CHAPTER 3

OPTICAL FIBERS AND CABLES

LEARNING OBJECTIVES

Upon completion of this chapter, you should be able to do the following:

1. Describe multimode and single mode step-index and graded-index fibers.
2. Explain the terms refractive index profile, relative refractive index difference, and profile parameter.
3. List the performance advantages of 62.5/125 μm multimode graded-index fibers.
4. Identify the two basic types of single mode step-index fibers.
5. Describe the vapor phase oxidation and direct-melt optical fiber fabrication procedures.
6. Describe the fiber drawing process.
7. List the benefits of cabled optical fibers over bare fibers.
8. Identify the basic cable components, such as buffers, strength members, and jacket materials.
9. Describe the material and design requirements imposed on military fiber optic cable designs.
10. Describe the advantages and disadvantages of OFCC cable, stranded cable, and ribbon cable designs.

OPTICAL FIBER AND CABLE DESIGN

Optical fibers are thin cylindrical dielectric (non-conductive) waveguides used to send light energy for communication. Optical fibers consist of three parts: the core, the cladding, and the coating or buffer. The choice of optical fiber materials and fiber design depends on operating conditions and intended application. Optical fibers are protected from the environment by incorporating the fiber into some type of cable structure. Cable strength members and outer jackets protect the fiber. Optical cable structure and material composition depend on the conditions of operation and the intended application.

OPTICAL FIBERS

Chapter 2 classified optical fibers as either single mode or multimode fibers. Fibers are classified according to the number of modes that they can propagate. Single mode fibers can propagate only the fundamental mode. Multimode fibers can propagate hundreds of modes. However, the classification of an optical fiber depends on more than the number of modes that a fiber can propagate.

An optical fiber's refractive index profile and core size further distinguish single mode and multimode fibers. The **refractive index profile** describes the value of refractive index as a function of radial distance at any fiber diameter. Fiber refractive index profiles classify single mode and multimode fibers as follows:

- Multimode step-index fibers
- Multimode graded-index fibers
- Single mode step-index fibers
- Single mode graded-index fibers

In a **step-index** fiber, the refractive index of the core is uniform and undergoes an abrupt change at the core-cladding boundary. Step-index fibers obtain their name from this abrupt change called the step change in refractive index. In **graded-index** fibers, the refractive index of the core varies gradually as a function of radial distance from the fiber center.

Single mode and multimode fibers can have a step-index or graded-index refractive index profile. The performance of multimode graded-index fibers is usually superior to multimode step-index fibers. However, each type of multimode fiber can improve system design and operation depending on the intended application. Performance advantages for single mode graded-index fibers compared to single mode step-index fibers are relatively small. Therefore, single mode fiber production is almost exclusively step-index. Figure 3-1 shows the refractive index profile for a multimode step-index fiber and a multimode graded-index fiber. Figure 3-1 also shows the refractive index profile for a single mode step-index fiber. Since light propagates differently in each fiber type, figure 3-1 shows the propagation of light along each fiber.

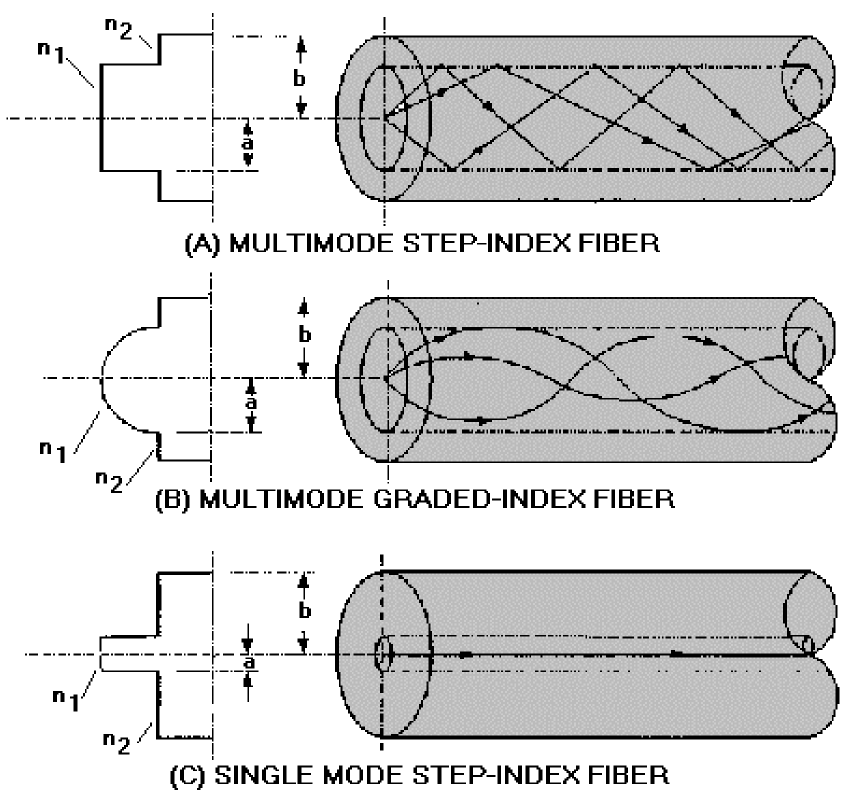


Figure 3-1.—The refractive index profiles and light propagation in multimode step-index, multimode graded-index, and single mode step-index fibers.

In chapter 2, you learned that fiber core size and material composition can affect system performance. A small change in core size and material composition affects fiber transmission properties, such as attenuation and dispersion. When selecting an optical fiber, the system designer decides which fiber core size and material composition is appropriate.

Standard core sizes for multimode step-index fibers are 50 μm and 100 μm. Standard core sizes for multimode graded-index fibers are 50 μm, 62.5 μm, 85 μm, and 100 μm. Standard core sizes for single mode fibers are between 8 μm and 10 μm. In most cases, the material used in the preparation of optical fibers is high-quality glass (SiO_2). This glass contains very low amounts of impurities, such as water or elements other than silica and oxygen. Using high-quality glass produces fibers with low losses. Small amounts of some elements other than silica and oxygen are added to the glass material to change its index of refraction. These elements are called material dopants. Silica doped with various materials forms the refractive index profile of the fiber core and material dopants are discussed in more detail later in this chapter. Glass is not the only material used in fabrication of optical fibers. Plastics are also used for core and cladding materials in some applications.

A particular optical fiber design can improve fiber optic system performance. Each single mode or multimode, step-index or graded-index, glass or plastic, or large or small core fiber has an intended application. The system designer must choose an appropriate fiber design that optimizes system performance in his application.

Q1. Describe the term "refractive index profile."

Q2. The refractive index of a fiber core is uniform and undergoes an abrupt change at the core-cladding boundary. Is this fiber a step-index or graded-index fiber?

Q3. Multimode optical fibers can have a step-index or graded-index refractive index profile. Which fiber, multimode step-index or multimode graded-index fiber, usually performs better?

Q4. List the standard core sizes for multimode step-index, multimode graded-index, and single mode fibers.

MULTIMODE STEP-INDEX FIBERS

A multimode step-index fiber has a core of radius (a) and a constant refractive index n_1. A cladding of slightly lower refractive index n_2 surrounds the core. Figure 3-2 shows the refractive index profile n(r) for this type of fiber. n(r) is equal to n_1 at radial distances $r < a$ (core). n(r) is equal to n_2 at radial distances $r \geq a$ (cladding). Notice the step decrease in the value of refractive index at the core-cladding interface. This step decrease occurs at a radius equal to distance (a). The difference in the core and cladding refractive index is the parameter Δ:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

Δ is the **relative refractive index difference.**

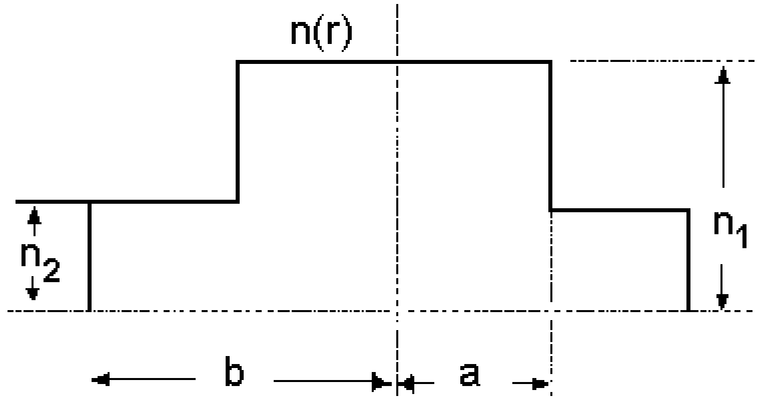


Figure 3-2.—The refractive index profile for multimode step-index fibers.

The ability of the fiber to accept optical energy from a light source is related to Δ. Δ also relates to the numerical aperture by

$$NA \simeq n_1\sqrt{2\Delta}.$$

The number of modes that multimode step-index fibers propagate depends on Δ and core radius (a) of the fiber. The number of propagating modes also depends on the wavelength (λ) of the transmitted light. In a typical multimode step-index fiber, there are hundreds of propagating modes.

Most modes in multimode step-index fibers propagate far from cutoff. Modes that are cut off cease to be bound to the core of the fiber. Modes that are farther away from the cutoff wavelength concentrate most of their light energy into the fiber core. Modes that propagate close to cutoff have a greater percentage of their light energy propagate in the cladding. Since most modes propagate far from cutoff, the majority of light propagates in the fiber core. Therefore, in multimode step-index fibers, cladding properties, such as cladding diameter, have limited affect on mode (light) propagation.

Multimode step-index fibers have relatively large core diameters and large numerical apertures. A large core size and a large numerical aperture make it easier to couple light from a light-emitting diode (LED) into the fiber. Multimode step-index fiber core size is typically 50 µm or 100 µm. Unfortunately, multimode step-index fibers have limited bandwidth capabilities. Dispersion, mainly modal dispersion, limits the bandwidth or information-carrying capacity of the fiber. System designers consider each factor when selecting an appropriate fiber for each particular application.

Multimode step-index fiber selection depends on system application and design. Short-haul, limited bandwidth, low-cost applications typically use multimode step-index fibers.

Q5. Multimode step-index fibers have a core and cladding of constant refractive index n_1 and n_2, respectively. Which refractive index, the core or cladding, is lower?

Q6. In multimode step-index fibers, the majority of light propagates in the fiber core for what reason?

Q7. Multimode step-index fibers have relatively large core diameters and large numerical apertures. These provide what benefit?

MULTIMODE GRADED-INDEX FIBERS

A multimode graded-index fiber has a core of radius (a). Unlike step-index fibers, the value of the refractive index of the core (n_1) varies according to the radial distance (r). The value of n_1 decreases as the distance (r) from the center of the fiber increases. The value of n_1 decreases until it approaches the value of the refractive index of the cladding (n_2). The value of n_1 must be higher than the value of n_2 to allow for proper mode propagation. Like the step-index fiber, the value of n_2 is constant and has a slightly lower value than the maximum value of n_1. The relative refractive index difference (Δ) is determined using the maximum value of n_1 and the value of n_2.

Figure 3-3 shows a possible refractive index profile n(r) for a multimode graded-index fiber. Notice the parabolic refractive index profile of the core. The **profile parameter** (α) determines the shape of the core's profile. As the value of α increases, the shape of the core's profile changes from a triangular shape to step as shown in figure 3-4. Most multimode graded-index fibers have a parabolic refractive index profile. Multimode fibers with near parabolic graded-index profiles provide the best performance. Unless otherwise specified, when discussing multimode graded-index fibers, assume that the core's refractive index profile is parabolic (α=2).

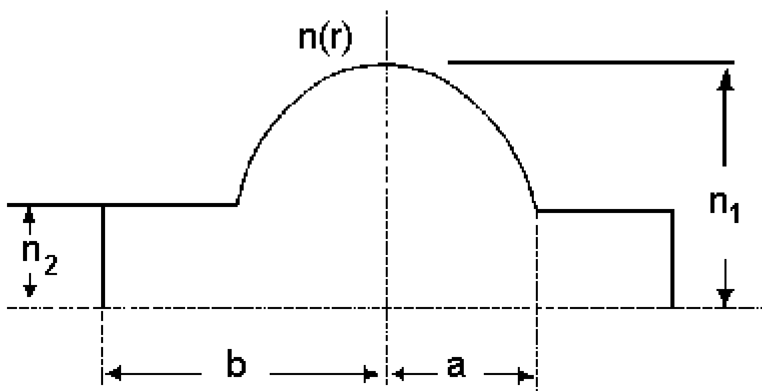


Figure 3-3.—The refractive index profile for multimode graded-index fibers.

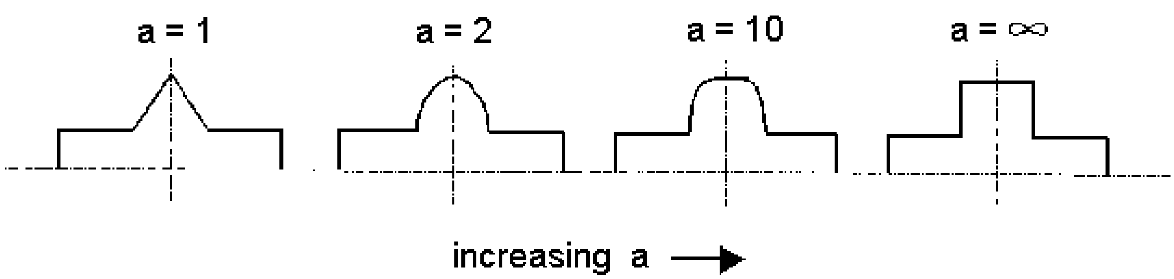


Figure 3-4.—The refractive index profiles for different values of α.

Light propagates in multimode graded-index fibers according to refraction and total internal reflection. The gradual decrease in the core's refractive index from the center of the fiber causes the light rays to be refracted many times. The light rays become refracted or curved, which increases the angle of incidence at the next point of refraction. Total internal reflection occurs when the angle of incidence becomes larger than the critical angle of incidence. Figure 3-5 shows the process of refraction and total internal reflection of light in multimode graded-index fibers. Figure 3-5 also illustrates the boundaries of different values of core refractive index by dotted lines. Light rays may be reflected to the axis of the fiber before reaching the core-cladding interface.

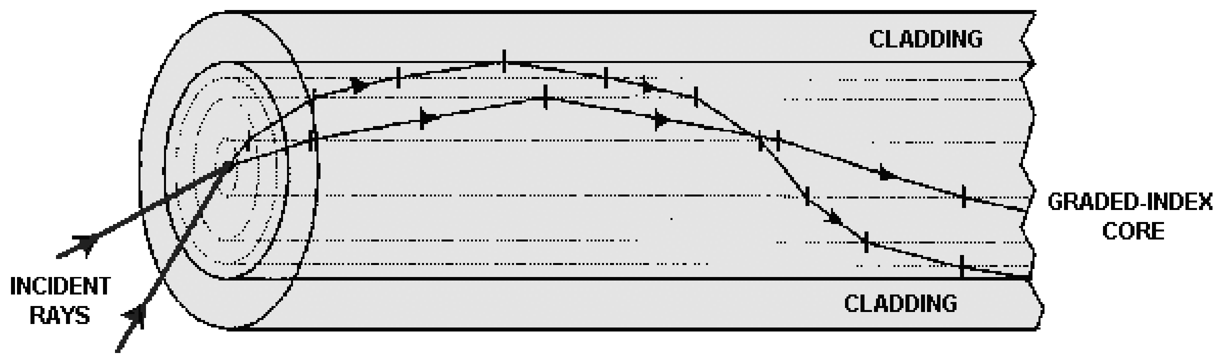


Figure 3-5.—Refractive index grading and light propagation in multimode graded-index fibers.

The NA of a multimode graded-index fiber is at its maximum value at the fiber axis. This NA is the **axial numerical aperture [NA(0)]**. NA(0) is approximately equal to

$$n_1\sqrt{2\Delta}\ .$$

However, the NA for graded-index fibers varies as a function of the radial distance (r). NA varies because of the refractive index grading in the fiber's core. The NA decreases from the maximum, NA(0), to zero at distances greater than the core-cladding boundary distance (r>a). The NA, relative refractive index difference (Δ), profile parameter (α), and normalized frequency (V) determine the number of propagating modes in multimode graded-index fibers. A multimode graded-index fiber with the same normalized frequency as a multimode step-index fiber will have approximately one-half as many propagating modes. However, multimode graded-index fibers typically have over one-hundred propagating modes.

Multimode graded-index fibers accept less light than multimode step-index fibers with the same core Δ. However, graded-index fibers usually outperform the step-index fibers. The core's parabolic refractive index profile causes multimode graded-index fibers to have less modal dispersion.

Figure 3-5 shows possible paths that light may take when propagating in multimode graded-index fibers. Light rays that travel farther from the fiber's axis travel a longer distance. Light rays that travel farther from the center travel in core material with an average lower refractive index.

In chapter 2, you learned that light travels faster in a material with a lower refractive index. Therefore, those light rays that travel the longer distance in the lower refractive index parts of the core travel at a greater average velocity. This means that the rays that travel farther from the fiber's axis will arrive at each point along the fiber at nearly the same time as the rays that travel close to the fiber's axis. The decrease in time difference between light rays reduces modal dispersion and increases multimode graded-index fiber bandwidth. The increased bandwidth allows the use of multimode graded-index fibers in most applications.

Most present day applications that use multimode fiber use graded-index fibers. The basic design parameters are the fiber's core and cladding size and Δ. Standard multimode graded-index fiber core and cladding sizes are 50/125 μm, 62.5/125 μm, 85/125 μm, and 100/140 μm. Each fiber design has a specific

Δ that improves fiber performance. Typical values of Δ are around 0.01 to 0.02. Although no single multimode graded-index fiber design is appropriate for all applications, the 62.5/125 μm fiber with a Δ of 0.02 offers the best overall performance.

A multimode graded-index fiber's source-to-fiber coupling efficiency and insensitivity to microbending and macrobending losses are its most distinguishing characteristics. The fiber core size and Δ affect the amount of power coupled into the core and loss caused by microbending and macrobending. Coupled power increases with both core diameter and Δ, while bending losses increase directly with core diameter and inversely with Δ. However, while these values favor high Δs, a smaller Δ improves fiber bandwidth. In most applications, a multimode graded-index fiber with a core and cladding size of 62.5/125 μm offers the best combination of the following properties:

- Relatively high source-to-fiber coupling efficiency
- Low loss
- Low sensitivity to microbending and macrobending
- High bandwidth
- Expansion capability

For example, local area network (LAN) and shipboard applications use multimode graded-index fibers with a core and cladding size of 62.5/125 μm. In LAN-type environments, macrobend and microbend losses are hard to predict. Cable tension, bends, and local tie-downs increase macrobend and microbend losses. In shipboard applications, a ship's cable-way may place physical restrictions, such as tight bends, on the fiber during cable plant installation. The good microbend and macrobend performance of 62.5/125 μm fiber permits installation of a rugged and robust cable plant. 62.5/125 μm multimode graded-index fibers allow for uncomplicated growth because of high fiber bandwidth capabilities for the expected short cable runs on board ships.

Q8. The profile parameter (α) determines the shape of the multimode graded-index core's refractive index profile. As the value of the α increases, how does the core's profile change?

Q9. Light propagates in multimode graded-index fibers according to refraction and total internal reflection. When does total internal reflection occur?

Q10. What four fiber properties determine the number of modes propagating in a multimode graded-index fiber?

Q11. Light travels faster in a material with a lower refractive index. Therefore, light rays that travel a longer distance in a lower refractive index travel at a greater average velocity. What effect does this have on multimode graded-index fiber modal dispersion and bandwidth?

Q12. What multimode graded-index fiber offers the best overall performance for most applications?

Q13. What are the most distinguishing characteristics of a multimode graded-index fiber?

Q14. How are source-to-fiber coupling and microbending and macrobending losses affected by changes in core diameter and Δ?

Q15. While coupled power and bending loss favor a high Δ, which Δ value, smaller or larger, improves fiber bandwidth?

SINGLE MODE STEP-INDEX FIBERS

There are two basic types of single mode step-index fibers: matched clad and depressed clad. **Matched cladding** means that the fiber cladding consists of a single homogeneous layer of dielectric material. **Depressed cladding** means that the fiber cladding consists of two regions: the inner and outer cladding regions. Matched-clad and depressed-clad single mode step-index fibers have unique refractive index profiles.

A matched-clad single mode step-index fiber has a core of radius (a) and a constant refractive index n_1. A cladding of slightly lower refractive index surrounds the core. The cladding has a refractive index n_2. Figure 3-6 shows the refractive index profile n(r) for the matched-clad single mode fiber.

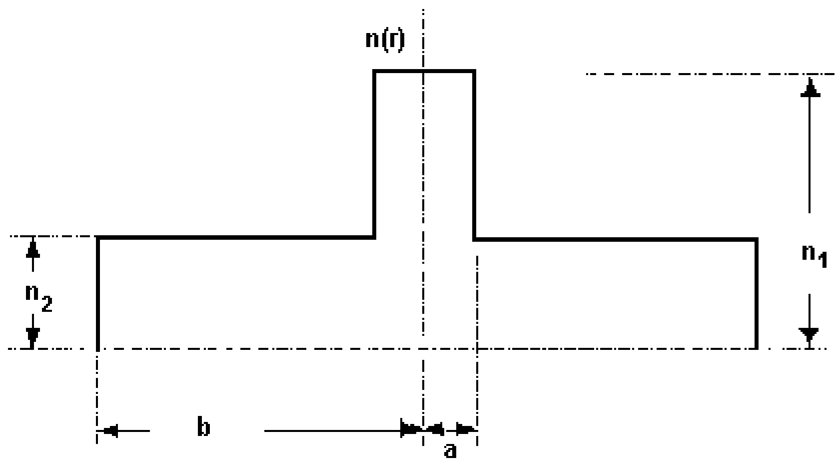


Figure 3-6.—Matched-clad refractive index profile.

Figure 3-7 shows the refractive index profile n(r) for the depressed-clad single mode fiber. A depressed-clad single mode step-index fiber has a core of radius (a) with a constant refractive index n_1. A cladding, made of two regions, surrounds the core. An inner cladding region surrounds the core of the fiber and has a refractive index of n_2. The inner cladding refractive index n_2 is lower than the core's refractive index n_1. An outer cladding region surrounds the inner cladding region and has a higher refractive index n_3 than the inner cladding region. However, the outer cladding refractive index n_3 is lower than the core's refractive index n_1.

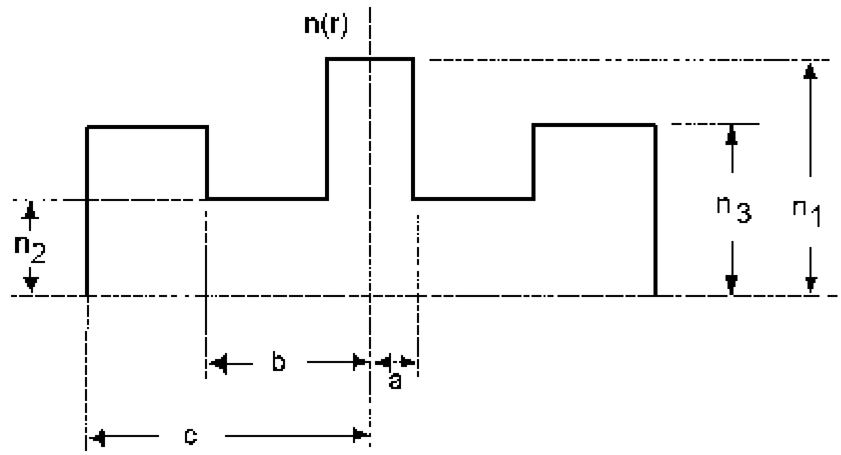


Figure 3-7.—Depressed-clad refractive index profile.

Single mode step-index fibers propagate only one mode, called the fundamental mode. Single mode operation occurs when the value of the fiber's normalized frequency is between 0 and 2.405 ($0 \leq V < 2.405$). The value of V should remain near the 2.405 level. When the value of V is less than 1, single mode fibers carry a majority of the light power in the cladding material. The portion of light transmitted by the cladding material easily radiates out of the fiber. For example, light radiates out of the cladding material at fiber bends and splices.

Single mode fiber cutoff wavelength is the smallest operating wavelength when single mode fibers propagate only the fundamental mode. At this wavelength, the 2nd-order mode becomes lossy and radiates out of the fiber core. As the operating wavelength becomes longer than the cutoff wavelength, the fundamental mode becomes increasingly lossy. The higher the operating wavelength is above the cutoff wavelength, the more power is transmitted through the fiber cladding. As the fundamental mode extends into the cladding material, it becomes increasingly sensitive to bending loss. Single mode fiber designs include claddings of sufficient thickness with low absorption and scattering properties to reduce attenuation of the fundamental mode. To increase performance and reduce losses caused by fiber bending and splicing, fiber manufacturers adjust the value of V. To adjust the value of V, they vary the core and cladding sizes and relative refractive index difference (Δ).

A single mode step-index fiber has low attenuation and high bandwidth properties. Present applications for single mode fibers include long-haul, high-speed telecommunication systems. Future applications include single mode fibers for sensor systems. However, the current state of single mode technology makes installation of single mode systems expensive and difficult. Short cable runs, low to moderate bandwidth requirements, and high component cost make installation of single mode fiber shipboard systems impractical at this time.

Q16. What are the two basic types of single mode step-index fibers?

Q17. Which fiber cladding, matched or depressed, consists of two regions?

Q18. In single mode operation, the value of the normalized frequency (V) should remain near the 2.405 level. If the value of V is less than 1, do single mode fibers carry a majority of the power in the core or cladding material?

Q19. What happens to the fundamental mode as the operating wavelength becomes longer than the single mode cutoff wavelength?

Q20. Give two reasons why the value of the normalized frequency (V) is varied in single mode step-index fibers?

SINGLE MODE GRADED-INDEX FIBERS

There are several types of single mode graded-index fibers. These fibers are not standard fibers and are typically only used in specialty applications. Information on single mode graded-index fibers can be found in the references in appendix 2.

FIBER ALTERNATIVES

In most applications, the standard multimode and step-index single mode optical fibers mentioned before have significant performance advantages over conventional copper-based systems. However, performance requirements and cost restraints may prohibit the use of these fibers in certain applications. Fiber manufacturers modify standard multimode and single mode fiber material composition and structural design to meet these additional requirements. Optical fiber design can depart from a traditional circular core and cladding, low-loss glass design. The intent of each change is to increase performance and reduce cost.

Optical fibers composed of plastic have been in use longer than glass fibers. Types of standard fibers using plastics include multimode step-index and graded-index fibers. Multimode step-index and graded-index **plastic clad silica** (PCS) fibers exist. PCS fibers have a silica glass core and a plastic cladding. Normally, PCS fibers are cheaper than all-glass fibers but have limited performance characteristics. PCS fibers lose more light through a plastic cladding than a glass cladding.

Multimode step-index fibers may also have a plastic core and cladding. All-plastic fibers have a higher NA, a larger core size, and cost less to manufacture. However, all-plastic fibers exhibit high loss in the thousands of decibels per kilometer. This high loss is caused by impurities and intrinsic absorption. PCS and all-plastic fibers are used in applications typically characterized by one or all of the following:

- High NA
- Low bandwidth
- Tight bend radius
- Short length (less than 10m to 20m)
- Low cost

Improved fabrication techniques provide the opportunity to experiment with material composition in both multimode and single mode fibers. Fiber manufacturers fabricate optical fibers using glass material whose characteristics improve system performance in the far infrared region. Fiber manufacturers add dopant material to reduce fiber loss and limit material and structural imperfections. Fiber material used in fabrication of low-loss, long wavelength optical fibers include the following:

- Heavy-metal fluorides (such as zirconium and beryllium fluoride)
- Chalcogenide glasses (such as arsenic/sulfur)
- Crystalline materials (such as silver bromide and silver chloride)

In shipboard applications, stringent environmental requirements dictate the design of special optical fibers. In some cases, manufacturers hermetically coat optical fibers to increase survivability and reliability in high-moisture and high-strain environments. Manufacturers also design radiation-hard fibers for nuclear power, space, and military systems. Radiation resistant fibers operate after exposure to nuclear radiation. Shipboard system performance requirements determine whether the use of hermetic and radiation resistant fibers or less costly commercial optical fibers is necessary.

Q21. Give two reasons why optical fiber manufacturers depart from the traditional circular core and cladding, low-loss glass fiber design?

Q22. What five characteristics do applications using plastic clad silica (PCS) and all-plastic fibers typically have?

Q23. List the types of materials used in fabricating low-loss, long wavelength optical fibers.

FABRICATION OF OPTICAL FIBERS

Basically, fiber manufacturers use two methods to fabricate multimode and single mode glass fibers. One method is vapor phase oxidation, and the other method is direct-melt process. In **vapor phase oxidation**, gaseous metal halide compounds, dopant material, and oxygen are oxidized (burned) to form a white silica powder (SiO_2). Manufacturers call SiO_2 the **soot**. Manufacturers deposit the soot on the surface of a glass substrate (mandrel) or inside a hollow tube by one of the following three methods:

- Outside Vapor Phase Oxidation (OVPO).
- Inside Vapor Phase Oxidation (IVPO).
- Vapor Phase Axial Deposition (VAD).

The soot forms the core and cladding material of the preform. The refractive index of each layer of soot is changed by varying the amount of dopant material being oxidized. Figures 3-8, 3-9, and 3-10 illustrate the different vapor phase oxidation preform preparation methods.

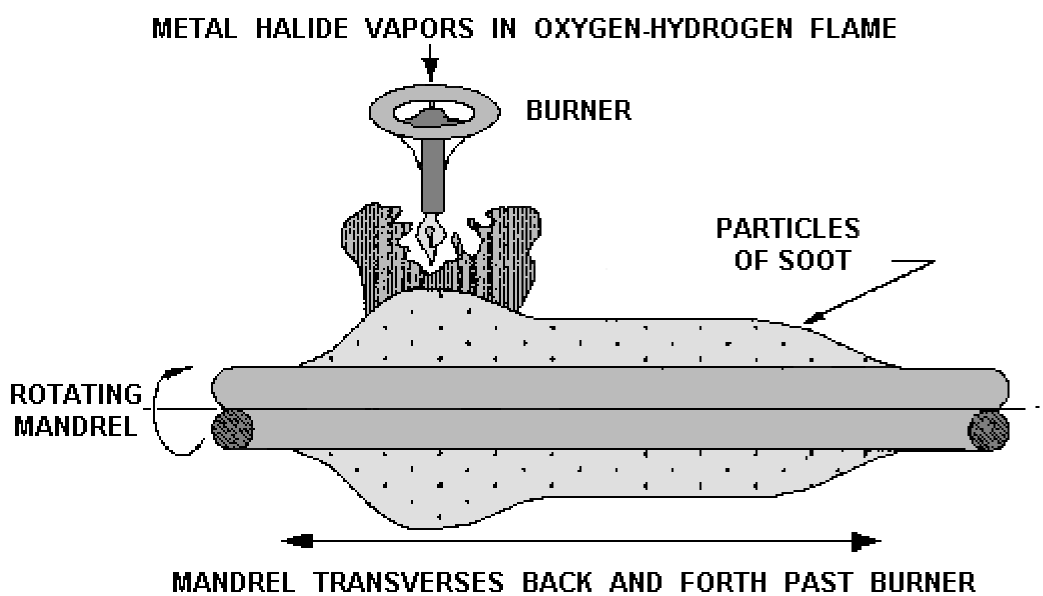


Figure 3-8.—OVPO preform preparation.

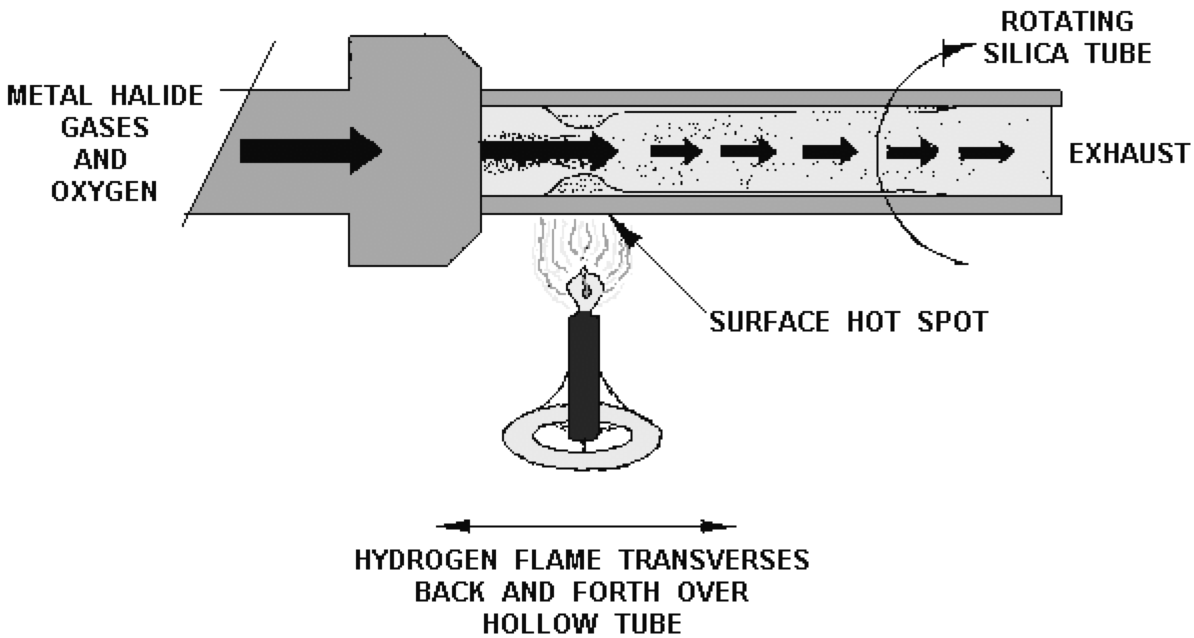


Figure 3-9.—IVPO preform preparation.

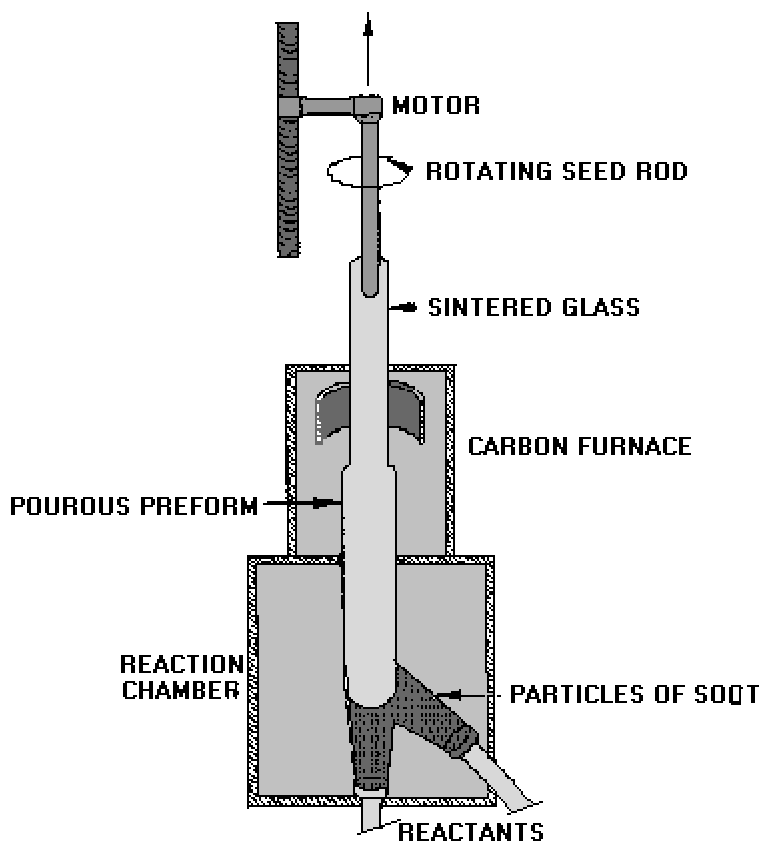


Figure 3-10.—VAD preform preparation.

During vapor phase oxidation, the mandrel or tube continuously moves from side to side and rotates while soot particles are deposited on the surface. This process forms cylindrical layers of soot on the surface of the mandrel or inside the hollow tube. This deposited material is transformed into a solid glass preform by heating the porous material (without melting). The solid preform is then drawn or pulled into an optical fiber by a process called fiber drawing.

The fiber drawing process begins by feeding the glass preform into the drawing furnace. The drawing furnace softens the end of the preform to the melting point. Manufacturers then pull the softened preform into a thin glass filament (glass fiber). To protect the bare fiber from contaminants, manufacturers add an acrylate coating in the draw process. The coating protects the bare fiber from contaminants such as atmospheric dust and water vapor. Figure 3-11 illustrates the process of drawing an optical fiber from the preform.

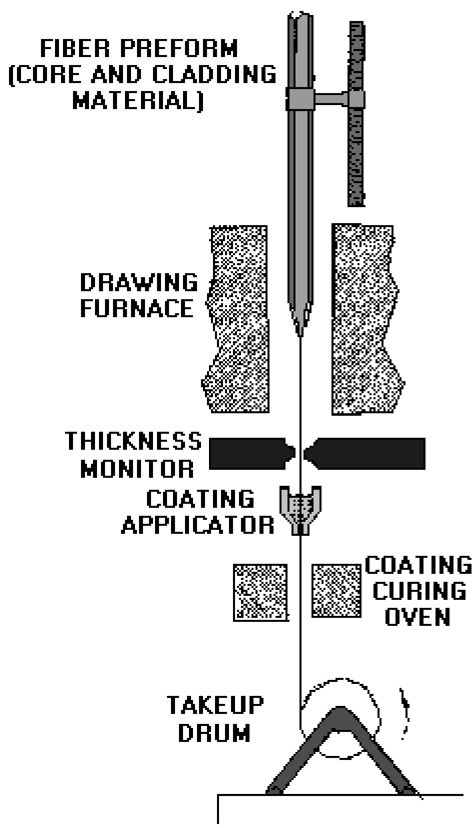


Figure 3-11.—Fiber drawing process.

In the **direct-melt process**, multicomponent glass rods form the fiber structure. Rods of multicomponent glass combine in a molten state to form the fiber core and cladding. The double-crucible method is the most common direct-melt process. The double-crucible method combines the molten rods into a single preform using two concentric crucibles. Optical fibers are drawn from this molten glass using a similar fiber drawing process as in vapor phase oxidation. Figure 3-12 illustrates the double-crucible drawing process.

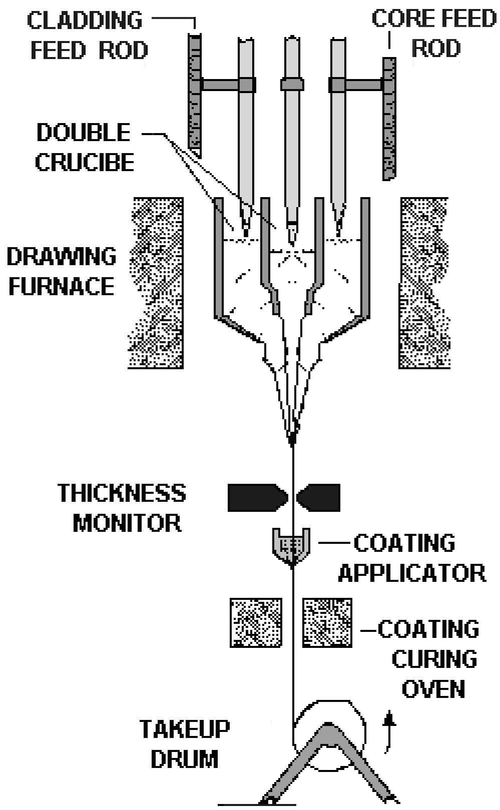


Figure 3-12.—Double-crucible fiber drawing process.

Q24. What are the two methods used by fiber manufacturers to fabricate multimode and single mode glass fibers?

Q25. Which method, vapor phase oxidation or direct-melt process, transforms deposited material into a solid glass preform by heating the porous material without melting?

OPTICAL CABLES

Optical fibers have small cross sectional areas. Without protection, optical fibers are fragile and can be broken. The optical cable structure protects optical fibers from environmental damage. Cable structure includes buffers, strength members, and jackets. Many factors influence the design of fiber optic cables. The cable design relates to the cable's intended application. Properly designed optical cables perform the following functions:

- Protect optical fibers from damage and breakage during installation and over the fiber's lifetime.
- Provide stable fiber transmission characteristics compared with uncabled fibers. Stable transmission includes stable operation in extreme climate conditions.
- Maintain the physical integrity of the optical fiber by reducing the mechanical stresses placed on the fiber during installation and use. Static fatigue caused by tension, torsion, compression, and bending can reduce the lifetime of an optical fiber.

Navy applications require that fiber optic cables meet stringent design specifications. Fiber optic cables must be rugged to meet the optical, environmental, and mechanical performance requirements imposed by Navy systems. Critical system downtime caused by cable failure cannot be tolerated. However, in commercial applications, the requirements imposed on cable designs are not as stringent. Each additional requirement imposed on the fiber optic cable design adds to its cost. Cost is always a main consideration of cable designers in commercial applications. Cost is also considered in Navy applications, but system reliability is the main goal.

Q26. List three benefits that properly cabled optical fibers provide.

FIBER BUFFERS

Coatings and buffers protect the optical fiber from breakage and loss caused by microbends. During the fiber drawing process, the addition of a primary coating protects the bare glass from abrasions and other surface contaminants. For additional protection, manufacturers add a layer of buffer material. The buffer material provides additional mechanical protection for the fiber and helps preserve the fiber's inherent strength.

Manufacturers use a variety of techniques to buffer optical fibers. The types of fiber buffers include tight-buffered, loose-tube, and gel-filled loose-tube. Figure 3-13 shows each type of fiber buffer. The choice of buffering techniques depends on the intended application. In large fiber count commercial applications, manufacturers use the loose-tube buffers. In commercial building and Navy applications, manufacturers use tight buffers.

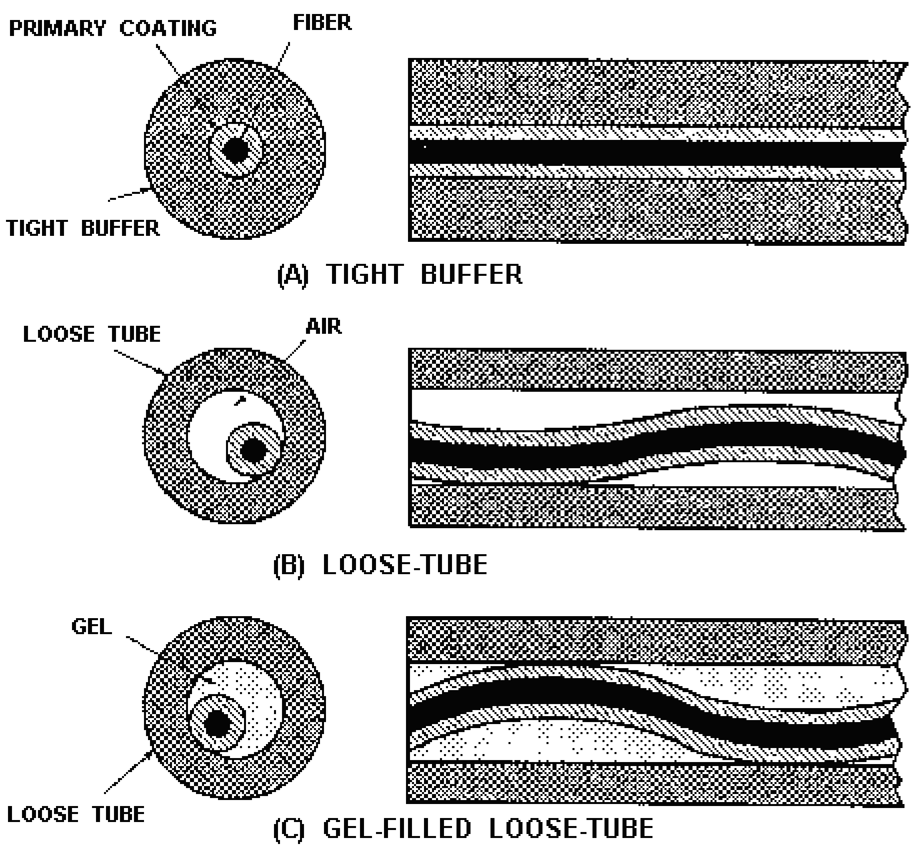


Figure 3-13.—Tight-buffered, loose-tube, and gel-filled loose-tube buffer techniques.

Q27. In addition to a primary coating, manufacturers add a layer of buffer material for what reasons?

Q28. List the three techniques used by manufacturers to buffer optical fibers.

CABLE STRENGTH AND SUPPORT MEMBERS

Fiber optic cables use strength members to increase the cables' strength and protect the fiber from strain. Fiber optic cables may use central support members in cable construction. The central support members generally have buffered fibers or single fiber sub-cables stranded over their surface in a structured, helical manner. The central members may support the optical fibers as cable strength members or may only serve as fillers. Strength and support members must be light and flexible. In commercial applications, the materials used for strength and support include steel wire and textile fibers (such as nylon and arimid yarn). They also include carbon fibers, glass fibers, and glass reinforced plastics. For Navy applications, only non-metallic strength and support members are allowed.

CABLE JACKET, OR SHEATH, MATERIAL

The jacket, or sheath, material provides extra environmental and mechanical protection. Jacket materials for Navy cables have the following properties:

- Low smoke generation
- Low toxicity
- Low halogen content
- Flame retardance
- Fluid resistance
- High abrasion resistance
- Stable performance over temperature

It is difficult to produce a material compound that satisfies every requirement without being too costly. Originally, the production of fire retardant cables included the use of halogenated polymers and additives. These fire retardant cables were also highly toxic. Commercial jacket materials currently used include polyethylene, polyvinyl chloride (PVC), polyurethane, and polyester elastomers. Most commercial jacket materials are unsuitable for use in Navy applications. Researchers have developed jacket materials that are suitable for Navy use.

Q29. List seven properties cable jackets should have.

CABLE DESIGNS

Manufacturers design fiber optic cables for specific applications. Is the cable buried underground or hung from telephone poles? Is the cable snaked through cableways, submerged in water, or just laid on the ground? Is the cable used in industrial, telecommunication, utility, or military applications? Each different application may require a slightly different cable design.

Agreement on standard cable designs is difficult. Cable design choices include jacket materials, water blocking techniques, and the number of fibers to place within the cable. The cable design chosen depends on the cable's intended application. There are presently many types of fiber optic cables. Some fiber optic cables are used in commercial applications, while others are used in military applications.

Standard commercial cable designs will develop over time as fiber optic technology becomes more established. However, this chapter provides only a short discussion on cable designs considered for Navy applications.

Navy systems require that fiber optic cables meet stringent environmental conditions. The types of cable designs considered by the Navy include the optical fiber cable component (OFCC), stranded, and ribbon cable designs. The cable must meet minimal levels of performance in safety (low smoke, low toxicity, low halogen content, etc.), durability (able to withstand shock, vibration, fluids, etc.), and optical performance. The cable must also be easy to install and repair. These factors greatly influence the design of the cables.

Optical Fiber Cable Component (OFCC) Cable

An OFCC cable consists of individual single fiber cables, called **optical fiber cable components (OFCCs)**. OFCCs are a tight-buffered fiber surrounded by arimid yarn and a low-halogen outer jacket. The OFCC outer diameter is typically 2 millimeters (mm). The fiber is typically buffered with a polyester elastomer to a total diameter of 900 μm. Figure 3-14 illustrates the design of the OFCCs. The size of the OFCCs limits the amount of fibers contained within an OFCC cable. An OFCC cable generally contains less than 36 fibers (OFCCs). An OFCC cable of 0.5-inch cable outer diameter can accommodate about 12 fibers.

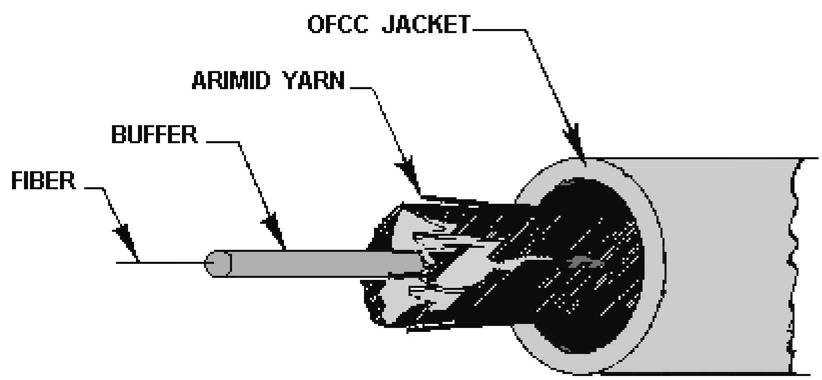


Figure 3-14.—The design of optical fiber cable components (OFCCs).

Figure 3-15 shows an isometric view of a four-fiber shipboard OFCC cable. In this multifiber cable design, the OFCCs surround a flexible central member in a helical manner. The central member may add to cable strength or only support the OFCCs. For additional protection, two layers of arimid yarn strength members encase the OFCC units. These strength members are stranded in opposing lays to minimize microbending of the fibers. The arimid yarn strength members may be treated with polymers that are water absorbing, blocking, and sealing. This treatment eliminates the need for additional water blocking protection. Finally, a low-halogen, flame-resistant outer jacket is extruded over the strength members.

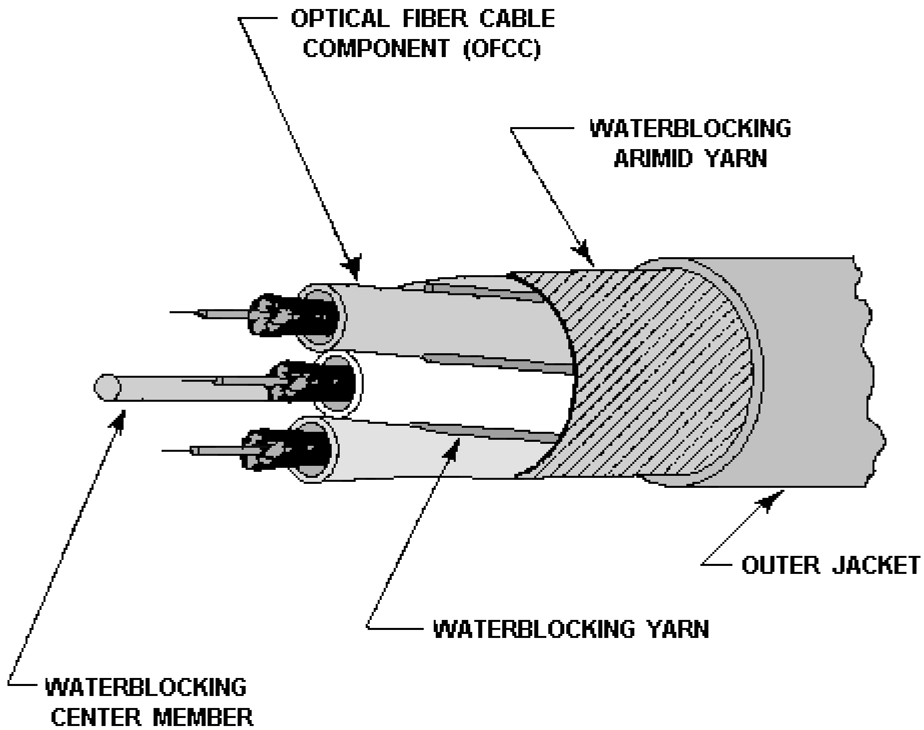


Figure 3-15.—An isometric view of a four-fiber shipboard OFCC cable.

OFCC cables are easy to handle because each cable contains its own subcable, the OFCC. These OFCC subcables make it easy to reconfigure systems and handle individual fibers. Rugged OFCC cable design permits cable use in harsh environments, including Navy applications. OFCC-type cable is recommended for use in low-density (less than 24 fibers) Navy applications. OFCC-type cable is also being evaluated for use in Navy applications with fiber counts up to 36 fibers.

Stranded Cable

A stranded cable is a fiber optic cable consisting of buffered fibers stranded down the center of the cable surrounded by strength members and a protective jacket. Figure 3-16 shows a cross-sectional view of the stranded cable. The fiber is typically buffered with a polyester elastomer to a total diameter of 900 μm. The recommended use of stranded cables is in medium-density (24 to 72 fibers) Navy applications. However, this recommendation is preliminary. Further test and evaluation of prototype stranded cable designs is continuing. Final approval of the stranded cable will occur only after prototype cables have passed all tests.

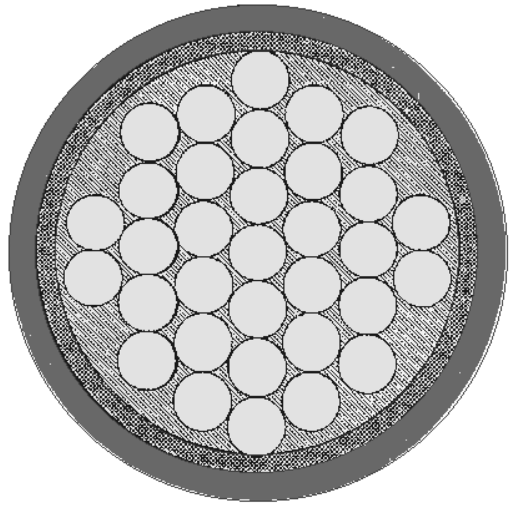


Figure 3-16.—Stranded cable design.

Stranded cable designs increase fiber counts without greatly increasing cable size. Stranded cables are used when fiber counts exceed the limits of OFCC-type cables. For example, the stranded cable design can accommodate about 48 fibers in a O.5-inch cable. The OFCC cable design can accommodate around 12 fibers. The individual fiber is not protected as well in the stranded design as in the OFCC design. For this reason more care is required in handling the individual fibers in the stranded design. The primary problem of the stranded cable design is in meeting the waterblocking requirements. Once manufacturers correct this design problem, the Navy expects that the stranded cable design will meet Navy performance requirements.

Ribbon Cable

A ribbon cable consists of optical fiber ribbons stranded down the center of the cable surrounded by a protective tube, strength members, and an outer jacket. The fiber optic ribbon consists of multiple-coated, 250 ∝m diameter fibers sandwiched in a plastic material. Figure 3-17 shows a cross-sectional view of a 12-fiber ribbon. Cable manufacturers stack these ribbons to form a rectangular cross-sectional array of fibers. Stacked ribbons are the basic building blocks of the ribbon cable. Figure 3-18 illustrates this cross-sectional array of ribbons. Manufacturers introduce a controlled twist to the stacked ribbons to minimize fiber stress when the cable is bent. An inner plastic tube, strength members, and an outer protective jacket surround the stacked ribbons, providing environmental protection.

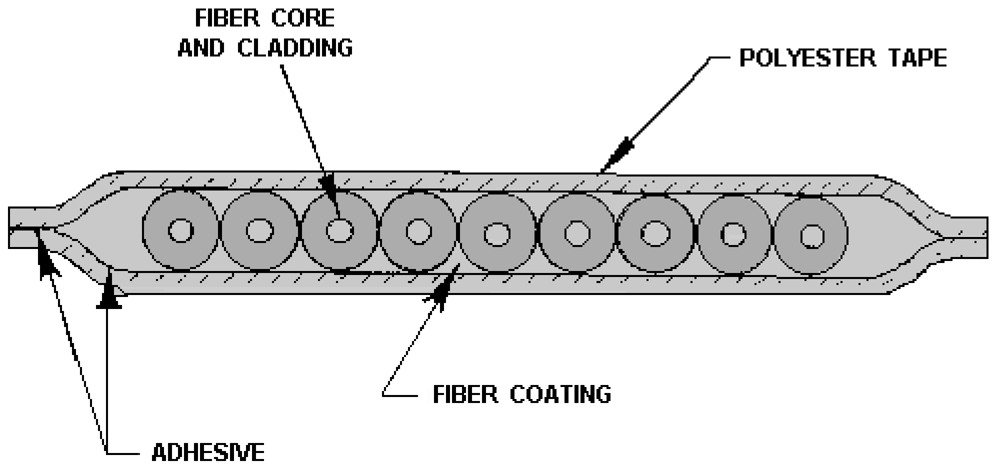


Figure 3-17.—Cross section of a fiber optic ribbon.

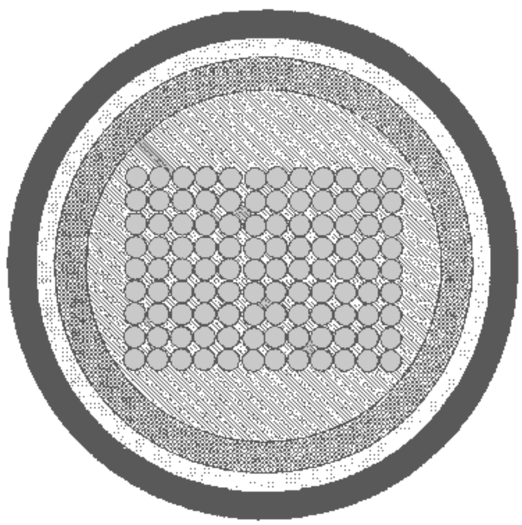


Figure 3-18.—Ribbon cable cross-sectional array of fibers.

The ribbon cable design has the highest fiber capacity. Ribbon cables can hold 204 fibers in a 0.5-inch cable. However, ribbon cables have worse bend performance than OFCC and stranded cables. Ribbon cables also have the poorest waterblocking capabilities of the three cable designs. The bend performance is expected to worsen if manufacturers add appropriate compounds to increase waterblocking capabilities.

Ribbon cables are also hard to handle. Individual fibers are highly susceptible to damage when separated from the ribbon. This susceptibility to fiber damage during fiber breakout makes it necessary to perform multifiber connections. Multifiber connections can introduce single points of failure in multiple systems. The use of multifiber terminations also introduces maintenance, reconfiguration, and repair problems. Currently, the Navy does not recommend the use of ribbon cables in shipboard systems.

Q30. List the three types of cable designs being considered by the Navy.

Q31. Describe an optical fiber cable component (OFCC).

Q32. Two layers of arimid yarn strength members encase the OFCC units. Why are these strength members stranded in opposing directions?

Q33. Why do cable manufacturers introduce a controlled twist to the stacked ribbons during the cabling process?

Q34. OFCC, stranded, and ribbon cables have different fiber capacities. What is the approximate number of fibers that each cable can accommodate in a 0.5-inch cable?

Q35. Which fiber optic cable (OFCC, stranded, or ribbon) has the worst bend performance?

SUMMARY

Now that you have completed this chapter, let's review some of the new terms, concepts, and ideas that you have learned. You should have a thorough understanding of these principles before moving on to chapter 4.

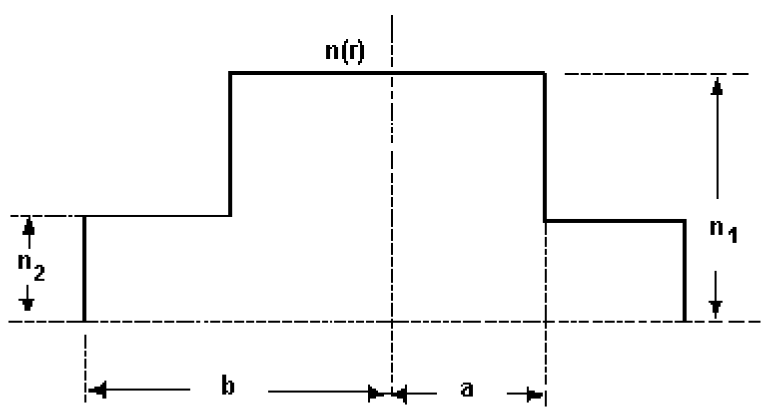
OPTICAL FIBER CLASSIFICATION depends on more than the number of modes that a fiber can propagate. The optical fiber's refractive index profile and core size further distinguish different types of single mode and multimode fibers.

The **REFRACTIVE INDEX PROFILE** describes the value of the fiber's refractive index as a function of axial distance at any fiber diameter.

In **STEP-INDEX** fibers, the refractive index of the core is uniform and undergoes an abrupt change at the core-cladding boundary.

In **GRADED-INDEX** fibers, the refractive index of the core varies gradually as a function of radial distance from the fiber center.

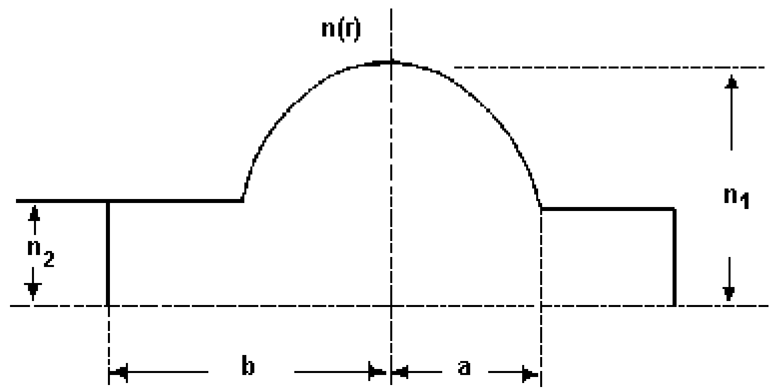
MULTIMODE STEP-INDEX FIBERS have a core of radius (a), and a constant refractive index n_1. A cladding of slightly lower refractive index n_2 surrounds the core.



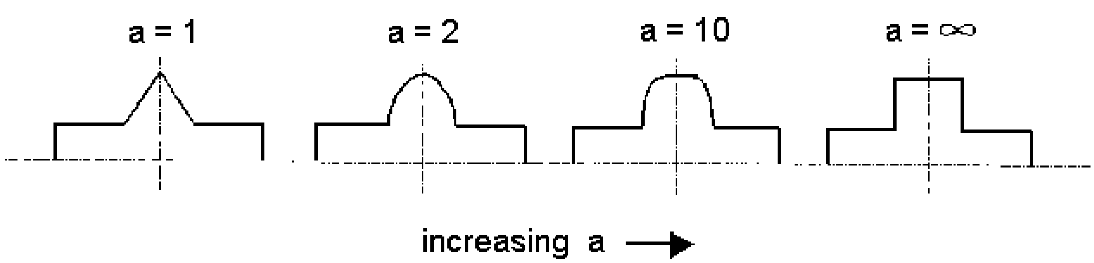
The **RELATIVE REFRACTIVE INDEX DIFFERENCE (Δ)** is the difference in the core and cladding refractive index. The ability of the fiber to accept optical energy from a light source is related to Δ.

MULTIMODE STEP-INDEX FIBERS have relatively large core diameters and large numerical apertures. Unfortunately, multimode step-index fibers have limited bandwidth capabilities and poor bend performance. Short-haul, limited bandwidth, low-cost applications use multimode step-index fibers.

MULTIMODE GRADED-INDEX FIBERS have a core of radius (a). Unlike step-index fibers, the value of the refractive index of the core (n_1) varies according to the radial distance (r). The value of n_1 decreases until it approaches the value of the refractive index of the cladding (n_2). Like the step-index fiber, the value of n_2 is constant and has a slightly lower refractive index than n_1.



The **PROFILE PARAMETER** (α) determines the shape of the core's refractive index profile. As the value of α increases, the shape of the core's profile changes from a triangular shape to a step.



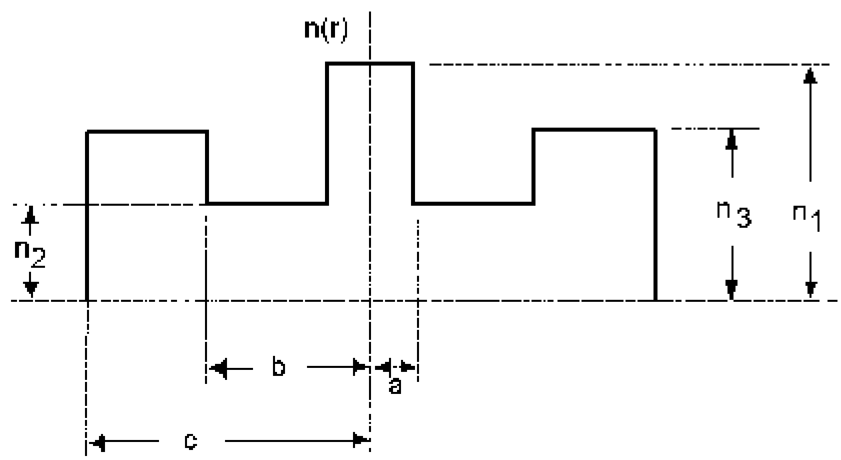
The gradual decrease in the core's refractive index from the center of the fiber causes propagating modes to be refracted many times.

Multimode graded-index fibers have less **MODAL DISPERSION** than multimode step-index fibers. Lower modal dispersion means that multimode graded-index fibers have higher bandwidth capabilities than multimode step-index fibers.

SOURCE-TO-FIBER COUPLING EFFICIENCY and **INSENSITIVITY TO MICROBENDING AND MACROBENDING LOSSES** are distinguishing characteristics of multimode graded-index fibers. 62.5 μm fibers offer the best overall performance for multimode graded-index fibers.

Coupled power increases with both core diameter and Δ, while bending losses increase directly with core diameter and inversely with Δ. However, a smaller Δ improves fiber bandwidth.

MATCHED-CLAD and **DEPRESSED-CLAD** are two types of single mode step-index fibers. Matched cladding means that the fiber cladding is a single homogeneous layer of dielectric material. Depressed cladding means that the fiber cladding consists of two regions: an inner and outer cladding region.



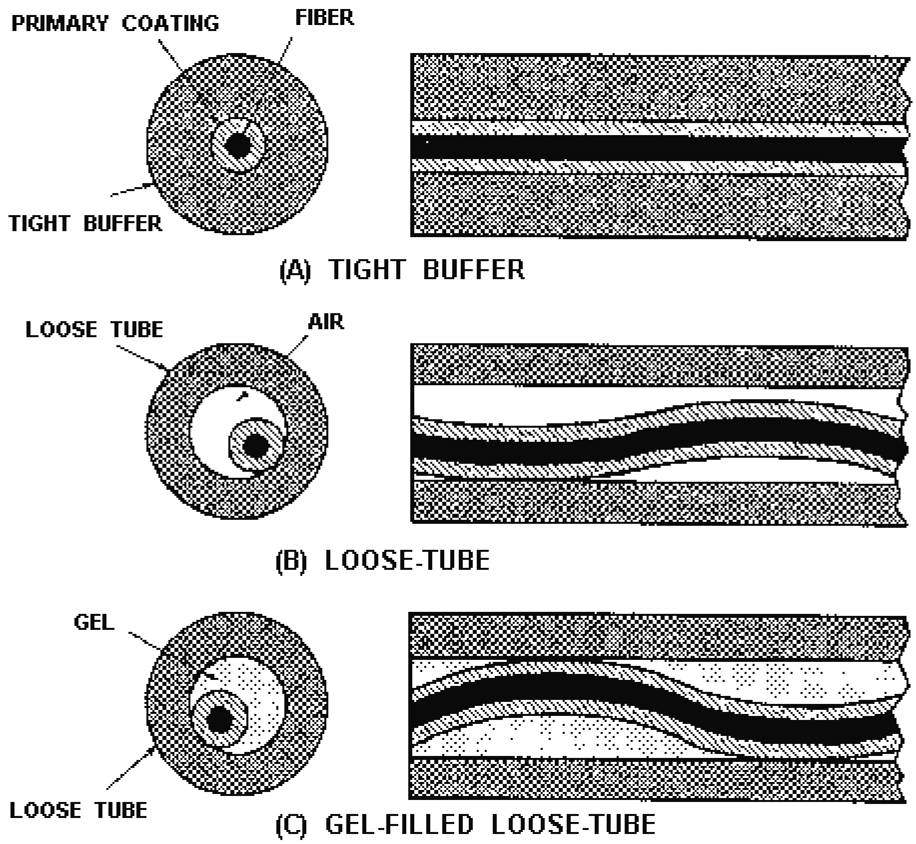
SINGLE MODE FIBER CUTOFF WAVELENGTH is the smallest operating wavelength where single mode fibers propagate only the fundamental mode. At this wavelength, the 2nd-order mode becomes lossy and radiates out of the fiber core.

SINGLE MODE FIBERS have low attenuation and high-bandwidth properties. Present applications for single mode fibers include long-haul, high-speed telecommunication systems.

VAPOR PHASE OXIDATION and **DIRECT-MELT PROCESS** are two methods of fabricating multimode and single mode optical fibers.

CABLE STRUCTURES include buffers, strength members, and the jacket, or sheath.

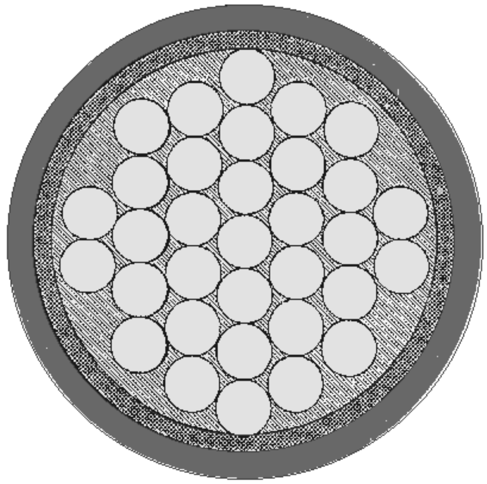
TIGHT-BUFFERED, **LOOSE-TUBE**, and **GEL-FILLED LOOSE-TUBE** are types of fiber optic buffering techniques.



FIBER OPTIC CABLES use strength members to increase the cable's strength and protect the optical fibers from strain.

JACKET MATERIAL should have low smoke generation, low toxicity, low-halogen content, flame retardance, fluid resistance, high abrasion resistance, and stable performance over temperature.

Navy systems require that fiber optic cables meet stringent environmental conditions. The types of cable designs considered by the Navy include the **OPTICAL FIBER CABLE COMPONENT (OFCC)**, **STRANDED**, and **RIBBON** cable designs.



ANSWERS TO QUESTIONS Q1. THROUGH Q35.

A1. *Refractive index profile describes the value of refractive index as a function of radial distance at any fiber diameter.*

A2. *Step-index.*

A3. *Multimode graded-index fiber.*

A4. *Multimode step-index fibers: 50 μm and 100 μm. Multimode graded-index fibers: 50 μm, 62.5 μm, 85 μm, and 100 μm. Single mode fibers: between 8 μm and 10 μm.*

A5. *Cladding.*

A6. *Most modes in multimode step-index fibers propagate far from cutoff.*

A7. *Make it easier to couple light from a light-emitting diode (LED) into the fiber.*

A8. *From a triangular shape to step.*

A9. *When the angle of incidence becomes larger than the critical angle of incidence.*

A10. *Numerical aperture (NA), relative refractive index difference (Δ), profile parameter (α), and normalized frequency (V).*

A11. *Decreases the time difference between light rays, which reduces modal dispersion and increases fiber bandwidth.*

A12. *62.5/125 μm multimode graded-index fiber.*

A13. *Source-to-fiber coupling efficiency and insensitivity to microbending and macrobending losses.*

A14. *Coupling efficiency increases with both core diameter and Δ, while bending losses increase directly with core diameter and inversely with Δ.*

A15. *Smaller.*

A16. Matched-clad and depressed-clad.

A17. Depressed.

A18. Cladding material.

A19. The fundamental mode becomes increasingly lossy.

A20. To increase performance and reduce losses caused by bending and splicing.

A21. To increase performance and reduce cost.

A22. High NA, low bandwidth, tight bend radius, short length, and low cost.

A23. Heavy-metal fluorides, chalcogenide glasses, and crystalline materials.

A24. Vapor phase oxidation and direct-melt process.

A25. Vapor phase oxidation.

A26.

- *a. Protect optical fibers from damage or breakage during installation and over the fiber's lifetime.*
- *b. Provide stable fiber transmission characteristics compared with uncabled fibers.*
- *c. Maintain the physical integrity of the optical fiber.*

A27. To provide additional mechanical protection and preserve the fiber's inherent strength.

A28. Tight-buffered, loose-tube, and gel-filled loose-tube.

A29. Low smoke generation, low toxicity, low halogen content, flame retardance, fluid resistance, high abrasion resistance, and stable performance over temperature.

A30. Optical fiber cable component (OFCC), stranded, and ribbon cables designs.

A31. OFCCs are tight-buffer fiber surrounded by arimid yarn and a low-halogen outer jacket.

A32. To minimize microbending of the fibers.

A33. To minimize fiber stress when the cable is bent.

A34. OFCC (12 fibers), stranded (48 fibers), ribbon (204 fibers).

A35. Ribbon.