

SINGLE-MODE CABLE FOR LONG-HAUL, TRUNK, AND LOOP NETWORKS

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In the seven years since their commercial introduction, lightguide systems have swept the telecommunications industry. The original multimode fibers have now given way to single-mode fibers designed for operation at 1310- and 1550-nm wavelengths. These developments have stimulated an evolution in lightguide cable designs to meet the specialized needs of the various applications such as long-haul, interoffice trunk and loop networks. Cables are used in underground duct systems, aerial, and direct-buried installations. At present, high-quality cables using single-mode fibers are being manufactured in volume. A review of the design and performance of AT&T single-mode lightguide cables is presented.

Introduction

Single-mode lightguide systems are rapidly being installed throughout the world, primarily because of the low loss and high bandwidth they offer. With attenuation values of less than 0.4 dB/km at 1310 nm, repeaterless spans of about 40 km are typical with transmission rates up to about 420 Mb/s. Service at 1.7 Gb/s at 1310 nm will be deployed within a year. Future system upgrades are also possible at 1550 nm where fiber losses are less than 0.25 dB/km. Single-mode fiber was first applied in long-haul networks and then in trunks linking central offices. In metropolitan areas, the interoffice trunks can generally be installed without repeaters. With increased production, the costs of fiber and system components are falling and single-mode fiber is beginning to find application in loop networks as well.

In cable design, the most important design features are: optical attenuation, environmental stability, mechanical protection, cable handling, and fiber splicing. The relative importance of each feature is dependent on the particular application. For example, in long-haul systems, economics requires the maximum repeater spacing. Here, very low loss cable and individual fiber splicing are generally used to mini-

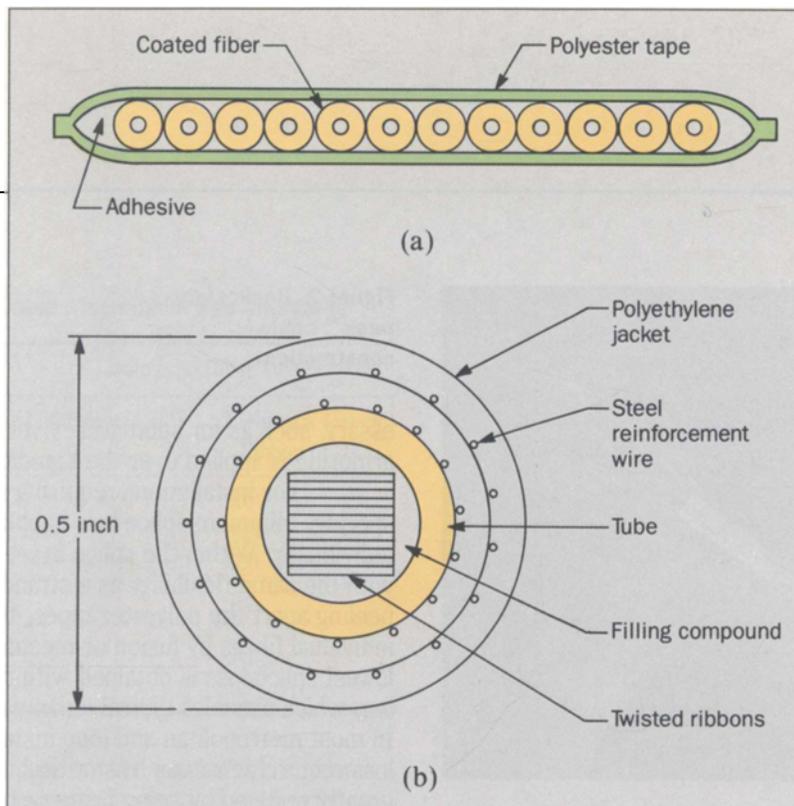


Figure 1. Adhesive sandwich ribbon (a) is composed of 12 fibers between two adhesive-backed polyester tapes. The ribbons are stacked and sheathed to form a cable (b).

mize the path loss. However, in loop distribution networks, easy cable handling and rapid splicing are essential. Small-diameter cables facilitate handling and installation and factory connectorization allows for rapid splicing.

In 1979, AT&T introduced its first commercially produced optical fiber cable. The cable was based on multi-mode technology. The fibers were packaged into 12 fiber ribbons which were preconnectorized in the factory. The packing density of the ribbon structure was high; as many as 144 fibers could be packaged in a $\frac{1}{2}$ -inch-diameter sheath. The cable sheath was reinforced with steel wire. The features allowed for easy installation and splicing.

The cable has been used extensively by AT&T and the Bell operating companies. During the past seven years, the cable has exhibited excellent optical and mechanical performance in both interoffice trunk and long-haul applications. Late in 1984, ribbon cable technology was extended to include single-mode fiber. Depending on the application, the fibers may be individually spliced or the cable may be factory-connectorized. For path lengths up to about 20 km, single-mode connectorized cable provides fast splicing and installation. This includes more than 90 percent of the

trunks between central offices. In long-haul applications, individual fiber splicing is used to minimize splice loss.

Early in 1985, AT&T began producing a cable design designated as Lightpack™ cable. The fibers are packaged into units which are bound with color-coded binders. A single large-diameter tube is extruded over the entire core. This design provides a rugged, compact, high-performance cable structure with easy fiber access. This paper summarizes the optical and mechanical performance obtained with production ribbon and Lightpack cable.

Ribbon Cable

As illustrated in Figure 1, the lightguide ribbon cable is based on a ribbon which is manufactured by packaging 12 fibers between two adhesive-backed polyester tapes.¹ Up to 12 ribbons may be stacked into a rectangular array for fiber counts as high as 144 per cable. After twisting the ribbon stack to ensure good bending performance, a loose plastic tube is extruded over the core. The tube is filled with a soft water-blocking compound. The filling compound allows for free movement of the ribbons within the core. This loose construction is essential in providing

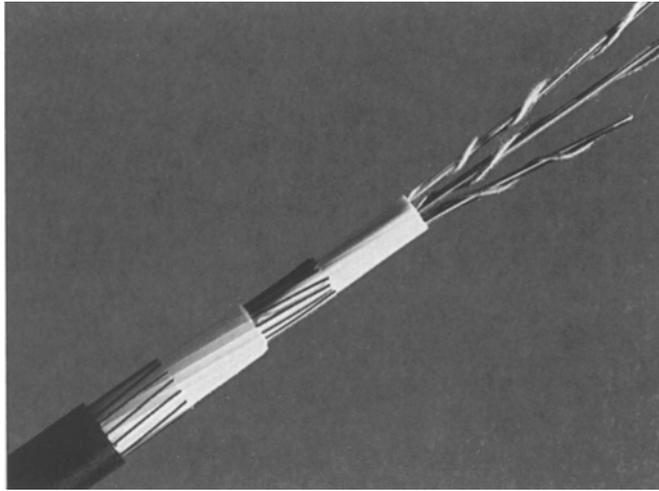


Figure 2. Basic Light-pack™ cable construction.

essary, such as for submarine river crossings. The wire armoring is applied over the standard sheath.

For installations requiring maximum repeater spacing, minimum splice loss is obtained by splicing fibers individually. Within the splice case, each ribbon is handled with the same flexibility as a stranded fiber unit. Simply by peeling apart the polyester tapes, the installer can splice individual fibers by fusion or mechanical techniques. The lowest splice loss is obtained with rotary mechanical splicing, which provides typical mean values less than 0.05 dB.⁴ In most metropolitan and loop installations, where splice loss requirements are less critical, splicing time can be greatly reduced by using factory-connectorized ribbons. Silicon chip array connectors are applied to each ribbon and high-productivity splicing is accomplished by simply joining two arrays together in the field. Twelve fibers are spliced simultaneously. Mean splice loss values of about 0.4 dB have been obtained under a large variety of field conditions.⁵ With array splicing, 144 single-mode fibers can be spliced in less than three hours by craft personnel.

Lightpack Cable

The basic Lightpack cable construction is shown in Figure 2. Up to 12 fibers are assembled in a Lightpack unit or bundle which is identified with a color-coded binder.^{6,7} Several units are then assembled into a cable core. A large-diameter filled tube is extruded over the core. As with the ribbon cable, an essential design feature is the free movement of the fibers in the filling material. This provides low optical loss and excellent mechanical performance. The cable is completed with a reinforced sheath with construction similar to that used for the ribbon cable.

The basic cable with the steel-reinforced sheath is available in two sizes. For 4 through 48 fibers, the diameter and weight are 0.4 inch and 0.08 lb/ft, respectively.

low optical loss. The ribbons are slightly longer than the tube, assuring that the fibers will be stress-free.

Finally, a steel-reinforced high-density polyethylene sheath is applied over the core tube.^{2,3} The cable has an outer diameter of 0.5 inch, a weight of 0.11 lb/ft and a tensile load rating of 600 lb. The steel reinforcing wires are applied helically in two layers with opposite stranding directions providing a torque-balanced cable, i.e., one easy to handle with no twist under tensile load. The helical pitches of the wire layers are set to provide good bending performance.

Complete electromagnetic isolation can be achieved with a nonmetallic sheath. The steel reinforcing wires are replaced with fiber-glass rods. The cable is isolated from lightning strikes as well as accidental crossing of metallic telephone or electric power cables.

Cables are also available with fire-resistant sheaths and heavy-duty wire armoring. In the fire-resistant design, the polyethylene is replaced with a fire-resistant polymer. The cable is used indoors, primarily to connect the outside plant cables to interconnection equipment in the central office. Heavy-duty wire armoring is used where exceptional levels of mechanical protection are nec-

Table I. AT&T Lightguide Cable Mechanical Specifications

Parameter	Cable type (fiber count)	
	Lightpack (4–48)	Lightpack (50–96) Ribbon (4–144)
Diameter, inch	0.4	0.5
Weight, lb/ft	0.08	0.11
Load rating, lb	600	600
Bend radius, inches		
No load	4	5
No load (RL protection)	6	8
Under load	8	10

The cable is the most compact in the industry. For fiber counts from 50 to 96, the sheath is identical to the ribbon cable sheath with an outer diameter of 0.5 inch. Both cable sizes have a 600-lb load rating. Nonmetallic and fire-resistant sheaths and wire armoring are also available.

Splicing options include both factory-installed array chips and individual fiber splicing. With individual fiber splicing, cable preparation is very simple. The end of the cable can be stripped back in about 5 minutes. After exposing and cutting the reinforcing wires with a pair of wire cutters, the core tube is ring-cut. The entire sheath then slides off the core, exposing the fiber units. The color-coded binders provide unit identification. The core design provides easy access to the individual fibers—a particularly important feature in loop-distribution networks.

Mechanical Performance

The most important function of the sheath is to protect the fiber from breakage during installation and while in service. Cables may be pulled into underground ducts, directly plowed or trenched into the ground, or lashed to a support strand in aerial installations. With these varied installation conditions, cables must be designed for a wide range of field conditions.

The three most important physical design param-

Table II. EIA Test Requirements

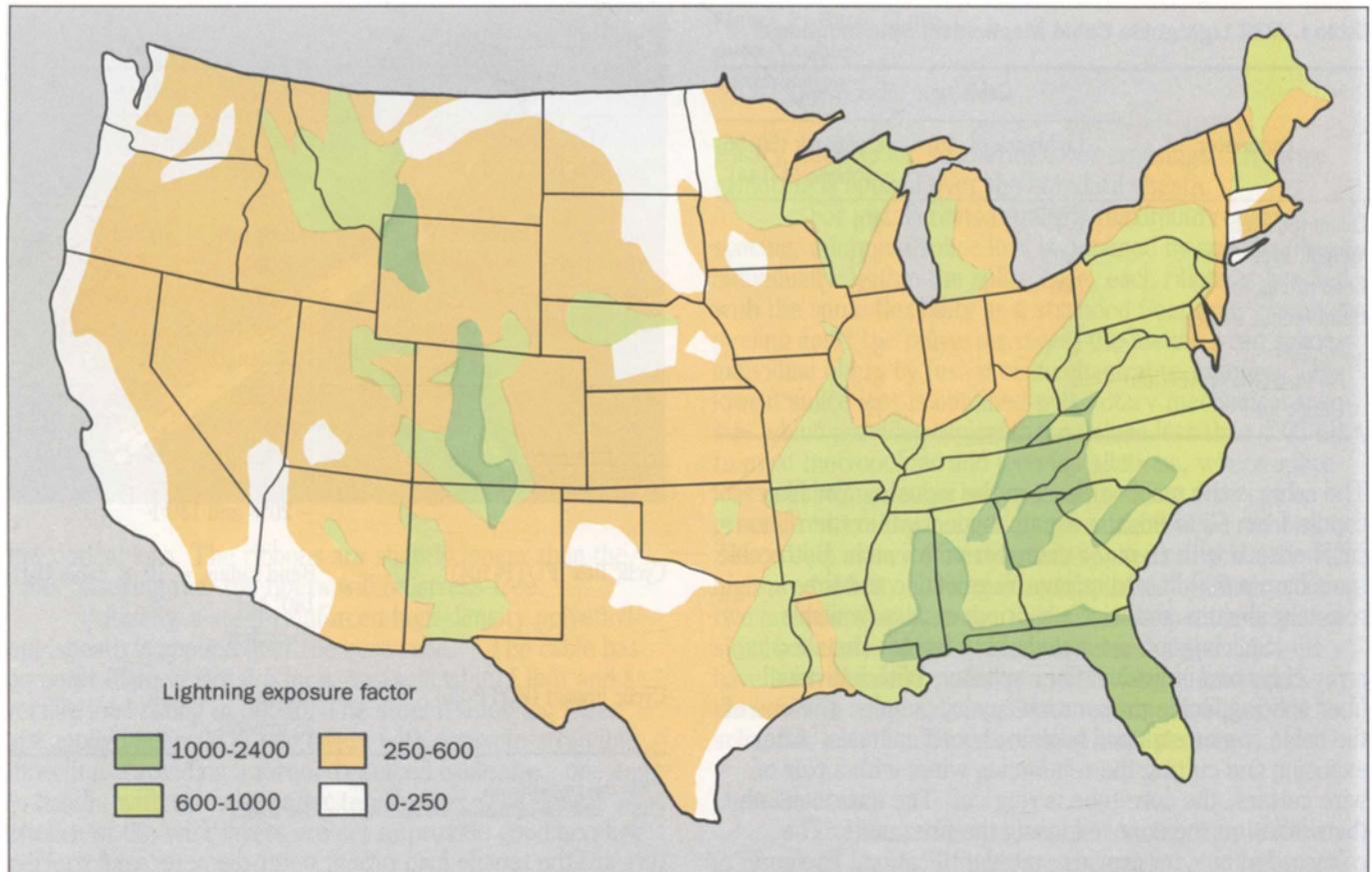
Test	Conditions
Tensile loading and bending (FOTP-33)*	Tensile load = 600 lb Bend radius = 20 × cable OD
Compressive loading (FOTP-41)	Linear load = 1000 lb 4-inch length
Twist (FOTP-85)	± 180° twist 13-ft length 10 cycles
Low- and high-temperature bending (FOTP-37)	Bend radius = 10 × cable OD† Four wraps – 20°F and 140°F
Cyclic flex (FOTP-104)	Bend radius = 10 × cable OD† 180° arc 25 cycles
Cyclic impact (FOTP-25)	Impact = 52 ft-lb 25 impacts

* EIA test procedure.

† 15 × cable OD for rodent- and lightning-protected sheath.

ters are the tensile load rating, outer diameter, and bending radius. The tensile load rating is determined primarily by duct-pulling requirements. For the AT&T cable designs, the small diameters and the 600-lb load ratings provide very high strength-to-weight ratios and allow for easy installation of long cables—up to 3 km under good conditions. These features are also extremely important in the urban environment with congested convoluted duct systems, typical in many of our cities.

The bend radius is determined by the requirements for pulling cable under tension through ducts, manholes and plow chutes. The radius is limited to prevent sheath damage or kinking. Under load, the bend radius



varies from 8 to 10 inches, depending on the cable diameter. The radius of coils for storing slack cable in manholes also must be manageable. For slack cable, the radius varies from 4 to 8 inches. Table I is a summary of the physical specifications of AT&T cable.

Both the ribbon and Lightpack cables have undergone extensive mechanical testing. Standard tests have been developed by the Electronics Industry Association (EIA) to qualify fiber-optic cable designs. These include: tensile loading and bending, compressive loading, twist,

Figure 3. Estimated lightning exposure factor for buried cable in the United States. The factor is defined as the square root of soil resistance times the annual number of thunderstorm days.

low- and high-temperature bending, cyclic flexing, and cyclic impact. In all of these tests, the conditions imposed are much more severe than those expected in the field. A summary of the tests condition is given in Table II.

In the tensile loading and bend test, a 500-ft

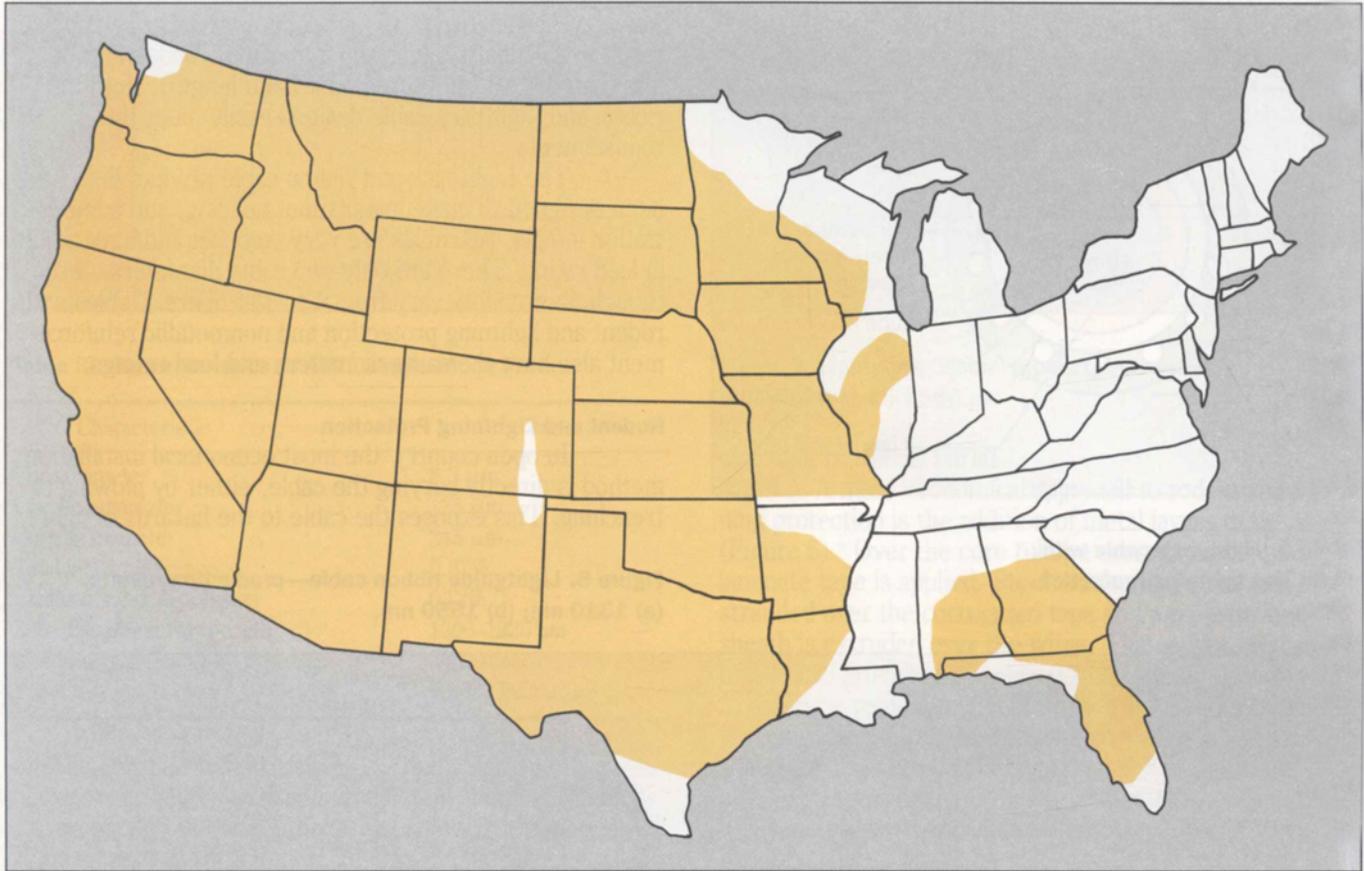


Figure 4. Gopher distribution in the United States. The shaded areas represent regions of high gopher population.

length of test cable is looped around sheaves and subjected to a 600-lb load. The sheave diameter is equal to 20 times the cable diameter. The compression test applies a 1000-lb force over a 4-inch cable length for a 10-minute period. In the twist test, a cable sample with a 13-ft length is rotated $\pm 180^\circ$ about its axis. The cable must endure a minimum of 10 cycles lasting a total time of 10 minutes. The ability

of the cable to endure bending at various temperatures is evaluated in the low- and high-temperature bend test; a cable sample is wrapped four times on a mandrel whose radius is 10 times the diameter of the cable at -20°F and 140°F . In the cyclic flex test, the cable sample is bent around a mandrel with a diameter equal to 10 times the cable diameter. The test is performed at a rate of 30 cycles per minute for a total of 25 cycles. The impact test is performed on a cable sample at the rate of 30 impacts per minute with total of 25 impacts. In all of these Electronic

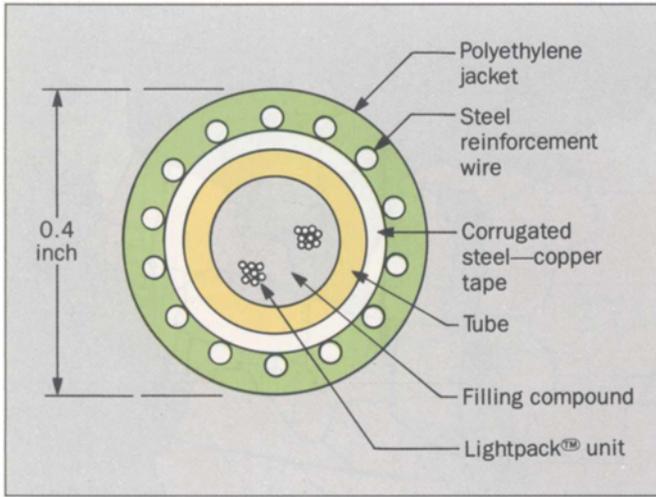


Figure 5. Lightpack cable with rodent and lightning protection.

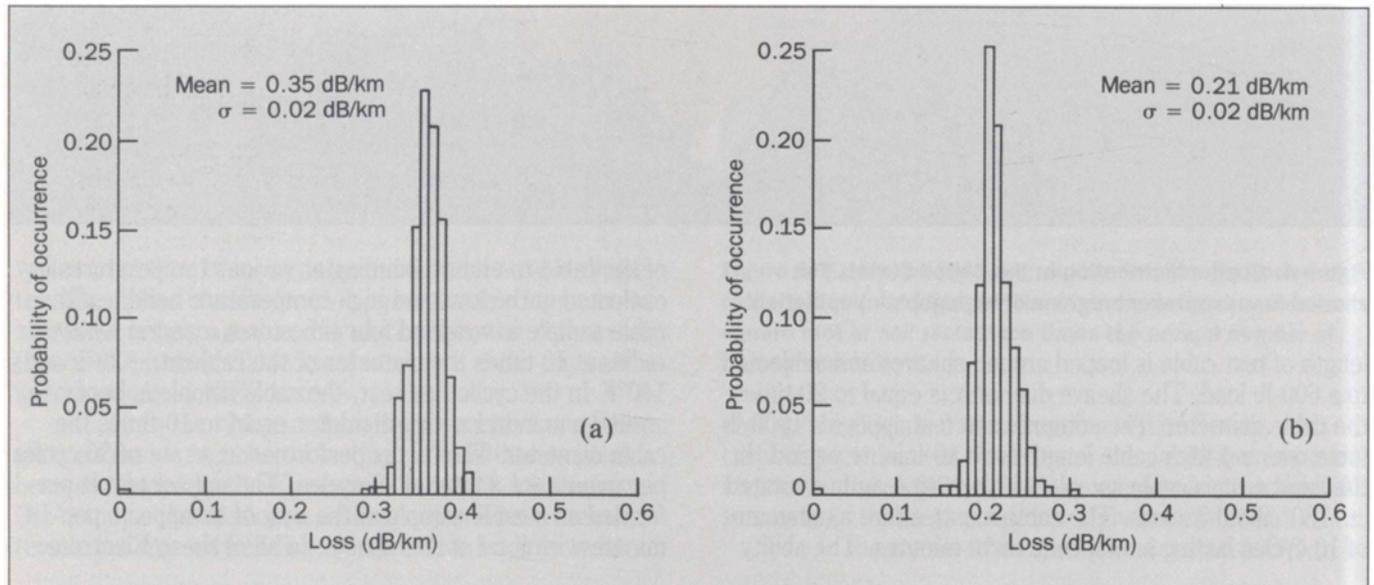
Industry Association (EIA) procedures, testing should result in no sheath failure and a maximum added loss of less than 0.2 dB (measured on a 1-km length). Both the ribbon and Lightpack cable designs easily meet these requirements.

The Lightpack and ribbon cable product lines have been designed to make installation, splicing, and administration simple. All cables are very compact and have a 600-lb load rating. There are only two cable diameters—even though fiber counts vary from 4 to 144 fibers. Cables with rodent and lightning protection and nonmetallic reinforcement also have the same diameters and load ratings.

Rodent and Lightning Protection

In open country, the most economical installation method is directly burying the cable, either by plowing or trenching. This exposes the cable to the hazards of light-

Figure 6. Lightguide ribbon cable—production results. (a) 1310 nm; (b) 1550 nm.



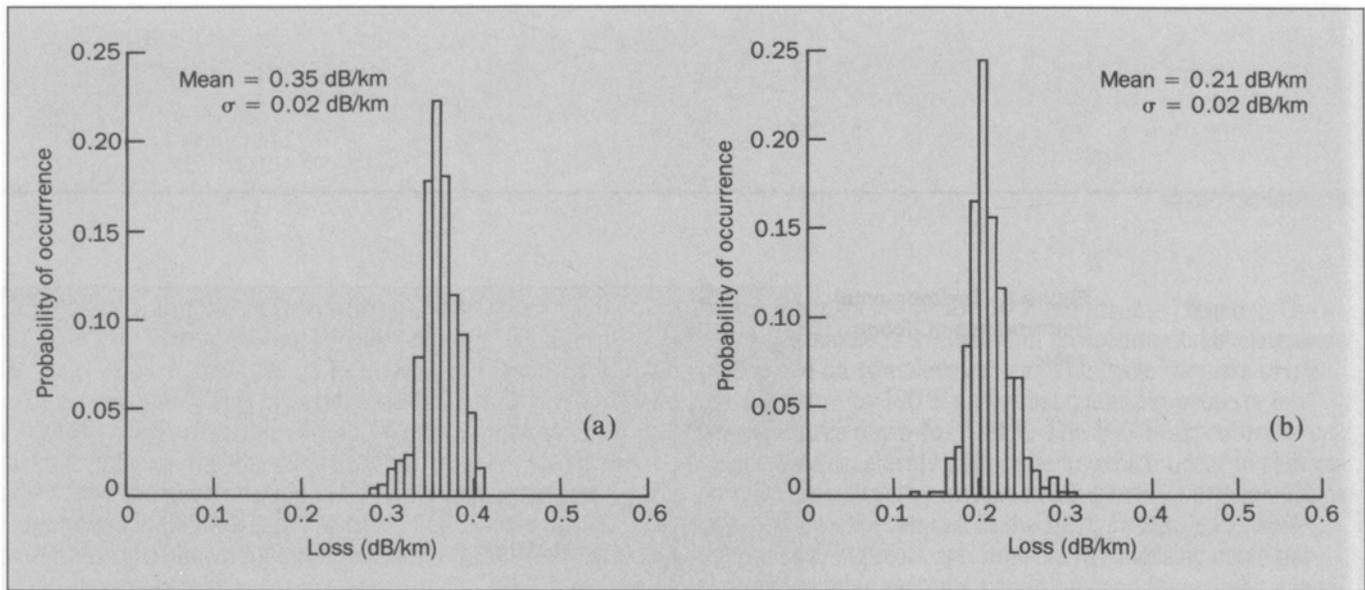


Table III. Characteristics of AT&T Single-Mode Fiber

Characteristic	Value
Core diameter	8.3 μm
Cladding diameter	125 μm
Coating diameter	245 μm
Total index difference	0.37%
Cladding index depression	0.12%
Zero dispersion wavelength	1300–1325 nm
Coating type	Ultraviolet-cured acrylate
Proof test level	50,000 lb/in ²

ning strikes and rodent attack. Lightning damage may occur in any region of the United States, but has the highest probability in the southeast and midwest (Figure 3). Rodent damage is caused by gnawing animals such as squirrels or gophers. Gophers in particular will gnaw right through an unprotected cable. The rodent hazard is also widespread, encompassing all states west of the Mississippi River and sections of Georgia, Florida, and Alabama (Figure 4).

For geographical areas not subject to rodent attack, direct burial of the nonmetallic cable provides excellent lightning protection. However, the cable must be pulled into a large-diameter rigid conduit in rodent-populated areas. A conduit diameter of about 3 inches prevents the rodents from gripping the conduit with their teeth, although then installation cost increases significantly

Figure 7. Lightpack cable—production results. (a) 1310 nm; (b) 1550 nm.

over that for direct burial.

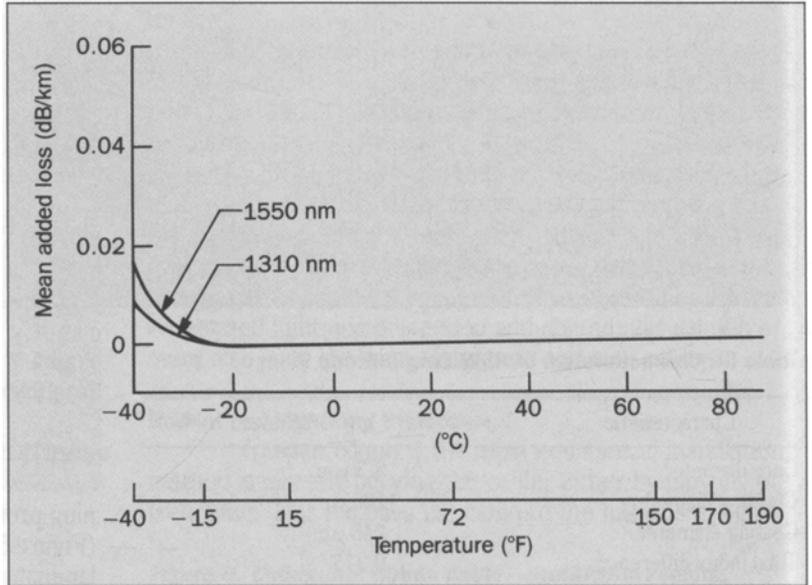
A more economical approach to rodent and lightning protection is the addition of metal layers to the sheath (Figure 5).⁸ Over the core tube, a corrugated copper-steel laminate tape is applied. Steel reinforcing wires are stranded over the corrugated tape and a polyethylene sheath is extruded over the wires. The copper layer is 5 mils thick, providing the electrical conductivity necessary to dissipate peak currents of up to 175 kA. Ninety-nine percent of the expected lightning strikes in the United States have lower peak currents.

The preferred steel for rodent protection is Type 304 stainless with a thickness of 3 mils. Type 304 has excellent resistance to corrosion, which is necessary to maintain protection after repeated rodent attacks. The sheath has been tested for rodent resistance by the Denver Wildlife Research Center, a part of the U.S. Department of Interior's Fish and Wildlife Service. Wild gophers were used in the testing and they were not able to penetrate the metal armor.

Optical Performance

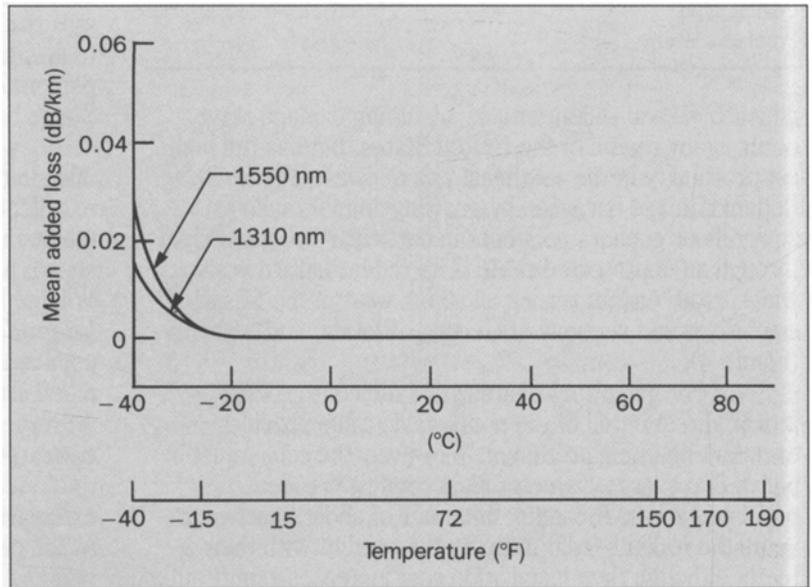
For both the ribbon and Lightpack cable design, extensive experience has been obtained with the standard AT&T depressed-cladding single-mode fiber. The core and cladding diameters are 8.3 μm and 125 μm , respectively.

Figure 8. Environmental performance of ribbon cable.



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Figure 9. Environmental performance of Light-pack cable.



The fiber is optimized for zero dispersion at about 1310 nm. The fibers are dual-coated with an outer diameter of 245 μm . The coating consists of a soft inner layer and a harder outer shell. The materials used in both layers are acrylates which are cured with ultraviolet radiation. The structure buffers the fiber from its environment, particularly at low temperature. The fiber characteristics are summarized in Table III. In Figures 6 and 7, optical loss histograms are shown for production ribbon and Lightpack cable, respectively. Results are presented at both 1310 and 1550 nm. The quantity of cabled fiber represented in Figures 6 and 7 is substantial—2900 km for ribbon and 1000 km for Lightpack cable.

For both designs, the mean cable loss is 0.35 dB/km at 1310 nm with a standard deviation of 0.02 dB/km. The maximum individual fiber loss is 0.4 dB/km. The mean loss and standard deviation at 1550 nm are 0.21 dB/km and 0.02 dB/km, indicating excellent upgrade capability at the longer wavelength. At both wavelengths the loss distributions are tight and the cabling process induces no added loss above the intrinsic fiber loss. The low cable losses are primarily due to the loose construction employed in both designs. With the combination of high-quality cable and low-loss rotary mechanical splicing, repeaterless span lengths between 55 and 60 km are possible. In many applications, particularly short-path-length loop or interoffice trunk systems, higher-loss fiber can be used effectively. For those short-path applications, customers may specify more typical mean loss values of 0.4 to 0.5 dB/km and 0.25 to 0.3 dB/km at 1310 and 1550 nm, respectively.

Environmental Stability

Cables in service experience daily and seasonal temperature variations. The effect of such variations on cable optical performance is a very important design consideration. For cables installed in underground ducts or directly buried in the ground, the temperature range is small, typically 20 to 90°F. The temperature range is much greater in aerial plant, -15 to 150°F for most regions of

the country and -40 to 170°F in extreme climates. Optical performance is evaluated in environmental cycling tests performed on complete cables. The cycle consists of a 5-day exposure to 190°F and subsequent exposure to low temperatures down to -40 °F. The 190°F exposure is selected to accelerate aging effects which occur in service and the entire cycle provides much more severe conditions than will be experienced in the field. Hence, extensive thermal cycling tests are valuable in assessing cable performance under extreme conditions and in evaluating long-term performance and product quality.

Environmental test results for a 48-fiber single-mode ribbon cable are shown in Figure 8. At both 1310 and 1550 nm, the mean loss change is very small, less than 0.02 dB/km, over the entire temperature range. The data show that the microbending sensitivity is slightly greater at 1550 nm as compared to 1310 nm. The increased sensitivity at 1550 nm is expected from theoretical considerations, since the optical power is less tightly bound to the core at the longer wavelength. For any individual fiber, there is no change in loss above about -15 °F. Below -15 °F, the acrylate fiber coating materials stiffen, which can result in microbending loss. In Figure 9, test results are shown for 72-fiber Lightpack cable. The results are similar to those for the ribbon cable. Above -15 °F, there is no temperature-dependent loss increase and below -15 °F, the mean increases are quite small, less than about 0.03 dB/km at 1550 nm and -40 °F.

Another important consideration in material selection and cable design is hydrogen gas generation. Hydrogen gas generated by aging or corrosion of lightguide cable materials may enter the optical fibers, causing an increase in attenuation. For example, a combination of materials to be avoided in cable construction is aluminum and steel since they can generate hydrogen by electrolytic corrosion. No hydrogen is generated with the copper-steel laminate used in the rodent lightning sheath. Other materials to be avoided are certain silicone fiber coating compounds. They can degrade with aging, forming hydrogen as a by-product.

In the AT&T cable designs, the problem of hydrogen gas release has been eliminated through material selection. Individual materials and complete cables have been tested by accelerated aging. Their behavior has also been verified with extensive long-term field experience.⁹

Conclusion

High-quality single-mode optical cable is manufactured by AT&T in both ribbon and Lightpack designs. Lightpack cable is particularly well suited for low to moderate fiber counts, while the ribbon cable is optimized for moderate to high fiber counts. Both cables are extremely compact, rugged, and easy to handle. A complete line of sheath designs is optimized to meet customer needs; they include features such as steel or nonmetallic reinforcement, rodent and lightning protection, fire-resistant sheaths, and heavy-duty wire armoring. The cables have low loss at 1310 and 1550 nm and excellent environmental stability. Individual fiber splicing or mass splicing using factory-installed silicon array connectors may be used with either design. Both cables have been used extensively with excellent results in underground ducts, buried plant, and aerial installations. Applications include long-haul, interoffice trunk, and loop distribution networks.

Acknowledgments

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