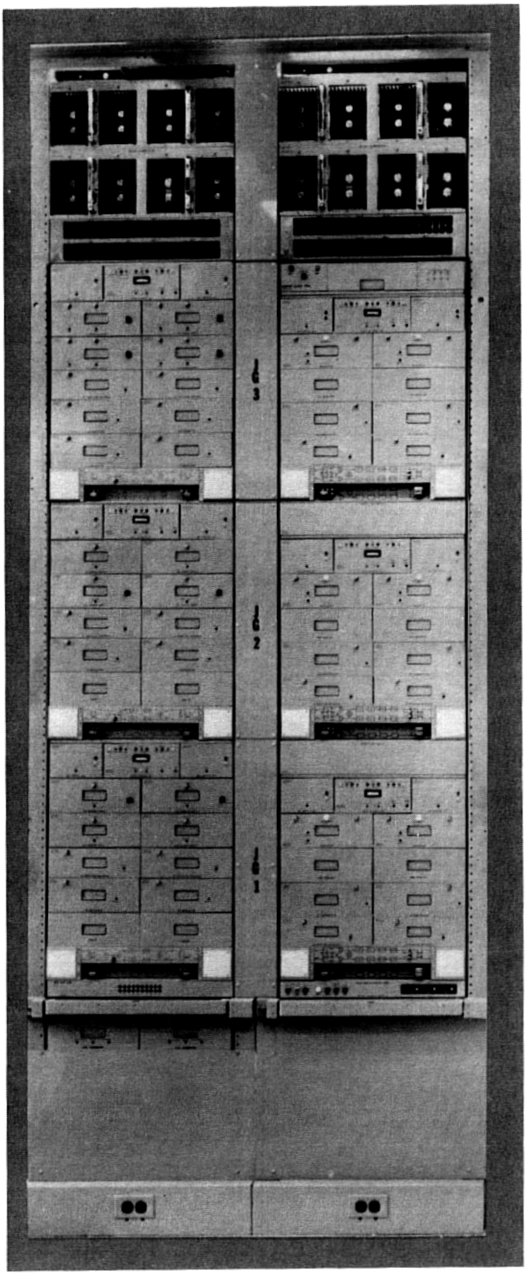


Fig. 18—Jumbogroup multiplex bay.

and, with few exceptions, all other wiring and cabling is confined to the center duct. Office cable connections to the bay are made through connectorized cables located at the top of the bay, making it unnecessary for the installer to enter the cable ducts.

The basic building block of the JMX bay is the jumbogroup shelf assembly shown in Fig. 19, which contains the modular plug-in units. For example, the receiving shelf contains the regulator, equalizer, demodulator, de-emphasis, transmission protection switch, logic switch control, and jack field. The framework and module construction for the transmitting side is the same.

Since all equipment modules performing similar functions are the same physical size, a variety of bay configurations can easily be accommodated. For instance, at a typical end office, the JMX bay with jumbogroups 1, 2, and 3 could be provided, whereas at intermediate stations the bay could contain all jumbogroups 1, 2, or 3 or any combination of jumbogroups 1, 2, or 3 up to the bay capacity of three.

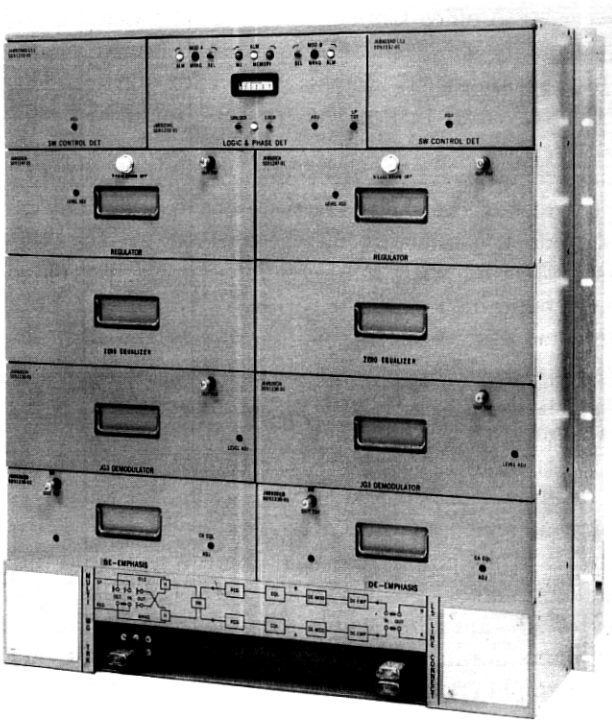


Fig. 19—Jumbogroup shelf assembly.

A lattice-type lightweight aluminum construction is used for the jumbogroup shelf to optimize the strength-to-weight ratio and virtually eliminate shelf deflection under load. To avoid scraping when the aluminum modules are inserted in or removed from the shelf, a low-friction tape is bonded to the load-bearing surface.

Each transmitting and receiving shelf assembly contains a built-in jack field for jumbogroup patching or testing. To facilitate maintenance, a functional schematic diagram is provided directly above the actual jack location. The jack field is recessed to minimize the possibility of a circuit patch plug accidentally being removed or damaged, thereby causing a service interruption. To aid the craftsperson in identifying jumbogroup equipment with its associated jack field, each jumbogroup position is framed with a colored plastic strip. Each of the three jumbogroup bay positions is identified with a different color. Matching color route assignment cards covered with glare-resistant plastic are also provided.

Directly above the writing shelves is a miscellaneous panel that provides access to office trunks, alarm cutoff switches, and indicators and the means for simultaneously testing all lamps in the bay. In the present bay, incandescent lamps are used for alarm indications; however, in the very near future, these will be replaced by light-emitting diodes (LED).

Modules are inserted from the front of the bay and held by a captive screw in the rear of the shelf. These units are essentially plug-in, without fixed mating connectors on the shelves. In this way, tolerance problems associated with mating connectors are avoided. Most assemblies are contained in 10-inch wide by 4-inch high by 12-inch deep aluminum modules, as shown in Fig. 20. Coaxial and pin connectors are provided at the rear for transmission and power connections.

Filters, amplifiers, and other types of apparatus have been mounted in separate housings for shielding, to facilitate manufacture and testing, and for efficient field repair. Interconnections within the modules are made by miniature coaxial cables.

During the development of the JMX and other L5 main-station equipment, it became apparent that there was a need for a family of very small amplifiers. To meet this need, the 509-, 510-, 511-, and 512-series of HIC amplifier codes were developed. More than 230 of these amplifiers are in a fully equipped JMX bay. The outside dimensions of the amplifiers are 2.75 by 1.5 by 2 inches high. Input and output connections are made through miniature 75-ohm coaxial connectors. The circuitry of the amplifiers is a HIC with some components

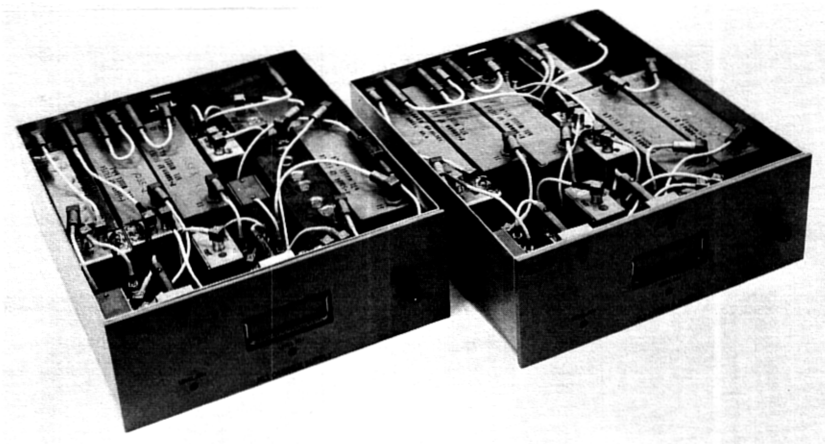


Fig. 20—JMX modules.

appliqued, such as transistors, inductors, or chip-capacitors. Special ground terminals are swaged into the chassis to ensure effective grounding.

Considerable care was taken to limit the mechanical stresses between the ceramic substrate and the chassis. For example, all connections are made with soft gold-coated copper ribbon wire, looped to allow slight mechanical movement of the substrate during thermal and mechanical shock. As shown in Fig. 21, the substrate is mounted by fitting the ends with silicone rubber gaskets and supporting them at opposite ends of the chassis with adjustable aluminum blocks. To efficiently conduct heat from the transistor, a spring-loaded heat sink described earlier connects the transistor mounted on the substrate directly to the cover of the amplifier.

As part of the overall JMX development, a complete thermal analysis of the bay was performed. Where possible, units dissipating the most power were arranged in the bay to avoid hot spots. A 4-inch space is provided for each jumbogroup shelf through the recessed jack field for a front-to-rear air flow. Temperature measurements indicate a 55°F maximum gradient between a transistor case in the JMX and room temperature. The complete thermal analysis shows that, even under the worst condition, the equipment in the bay is well within the temperature limits necessary for reliable performance.

The 24-volt power for the JMX is supplied by the office power plant over two separate feeders to the 24-volt to 25-volt regulated converters.

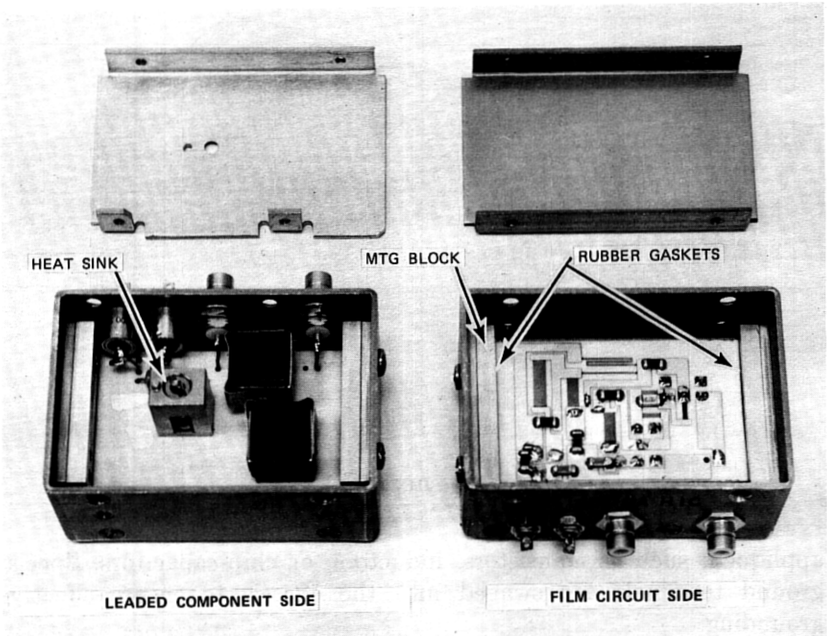


Fig. 21—HIC amplifier.

The feeder-converter assignments have been arranged so that the loss of a feeder or a single converter will not result in a loss of service.

3.2.2 Basic jumbogroup trunk bay

The interface between JMX and the lesser units in the multiplex hierarchy is the basic jumbogroup trunk bay[7] (BJGT). This bay offers a very high degree of flexibility for the user in that it is designed to allow a maximum of four inputs per jumbogroup and to include designs for inputting radio signals, L-carrier mastergroup digital (LMD) signals, L4 coaxial-carrier system signals, etc. The active circuits are redundant and are packaged in pull-out drawers and fixed shelves. The combinations of circuits available are so numerous that normal bay coding or even normal panel coding is virtually impossible. Only typical bay layouts are offered as a guide for ordering, and the specific short- and long-range requirements of an office dictate the composition of any BJGT shipped from the factory. Intra-bay cabling is laid out to accommodate multi-input options and suggested bay layouts allow space for modular future growth.

3.2.3 Jumbogroup frequency supply

The jumbogroup frequency supply (JFS) furnishes three highly reliable and precise signals to the JMX to generate the necessary carriers.[8] These signals, at frequencies of 1.024, 2.560, and 20.48 MHz, have an accuracy well within the one part in 10^8 requirement imposed by the JMX. This accuracy is realized by comparison with a reference signal from a primary frequency source; however, even if the reference signal is lost for several weeks, the inherent stability of the JFS will maintain the required accuracy.

The JFS, shown in Fig. 22, is mounted in a unitized double 9-foot high framework. A front aisle is required for normal maintenance and a rear aisle for installation wiring. Since the number of JFS bays required for coaxial systems is relatively low, the 9-foot bay arrangement is provided for use in current design of main stations. A 7-foot version of JFS is also available for future offices with the lower ceiling height.

The JFS is a fully shop-assembled, shop-wired, and shop-tested bay. It also is completely solid-state, utilizing digital and thin-film hybrid-integrated circuit (HIC) technology. The most important design objectives were precision and high reliability. To accomplish this, very stable oven-controlled 39-type oscillators and one-for-one redundancy automatically switched are employed.

The jumbogroup frequency generator (JFG) is the basic building block of the JFS bay, and the 39-type oscillators are the heart of the JFG. Each JFS contains three JFG's (master, regular, and standby). The master JFG serves as a buffer between the reference signal and both the regular and standby JFG's, thereby keeping the JFS output relatively immune from loss and/or disturbance of the reference signal. As shown in Fig. 23, an integral part of the JFG is the alarm display panel, which indicates whether the JFG is operating as the master, in-service, or idle. It also indicates frequency offset, level failure, and the frequency alarms. Test access points are provided for measuring the 25-volt, 6-volt, and 5-volt power.

The JFG patch panel provides patching facilities not only to remove a failed JFG from service but to rearrange the JFG's by function (master, regular, standby) to realize the best use of the remaining two. When a JFG is removed from service, the protection switching logic must be restructured to accommodate rearrangement of JFG functions. This is accomplished by operating the JFG "out-of-service" switch on the alarm and switch control panel when the patching has been completed. The faceplate of the JFG patch panel is a schematic block diagram with

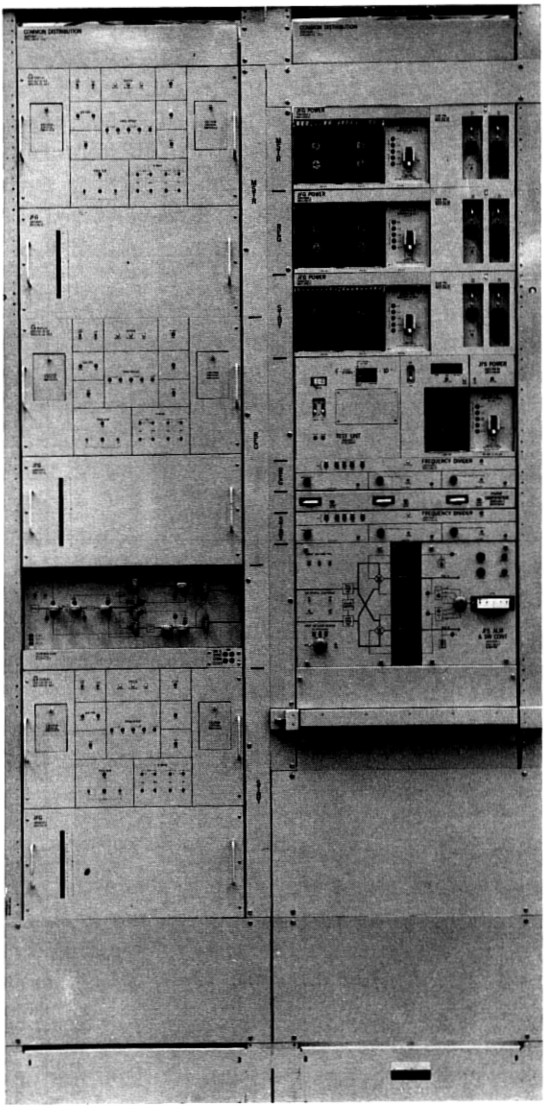


Fig. 22—Jumbogroup frequency supply bay.

appropriately positioned jacks interconnected with color-coded paths to indicate the placement of patch plugs for the JFG, master, regular, or standby failure conditions. As in the JMX, the panel is recessed to prevent damage and possible circuit interruption.

The control center for the JFS is the alarm and switch control panel. It is a visual continuation of the patch panel schematic block diagram and contains the level detectors and coaxial switch and the logic required for the alarm and switch functions.

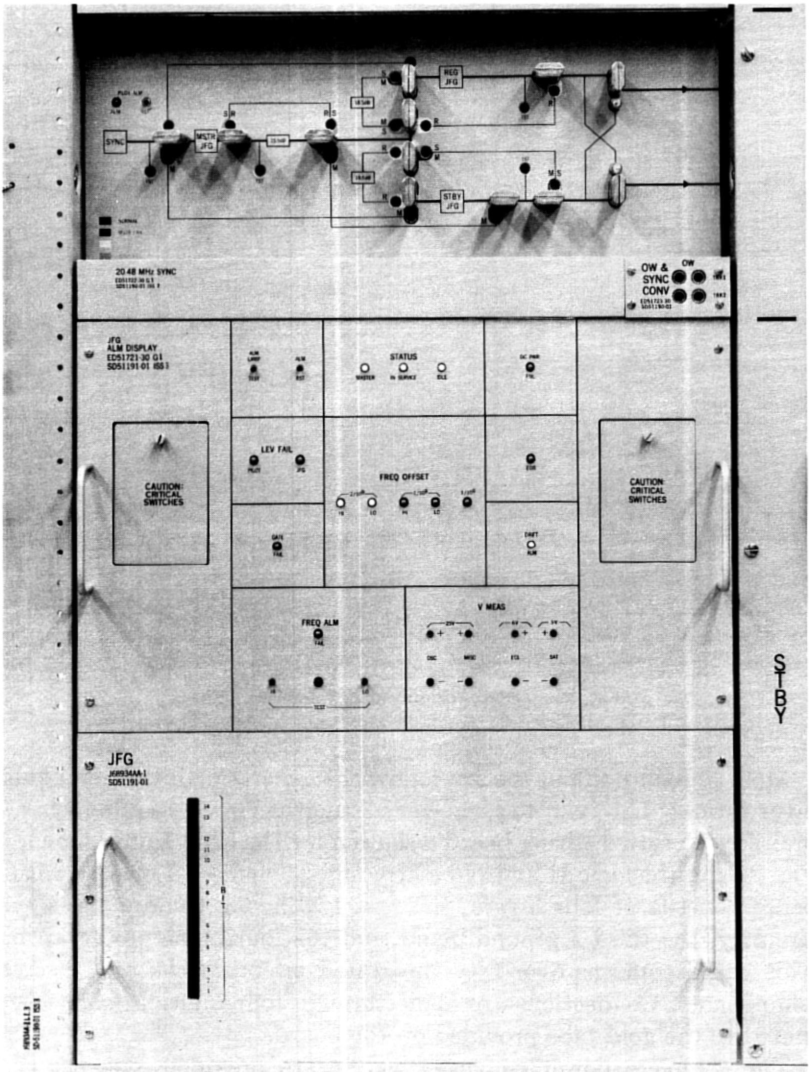


Fig. 23—Jumbogroup frequency generator and patch panel.

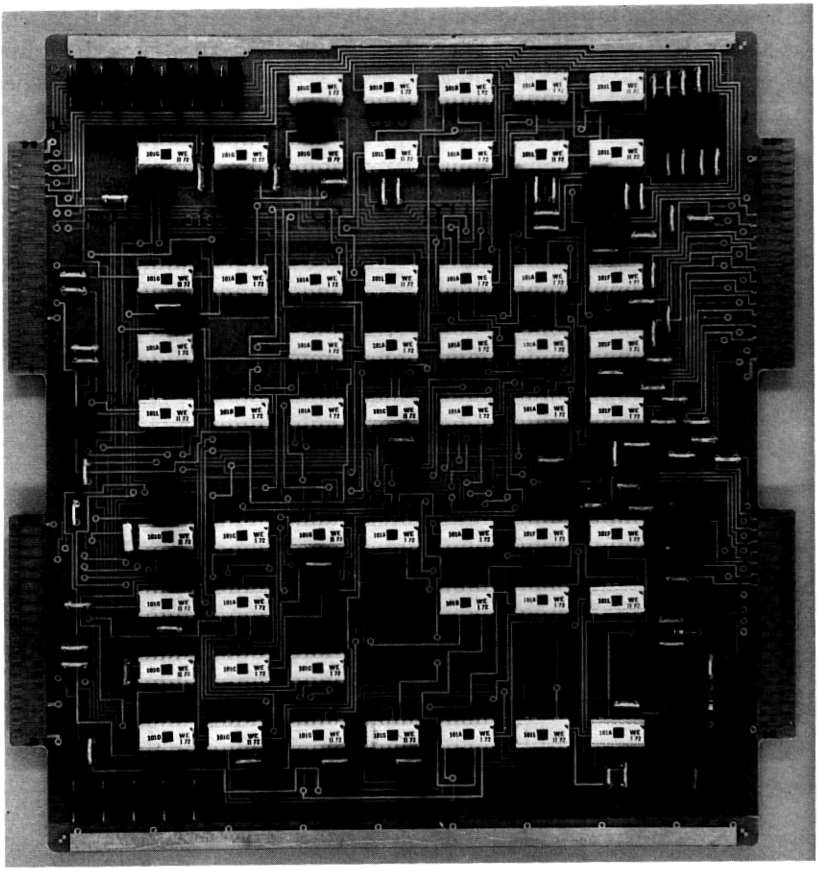


Fig. 24—JFS alarm and switch control logic.

Most plug-in units in the JFS follow the general main-station equipment format; however, to meet very stringent circuit requirements, a multilayer printed wiring board was used for the logic I unit shown in Fig. 24 and the logic II and JFG alarm units. The logic I printed wiring board consists of four layers; the first two layers contain the signal circuitry, the third a ground plane, and the fourth the power wiring. This board contains over fifty integrated circuit packs and discrete components. Connections are made through four multipin connectors mated to the gold tabs provided on the board.

The complete power converter panels are provided, one per JFG. Each converter receives power from a separate office feeder lead. This ensures that, even if a feeder is accidently damaged or a main fuse operates, the JFS will continue in service.

3.3 Surveillance equipment

The L5 surveillance[9] physical designs cover the widest cross section of types of equipment, ranging from the pure functional types located in manholes to the sophisticated equipment located in the center of activity in a control terminal or terminal-main station. In addition to being influenced by functional design considerations, the latter type of equipment was strongly influenced by human-engineering design considerations and, since it is constantly in the forefront and under scrutiny, was designed to have an aesthetically pleasing appearance. While the repeaters may be the heart of the L5 system, the transmission surveillance system (TSS) equipment is its nervous system, feeding back information on the health and well-being of the system.

3.3.1 Fault-location oscillator and logic gate

The fault-location oscillator (FLO) unit and the 31A gate are the manhole-mounted units of the TSS. A FLO unit is installed in every apparatus case, a unit with eight outputs located centrally in a basic repeater apparatus case (see Fig. 2, Section 1.1) and a unit with four outputs for use with regulating and equalizing repeaters. The FLO is a rugged unit made up of an inner chassis and an outer, fabricated, shell-like housing. The inner chassis supports the face plate and contains the four tone generators (two high frequency, two low frequency), the combining circuitry, and the coaxial switches and associated logic circuitry to turn on the unit. Connections within the unit are made with miniature coaxial connectors and connections for the tone outputs are by way of large Bell System coaxial jacks located in the face plate. The coaxial patch cords used to connect the FLO tone outputs to the input and output of every repeater (through the twin coaxial-jack assemblies located on the apparatus case chassis) are shipped with the apparatus case and provide continuity through the apparatus case for cable acceptance and corona testing. For this reason, the cords are required to be high-voltage designs, even though they are primarily intended to be used at low voltage. The protective, outer covering of the FLO unit consists of a long, thin-walled, rectangular, aluminum housing closed at one end, where it is welded to a rugged, cast, mounting base. This base holds the multicontact connector for input power and logic connections, and contains the large retainer guides that mate with the retainer pins on the apparatus case chassis.

The 31A gate, the logic unit for the FLO's, is used on a one-per-manhole basis and is located in the cross-connect apparatus case (Section 1.1). It consists of a large epoxy-glass PWB assembly housed in a sheet-metal, fabricated can mounted on a hinged shelf that swings out to allow access to wire terminals and protector blocks inside the cross-connect apparatus case.

3.3.2 Line access bay

Rectifiers used to power the FLO units and control circuitry for the FLO units are located in the main station in the line access bay that serves as the interface between the line and the surveillance[9] equipment. Connections to the surveyed functions in the line bays are made with solid-dielectric, coaxial-cable runs to the line access bay where provisions are made to store the excess cable created by the requirement for equal-length, balanced connections. Switched access to the line bays is provided by 1-by-12 dry-reed coaxial switches mounted on a panel together with installer-wired arrays of coaxial jacks located on jack strips designed to be removable from the panel for easy access. "Hairpin-type" plugs are used for interconnections, and the entire panel is recessed behind the bay uprights to protect the plugs from inadvertent disconnects. The recessing is evident in Fig. 17, where the line access bay appears as the third bay in the lineup. The lower part of the bay contains the order-wire-access panel followed by several fixed shelves containing cable equalizers. The last element in the bay is a removable drawer-type storage shelf for the equalizer adjustment unit (EAU) described below.

3.3.3 Surveillance and distribution

The transmission surveillance system is made up of the transmission surveillance center (TSC) and distribution bay combination for control offices along an L5 backbone route and the transmission surveillance auxiliary (TSA) for other than control main stations.

The TSC is a large desk-type console that houses, in its sides, a commercial computer, a transmission measuring test set, and associated equipment. The central portion of the console contains the manual control panel that displays an array of keys and status indicators within convenient reach of an operator. The TSA is virtually a TSC without the computer and is a standard 26-inch wide unequal flange duct-type bay.

Conduction and natural convection were inadequate to transfer heat from the thermal sources within the TSC. To avoid local hot spots, forced convection is required, and a fan is installed as part of the TSC equipment.

3.4 Peripheral equipment

Associated with a project of the magnitude of an L5 system is a whole series of peripheral items of equipment too numerous to cover in full detail here but of obvious importance to the system and its workings.

Order-wire bays have been coded and, for the first time, make convenient mounting arrangements available to the field where, heretofore, only miscellaneously mountable equipment was provided. In addition, connectorized versions of these bays have been designed to avoid difficulties encountered during the L5 initial installation to accomplish the myriad wiring connections for complete order-wire fan-out in an office.

Multi-mastergroup restoration and zero-loss trunk bay designs involve the use of inexpensive "pseudo-plug-in" construction where simple modules are arranged on a shelf and connected at the rear of the bay with jack-terminated cable arms that are part of the bay wire harness.

Because of the relative inaccessibility of repeaters in manholes and the expense involved in entering a manhole, repeaters that are fully tested before leaving the factory are again tested at field maintenance centers before being dispatched to the manholes. For this purpose, a special repeater test stand and associated warm-up rack were designed for repeater acceptance testing. The test stand simulates the apparatus case chassis details, which make provisions for mounting the L5 manhole plug-in units for verification prior to installation. The verification procedure is speeded up by pre-heating the repeaters on the warm-up rack, which is comprised of five mounting panels, each of which can hold two basic repeaters or one regulating repeater, yielding a total capacity of ten basic or five regulating repeaters. The same retainer guide pins that are part of the apparatus case chassis are used to secure the repeaters on the warm-up rack panels. Powering is by a commercial power supply, and the entire unit is mounted on casters for additional flexibility in those offices designated as maintenance centers.

Required settings on manually adjustable E1 and E2 equalizers are made using the equalizer adjustment unit (EAU) designed as a compact, lightweight, portable test set (see Fig. 25). The unit uses PWB plug-in modules, is designed for ease of assembly, offers accessibility for main-

Fig. 25—Equalizer adjustment unit.

tenance, and is stored in the pull-out drawer at the bottom of the line access bay.

IV. RELIABILITY

With the Bell System providing the major long-haul communications networks for the country, Bell Laboratories designs have always been motivated toward reliability. Systems like the J- and K-carrier systems designed in the 1930's and installed in the 1940's are still providing reliable service. These systems, however, were limited to transmitting 12 two-way telephone conversations over a cable pair, whereas the new L5 carrier system transmits 10,800 conversations per coaxial pair and 108,000 conversations on a fully loaded 22-tube coaxial cable. To accomplish this, new more sophisticated technology was required and to complement this effort a more definitive reliability program was initiated.

We define reliability as ensuring that a given component, equipment, or system will perform a required function, under stated conditions for a needed period of time.

This comprehensive reliability program was instituted almost from the start of the L5 carrier system development and has been proceeding concurrently with it. This overall program covered the following nine functional steps, some of which must still be completed and, therefore, will not be part of this report:

(*i*) Derive early estimates of equipment and system failure rates, mean time to failure (MTTF), and availability.

(*ii*) Monitor the actual laboratory prototype experience.
(*iii*) Analyze field-trial production experience.
(*iv*) Acquire and analyze actual field-trial data.
(*v*) Review and revise, if required, early estimates based on laboratory and field-trial experience.
(*vi*) Monitor the Western Electric manufacturing and installation initial route experience.
(*vii*) Conduct a full-scale reliability study of the initial service route.
(*viii*) On a continuing basis, obtain and analyze data on all L5 units returned for repair.
(*ix*) Conduct a reliability study on a subsequent route, installed about two years after the initial route.

The purpose and objectives of this program are to obtain accurate data on the reliability performance of the L5 carrier system as early as possible, to aid in formulating the early system design concepts, to uncover potential problem areas so that corrective action can be expedited before the first system is turned up for service, to compare the actual system reliability performance with the early estimates, and to review the reasons for any major differences, so that more accurate estimates can be made on future systems.

Very early in the development program, a reliability study of the L5 system design was made. As a first step, "black box" failure rate estimates were made on all the repeaters and equipment units. While it is impossible to predict for any individual electronics part either its life or its rate of degradation under known stress, it is possible to treat large populations of such parts on a probabilistic basis with acceptable results. These results can then be related to the statistical behavior of the system. The "black box" failure rates were calculated by summing the failure rates of the components and parts. The component rates used were based on experience in well-defined systems, operating under normal Bell System conditions and environment. For new devices or technology with little or no previous experience, estimated failure rates were derived after consultation with the device or component designers. In these cases, the rates reflected a very conservative estimate.

Using the basic repeater which is the most numerous and least sophisticated of the line repeaters as an example, it was estimated that the failure rate would be about 900 FIT's, with a FIT defined as one failure expected or experienced in 10^9 hours of service. This results in an estimated MTTF of over 125 years for each basic repeater. The regulating, equalizing, and main-station repeaters being substantially more complex have shorter MTTF estimates.

To obtain overall estimates, two basic system models were selected. Both were 4000 miles long and employed automatic protection switching for the coaxial tubes. In one case, the calculations were based on switching section lengths at a maximum of 150 miles and, for the second, a nominal 120-mile spacing was used, based on the L4 coaxial-system route layout experience. There were some obvious trade-offs in the two models selected. For instance, using the maximum length section resulted in more line repeaters per switching section; however, in a 4000-mile route the number of main stations are reduced from 33 in a route with normal switching section lengths to 27 for the maximum length sections.

An important consideration in the system availability estimates is the average time to repair or restore service. Since it was difficult to arrive at a time that was acceptable, calculations were made based on optimistic and pessimistic restoral times. The optimistic times were defined as an average of 15 minutes for main-station equipment and three hours for manhole equipment, and the pessimistic times as three hours for main-station equipment and six hours for manhole equipment. Recent data on the service restorals for existing coaxial systems show that the average repair times actually being experienced are very close to the optimistic figures.

It is estimated that, for a pair of coaxial tubes in a fully equipped 22-tube cable, with a 1-for-10 automatically switched redundancy, the availability of the electronics and switching contained in a 4000-mile route using the optimistic restoral times would be 99.986 percent for an average outage time of about 1 hour and 15 minutes per year. If the pessimistic repair times are assumed for the same system, the availability would be 99.948 percent per year for an average of about 4.5 hours per year outage.

One very early system question was whether, with double the number of repeaters in a L5 switching section as compared with the L4 system, the ratio of one spare coaxial automatically protecting ten working coaxials was adequate to ensure reliable service. Availability calculations were made on the system model with 120-mile switching sections and optimistic repair times employing 1-for-10 and 2-for-9 protection ratios. With the 2-for-9 arrangement, the probability of three simultaneous failures in a switching section was remote; however, the estimated outage attributable to the more sophisticated switching system resulted in outage times for both strategies being relatively close. Based on previous experience, cable failures constitute a greater outage hazard in terms of system unavailability than do the electronics. Therefore, using additional coaxials within the same cables as protection for most cable faults would be counter-productive. Taking into account these factors and the revenue lost by dedicating a second coaxial for protection, the 1-for-10 protection ratio was continued for the L5 system.

The field trial of the L5 carrier system started on July 1, 1970 and continued through June 1972 on a 125-mile cable route between Cedarbrook and Netcong, N. J., shown in Fig. 26. The purpose of the field trial was to test the L5 as a complete system operating in the field environment before going into full-scale production and regular service. The 240 basic repeaters and 48 regulating repeaters required for the trial were constructed by Western Electric on a special basis because the quantities exceeded Bell Laboratories model shop capabilities. Since problems in the field can often be anticipated from experience gained during manufacture, a data acquisition program was initiated by Western Electric for the field trial equipment and, eventually, standard production.

A reliability study was made on the performance of the field trial route. This was intended as prelude to a study of the initial L5 service route between Lillyville, Pa. and Hillsboro, Mo. Data were collected on all failures of equipment and all system outages. A thorough investigation was made on any units that failed. A case in point was the failure of a basic repeater traced to the earth-ground filter. After further analysis, including the X-ray photograph shown in Fig. 27, it was found that high-voltage shorting was caused by a capacitor unit assembled off-center without outer insulating material. To prevent this in the future, high-voltage test screening was specified and tighter quality controls were instituted by the supplier. Failure rate calculations were made based on the field data; however, it was recognized that the population was small, the equipment was not from standard production, and, because of the level of field activity, it was difficult to keep accurate data on every single occurrence.

Our experience with previous systems such as the L4 coaxial system and the L5 field trial pointed out the need for even greater emphasis on obtaining accurate data on the manufacturing testing results, the initial defect rates in the field, the infant mortality rates (the infant mortality period is defined as the first six months of service), and, finally, the steady-state system reliability performance more commonly known as the normal use period of the "bathtub" curve. To accomplish

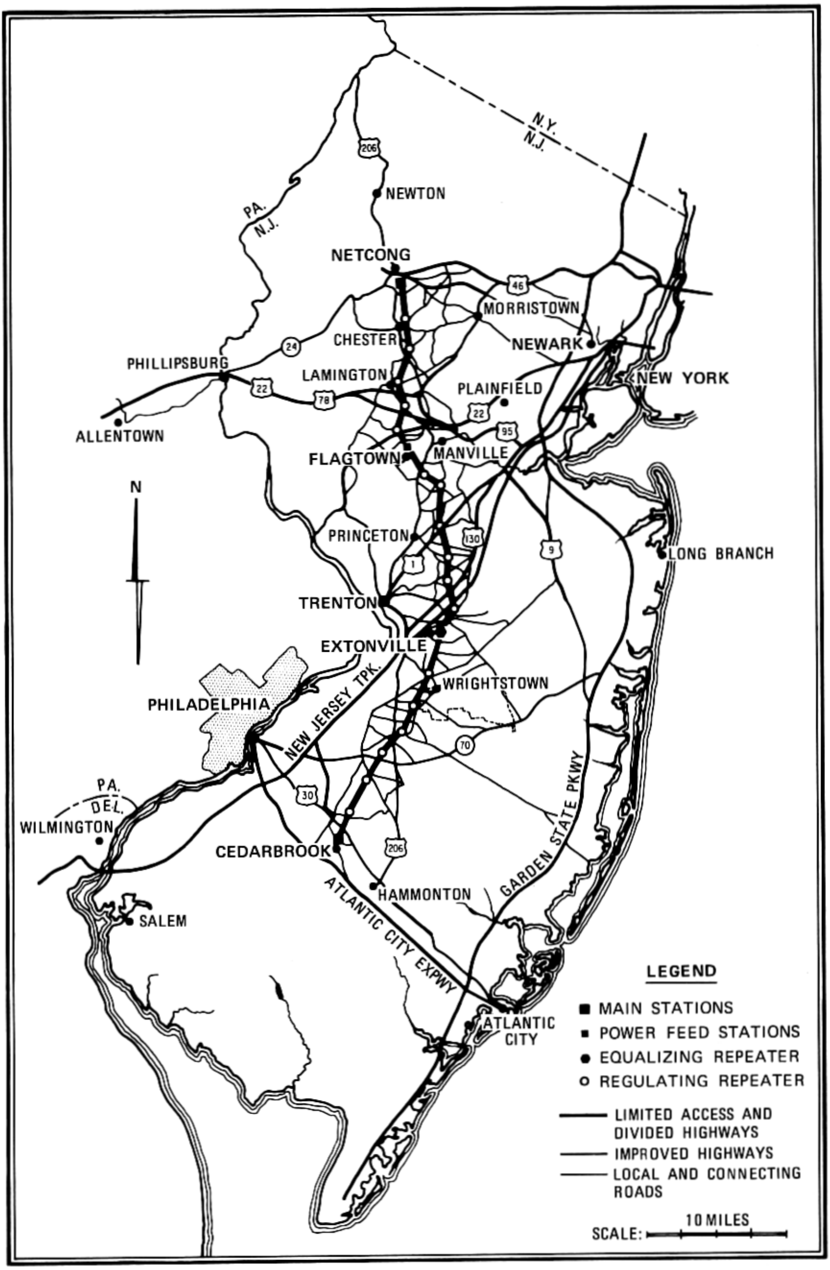


Fig. 26—L5 field trial route.

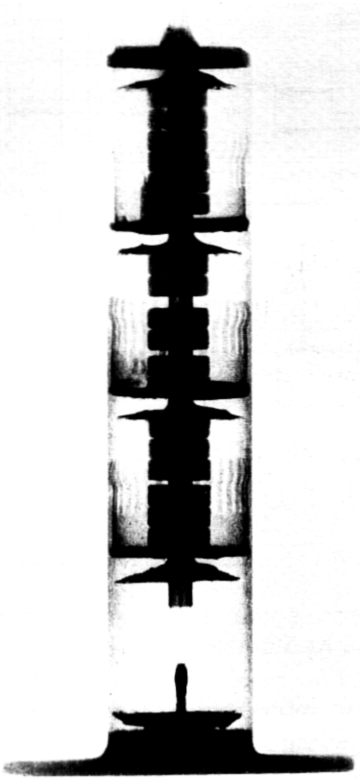


Fig. 27—X-ray of earth-ground filter.

this, an elaborate data collection program was initiated. Subunits such as coded amplifiers and even HIC substrates were serial-numbered. Special envelopes and data forms were attached to each unit at the start of manufacture. As the unit was processed through the various stages of manufacture, the test results were recorded on punched tapes and stored in the envelopes. If components are removed at some stage, they are stored in the envelopes and the data recorded on the forms. When, for instance, a repeater is ready to ship, a complete pedigree has been established for analysis and future reference. The components removed are forwarded to the experts for analysis to determine the failure mechanism. Through this program, we are able to detect failure trends and initiate corrective action.

An important part of the reliability program is to establish the initial field defect rate. In Fig. 28, a block diagram traces the pro-

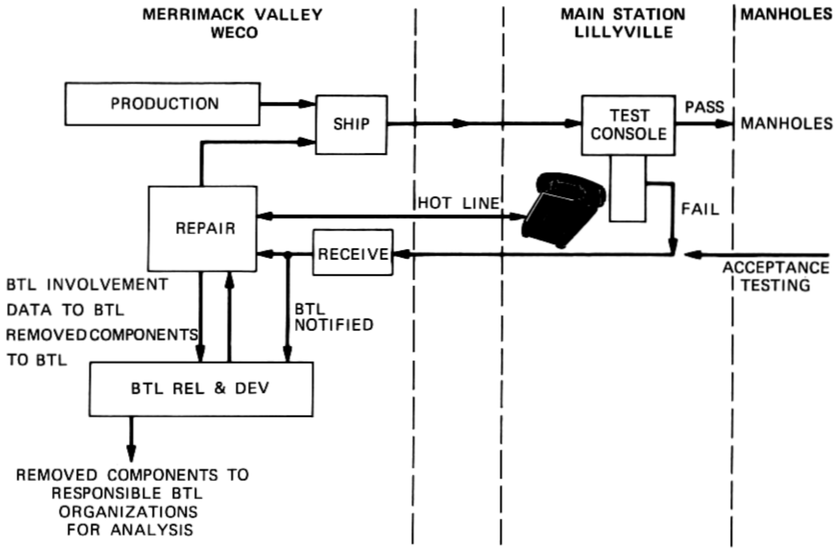


Fig. 28—Initial L5 route returns repair-reliability program.

cedures set up to process units returned for repair. Note that a "hot line" was established by Western Electric to expedite the replacement of any units returned for repair so that the service schedules would be met. When units are returned for repair, the designers are able to participate in diagnosing the problems. Data are recorded on all repairs, and the components removed are kept for further analysis. For the initial route, about 3200 basic repeaters were tested and installed in manholes. Approximately 1.5 percent were returned for all reasons. After further testing, it was determined that about 35 percent of these met all test requirements, resulting in a 1-percent initial return rate.

On January 3, 1974, the L5 route between Lillyville and Morgantown, Pa., was put into regular service, and the L5 field reliability program was started. On January 25, the section from Morgantown to Hillsboro, Mo., was put into service, and this section was added to the reliability study. Before the start of service, visits were made to all offices on the route to discuss the objectives of the study and the type of data required. During the early service period, each office is contacted on a weekly basis to report all field problems, even those not affecting reliability. The purpose is to get immediate feedback on the system performance. A complete listing of all equipment in the initial route by serial number was made so that the hours of service necessary for availability calculation can be accurately computed.

L5 COAXIAL SYSTEM RELIABILITY STUDY
LILLYVILLE - HILLSBORO
OUTAGE AND EQUIPMENT FAILURE

STATION REPORTING Lillyville, PA
DATE 11-2-73

I. SWITCH TO PROTECTION COAX (ONE MINUTE OR MORE)

☑ AUTOMATIC ☐ MANUAL AUTO LINE TERMINATE ☐ YES ☐ NO

LINE NO REGULAR L503 PROTECTION L501

DATE/TIME ON 11-2 (DATE) 1620 (TIME) DATE/TIME OFF 11-2 (DATE) 1835 (TIME)

REASON LINE FAILURE (EXPLAIN IN II) ☑ MAINTENANCE (EXPLAIN IN III) ☐ RESTORATION ☐

II. CAUSE OF LINE FAILURE
- ☑ LINE EQUIPMENT FAILURE
- ☐ CABLE FAILURE
- ☐ TERMINAL EQUIPMENT
- ☐ H V CONVERTER FAILURE
- ☐ OTHER CAUSES
- SPECIFY ______

III. MAINTENANCE
- ☐ MODIFICATION
- ☐ OTHER

IV. OUTAGE TIME CAUSED BY (IN ADDITION TO SECT II)
- ☐ PROT COAX IN USE
- ☐ PROT COAX IN USE FOR RESTORATION
- ☐ SWITCHING FAILURE
- ☐ TANDEM FAILURE LOCATION ______ (IF KNOWN)
- ☐ SIDE LEG FAILURE LOCATION ______ (IF KNOWN)

V. LINE AND TERMINAL EQUIPMENT FAILURE *

CODE AND LIST J68919AA-1 L1,L3 SERIAL NO 1375 LOCATION 2081-0270 (MANHOLE DESIG. OR MAIN STATION)

DATE IN SERVICE 1-8-73

DATE/TIME OF FAILURE 11-2 (DATE) 1620 (TIME)

DATE/TIME RESTORED 11-2 (DATE) 1835 (TIME)

* SEE INSTRUCTIONS FOR EQUIPMENT TO BE REPORTED

FAILURE SERVICE AFFECTING? ☐ YES ☑ NO

NATURE OF FAILURE CODE ______ (SEE CODE ON OTHER SIDE) OTHER ______

ENG COMPLAINT # ______

VI. LINE OUTAGE

LINE(S) FAILED L# ______ L# ______ L# ______ DATE/TIME ______ (DATE) ______ (TIME)

LINE(S) RETURNED TO NORMAL (DATE) (TIME)

L# ______ DATE/TIME ______ ______
L# ______ DATE/TIME ______ ______
L# ______ DATE/TIME ______ ______

MAIL TO MR W C WESTPHAL, ROOM 3B13
BELL TELEPHONE LABORATORIES
1600 OSGOOD STREET
NO ANDOVER, MASS 01845

REMARKS

Fig. 29—Return data form.

A data form shown in Fig. 29 is filled out and returned to Bell Laboratories for failures of any type, even if service was not affected, and for the use of the spare line facilities for protection and for maintenance. These forms are returned to Bell Laboratories weekly for compilation. Arrangements have been made so that complete data will be recorded by Western Electric when the units are returned for repair. At the time this paper was written, the system was in service for a very short period of time and the field data were limited; therefore, no reportable results were available. This reliability study is intended to continue for a minimum of one year.

As part of our continuing transmission system reliability program, the general performance of the L5 system will be continually monitored by our computer-aided reliability program (CARP), which utilizes data received from the service centers on all units returned from any route for repair. In addition, in about two years we intend to conduct a reliability study similar to the one presently in operation on another route.

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