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A Guideline for Application of High-Density Fiber Optic
Interconnects to Aerospace Platforms

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FOREWORD

This document details various aspects of a Generation II high-density fiber optic interconnect system and related interface and installation hardware concepts for aircraft applications. The currently utilized Generation I fiber optic interconnect hardware, represents an extension or duplication of existing aircraft electrical cabling and connector technology to fiber optic media. It is therefore desirable to consider at the outset guidelines for an advanced high density interconnect system based on emerging technology concepts so that avionics interconnect systems can accommodate growth as the technology matures. This high-density interconnect will represent a revolutionary advance in interconnect systems based on optical fiber's unique performance characteristics. The concept should be compatible with all advanced aerospace system concepts including "fly-by-light", broadband multimedia networks such as passenger entertainment systems, advanced avionics computer interconnects (e.g. optical backplanes) and "smart structures". The vision is to attain a "mobile vehicle information distribution system" analogous to the "premises distribution systems" provided for buildings where all elements of a fiber optic interconnect are designed for compatibility and interchangeability.

This guideline addresses industry and government concerns with the affordability of first generation of interconnect hardware in order to provide solutions for improved second-generation hardware. This second-generation hardware should take into account advanced commercial network and "fly-by-light" systems implementation as well as recent technology advances by the commercial photonics industry. It is proposed that existing and planned industry wide consortia and working groups be used to provide input for this interconnect system for future military and aerospace applications since expertise from many disciplines and diverse organizations is required to arrive at workable solutions. It is also proposed that the automotive community participate in this effort to gain the economy-of-scale which can be achieved by possible dual-use aerospace/automotive application. Contributions and suggestions have been supplied by attendees of the AS-3C meetings held from October 1992 through April 1999.

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1. SCOPE:

This SAE Aerospace Information Report (AIR5271) covers the basic attributes of a second-generation robust, reliable high-density fiber optic interconnect system for aerospace applications. The intent is to take advantage of recent commercial developments in materials, components and manufacturing methods to develop rugged high-density fiber optic interconnects optimized for aerospace and automotive applications, which can accommodate a variety of optical fiber waveguide types. These waveguide types include single mode and multi-mode glass/glass fibers and waveguides, plastic clad silica fibers and waveguides, and all polymer fibers and waveguides. This second generation interconnect system should represent a dramatic improvement over first generation. The cable should be extremely robust eliminating any concerns over cable damage or fiber breakage in an aerospace environment.

A high-density fiber optic interconnect system provides the physical medium for optical data and control communication in aerospace vehicles. As such, it consists of the cables and harnesses, connectors, splices, backplane interfaces, transceivers, fiber optic couplers, and includes test and maintenance concepts for these items. Also included are manufacturing, installation and repair tools, processes and training programs. The high-density format should provide for both redundant serial data transmission or parallel data transfer by providing a scaleable fiber count. Connectors should provide an extremely small footprint, with low mass connector shells and array inserts, and accommodate both single and multi-mode fibers. Fiber spacing and cladding diameter should be standardized and coatings utilized to guarantee long term reliability. The cable connector interface shall be optimized to preclude damage during installation and/or maintenance actions as well as ease of termination. All elements of the cable plant should be compatible including splices and couplers with minimum weight, volume and footprint. This optimized cable plant shall serve as an integrated information distribution system capable of transferring all information on military and commercial aircraft with dramatic improvements in affordability, reliability, fault tolerance, EMI/EMP immunity and safety. Utilization of this cable plant will improve aircraft performance and fuel economy, providing operational cost effectiveness while reducing new aircraft certification costs.

2. AVAILABLE REFERENCE DOCUMENTS:

The following documents represent the current database for application of interconnects and related components to aerospace platforms:

MIL-STD-1678A	Fiber Optic Test Methods and Instrumentation
MIL-C-38999	Connector, Electrical Circular, Miniature; Specification for
MIL-C-83723	Connector, Electrical Rectangular; Specification for
MIL-E-5400T	Electrical Equipment, Aerospace General; Specification for
MIL STD 883	Microcircuits; Specification for
MIL-STD-1344	Test Methods for Electrical Connectors
MIL-STD-202	Test methods for Electrical and Electronic Component Parts
MIL-I-1760	Aircraft/Stores Electrical Interconnection System
MIL-C-83522	General Specification for Single Terminus Fiber optic Connectors
MIL-C-85045	General Specification for Fiber Optic Cable-Shipboard
MIL-F-49291	General Specification for Optical Fiber

2. (Continued):

MIL-T-29504	General Specification for Removable Fiber Optic Termini
MIL-STD-461	Requirements for the Control of Electro-magnetic Interference Emissions and Susceptibility
MIL-STD-462	Measurement of Electro-magnetic Interference Characteristics
MIL-W-5088	Wiring, Aerospace Vehicle
AS1773	Fiber Optics Mechanization of an Aircraft Linear Time Division Command/Response Multiplexed Data Bus
ARP5061	Guidelines for Testing of Aerospace Fiber Optic Inter-Connection Systems
ARINC 404-A	Air Transport Equipment Cases and Racking
ARINC 600-10	Air Transport Avionics Equipment Interfaces
ARINC Project Paper 628	Cabin Equipment Interfaces (CEI) Part 6 Fiber Optic Cable Assembly General Specification
ARINC 629P1-4	Multi-Transmitter Data Bus, Part 1, Technical Description
ARINC 629P2	Multi-Transmitter Data Bus, Part 2, Application Guide
ARINC 636	Onboard Local Area Network (OLAN)
ARINC 659	Backplane Data Bus
BELLCORE GR-326-CORE	Generic Requirements for Single-Mode Optical Fiber Connectors
DIN 47256	General Specification for Single Terminus Fiber Optic Connectors
RTCA DO-160C	Environmental Conditions and Test Procedures for Airborne Equipment
TIA/EIA-455-XX series	Fiber Optic Test procedures (FOTPs)
TIA/EIA-455-XX series	Optical Fiber System Test Procedures (OFSTPs)
TIA/EIA-604-X series	Fiber Optic Connector Inter-mateability Standards (FOCIS)

2.1 Sources for Reference Documents:

Reference Documents or additional information concerning reference documents can be obtained from the following sources¹:

Aeronautical Radio Inc. (ARINC, USA, 1-410-266-4110)
[HTTP://WWW.ARINC.COM/Ind_Govt_Srv/Characteristics/](http://WWW.ARINC.COM/Ind_Govt_Srv/Characteristics/)

Defense Supply Center (Dept. Of Defense, DSCC, USA, Art Hudson, 1-614-692-0657) [HTTP://WWW.DSCC.DLA.MIL](http://WWW.DSCC.DLA.MIL)

Institute of Electrical and Electronic Engineers (IEEE, USA 1-908-981-0060)
[HTTP://WWW.IEEE.ORG/](http://WWW.IEEE.ORG/)

International Electro-technical Commission IEC, Switzerland +41-22-919-0211
[HTTP://WWW.IEC.CH/](http://WWW.IEC.CH/)

Radio Technical Commission for Aeronautics (RTCA), USA, 1-202-682-0266

Society of Automotive Engineers (SAE, USA, 1-412-776-4841, [HTTP://WWW.SAE.ORG](http://WWW.SAE.ORG))

¹ Horwitz, Page 9

2.1 (Continued):

Telecommunications Industry Association (TIA, USA, 1-703-907-7700)
[HTTP://WWW.TIAONLINE.ORG/](http://www.tiaonline.org/)

2.2 Definitions:

FIBER OPTIC CABLE CONDUIT. A rigid or semi-rigid tube within which the signal carrying media may be placed. It also serves the function of an external strength member to provide crush and abrasion resistance.

FIBER OPTIC RIBBON. An unprotected assembly of optical fibers arranged side by side in a flat configuration and held together by an adhesive or adhesive tape.

FIBER OPTIC RIBBON CABLE: A ruggedized stand alone assembly of two or more optical fibers arranged side by side in a flat configuration. The assembly may also provide mechanical strength for the fibers and a suitable protective coating to cover the buffered fibers for environmental protection and to maintain the subassembly configuration. The assembly shall be fabricated to meet optical, mechanical and environmental specifications.

FIBER OPTIC RIBBON CABLE BREAKOUT. An arrangement to physically and optically separate a particular information channel from all or several of the individual information channels contained in a fiber optical ribbon cable for the purpose of branching to another physical location. The individual fiber channel(s) to be separated shall detach cleanly from the ribbon matrix or adhesion materials without residue adhering to the separated fiber and a suitable means must be provided to maintain the physical durability and long term reliability of the cable at this detachment point.

HIGH-DENSITY FIBER OPTIC CABLE CONNECTOR. A quick disconnect mechanical assembly to physically constrain and position optical fibers in a fiber optic cable for the purpose of repeatedly and optimally transferring the optical signals in the fiber optic connector to an adjacent assembly which contains the following: (a) another fiber optic cable, (b) an array of optical sources, (c) an optical coupler, (d) an array of optical detectors, (e) and optical transceiver, (f) an optical switch or (g) an optical sensing device. The connector shall be fabricated to meet optical, mechanical, and environmental specifications.

FIBER OPTIC RIBBON CABLE SPLICE. A mechanical assembly to physically constrain and position optical fibers in a fiber optic cable. The assembly makes a permanent or temporary connection to transfer the optical signals in the fiber optic connector to an adjacent assembly containing another fiber optic cable, an array of optical sources, an optical coupler, or an array of optical detectors. The splice shall be fabricated to meet optical, mechanical, and environmental specifications.

FIBER OPTIC RIBBON CLEAVING TOOL: A mechanical or electro-mechanical device to simultaneously create physical break in all the fibers contained in a fiber optic ribbon cable which results in a flat surface on both facets on the severed optical fiber with minimal mechanical damage to the optical fiber. The flatness of the fiber surfaces and surface quality shall be specified to minimize optical loss.

2.2 (Continued):

OPTICAL BACKPLANE INTERCONNECT: A rigid stand-alone assembly consisting of optical waveguides, optical waveguide connectors and optical couplers that provides optical information transfer between standard electronic modules. This assembly provides structural support for the modules through a suitable connector interface as well as environmental and mechanical protection for the waveguides.

OPTICAL COUPLER. A component or device to provide optical power extraction from an input fiber or plurality of input fibers to a plurality of output optical fibers.

2.3 First Generation Fiber Optic Interconnect Constraints:

High-density fiber optic interconnects for aerospace applications offer the potential to simplify the harness complexity, reduce weight, simplify installation and reduce the maintenance. Additional benefits include operation in a high electromagnetic environment, improved cost effectiveness, increased aircraft performance and fuel economy, improved system performance capabilities, and reduced new aircraft certification costs. The multi-mode optical interconnects installed on aircraft to date have fundamentally been patterned on existing electrical cabling, connectors and harness concepts as well as currently utilized installation, test and maintenance procedures associated with electrical wiring. While this first generation hardware has been successfully implemented in several military and commercial aircraft, the extensive use once projected has not yet occurred because of issues related to cost, and ease of installation, test, and maintenance. In the commercial telecommunications industry, optical fiber high-density cable technology is receiving widespread use and provides compact cables providing a large number of fibers. This technology offers the benefits of low cost, mass termination and ease of installation. Complementary electro-optic component technology is also being developed to reduce the cost of commercial optical interconnects. This fiber optic high-density cable technology is also to provide a more cost effective second generation interconnect system for aerospace applications with projected widespread use of optical interconnects. This hardware is optimized around the unique properties of optical fiber rather than being an extension of electrical wiring and shall also provide increased long term reliability through cost effective built-in-test and affordable redundancy. The use of single mode fiber for aerospace applications is also optimized with a high-density cabling approach and is compatible with multi-mode fiber approaches.

2.4 System Requirements:

Operating Environmental Conditions:

Components of the cable plant shall not suffer damage, deterioration or degradation of performance, when subjected to any environment or natural combination of environments specified below:

Altitude: Sea Level to 70,000 feet with a maximum climb rate of 90,000 feet per minute.

Temperature Range: Dependent on actual and projected operational environment:

Class A: -40 to + 85 °C continuous, -55 to +125 °C for 5 minutes

Class B: -55 to + 125 °C continuous

Class C: -55 to 150 °C continuous, -65 to ≥ 200 °C for 5 minutes.

Humidity: Operating and non-operating conditions of 0 to 100 percent, including condensation in and on components where applicable.

Sand and Dust: Operating and non-operating conditions during and after exposure to sand and dust particles as encountered in desert areas.

Fungus: Operating and non-operating conditions during and after infinite fungus growth as encountered in tropical regions.

Salt Fog Atmosphere: Operating and non-operating conditions during and after exposure to a salt/sea environment as encountered in carrier service.

Shock and Vibration: Requirements for shock, sinusoidal and random vibration will be Established for survival in the severest flight test application.

Acoustic Noise Susceptibility: Requirements for acoustic noise susceptibility will be established for survival in the severest flight test application.

Electromagnetic Radiation: Per MIL-STD 461/462

2.5 Fiber Optic High-Density Cable Plant Benefits:

An optimized fiber optic high-density cable plant for both single and multi-mode fiber shall provide the following benefits:

TABLE 1

BENEFIT	METHOD OF ATTAINMENT
Operation in a High Intensity Electromagnetic Environment	Cable Plant Qualification to Aerospace Environmental Specification
Improved Cost Effectiveness	Greater Commonality, Built-in-Test, Parts Reduction, Low Cost Redundancy, Greater Reliance on Commercial Parts, Ease of Installation, Batch Fabrication
Increased Aircraft Performance and Fuel Economy	Weight Reduction
Improved System Performance	Growth Margin through Spare Fibers, Greater Availability through Redundancy, Fault Tolerance and Built -In-Test (BIT)
Reduced Certification Costs	Meet Aircraft EMI Requirement at the Box Level vice the Platform Level

It is the intent of this document to detail the main characteristics for a high-density cable interconnect system for aerospace applications which must be detailed in future standards and specifications.²

3. ADVANCED INTERCONNECT/HARNESS REQUIREMENTS:

The component requirements in this document are derived from the following sources:

1. Information on new systems needs and performance information on similar systems previously in actual use
2. Applicable portions of military specifications
3. Applicable portions of commercial specifications
4. Data from military and commercial technology demonstration programs.
5. Available or developmental commercial component and hardware technology

Formulating requirements derived from the above sources will permit qualification of a high-density fiber optic interconnect to provide reduced life cycle cost and technology transparency.

² Weaver et al., Sections 1-1, 1-2, 2-2, 2-8

4. EMERGING TECHNOLOGY TRENDS:

The telecommunications and CATV industries are striving to enhance service to subscribers. A convergence of these industries is taking place. This is driven by the emergence of high definition digital TV and digital video transmission over the internet. This convergence is driving bandwidth requirements for both "fiber-to-the-home" and "fiber-to-the desk". The competitive pricing of both wireless and satellite services are driving affordability of fiber optic components for using fiber for the "last mile". To increase bandwidth, wavelength division multiplexing (WDM) and sub-carrier multiplexing (SCM) technology are being pursued by the commercial sector. High-density cable and connector concepts are being rapidly advanced and a new family of lasers, modulators, couplers, filters, switches and detectors are emerging from the research laboratories.

Future incorporation of a fiber optic interconnect system on military platforms (e.g. aircraft) will permit the multiplexing of different information types/formats on a single optical fiber. When digital data transmission fiber is passing through a region of the aircraft that requires analog/RF communications signals to the core processor, it may be reasonable to use a different wavelength than the digital data and organize the new wavelength bandpass into a Frequency Division Multiplexed (FDM) optical channel. The process of modulating the optical light carrier with another frequency carrier is called Sub-Carrier Multiplexing. The FDM information on another wavelength can now pass down the optical fiber while not interfering with the original digital information. At the analog/RF pick-off point, a wavelength selective optical filter and/or detector is used to convert the RF information back into electrical. No reason exists to preclude utilization of two or more of these digital fibers for broadband ring or LAN networks, operating on different optical wavelengths. The advantage provided is information rate growth and a corresponding platform capability improvement through multiplexed photonics. With thoughtful initial design, which includes redundancy, fault tolerance and built-in-test (BIT), a scaleable cable plant can be designed for the life of the airframe so that no optical cable upgrades would ever be required.

Emerging technology trends, which require high-density fiber optic interconnects are resulting from many diverse efforts. One example effort is the military sponsored True Time Delay (TTD) development for phased array antennas. These efforts are expanding the spectral performance limits of existing photonics interconnect elements; including: external optical modulators, photonic selective time delays, wide band photodetectors, lower Relative Intrinsic Noise (RIN) laser techniques and optical switching. Another characteristic of lasers is the spectral line width. The higher line widths the greater phase noise placed on the signal near DC. Fortunately methods to increase optical power tend to improve the spectral line width and RIN. The majority of these devices are being developed for control of Phased Array antennas and Analog/RF links through fiber optic interconnects, possibly via WDM on other normal interface optical cables. As photonics develops in the military platforms it will be necessary for growth to be accomplished without constantly laying new optical fiber cables.

4. (Continued):

Fly-by-light demonstrations are advancing through continuing flight tests and there is an increasing requirement for diagnostics and health monitoring of structural, propulsion, and avionics systems on all aerospace platforms. Antenna Systems are being incorporated into the skins of aircraft and structural elements are being monitored and controlled by embedded sensors and actuators. “Fly-by-light”, “smart skins” and “smart structures” will require efficient data transfer in a severe environment and must be subjected to the same environmental stress as the airframe. High-density optical cables and connectors can be exploited for this purpose. The interconnect can be embedded into structures, laminated on the surface of structures and/or routed in a conventional means to transfer data and serve as an optical sensing mechanism.

4.1 Optical Fibers for High-Density Cables:

Conventional optical cables consist of a single fiber or fibers that are laid up with suitable longitudinal strength members in a bundle connector. These fibers and strength members are configured in a bundle configuration over which is placed a protective sheath. The sheathing can be helical wrapped or extruded and a final cable jacket is placed over the assembly to form a cable. An alternative option for assembling optical fibers is to configure the fibers in a side by side configuration to form a flat ribbon which can then be utilized to form various cable configurations. Figure 1 shows a cross section of such a fiber optic ribbon wherein the unprotected fibers are held in position by an adhesive.

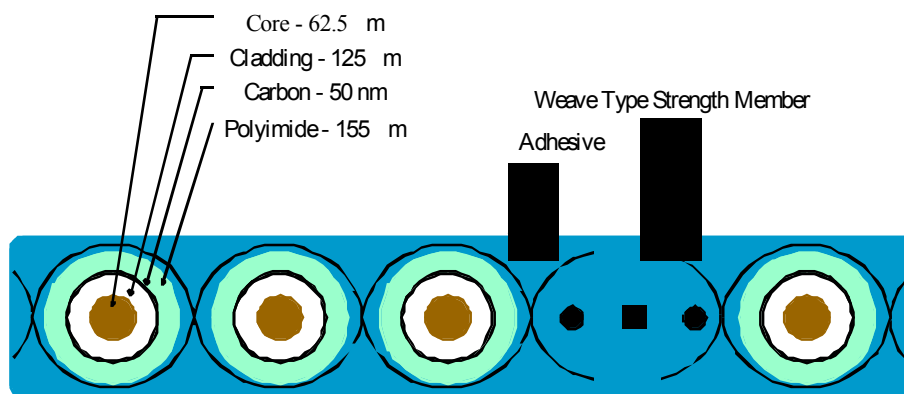


FIGURE 1 - Cross Section of a Fiber Optic Ribbon

- 4.1.1 Glass Fibers: Driven by the long distance telecommunications market, the glass optical fiber industry has produced low loss, low dispersion single mode glass fiber with loss minima in the 1.3 micrometer and 1.5 micrometer wavelength windows. Further stimulated by the Community Antenna Television CATV market (i.e. cable TV), National Information Infrastructure developments, and the market for local area networks (LANS), the industry is emphasizing development of multi-mode glass fiber with more emphasis on affordable cost. These multi-mode systems operate in the .85 micrometer, 1.3 micrometer, and 1.5 micrometer loss windows. The fiber industry has now recognized the advantages of applying hermetic coatings to fibers long term reliability and some manufacturers now provide such coatings in their product inventory.

Hermetically coated single mode and multi-mode glass fibers are now commercially available for aerospace applications. In the past, the unavailability of MIL-SPEC lasers, single mode connectors and reliable couplers has also been a problem, which has prevented the introduction of single mode fibers into aerospace applications. Some sensor applications will require single mode fiber optic technology on aerospace platforms. Broadband networks will require laser sources to meet the bandwidth requirements of next generation video and sensor data transmission. It is therefore imperative that next generation aerospace cable plants incorporate the requirement for both single mode and multi-mode technology. The broad telecommunication market will help to lower costs associated with single mode technology while the Local Area Network (LAN) and fiber-to-the desk market should help reduce the cost of multi-mode fiber.

Commercial single mode and multi-mode fibers have adopted de facto standards for fiber core and cladding. The most common commercial multi-mode core cladding diameters are 62.5/125 μm and 50/125 μm . Likewise single mode fibers have also adopted a 125 μm cladding dimension. The first generation aerospace cables have adopted de facto standard of 100/140 μm and 200/280 μm and utilize a polyimide or silicone buffer to provide high temperature capability. Commercial fibers utilize an acrylate coating which cannot meet the higher temperature aerospace requirements.

A new family of commercial multi-mode fibers has been introduced by Corning with superior technology and profile control that provides performance previously available only with single mode fiber. The InfiniCor CL 1000 fiber is guaranteed for transmission distances up to 500 meters at 850 nm and up to 1000 meters at 1300 nm for gigabit Ethernet compliant systems. This is the first multi-mode fiber to eliminate the need for a mode-conditioning patch cord in the 1300 nm window and is specifically designed for laser-based systems. The fiber performance characteristics are based on actual laser bandwidth measurements. Typical applications are local area networks using 850 nm VCSELs, 980 nm CD lasers, and 1300 nm Fabry-Perot lasers. The fiber is designed to operate from -60 to +85 °C.³

³ Corning Press Release of 23 Feb.'99 and related data sheets

- 4.1.2 Plastic Optical Fibers (POF): Plastic optical fibers are flexible and easy to terminate, they are usually large in diameter and durable, the cost to connect in a system is low and they can operate in the visible and infrared regions. Early development of step index POFs provided fibers mostly for lighting, illumination and display. A fraction of fibers were used for data communication. With the invention of high bandwidth PMMA (polymethyl methacrylate) based graded index POFs⁴, they became suitable for communication and with the development of new perfluorinated graded index fibers⁵ they can now operate in the infrared region. As the components such as opto-electronic devices and connectors for the POFs are becoming available, their penetration into the communication marketplace can be significant.

Typically step index fiber consists of a PMMA core with a fluorinated polymer cladding. The graded index fiber has a doped PMMA core with a PMMA based cladding. The newer perfluorinated graded index fiber has a doped core that diffuses to outside clad during the fabrication process. Boston Optical Fiber (BOF) Corp. is utilizing three methods to produce GIPOFs⁶: the interfacial gel polymerization (IGP) method and two diffusion techniques. All three methods use low molecular weight dopants to vary the refractive index of the core. All dopants decrease the glass transition temperature of the fiber core.

- 4.1.2.1 Optical Characteristics of POF: Optical attenuation of POF is measured⁷ using a cut back method where the fiber is cut at a length of 2 to 5 m from the end. Ends of fiber are polished. Optical power through the fiber is then measured and the attenuation is calculated using the input and output powers per unit length. A typical attenuation result for a step index fiber is shown in Figure 2. A typical attenuation result for a graded index fiber (BOF) is shown in Figure 3.

A typical attenuation result reported⁸ for a perfluorinated GIPOF was less than 100 dB/km at 650 to 1300 nm wavelengths and the lowest attenuation of 50 dB/km was observed at 1300nm.

Some of the optical properties, such as, optical attenuation, bandwidth, and numerical aperture (NA) are summarized in Table 2.

A typical bend radius POF can withstand is around 25 mm. Bending loss depends on the number of bends, bend radius, and fiber numerical aperture (NA).

⁴ Koike et al., p. 46

⁵ Yoshihara et al., p. 27

⁶ Illashenko and Berman, 1998

⁷ JIS C 6863 , 1990

⁸ Yoshihara et. al, p. 27

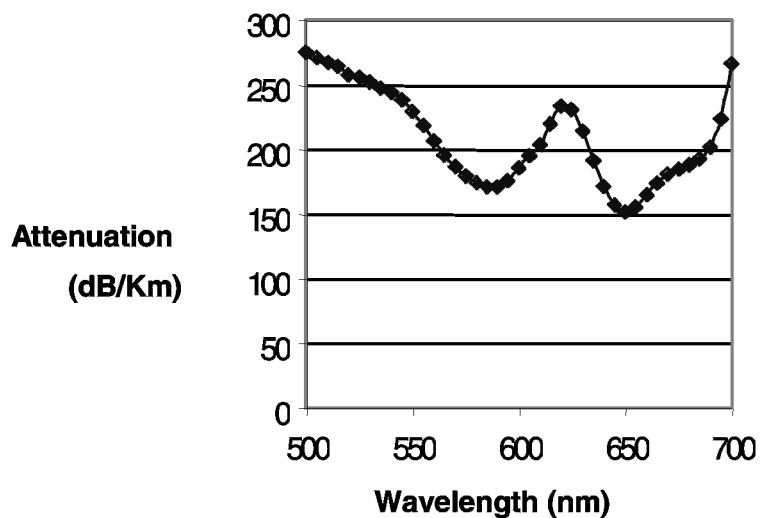


FIGURE 2 - Typical Attenuation Plot For A Step-Index POF

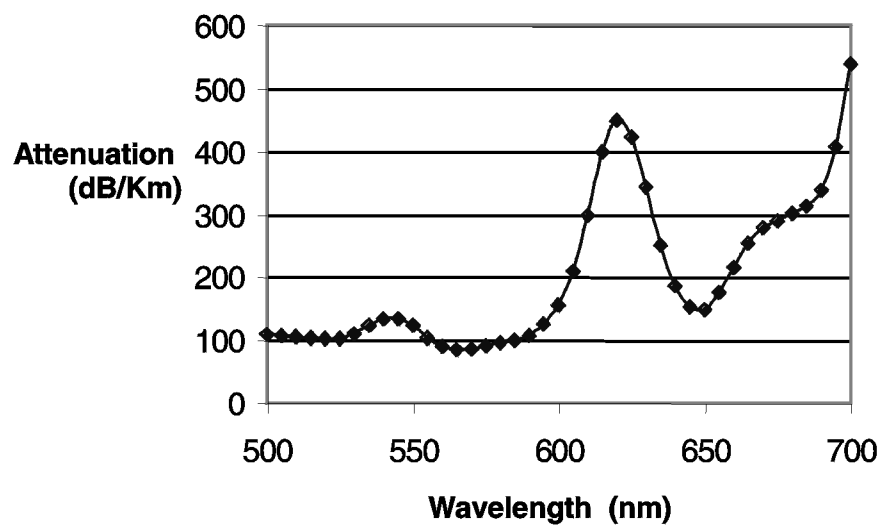


FIGURE 3 - Typical Attenuation For A Graded-Index POF

TABLE 2 - Optical Properties of Different POFs

Properties	SIPOF	GIPOF (PMMA)	GIPOF (Perfluorinated)
Attenuation (dB/km) @650 nm	140-150	150-180	<100 (650-1300 nm)
Bandwidth (MHz/100 m)	100-1000	1000-2500	3000-6000
Numerical Aperture	0.3-0.5	~0.2	~0.2

4.1.2.2 Mechanical Characteristics of POF: Typically tensile testing is done using a tensile tester. In this test, a finite length of fiber (25 to 50 cm) is wrapped around top and bottom capstans and the fiber is pulled in tension. Typically the yield force, breaking force, and elongation are recorded.

Typical breaking force for the SIPOF is around 9 kg with an elongation of nearly 100%, whereas for the graded index fibers the breaking force is lower due to additional dopants into the core.

When the SIPOFs are subjected to compressive loading, typical added attenuation was reported to be <0.2 dB for a 50 kg load⁹.

When the fibers are subjected to different temperatures and humidities, SIPOFs and GIPOFs behave differently. Typically, the SIPOFs can withstand temperatures up to 85 °C without any change in attenuation for 1000 hours. As the fibers are exposed to humidity at 85 °C, the attenuation increased to nearly 3 dB/100 m.¹⁰ In the case of GIPOFs, an attenuation increase of 10 dB/km was reported¹¹ when the fibers were exposed to 70 °C for 1000 hours. When the SIPOFs are exposed to room temperature water for nearly 3 months and later tensile tested at ambient conditions, the breaking force of the fiber dropped by ~15%.¹² POFs in general can withstand different harsh environments such as seawater, sodium hydroxide, engine oil and sulfuric acid.¹³

⁹ POF Data Book, Published by MRC Techno Research Inc. (1993).

¹⁰ Technical Bulletin, Toray Industries Inc.

¹¹ Lucina Optical Fiber, Asahi Glass.

¹² D Biswas, V. Ilyshenko and G. Hulse, p.44

¹³ Technical Bulletin, Toray Industries Inc.

4.1.2.2 (Continued):

Plastic Optical Fiber (POF) has the potential for significant improvement in termination complexity, interface robustness, and cable repairability over glass fiber and copper media. Current POF technology is limited by the base material polymethylmethacrylate (PMMA) which restricts the operating distance to 50 meters, the operating temperature to 85 °C, and the transmitter wavelength to 650 nm. New material development using Fluoropolymer Graded Index POF (FGIPOF) will improve the attenuation for wavelengths of 650 to 1300 nm allowing the use of gigabit 850 nm VCSELs and 980 nm ruggedized lasers. FGIPOF will increase the operating temperature range to (-55 to 150 °C) overcoming the temperature restrictions of aerospace applications. Distance and bandwidth capability will also increase providing a fiber link capable of greater than 1Gb/s over 100 m or 2.5 Gb/s over greater than 30 m.¹⁴

4.1.3 Hard Clad Silica (HCS) Fibers: A new family of fibers with a pure silica glass core and hard polymer (with proprietary composition) cladding is being considered for aerospace applications because of the inherent strength and ease of termination. These fibers are also receiving attention for local area networks in the commercial sector.^{15,16}

4.1.4 Radiation Hardness: Past radiation hardened fiber based system designs have evolved from the requirements to survive nuclear weapons effects. Current system designs have focused on other environmental needs (i.e. nuclear power plants, nuclear waste management, and the natural space environment). These new adverse environmental requirements along with nuclear weapon survivability criteria have increased interest in the development of radiation hardened optical fibers and associated components. These new requirements have also increased the spectrum of survivability as well as the types of degradation. The most common fiber types that have been considered for space systems are large core (>100 µm), step index, multi-mode fibers for data transmission and polarization preserving single mode fibers for sensors.

The natural space environment, while less severe than the effects of nuclear weapons, is very important because of the wide variety of nuclear phenomena it encompasses. The principal concerns for fiber based systems in the space environment include total dose due to electrons and protons in the Van Allen Belts, solar flare particles and ionizing energetic ions (cosmic rays). Table 3 presents a summary of the most dominant radiation effects on elements of a fiber based system.¹⁷

¹⁴ Cirrilo and Steele

¹⁵ U.S. Patent 5,381,504

¹⁶ Novak et al.

¹⁷ Greenwell and Barnes, p.215, Table 1.

TABLE 3 - Most Dominant Radiation Effects On Elements of A Fiber Based System

Element of Fiber Optic System	Nuclear Radiation Type				
	Total Dose	Prompt Transient	Proton Fluence	Neutron Fluence	Charged Energetic Particles
Transmitter	Circuit Noise Increase	Circuit Upset/Burnout	Circuit Gain Decrease	Circuit Gain Decrease	Single Event Upset/Latchup
LED	Other Effects Dominate	Other Effects Dominate	Light Output Decrease	Light Output Decrease	Other Effects Dominate
Laser Diode	Other Effects Dominate	Other Effects Dominate	Threshold Current Increase	Threshold Current Increase, Quantum Effect Decrease	Other Effects Dominate
Coupler/Connector	Attenuation Increase	Other Effects Dominate	Other Effects Dominate	Other Effects Dominate	Other Effects Dominate
Optical Fiber	Attenuation Increase	Increased Attenuation Luminescence	Attenuation Increase	Other Effects Dominate	Other Effects Dominate
Photodiode	Leakage Current Increase, Optical Responsivity Decrease	Induced Photocurrent	Leakage Current Increase	Responsivity Decrease, Leakage Current Increase	Transient Photocurrent
Receiver	Circuit Noise Increase, Circuit Sensitivity Decrease	Circuit Upset/Burnout	Circuit Gain Decrease	Circuit Gain Decrease	Single Event Upset/Latchup

4.2 Optical Fiber Physical Properties:

In order to adequately specify and standardize on a fiber optic high density cable for aerospace applications, the following physical fiber characteristics must be specified as well as parameters for assuring uniformity from fiber to fiber.

- Fiber Core and Cladding Composition
- Fiber Core and Cladding Diameter
- Fiber Core/Cladding Concentricity
- Fiber Buffering Diameter
- Fiber Buffering/Cladding Concentricity
- Fiber Core Non-circularity
- Fiber Coating Material Composition
- Fiber Coating Diameter
- Fiber Core/Cladding/Buffering/Coating Concentricity
- Fiber Color Coding
- Buffered Fiber Flammability Resistance
- Resistance to Fluids
- Fiber Minimum Bend Radius
- Fiber Tensile Strength
- Fiber Temperature and Humidity Tolerance

4.3 Optical Properties of Fibers:

In order to adequately specify and standardize a high-density cable plant for aerospace applications, the following optical characteristics shall be specified as well as uniformity in optical properties from fiber to fiber.

- Fiber Numerical Aperture
- Fiber Index Profile
- Fiber Mode Field
- Fiber Operating Wavelength
- Fiber Attenuation vs. Wavelength
- Fiber Micro-bending Loss
- Fiber Bandwidth
- Fiber Modal Characteristics

4.3 (Continued):

- Fiber Polarization Characteristics
- Fiber Radiation Hardness
- Fiber Cutoff Wavelength
- Fiber Chromatic Dispersion

4.4 Fiber Optic Ribbon Cable Construction:

Ribbon fiber optic cable for aerospace applications can be categorized as: (1) encapsulated fiber optic ribbon cables and (2) Non-encapsulated fiber optic ribbon cables.

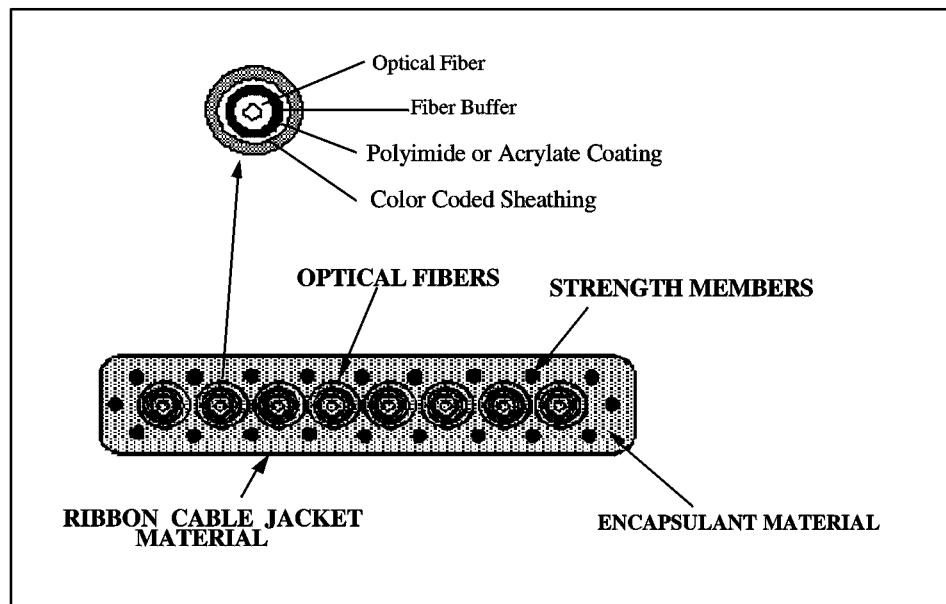


FIGURE 4 - Cross Section of an Encapsulated Fiber Optic Ribbon Cable

- 4.4.1 Encapsulated Fiber Optic Ribbon Cables: The encapsulated fiber optic ribbon cable utilizes a grid like structure wherein a fiber optic ribbon and a strengthening member are positioned and held in a composite structure in a manner to optimize the optical and physical properties of the cable. The strength members, which are embedded in a flexible encapsulant material are comprised of longitudinal or helically wound fibers of glass, Kevlar, or other suitable materials or comprised of a woven fiber fabric which surrounds the optical fibers. A suitable encapsulant material, such as an elastomer, is applied to a matrix of the optical fibers and strength members to seal the structure providing mechanical and environmental protection for the fibers and forms a flexible sheet. A further coating is applied over the encapsulant to provide scuff and abrasion resistance. Figure 4 depicts the cross section of a typical encapsulated fiber ribbon cable with a jacket to surround eight optical fibers and encapsulant. Figure 7 is a photo of an encapsulated fiber optic ribbon cable.

- 4.4.2 **Non-Encapsulated Fiber Optic Ribbon Cables:** A non-encapsulated fiber optic ribbon cable is similar in construction to currently utilized fiber optic cables. Individual optical fibers are retained in a side-by-side flat configuration through the application of a suitable adhesive material or use of an adhesive strip to form a fiber optic ribbon. This ribbon of optical fibers, held in place by the adhesive, is helically wrapped with a suitable material to provide mechanical and environmental protection to the adhesively joined fibers. Longitudinal strength members are placed over and under the wrapped ribbon fibers and a final tubular jacketing is applied to form a stand alone flat fiber optic ribbon cable. Figure 5 is a cross section of a non-encapsulated cable and Figure 6 is a photo of a cable with this type construction.
- 4.4.3 **Fiber Optic Ribbon Cable Physical Properties:** A next generation ribbon cable plant shall utilize an optimum ribbon cable construction for the particular application. The choice of cable construction and materials will impact many physical and optical properties including micro-bending sensitivity, splice ability, fiber stress corrosion, thermal stability, aging stability, ease of termination, breakout capability etc. Properties of cabling materials, which must be considered, include Young's modulus, melting point, adhesion, viscosity, etc. .

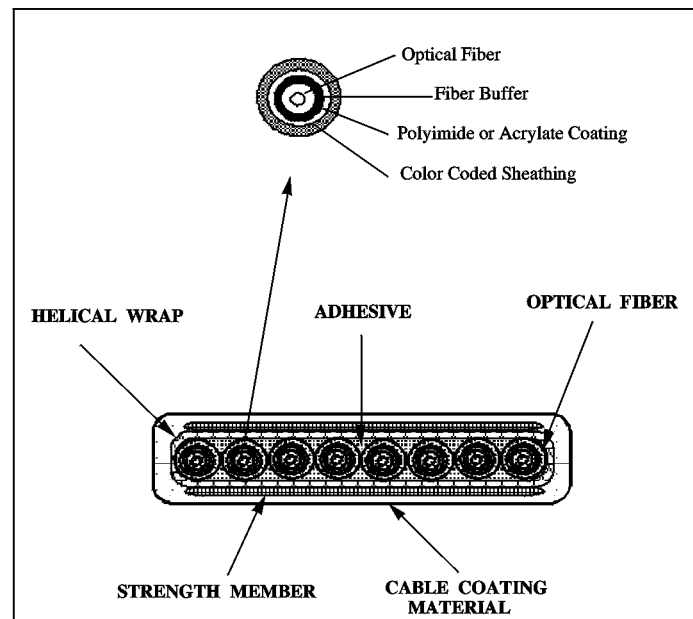


FIGURE 5 - Cross Section Of An Non-Encapsulated Fiber Optic Ribbon Cable

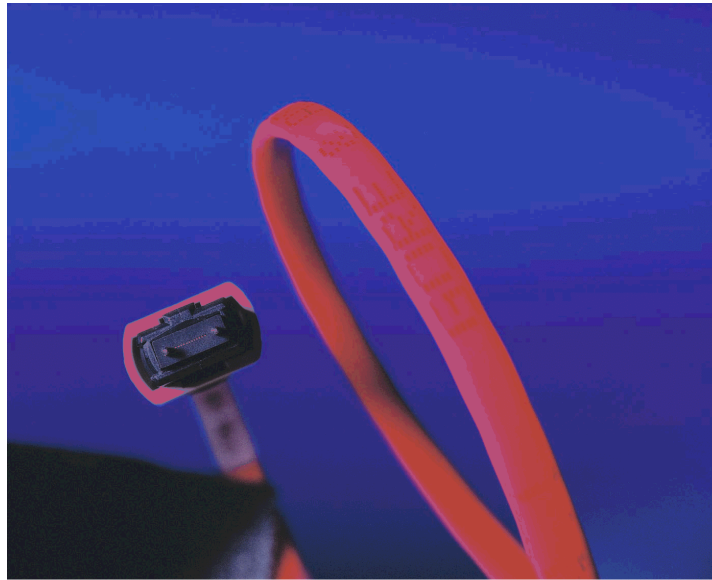


FIGURE 6 - A Non-Encapsulated Ribbon Cable With an MT Connector (Courtesy Gore Associates)



FIGURE 7 - An Encapsulated Fiber Optic Ribbon Cable With a Woven Strength Member From Patsi With Silicon V-Groove Connectors from Fotron Corp. (Courtesy Lockheed Sanders Corp.)

4.4.3 (Continued):

Below is a list of physical cable parameters and applicable documents, which detail the parameters which shall be specified to meet performance and environmental requirements for aerospace applications

- Cable Type
 - Encapsulated
 - Non-encapsulated
- Cable Strength Member
 - Woven
 - Longitudinal
 - Wrapped
- Number of Fibers in Cable
- Fiber Spacing in Cable
- Cable Geometry
- Cable Cross Section Dimensions
- Cable Tensile Strength
- Cable Cyclic Flexing
- Cable Bend Sensitivity
- Cable Torsion Resistance
- Cable Temperature Tolerance
- Cable Humidity Tolerance
- Cable Crush Resistance
- Minimum Cable Bend Radius
- Cable/Fiber Coating Colors
- Cable Aging Stability
- Cable Water Blocking
- Cable Breakout and Stripability
- Skew Properties
- Cable Fluid Resistance

- 4.4.4 Stacked Fiber Optic Ribbon Cables: Because of the flat nature of fiber optic ribbons, these ribbons can be stacked to form an organized two dimensional array of fibers. Ribbons shall be cabled in various configurations to achieve even higher packing density than a single ribbon cable. Figures 8 and 9 show isometric views of commercial circular stacked fiber optic ribbon cables. This organized, and indexed fiber cabling approach is analogous to the ribbon organized interconnect (ROI) utilized for electrical wiring on the Navy V-22 Osprey tilt rotor aircraft.

4.4.4 (Continued):

The stacked ribbon approach can also be utilized for an encapsulated ribbon to form a two dimensional cross section square or rectangular cable. In the case of encapsulated ribbons, the encapsulant must be used to encase the multi-ribbon stack including strength members in the fabrication process while in the non-encapsulated case; the individual ribbon cables may be contained in a common jacket to form a stacked ribbon cable. As with the flat ribbon cable, these cables provide the option for batch cleaving and polishing as well as cost effective termination concepts.

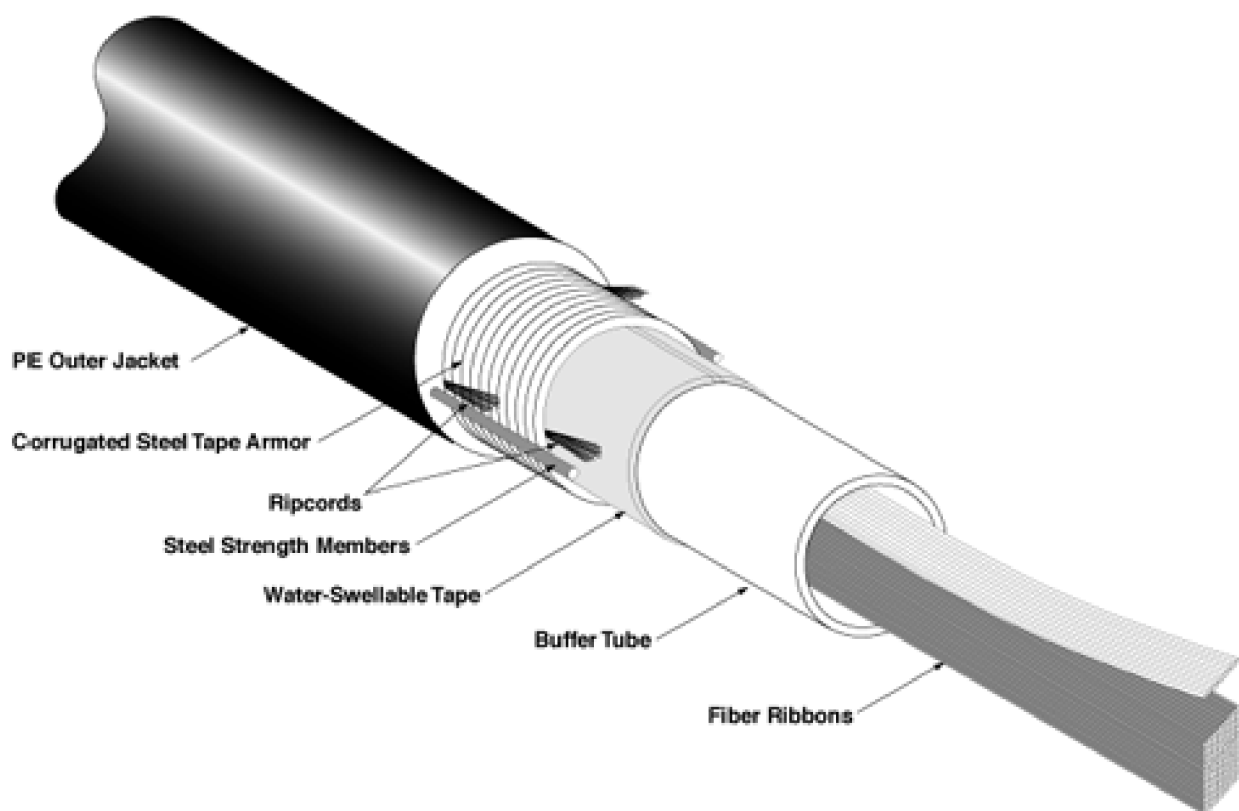


FIGURE 8 - An Armored Circular Stacked Fiber Optic Ribbon Cable¹⁸

¹⁸ <http://www.siecor.com/public/p-altosa.htm>

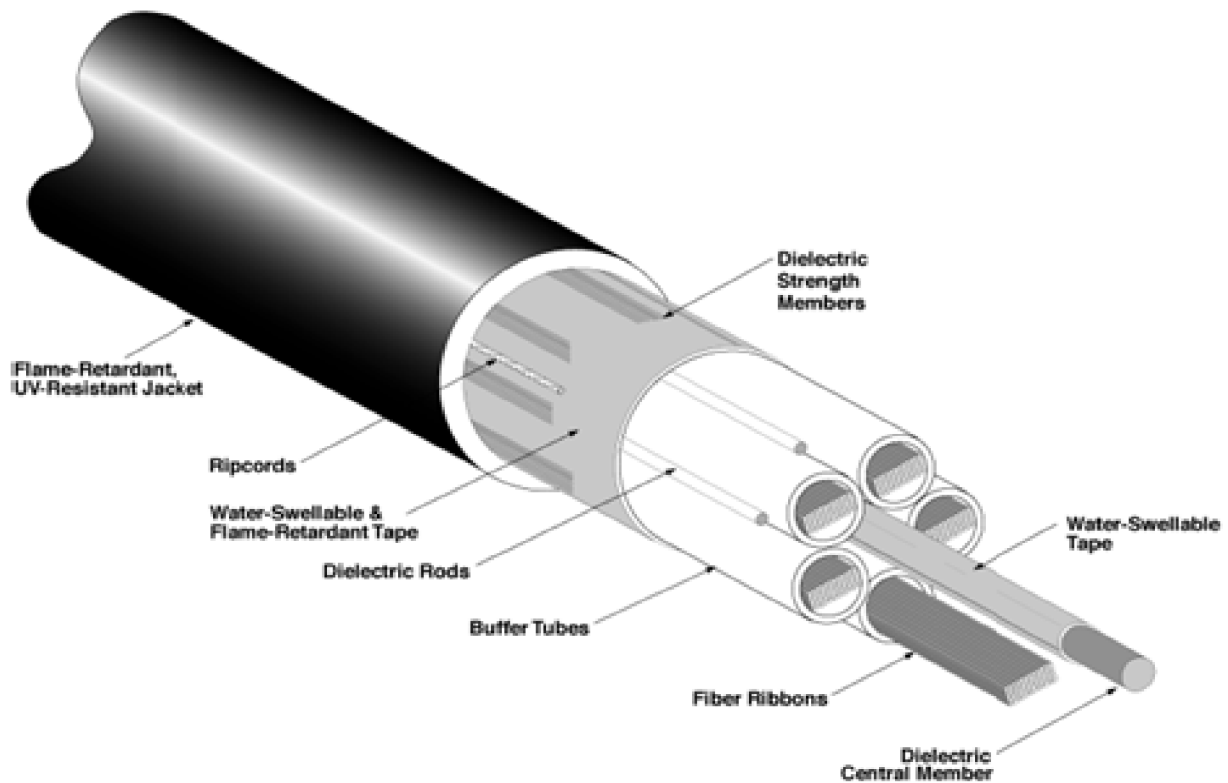


FIGURE 9 - A Commercial Stacked Ribbon Cable With Dielectric Strength Members¹⁷

4.4.5 Suggested Cable Test Procedures: Cables shall be tested in accordance with applicable EIA/TIA or equivalent MIL Standards to assure compliance with operational and environmental requirements. To perform testing, launch conditions shall be in accordance with applicable EIA/TIA and or MIL standards.

4.5 High Density Fiber Optic Termination Concepts:

The flat configuration of fiber optic ribbon permits the use of batch fabricated and grooved planar multi-fiber termini concepts. The termini can be batch fabricated by chemical etching, molding, electro-forming etc., to provide alignment of the individual fibers in a ribbon. The photo-lithographic definition and/or precision micro machining of these grooves provide very accurate dimensional tolerance. The commercial telecommunications industry has been exploring mass array terminations at low cost and high volume. These commercial termination concepts can be adapted to aerospace applications at a reasonable cost. Figure 10 is a cross section of a single crystal silicon chip in which a V-groove has been photographically defined and chemically etched along a preferred crystallographic plane. The V-grooves are etched to accommodate a specific fiber size and suitable alignment features may also be defined on the edges of the chip.

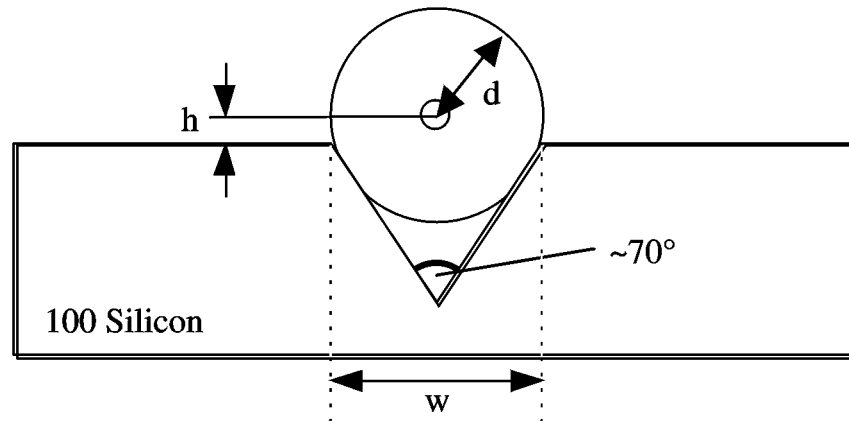


FIGURE 10 - Cross Section Of A Silicon V-Groove Etched In A Silicon Substrate

4.5 (Continued):

The fibers are laid into the V-groove after the cabling and coatings have been stripped from the fiber. Certain coatings such as polyimide may be retained on the fiber after placement in the groove. A mated silicon V-Groove chip shall be bonded over the fibers to form a registered pair with external alignment and registration grooves. This batch termini block shall be placed in a circular or rectangular backshell with a suitable retention, sealing and mating mechanism. To implement a lens into a silicon V-groove termini block, (1) an extended V-groove shall be etched in the silicon to place a graded index rod in front of the optical fiber to expand the optical beam or (2) another groove shall be etched to align a spherical lens in front of the optical fiber. Also micro-lens arrays fabricated as a monolithic window can be placed in front of the silicon alignment block to protect fiber surfaces and enhance optical performance. Figure 11 is a photomicrograph of an etched silicon substrate containing silicon v-grooves.¹⁹

To terminate stacked fiber ribbon cables silicon alignment blocks shall be stacked and bonded to provide registration of the fibers in a stacked fiber ribbon cable. Connectors utilizing silicon V-Groove multi-fiber termini are currently manufactured by Berg, AT&T, Fotron Corp. et. al. Figure 12 is a picture of a commercial connector that utilizes the silicon V-groove termination. A military version of this that utilizes the same V-groove termination concept is available for military systems.

¹⁹ <http://www.siecor.com/public/p-altosd.htm>

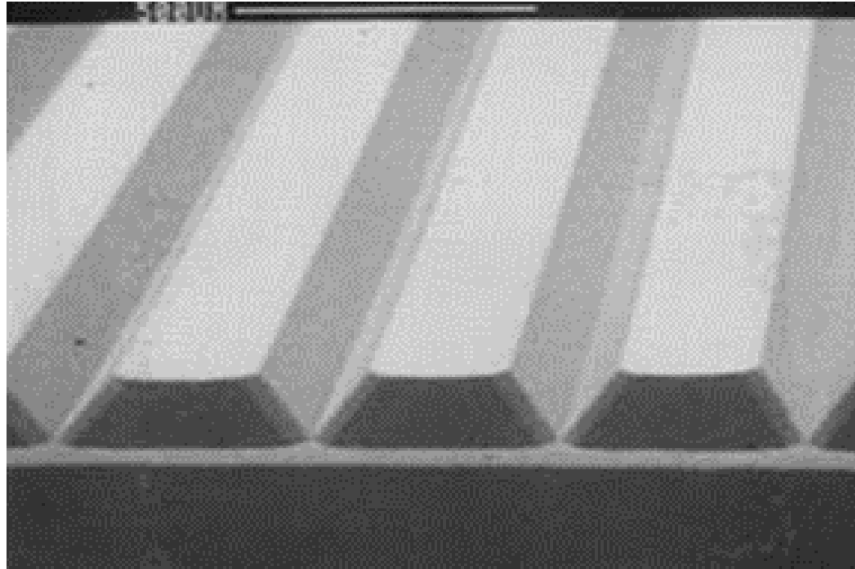


FIGURE 11 - A Photomicrograph of an Etched Silicon Substrate Containing Silicon V-Grooves



FIGURE 12 - A Silicon V-Groove Connector (Courtesy Berg Electronics)²⁰

4.5 (Continued):

Another solution to the difficulties of fabricating a high-density optical connector is precision molding techniques. One example of such a multiple contact termination connector that is commercially available is the MT connector. The MT ferrule of Figure 13 is a multi-fiber termini that is commercially available in 4, 8, 12, and 16 density for a single connector. Additionally, stacks of five 16-fiber connectors are available creating an 80-fiber connector assembly.²¹

²⁰ http://www.bergelect.com/product/optic/optic_mini.htm

²¹ Satake et al., p.997

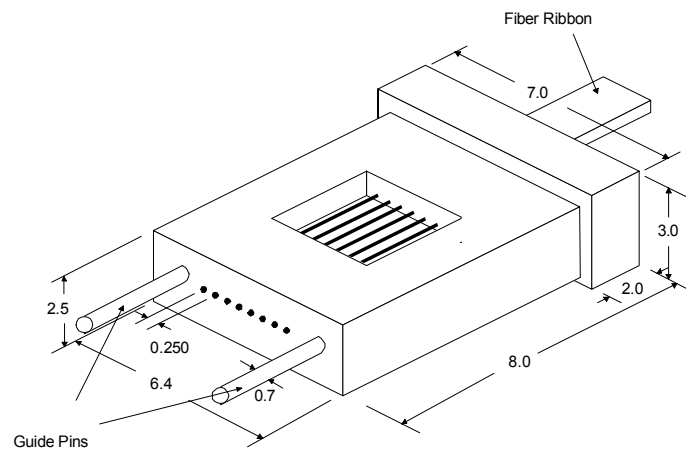
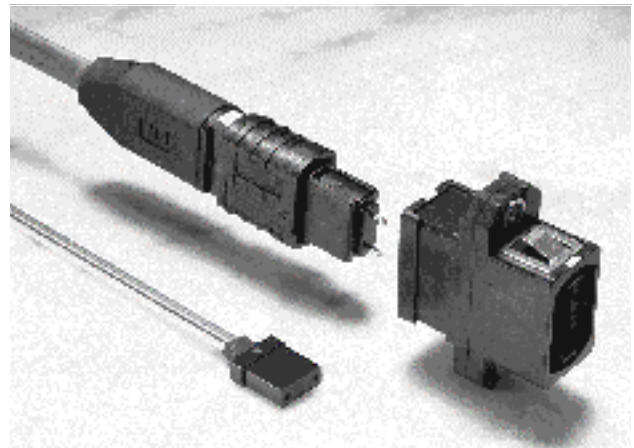


FIGURE 13 - A Molded MT Array Ferrule



(1)



(2)

FIGURE 14 - A Molded Connector (Courtesy (1) USCONEC²² and (2) Molex²³)

²² <http://www.usconec.com/products/>

²³ <http://www.molex.com/product/fiber/fomtcabl.html>

4.5.1 Fiber Optic Termini Properties: The relevant properties of connector Termini that must be specified are listed below:

- High Density Interface Definition
 - Silicon V-Groove
 - Machined Ceramic Insert
 - Alignment Bearings
 - Hexagonal Packed arrays
 - Molded V-Grooves
 - Micro-lens arrays
- Alignment Mechanisms
 - Dowel Pin Spacing
- Fiber geometry and spacing
- Connector Optical Interface
 - Butt Joint Flatness
 - Angle polish specification
 - Spherical lens properties
 - Graded Index Rod lens properties
 - anti-reflection coatings
- Maximum optical Attenuation
- Reflectance

4.5.1.1 Multi-Fiber Array Ferrule Termination Procedures: The following termination procedure for the MT ferrule has been developed by USCONEC Corp. The termini and equipment for this termination is commercially available through document CD A01-003, Issue –2, of January 1998.²⁴

Fiber Ribbon Preparation: . Mark the ribbon approximately 25 mm from the end.

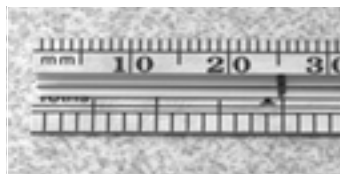


FIGURE 15 - Ribbon Preparation Procedure Step 1

Place the ribbon in a ribbon holder.

²⁴ <http://www.usconec.com/MTPprocs.htm>



FIGURE 16 - Ribbon Preparation Procedure Step 2

4.5.1.1 (Continued):

Using a hot ribbon stripper, remove the ribbon material and the fiber coating.



FIGURE 17 - Ribbon Preparation Procedure Step 3

Clean the bare fiber strands with a lint-free wipe and alcohol to remove coating residue.



FIGURE 18 - Ribbon Preparation Procedure Step 4

Place the ribbon holder into a fiber-cleaving device and cut the fibers evenly at a length of 10 (± 3) millimeters. Check for damaged or broken fibers. Note: A smooth, even cut will aid fiber insertion into the ferrule. Remove the ribbon from the holder. Slide a rubber ferrule boot onto the ribbon taking care not to break the bare fibers. The boot should be oriented so that the thicker half, which contains a small number, is closest to the bare fibers.

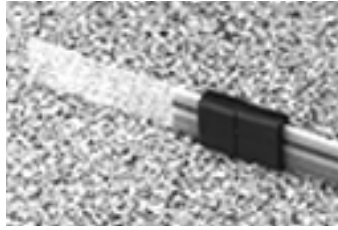


FIGURE 19 - Ribbon Preparation Procedure Step 5

4.5.1.1 (Continued):

Determine which edge of the ribbon is the #1 fiber. Typically, the #1 fiber has a black stripe on the ribbon or is the dark blue colored fiber in the ribbon matrix.

Obtain a ferrule and find the colored dot on the side.

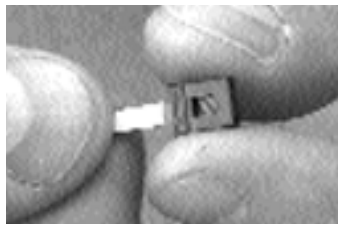


FIGURE 20 - Ribbon Preparation Procedure Step 6

With the #1 fiber to the side of the ferrule marked with the colored dot, insert the fibers into the rear of the ferrule. Tilt the ribbon slightly while looking through the window of the ferrule, watch the fibers move along the guide grooves and gently insert them into the ferrule. The fibers should slide into the holes and pass smoothly through the ferrule end face, however, if any resistance is felt, back the fiber out slightly and try again, watching in the window to ensure all fibers are in the proper track. Any bending of a fiber signifies misalignment and will cause fiber breakage. After confirming the fibers fit into the ferrule, remove the ferrule from the ribbon. MT installation onto single-mode fiber requires EPO-TEK 353 ND (clear) Epoxy. Combine the main part (transparent; part A) to the catalyst part (amber; part B) with a ratio of 10 to 1 (A to B) by weight in a container. Mix and de-gas thoroughly. Cure time for this epoxy at 80 ($\pm$ 5) degrees Celsius is 55 minutes. MT installation onto multi-mode fiber requires Fiber-Fix FA-06 (white) Epoxy. Combine the resin (white; part A) with the catalyst (amber; part B) using a ratio of 25 to 7 (A to B) by weight in a container and mix thoroughly. Cure time for this epoxy at 85 ($\pm$ 5) degrees Celsius is 15 minutes. Notice: The use of safety glasses for eye protection is recommended.

4.5.1.1 (Continued):

MT Ferrule Termination: Prepare the epoxy according to the fiber type you are working with. Instructions for epoxy preparation are found at the beginning of this section. Turn on the suction pump or prepare suction syringe. Using a toothpick, apply a drop of epoxy through the front edge of the ferrule window and place along the grooves.

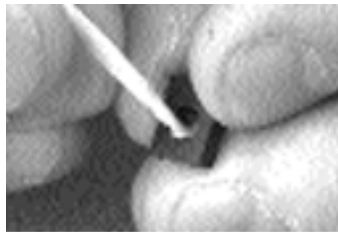


FIGURE 21 - Ferrule Termination Procedure Step 1

Insert the ferrule end face into the suction tube nozzle until the front edge of the ferrule window lines up with the tip of the nozzle. Cover the rear of the ferrule so that the guide pinholes are blocked. Allow the vacuum to draw epoxy through the fiber holes for approximately 5 seconds, or until epoxy has filled all the fiber holes. Note: Failure to follow this step will lead to inconsistent epoxy coverage between the fibers and holes, resulting in poor performance of the connector. After removal from the nozzle, a bead of epoxy covering the fiber holes should remain on the ferrule end face.



FIGURE 22 - Ferrule Termination Procedure Step 2

With the #1 fiber to the side of the ferrule with the colored dot, insert the fibers into the rear of the ferrule. Tilt the ribbon slightly while looking through the window of the ferrule. Watch the fibers move along the guide grooves and gently insert them into the ferrule. The fibers should slide into the holes smoothly and pass through the ferrule end face; however, if any resistance is felt, back out slightly and try again, watching through the window to ensure that all fibers are in the proper track. Any fiber bending signifies misalignment and will cause fiber breakage.

4.5.1.1 (Continued):

Look into the ferrule window and make sure the edge of the ribbon matrix is located between the back edge of ferrule window and the step marking the end of the grooves. Note: Pushing the edge of the ribbon matrix past the step and onto the grooves may cause the fibers to break. Carefully slide the boot into the back end of the ferrule until it stops. When in proper position the edge of the boot will be visible in the back of the window.



FIGURE 23 - Ferrule Termination Procedure Step 3

Check the end face to ensure there is an epoxy bead around the protruding fibers. If not, carefully apply a drop of epoxy to form the bead, making sure that no epoxy is applied inside the guide pinholes. Apply epoxy into the window until the cavity is full. Take care that no air pockets are formed inside the ferrule cavity.



FIGURE 24 - Ferrule Termination Procedure Step 4

Place the ferrule into the ferrule heater. Recheck the epoxy level in the window and add if necessary (some settling may occur due to the epoxy spreading to fill the cavity). Care should be taken not to overfill the cavity, as excess epoxy will have to be removed after curing.



FIGURE 25 - Ferrule Termination Procedure Step 5



FIGURE 26 - Ferrule Termination Procedure Step 6

4.5.1.1 (Continued):

Follow the cure procedure. This information may be found in the epoxy instructions at the beginning of this section. After curing, remove the ferrule from the oven and allow it to cool. Using a scribing tool, etch the fibers along the epoxy bead on both sides of the ferrule. Grasping the fibers between the thumb and forefinger, gently pull the fibers straight away from the end face.

Route the ferrule to polishing.

Commercial polishing equipment is now available for obtaining the desired end finish of the termini. Figure 27 is a polisher commercially available from USCONEC. Other manufacturers are also offering automated polishing equipment for array ferrules.



FIGURE 27 - Computerized Connector Termini Polishing Equipment
For MT Ferrules Available Through USConec²⁵

²⁵ <http://www.usconec.com/Polisher/MTA030.htm>