Fiber Optic Cable Assemblies for Space Flight Applications:
Issues and Remedies

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Introduction

The following is the first in a series of white papers which will be issued as a result of a task to define and qualify space grade fiber optic cable assemblies. Though to qualify and use a fiber optic cable in space requires treatment of the cable assembly as a system, it is very important to understand the design and behavior of its parts. These papers will address that need, providing information and "lessons learned" that are being collected in the process of procuring, testing and specifying the final assemblies. This installment covers information on optical fiber, coatings, cable components, design guidelines and limitations, radiation and reliability.

Fiber optic cable has been qualified and used in space by NASA GSFC and JPL. It is becoming a defacto standard for telemetry and command data transfer at GSFC and on New Millennium spacecraft through the use of the MIL-STD-1773 fiber optic bus. A new JPL design plans to use optical cable in an extra-vehicular application where additional radiation shielding will be required and atomic oxygen effects are a concern. Applications which have flown optical cable have used multimode fiber although single mode fiber is now finding its way into designs. The loss of the heritage fiber (Corning 100/140 micron fiber) requires qualifying multimode cables once more.

The original design of the flight MIL-STD-1773 bus used jacketed, buffered fiber and simplex connectors. More recent designs, including the arrangement used with the Hubble Solid State Recorder (SSR), also include buffered fiber pigtails with no strength members or jackets. This creates a significantly different cable configuration with respect its durability and ease/reliability of termination. New coating and cabling approaches have also emerged since NASA qualified its heritage design in the 1980’s. Military users have done quite a bit of work to define and test some of the new cables available but have not addressed some areas of performance of unique interest to NASA. A NASA contractor for the Space Station program has been instrumental in uncovering problems and researching alternatives. This paper is part of a larger body of work, sponsored jointly by NASA GSFC and JPL, which will communicate relevant results found to date for promising cable assembly designs and will investigate areas not covered by other users or still in need of solutions.

The information below is intended to communicate the most relevant issues being discussed at this time within the user and manufacturing community, relating to space grade optical cable designs. This information has been used to coordinate two prototype cables which are being fabricated and procured at this time. Specifications which describe these designs will be available shortly [1]. Pre-qualification testing of these designs is planned for the 2nd and 3rd quarter of 1997. Subsequent white papers will discuss issues related to optical connectors being used in space and the results of tests on protoflight cable assemblies.

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Next Section: Materials

Materials in Use in Flight Grade Cable

The performance and manufacturability of most electrical and electronic parts are heavily dependent on the material selections. This is equally true for fiber optic cable assemblies. Many of the advantages and successes of the materials in use today are the result of their development for use in electrical wire and cable constructions and of the manufacturers' experience in using them for fiber optics over the last ten years. The standard cable construction includes the coated fiber, which is supplied by a fiber house and has a unique part number, a tight or loose tube buffer, woven or spiraled strength members and an outer jacket. Each cable component performs an important function in the overall mechanical reliability of the fiber and the termination. The coating, physically in contact with the fiber, will most greatly affect optical performance. Part number traceability is limited to the finished cable and the coated fiber.

Most optical cable jackets considered for use in space flight are extruded Teflon or Tefzel. Materials being used for loose tube buffers are Teflon, Tefzel, Kynar (PVDF) or Hytrel. Tight buffer choices are silicone, Teflon and Tefzel. Strength members can be Teflon impregnated fiberglass or Kevlar (Aramid). The options for coatings are acrylates or polyimides with or without an amorphous carbon undercoating, which provides hermeticity. Properties of these materials are outlined in Table 1.

Table 1. Materials Used in Flight Grade Fiber Optic Cable*

Material	Temperature Limits	Coefficient of Thermal Expansion (in/in/°F)	Tensile Strength
Tefzel 200	Melting Point: 270°C (518°F) Operating Range: -70°C to 200°C	20°C to 30°C (68°F to 86°F): 5×10^{-5} 50°C to 90°C (122°F to 194°F): 5.2×10^{-5} 140°C to 180°C (284°F to 356°F): 7.8×10^{-5}	44.8 MPa (6.5 kpsi)
Teflon, PFA	Melting Point: 300°C (572°F)	$6.7\ 10^{-5}$	27.6 MPa (4 kpsi)
Tefzel (ETFE)	Operating Range: -70°C to 200°C (-94°F to 392°F)	$\approx 10^{-5}$	34.5-46.9 MPa (5 - 6.8 kpsi)
Kevlar 49	Max Operating: 177°C	$-2.2\ 10^{-6}$	400kpsi 12mm diam
Teflon PTFE	Melting Point 343°C (620°F), Operating Range: -80°C to 260°C	4×10^{-5}	3 kpsi
Teflon FEP	Melting Point 285°C Operating Range: - 200°C to 200°C	$\approx 5 \times 10^{-5}$	2.9 kpsi
Gore-Tex Expanded PTFE	Melting Point 327°C Operating Range: -200°C to 260°C	$\ll 10^{-6}$	> 5 kpsi
Kynar (PVDF)	Melting Point 347°F Max Operating: 135°C	40×10^{-6}	5 kpsi
Hytrel	Operating Range: 50°C		2 - 7 kpsi

* These numbers are intended for reference only. For manufacturer's ratings, see the manufacturer's data sheet.

It is interesting to note that the coefficient of thermal expansion for Kevlar is negative, which means that as the temperature increases the material tends to contract rather than expand. The other materials in Table 1 have positive CTE's. Though no negative impact on performance has been reported by users of flight grade cable with Kevlar strength members, the behavior of the coating material with temperature causes an increase in loss as the temperature is reduced. This is why it is critical to characterize and life test optical fiber with an emphasis on the low end of the rated temperature range.

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Shrinking Cable Components

Materials Being Used: Fluoropolymer materials such as Teflon® (TFE, FEP, PFA) and crosslinked Tefzel® (ETFE) successfully applied in electrical cabling, have been similarly applied in optical cable designs as buffers and jackets. These materials are rated for high and low temperatures required for space flight application and meet standard outgassing requirements. In most mulitmode cable the buffer (loose or tight) and outer jacket are both fluoropolymers however Hytrel and Kynar can also be used. Regardless of the tradename, fluoropolymer materials have shrinkage problems. Kynar, a somewhat stiffer alternative to Tefzel, also shrinks. Vendors claim that the method of extrusion used in buffer and jacket manufacture can leave stresses in the material that only relax at elevated temperatures. There are also other extrusion process techniques which can eliminate some of the tendency to shrink. It is important to note that this shrinkage behavior is not driven by the material's CTE.

Effect of Shrinking Cable Components: This shrinkage problem has been reported by flight cable users including McDonnell Douglas (for Space Station), NASA Goddard, and Lockheed-Martin. This property of fluoropolymers has no effect on electrical cable performance but will directly affect signal attenuation in an optical cable. For the cable to accommodate the shrunken ETFE jacket, the fiber is forced to bend repeatedly inside the cable. These microbend cause the attenuation increase. In single mode applications that use tight buffers, the shrinkage problem could have a much greater impact on optical performance in the form of higher losses or a shift in polarization state if the application demands birefringent fiber. Jacket shrink data taken at GSFC showed that all of the cable components (the buffer, strength members and the jacket) shrank together and the coated fiber remained its original length. It has not been shown whether the cable components all shrank equally or whether the shrinking of the jacket pulled the other cable components back with it. The optical effect is the same in either case.

Collected Data: Evaluations by the users named above have shown that thermal cycling with temperature excursions between -45°C and 85°C (and wider ranges) will cause an ETFE jacket to shrink between 0.4% and 1.5% for cable lengths 10 feet and above. Loss was found to increase by a factor of 2 and 3 for shrinks of 0.6% and 3.6% respectively. No additional effect was found due to exposure to vacuum conditions. The shrinking tended to flatten out after about 50 cycles.

Preconditioning Procedure: Thermal conditioning procedures are now being used by McDonnell Douglas and Lockheed-Martin to force as much shrinking as possible before the cable is terminated. The following procedure has been found to be effective for "empty" cable: a 6 cycle exposure to temperature extremes of 140°C and minus 30° with heat transfer transient times of 50 and 40 minutes respectively. Meaning there should be 40 to 50 minutes to allow the fixtures to reach the temperature of the thermal chamber. Dwell times (at temperature extremes) need be no longer than 1 minute since the length of time spent at the steady state temperature extremes does not affect the shrinkage mechanism of the cable materials. Although the ramp rate does not affect the shrinkage, what has been used was 5°C/minute due to constraints of the thermal chamber. However, the goal is to precondition and not temperature shock the materials. As a reference in the EIA-455-3 (test procedure to measure temperature cycling effects on optical fiber, optical cable, and other passive fiber optic components) it is specified for cable containing optical fiber that the ramp rate be at maximum 40°C/hour. The preconditioning procedure described here is for cable without the fiber inserted.

Kynar has a lower temperature rating than that of Teflon which may make this procedure less effective for cables with a Kynar buffer. Kynar's melting point is around 182°C while Teflon's limit is 343°C. A procedure has not been identified for cable which includes the fiber and it should be noted that the coatings being recommended for flight grade fiber will not withstand exposure to 140°C. An evaluation is being designed at GSFC which will include more investigation into cable component shrinkage and suitable preconditioning procedures. The best solution remains having the manufacturer precondition the materials before the fiber is included in the cable.

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Strength Member Issues and Concerns

Hygroscopic Qualities of Kevlar: Though Kevlar has been used in telecommunication optical cables for years it was avoided by NASA due to its tendency to retain moisture and inability to meet the standard outgassing requirement. Lockheed Martin studied these moisture and contamination questions and reported that untreated Kevlar yields a total mass loss (TML) of 0.6% and a collected volatile condensable material value (CVCM) of less than 0.01. When treated with lubricants or polymers, as is very often the case, Kevlar outgasses beyond typical acceptance limits. Lockheed's study also showed that Kevlar strength members which are exposed to a humid environment will quickly (after 2 hours or so) absorb moisture beyond the TML limits. They found that it will only wick six inches into a cable with exposed ends. Even if the Kevlar has been exposed to a humid environment during manufacture, if an extrusion process is used to apply the jacket, the absorbed moisture is completely driven away in process and no moisture remains trapped inside of the cable. Though no data was provided, a conditioning bake would likely drive off wicked moisture in the cable ends. The report suggests capping the ends of un-terminated cable and highlights the necessity to specify untreated Kevlar for use in space grade optical cable [2].

Though Kevlar's ability to wick uncured epoxy out of a connector has not been documented, if it occurs, the results could cause failure of a termination. This behavior will be studied and documented as part of a future evaluation effort.

Teflon Impregnated Fiberglass Strength Members: A concern has been raised regarding the bondability of Teflon impregnated fiberglass strength members using epoxy when terminating to connectors. The concern is that Teflon is hard to bond to and that crimping on fiberglass causes the strength members to break. This issue is still in review.

Strength Member Weave: One of the leading advantages of the FC style single fiber connector is its "pull-proof" design. To make the connector pull proof the spring, which maintains the ferrule's PC contact, is mechanically isolated from the connector shell. When one pulls on the back, no force is extended to the ferrule and the optical connection is maintained. This is an improvement over the ST design which, when one pulls on the back of the connector, allows separation of the mated ferrules. The lay of the strength members has been found to affect the independent movement of the cable around the stationary fiber (or fiber and tight buffer, depending on the cable construction and termination configuration). Strength members which lay in the cable in a woven configuration, similar to that used for electrical cable shielding, tend to be too tight to allow the necessary movement of the cable components in a "pull-proof" connector. A spiral or lateral lay has been found to allow sufficient movement, at least 1 mm. A jacket that is too tight can have the same effect. An ability to move the fiber (or fiber/tight buffer) at least 1 mm back into the cable must be part of the cable specification to enable use of the cable with a pull-proof connector.

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Fiber Optic Coating Materials

Acrylates and Polyimides. Acrylates and polyimides were being designed into flight grade optical fiber in the 1980's. Optical cable with acrylate coated fiber was qualified by GSFC during that period and is now considered the heritage design for flight projects. Like the array of materials used for cable jacketing, fiber coating materials each have advantages and disadvantages. The advantages of the acrylate material is that it can be selected for strippability (example: methylene chloride) and is fairly soft which makes the fiber more flexible. Its disadvantages are that acrylates tend to have low temperature ratings (usually around 85°C although some are available that are rated as high as 200°C) and it is a well known outgasser (e.g. TML greater than or equal to 5%, CVCM greater than or equal to 0.5% [3]). Though terminated cable does not allow enough venting to consider acrylate coated fiber in a cable assembly a problem, acrylate can be a contamination problem when the fiber is used in a non-hermetic coupler.

Polyimide has been used successfully for coating space grade optical fiber and it comes with the advantage of a 125°C temperature rating. This is critical to programs such as Space Station and some JPL applications. Polyimide will tend to make the fiber seem stiffer than an acrylate coated fiber. Silicone and Gore-Tex,® applied as a second coating, have been used to improve the flexibility of polyimide coated fiber. Silicone has the disadvantage of introducing a contamination concern. Silicone is also a known outgasser. Even in a cable configuration (where when using small amounts of outgassing material the outer jacket could protect the system), large quantities of silicone are currently used and could cause problems as a result of this outgassing. The Gore-Tex® construction will be evaluated.

Of even more significance are the difficulties associated with stripping polyimide. Polyimide coating can be stripped chemically, with hot sulfuric acid, or mechanically, using a hot tweezers. Users find hot sulfuric acid to be dangerous and non-portable. Mechanical stripping methods are not recommended for flight cable assemblies because they have the capacity to introduce surface flaws to the glass fiber, compromising long term reliability. Connector manufactures have tried to circumvent this problem by offering a ferrule hole size that will accommodate the unstripped polyimide coating's outer diameter. This approach has not been accepted readily by the industry because they make the connectors considerable more expensive and force the user to commit to a non-standard configuration. It tends to be a more viable option when military specified removable ferrules (MIL-T-29504) are being used, such as in the MIL-C-38999 (mini-circular, multi-terminus) or MIL-C-28776 (hermaphroditic, circular, multi-terminus) connectors. When polyimide coating is used in single mode applications (where perfect alignments are crucial to limiting the insertion losses), it must be removed before termination due to the tighter tolerance contraints of the single mode connectors.

Fibers coated with polyimide have been found to outperform acrylate coated fiber, using identical glass, in ionizing radiation testing. This phenomenon is discussed in detail in the Radiation Effects section.

Hermetic Coating: It has been established in fiber optic industry literature that exposure to water and/or water vapor can hinder the long term reliability of fiber optics and will accelerate the aging process. Hermetic coatings are currently being fabricated on fiber optics that require longer duration reliability and are generally in the form of a 200 angstrom layer of amorphous carbon applied directly to the outside of the cladding. The process by which an hermetic coating is applied can be crucial to the survivability of the fiber itself. In cases where hermetic coatings have been achieved using a sputtered metal the fiber can become embrittled. Though polyimide coating over amorphous carbon is the more available hermetic arrangement at this time, acrylate can be applied over amorphous carbon as well lending its advantages of mechanical flexibility to the hermetic design.

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Radiation Effects

Much study has been made of the effects of ionizing radiation, both Gamma and from source natural to the space flight environment, on optical fiber. Information can be found in the literature documenting the dependency of a fiber’s performance in a radiation environment on the materials used to make the glass, the processes used, coatings used, dose type and rate and total dose. Recovery times, self-annealing and photobleaching effects have also been well documented. Manufacturers interested in the space flight market are aware of these dependencies and have developed manufacturing processes which produce products which can withstand tens to hundreds of kRads(Si) total dose with less than one dB increase in loss per kilometer of fiber. Flight projects using multimode fiber, use lengths much shorter than a kilometer and have tended to consider radiation sensitivity a non-issue. With the emergence of the use of single mode fiber, the radiation issue is being revisited to examine the compatibility of the recovery times (^{3} 2 sec) with the high data rates being applied.

Optical fiber will darken due to ionizing radiation creating centers of absorption where unwanted elements and other optical defects occur in the fiber. Generally a fiber will experience defects during the drawing process making them hard to isolate and eliminate, regardless of the purity of the glass pre-form. Radiation performance can also be affected by the coatings. There is evidence that suggests that the primary coating on the fiber has a much greater impact on the radiation performance of a fiber than does the secondary coating. Polyimide coatings undergo a heat cure while acrylates undergo a ultraviolet (UV) cure. It has been surmised that the high temperature cure inherent in the polyimide coating process can actually anneal the defects induced in the fiber by the drawing process. [4]

Germanium, used to dope fiber cores in order to raise the waveguide index of refraction, causes radiation sensitivity. Phosphorous doped fiber (for the core or cladding) has been well documented as not acceptable for use in space environments due to its radiation sensitivity[5]. Lower temperatures produce the largest radiation induced attenuation in fibers. The radiation induced loss sensitivity can vary by a factor of 25 between temperature extremes where the worst case is at the low end of the temperature range. At lower temperatures the annealing of color centers decreases. In general it is best to use pure silica in space applications when total dose requirements exceed 5kRads(Si) [6].

Dose rate will have an effect on the results of radiation testing when they are above 960 rads(Si)/hour [6,7]. Often bit error rate has been used as a pass/fail criterion making dose rate dependence much less obvious. When attenuation is measured, special attention should be given to dose rate and kept as low as feasible Test data has been generated for many fibers with a variety of material formulations to total dose levels through and beyond 1 MRads(Si) [6]. An algorithm has been established by NRL which allows extrapolation of radiation performance data for varying values of total dose, temperature, and dose rate [8].

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Long Term Reliability

Bend Radius. Other than permanent damage due to extreme ionizing radiation, fiber failure is caused by crack growth which extends through the glass causing it to break. Tensile loading during cable installation and static bending induced stress contribute to fiber aging by inducing and growing cracks. These stresses are most often the focus of studies which look at long term reliability. The test assumes that long lengths of fiber are used, as in the telecommunication industry, and that a derated tensile strength, which provides a safety margin, can be calculated based on the proof strength. In other words, σ_{max} must be some fraction of the actual proof strength or

$$\sigma_{max} = \sigma_f / f$$

where σ_{max} is the maximum amount of tensile stress that the fiber can withstand safely during use, σ_f is the proof strength of the fiber, and f is the safety coefficient.

A typical safety coefficient is $f = 5$. Uncoated optical fiber has a stress limit of 500 kg/mm^2 or 700 kpsi (where the conversion is 1 kg/mm^2 = 1.422 kpsi). Advertised proof strengths for coated space grade multimode fiber are in the 100 to 200 kpsi range. The relationship between tensile load and tensile strength for an optical fiber is

$$\sigma_f = W/\pi d_f^2$$

where d_f is the fiber outer diameter, W is the tension load value applied to determine the tensile stress. The expression for determining tensile stress for coated optical fiber is

$$\sigma = \frac{1}{1 + \frac{Ep}{Ef}\left[\left(\frac{dp}{df}\right)^2 - 1\right]} \frac{W}{\pi df^2}$$

where: E_p = Young's modulus of the coating, E_f = Young's modulus of the fiber, d_p = coating outer diameter, d_f is fiber outer diameter[9]

Notice that the second term is the expression for tensile stress of an uncoated optical fiber. Therefore, the relationship between the tensile strength of a coated fiber and an uncoated fiber can be expressed as $\sigma = A\sigma_f$ where A is the expression

$$A = \frac{1}{1 + {}^{Ep}\!/\!{}_{Ef}\left[\left({}^{dp}\!/\!{}_{df}\right)^2 - 1\right]}$$

The value for ***A*** will then describe by how much a given coating system can reduce the tensile stress induced upon the fiber optic strand given a constant load ***W***. If we assume that the value of E_p= 200 kg/mm^2, E_f = 7100 kg/mm^2, an outer diameter for fiber d_f =140 microns, and an outer diameter d_p for the coating of 250 microns, then the tensile strength is $\sigma = 0.94\sigma_f$. In other words, the coated fiber system is 6% stronger than bare fiber. This value can be increased by increasing the values of d_p, the outer diameter of the coating, and/or by increasing the Young's modulus, which implies use of another type of material with a larger E_p. For example, with the same E_p used above, increasing the outer diameter to 500 microns will increase the strength of the coated fiber by 25%. Using the same diameter value as above and increasing E_p to 300 kg/mm^2 will improve the tensile strength by 33%. Note that UV curable, soft, acrylates have an E_p in the range of **0.1 to 0.3** kg/mm^2 and UV curable hard acrylates have an E_p in the range 50 to 100 kg/mm^2. In most acrylate coated fibers, two coating layers of are used to increase both the outer diameter and the modulus.

If σ is the rupture strength of the coated fiber optic strand and a safety coefficient of 5 is used, then the safe-stress must be less than 0.2σ, or $\sigma_{max} < 0.2\sigma$. Based on the results found previously we can express the relationships between the minimum bend radius of the coated fiber and the outer diameter of the fiber coating which optimizes long term reliability. By increasing the outer diameter of the coating it was shown that the strength of the fiber increases. That being so, the minimum allowable stress σ_{max} can be related to long term bend radius by $\sigma_{bend} = E_f d_f / 2R$, where R is the bend radius and E_f & d_f are defined above. If the limit on bending stress is that it be equal to the safe stress value σ_{max} then the equation can be rewritten as $R = E_f d_f / 2 \sigma_{max}$. As the safe stress increases with a larger diameter coating and/or by a coating material that increases Young's modulus, the safe minimum bend radius decreases.

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Summary and Definitions

The information presented above highlights some of the most important issues with respect to identifying and using a new optical cable for space flight applications. The new designs will take advantage of the materials in use for hermeticity while maintaining easy coating strippability and maximizing mechanical strength. Testing is planned to address termination issues, radiation tolerance and to quantify mechanical durability.

Definitions:

ETFE (Tefzel if crosslinked) Ethylene Tetrafluoroethylene Hytrel: Polyester Elastomer

Kevlar: Aramid Fiber

Kynar (PVDF) Polyvinylidene Fluoride: Does not lose weight when prolonged exposed to 250 C. Self extinguishing. High radiation tolerance.

Proof Strength: tensile strength of a coated fiber. A proof test imposes a given load on a coated fiber causing any cracks which cannot withstand the tension to grow and ultimately break the fiber. The proof test is used to screen a coated fiber for a particular strength rating.

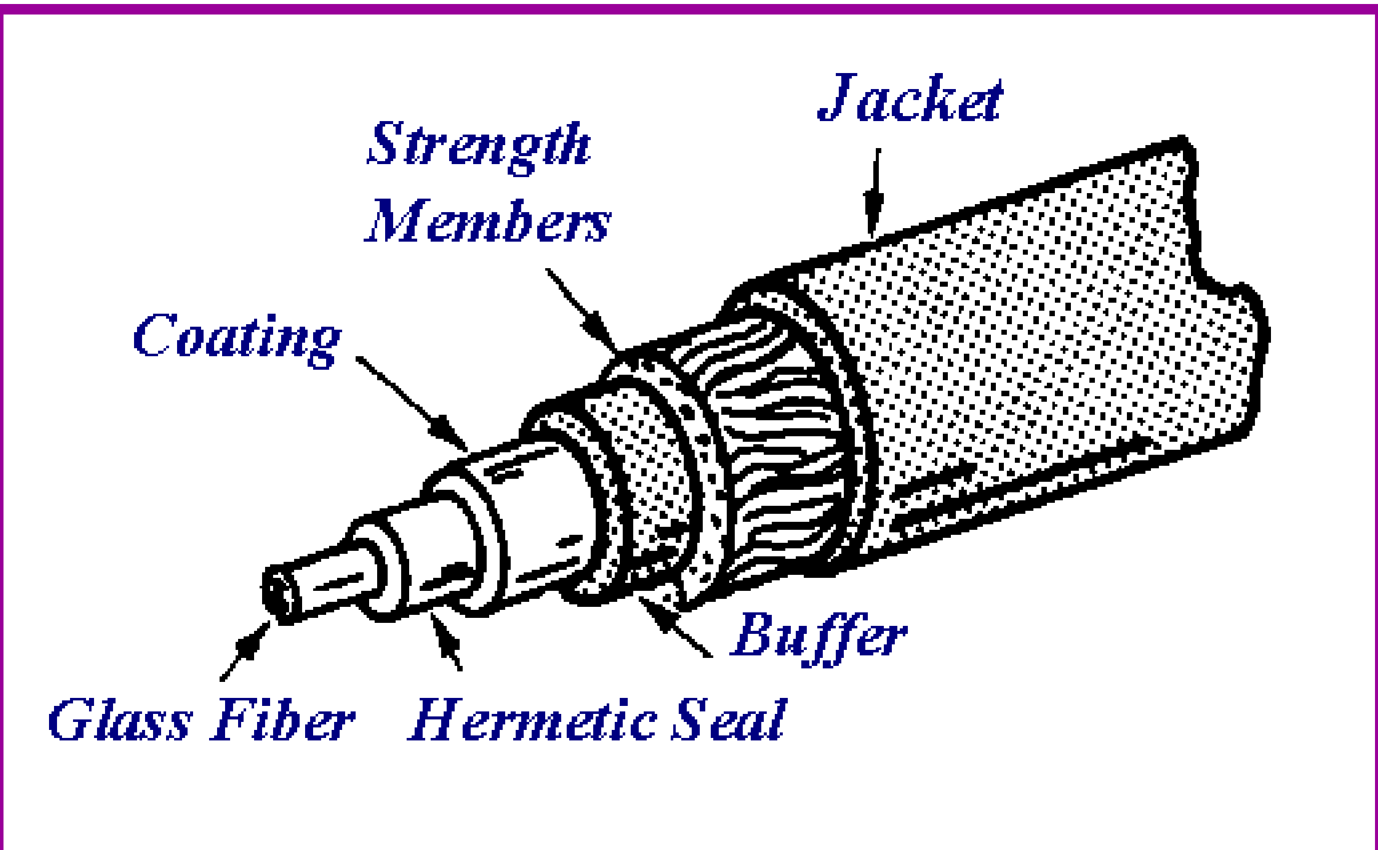
PTFE (Teflon) Polytetrafluoroethylene, non-flammable

Simplex Connector: single fiber, single ferrule connector.

Teflon: Fluorocarbon Resin

Tefzel Fluoropolymer Resin

Fiber Optic Cable Components:



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