

FIBER OPTICS-FAILURE MODES AND MECHANISMS

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KEY WORDS: Failure, Degradation modes, Transmitters, Receivers, Fiber and Cable, Splices and Connectors

SUMMARY AND CONCLUSION

With the increased use of fiber optics in military systems comes the need to address the failure modes and mechanisms associated with this technology so that preventive design measures can be instituted to improve reliability. The purpose of this study was to investigate the frequency and cause of failures of fiber optic transmitters, waveguides, receivers, connectors and splices. To accomplish this, quantitative and qualitative data were collected and evaluated to determine why and when failures occurred and to identify design options which can be made to avoid these failure conditions. An understanding of fiber optic device failure modes and mechanisms is critical to insuring unit reliability, improving the manufacturing process and allowing design flexibility of the overall fiber optic system.

This paper summarizes the specific failure modes uncovered for typical items such as transmitters, receivers, fiber, cable, connectors and splices. In general, these items constitute the necessary components (reference Figure 1) for a typical fiber optic system. This paper includes discussions of fiber optic performance criteria, design considerations, failure rate data and failure mode information, all of which will aid designers and planners of fiber optic systems in ensuring a reliable system with lower support costs.

INTRODUCTION

The fiber optic technology is a relatively new process when compared with most electronic devices. As a result, their specific failure modes and reliability levels have not been well documented. The general state of failure

documentation is that commercial manufacturers have a great deal of experience and internal files and are reluctant to share. On the military side, the usage level is limited with one-of-a kind systems being the normal procurement. To overcome this deficiency, this project collected device information from a number of published sources such as journals and symposium proceedings. In addition, in house data were accumulated based on advanced development model tests performed for Rome Laboratory. All data were reviewed and evaluated to determine how these devices failed in a fiber optic system and their relative reliability figure of merit.

To make sure everyone understands the definition of a fiber optic system as used in this paper, the following are provided and highlighted in Figure 1:

Transmitters - A fiber optic component that transmits light; an amplifier. Example devices are Light-Emitting-Diodes (LEDs) and Laser Diodes (LDs).

Receivers - A fiber optic component that receives light signals. Example devices are Avalanche Photodetectors (APD) and Positive-Intrinsic-Negative (PIN) photodetectors.

Information Channel - The path between the transmitter and receiver. The channels are usually glass or plastic fiber cables.

Connectors and Splices - Used to interconnect optical fibers. The connector and splice schemes used are mechanical and fusion.

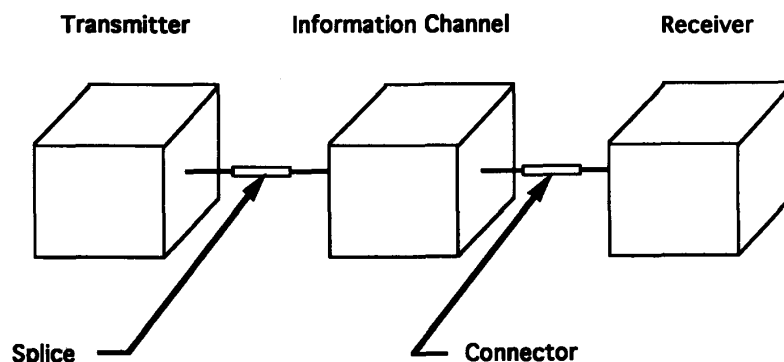


FIGURE 1

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RELIABILITY NUMERICS

Establishing reliability figures of merit for fiber optics was accomplished by collecting and analyzing data from one-of-a-kind military systems and limited commercial systems. This process was started by performing an in-depth literature search, a review of technical reports, consultation with fiber optic component experts and discussions with component vendors. The bulk of failure and operating data was collected by Vitro Corporation and reported in reference 1.

These failure and operating data covered a wide range of part types, environmental conditions and test procedures. For most cases, limited data points were established resulting in the need for small sample statistics to evaluate the reliability values.

Utilizing the properties of the Central Limit Theorem (CLT), which states that a distribution of means approaches the normal as the sample size increases, we can begin to place bounds on the mean-time-between-failure (MTBF) data that is available thus far. Due to the limited nature of the data, Chebyshev's inequality will be used to establish confidence bounds on the failure rate of various technologies associated with optical systems.

In theory, three estimates can serve as points on a distribution curve. The mode (M) of this distribution is the most likely estimate of the MTBFs, where $\lambda = \frac{1}{\text{MTBF}}$ while the extremes estimates will serve as the optimistic and pessimistic values of the MTBF, A and B, respectively.

These values are then used in Chebyshev's to place confidence bounds on the λ estimates.

The mean, μ is estimated as:

$$\mu = \frac{a+4m+b}{6}$$

and the variance as: $\sigma^2 = \frac{(b-a)^2}{6}$

Their values are then used in Chebyshev's to bound the estimates on the MTBF which is then converted to a failure rate.

$$P\{|X - \mu| \geq K\sigma\} \leq \frac{1}{K^2}$$

where $1 - \frac{1}{K^2}$ = confidence level

The data set that was collected for reliability analysis included operation of fiber optic components in a wide range of environments. As is noted in many reliability handbooks and standards (i.e. MIL-HDBK-217, Reliability Prediction of Electronic Equipment), the environment influences the part reliability. For this analysis, ground fixed was determined to be the dominant environment applicable for the data set, so other environments were merged by application of the MIL-HDBK-217 environmental factors to the failure and operating time. For example, connector operating times for ground mobile conditions were expanded by a factor of 8.0 and diodes by 9.0. These values are the ratios for environmental factors for mobile to ground.

The following table depicts the calculated failure rates and MTBFs using this analysis technique. In calculating these failure rates a confidence bound of 80% was used. This means that for the fiber we expect the failure rate for normal operating conditions to be between 4.3×10^{-6} and 5.26×10^{-6} failures per hour 80% of the time.

COMPONENT TYPE	FAILURE RATE (10^{-6}) HRS	MTBF (10^6) HRS		
		A	M	B
FIBER	4.35 - 5.26	.18	.21	.26
CABLE	1.15 - 1.81	.4	.75	.84
SPLICES	.022 - .64	14	27	54
CONNECTORS	# OF MATINGS	N/A		
MIL - T - 29504	1000			
MIL - C - 28876	500			
MIL - C-38999	500			
MIL - C-83522	500			
MIL - C-83526	1000			
FC- STYLE	1000			
LEDs				
AlGaAs/GaAs	.13 - .88	1	4	10
InGaAsP/InP	.78 - 1.92	.5	.85	1.5
InGaAs/Si	2.08 - 8.33	.01	.32	.5
LASER DIODES				
AlGaAs/GaAs	1.27 - 9.1	.08	.41	1.0
1.3 μ m wavelength	.79 - 9.1	.05	.62	1.6
InGaAsP/InP	.13 - 2.4	.04	3.7	10
PHOTODETECTORS				
APD	.12 - 1.54	.1	4	10
PIN	.57 - 3.58	.02	1	2

COMPONENT FAILURE RATES

The values A, B & M represent estimates of MTBF's for the various devices presented in the table. These estimates were assumed to be normally distributed about the true mean, with parameters μ and σ^2 where:

A=pessimistic estimate of the MTBF

B=optimistic estimate of the MTBF

M=most occurring observation of the MTBF

TRANSMITTERS

In a fiber optic system, light is the media in which information is transmitted. The predominant light sources used at this time are LED's and laser solid state devices.

A basic problem in determining the failure modes and mechanisms for these devices is what constitutes a failure. After surveying the laboratory technical community the most common definition was; 50% reduction in optical output power for LEDs and a 50% increase in threshold current for lasers. Operating below or above these values was considered to be degraded too give acceptable results.

Rapid and slow degradation are the most common failure modes associated with LEDs. Rapid degradation is caused by the formation of dark line defects (DLDs) and dark spot defects (DSDs). DLDs and DSDs are areas of nonradiative recombination in the active region caused by material impurities or crystal lattice defects generated during the manufacturing process. The lines and spots

cause a loss of output power, which is commonly measured in decibels (dB), resulting in degraded performance. Slow degradation is not dependent on DLDs or DSDs but contingent upon temperature. An expression in terms of optical output power, $P(t)$, that is frequently used in deriving the degradation rate is as follows:

$$P(t) = P_0 e^{-\beta t}$$

Where $P(t)$ is the output power as a function of time

P_0 is the initial output power

The degradation rate is given by :

$$\beta = \beta_0 e^{-E_a/kT}$$

Where β_0 is a proportionality constant

E_a is the activation energy in electron volts (eV)

k is Boltzmann's constant in joules/Kelvin

T is the temperature in Kelvin

This equation shows that the output power will vary as a function of temperature (T) and time (t). As the temperature increases, β will increase which in turn reduces optical output power $P(t)$ resulting in degraded performance.

Independent studies 4,5 have revealed three obvious conditions which cause lasers to degrade. In this case, the researchers investigated threshold current as the predominant failure mechanism and Figure 3 depicts those modes associated as a function of threshold current (I_{th}). These are the incubation mode, saturable current mode, and wear out mode.

Incubation mode (infant mortality) is the early failure period caused by inherent defects due to material selection, poor manufacturing process or other latent defects. A majority of these failures can be eliminated via an extensive manufacturer's burn-in test and screening procedures.

Saturable current mode is the rise in leakage or shunt current around the active region due to temperature and terminal current. This leakage current lends itself to the formation of DSDs which will reduce the optical power and increases the threshold current. These factors are the ingredients for a failed device. Leakage current can be minimized by employing a passivation layer to the device which helps reduce surface contamination and in-migration of atoms from contact deterioration (formation of DSDs). This reduces threshold current which in turn increases the life expectancy of the device. Once the threshold current has reached a stabilized condition, the DSDs remain constant and are unlikely to increase. This is reflected on Figure 3 at the "Knee" where the transition to wear out mode begins.

Three common failure mechanisms that are associated with wear out are facet oxidation, contact degradation and crystal grown-in defects.

Facet oxidation is due to photo-oxidation which is caused by extended high threshold currents. These squalid facets are most prevalent when lasers are operated in moist environments and when no prior passivation of the device has been performed. When facet curtailment occurs, the reflectivity diminishes. This affects the quantum efficiency in addition to the device exhibiting a temperature rise. These factors will contribute to a higher threshold current and a failure will be manifested over a period of time. To avoid photo-oxidation many manufacturers apply either an aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), or silicon nitride (Si_3N_4) coating. Care should be taken in applying this coating, for if applied too thick the reflectivity will be impaired and threshold current will be raised resulting again in a limited life situation.

Contact degradation is due to the heat transfer by conduction when the heat flows across the interface between two contacting surfaces. Because contact interfaces have relatively high thermal resistances and often are located in regions where the entire dissipation of an assembly flows across them, significant temperature differences can occur across such interfaces. As the operating temperature rises, the junction temperature follows accompanied by an increase in the threshold current and the reliability of the device is compromised. The increase in thermal resistance is dependent upon the type of solder used, the current density and the temperature. Environmental control is a prime factor in reducing contact degradation problems.

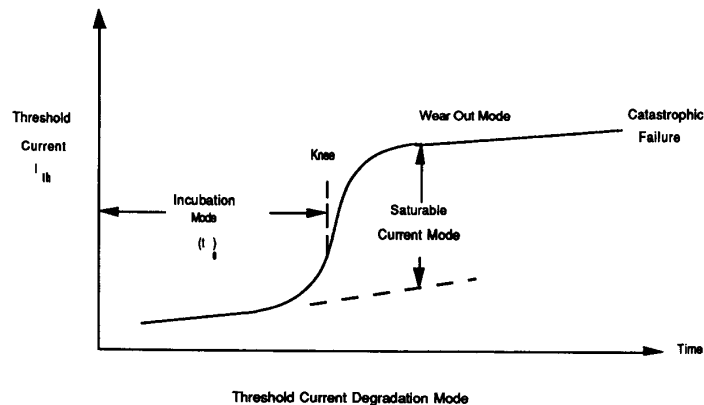


FIGURE 3

Lattice defects are introduced during the manufacturing process and impact the quantum efficiency of the device. Formation of Dark Line Defects (DLDs) from the lattice defects can spread over a larger surface area causing the optical output to decrease which in turns increases the threshold current. An increase in threshold current causes the temperature to rise which slowly causes a failure of the device over a period of time. The time to failure is a function

of device ratings and current values. Material selection plays a important criteria in part life expectancy. The use of material with low lattice defects will help to curtail the propagation of the DLDs to the active region. Quality control is a vital factor in selecting and testing for low lattice material.

Table 1 provides a synopsis of the common transmitter failure modes/mechanisms and their cause and prevention.

MODE	CAUSE	PREVENTION
FACET DAMAGE	PULSE WIDTH OPTICAL POWER DENSITY	ANTI-REFLECTIVE COATING APPLIED TO FACETS
LASER WEAR OUT	PHOTO-OXIDATION CONTACT DEGRADATION CRYSTAL GROW-IN DEFECTS	COATING FACETS REDUCE TEMP & CURRENT DENSITY USE HIGH QUALITY MATERIALS
LASER INSTABILITY DUE TO REFLECTIONS	OPTICALLY COUPLE OUTPUT POWER FROM LASER REFLECTS BACK	ANTIREFLECTION COATING,SLIGHTLY DEFOCUS THE GRADED INDEX COUPLING ELEMENT
WHISKER FORMATION	DETERIORATION OF SOLDER	ANTICIPATE SYSTEM LIFETIME & TEMPERATURE SOLDER TOLERANCES
DARK LINE DEFECTS DARK SPOT DEFECTS	NON-RADIATIVE CENTERS	MATERIAL SELECTION & QUALITY CONTROL

COMMON FAILURE MECHANISMS (TRANSMITTERS)

TABLE 1

Based on the analysis (Reliability numerics), Table 2 depicts the failure rates associated with these device types.

COMPONENT TYPE	FAILURE RATE (10) HRS	MTBF (10) HRS		
		A	B	C
LEDs				
AlGaAs/GaAs	.13 - .88	1	4	10
InGaAsP/InP	.78 - 1.92	.5	.85	1.5
AlGaAs/Si	2.08 - 8.33	.01	.32	.5
LASER DIODES				
AlGaAs/GaAs	1.27 - 9.1	.08	.41	1.0
1.3 μ m wavelength	.79 - 9.1	.05	.62	1.6
InGaAsP/InP	.13 - 2.4	.04	3.7	10

COMPONENT FAILURE RATES

TABLE 2

RECEIVERS

An optical signal needs to be transformed into an electrical signal and the two most common ways to do this in a fiber optic system is by using an Avalanche Photodetector (APD) or a Positive-Intrinsic-Negative (PIN) photodetector. Table 3 gives a listing of these devices by material type, related wavelengths and dark currents associated with each. The predominant failure mode of these two detector types is dark current, which is reverse current paths that drifts through a reverse-biased diode. Dark current is generated by thermal evolution of free charged carriers in the diode. This condition is representative of all diodes and will increase as the

temperature rises. Some researchers² have stated that for each 10°C increase in temperature, the dark current will double. As Table 3 shows, dark current can range from one nanoampere to hundreds of nanoamperes. Material selection plays an important criteria in use of these part types. If the operating characteristics are similar, that is comparable wavelengths, it would be more beneficial to choose detectors that inherently have low dark current.

In addition to the dark current problem, it has been found that a relative humidity condition of 85% or higher causes electrical shorts because of electro-chemical oxidation. If a designer of a fiber optic system intends to operate a system under this environment it is necessary to select hermetically sealed devices.

MATERIAL	CONSTRUCTION TYPE	WAVELENGTH (nm)	DARK CURRENT (na)
silicon	PIN	300-1100	1
germanium	PIN	500-1800	200
InGaAs	PIN	1000-1700	10
silicon	APD	400-1000	15
germanium	APD	1000-1600	100

PHOTODETECTORS

TABLE 3

One other failure cause is temperature cycling of lead-bond devices using plated contacts. To prevent this condition from occurring many designers are using devices with evaporated contacts instead.

Table 4 depicts the prevalent failure causes and prevention measures associated with receivers.

Based on the analysis (reliability numerics), Table 5 depicts the failure rates associated with these device types.

MODE	CAUSE	PREVENTION
TEMPERATURE CYCLING STRESS	LEAD-BONDS IN PLATED CONTACTS	USE EVAPORATED CONTACTS
HUMIDITY INDUCED	ELECTRO-CHEMICAL OXIDATION	USE HERMETICALLY SEALED PACKAGE
PIN DARK CURRENT	ACCUMULATION OF MOBILE IONS	InGaAs OR In LAYER GROWN ONTO ACTIVE REGION & REDUCE THE TEMPERATURE
ADP DARK CURRENT	THERMAL DETERIORATION OF THE METAL CONTACT	SELECT AN ADP AT 1.3 μ m & REDUCE THE TEMPERATURE

COMMON FAILURE MECHANISMS (RECEIVERS)

TABLE 4

COMPONENT TYPE	FAILURE RATE (10 ⁻⁴) HRS	MTBF (10 ⁴) HRS		
		1	5	3
PHOTODETECTORS				
APD	.12 - 1.54	.1	4	10
PIN	.57 - 3.58	.02	1	2

COMPONENT FAILURE RATES

FIBER AND CABLE

TABLE 5

Optical fiber and fiber optic cables are used in communication systems, process control, computer application, data transmission and other disciplines. Fiber optic cables have numerous operating advantages over established copper cables such as immunity to electromagnetic interference (EMI), reduced radio frequency interference (RFI), and low size and weight. However, no technology is immune to failures and so is the case with fiber optic cables, whether it be inherent or induced, each has its own peculiarity because of manufacturing, environment or application. We need to understand the fiber construction and characteristics in order to identify why a failure will occur.

There are four manufacturing processes for fiber optic cable which are; Outside Vapor Deposition (OVD), Vapor Axial Deposition (VAD), Modified Chemical Vapor Deposition (MCVD), and Plasma Chemical Vapor Deposition (PCVD). A common factor to all these fiber drawing processes is cleanliness. Impurities and pollutants caused by imperfect mixing and dissolution of chemicals can become trapped during the drawing process causing the density property to be compromised. The fiber drawing process influences the optical attributes, size and strength of the fiber.

The dominant failure mechanism for fiber is a fracture due to stress caused by proliferation of microcracks. During the cabling procedure, all fiber is vulnerable to stresses and microcracks due to residual or threshold tension and bending radius applied. Therefore, handling and bending radius must be specified and inspected during all installations.

Another failure mode for cables is when hydrogen migrates into the core of the fiber causing optical signal loss. Silicon has proven to be one material which has experienced problems with hydrogen migration. To avoid this hydrogen migration many manufacturers achieve an OH impurity less than few parts per million during the glass manufacturing.

Construction styles of the cables dictates the application for which the cable will be used. In a laboratory environment, the fiber alone should suffice, for crossing the Atlantic an armored cable (shark bites) is warranted. Strength members can also be incorporated in the design of the cable. Two common strength enhancing construction

styles used are central and circumferential (reference Figure 4).

Central strength members are normally rigid material which limit the bending radius of the cable. This will help in avoiding microcracks which will cause a loss of attenuation.

Circumferential strength members are located on the outer edge of the cable. This protects the fiber by providing a ring of strength members (steel in the form of strands) encircling it. This technique provides an armored cable which may be used in a tactical, rodent and aerial environment.

Some other factors upon which cables are dependent on and which need to be considered during construction are tensile strength, crush resistance, abrasion protection, vibration isolation, radiation, moisture and chemical protection. Any of these factors can result in a loss of attenuation to the point where system performance is jeopardized.

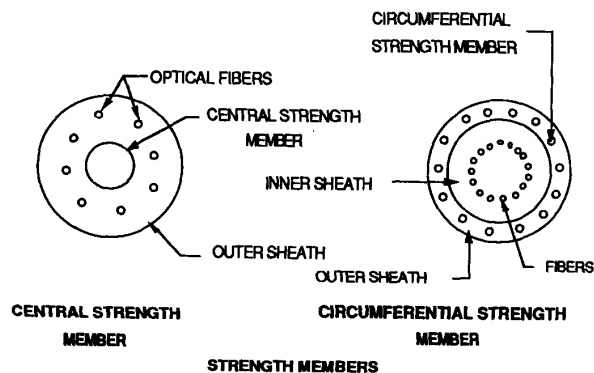


FIGURE 4

Tables 6 and 7 depict the common fiber and cable characteristics to aid in the decision process in developing a reliable system.

FIBER TYPE	WAVELENGTH	INDEX PROFILE	ATTENUATION (db/Km)	EASE OF SPLICING AND CONNECTING
MULTIMODE	850,1300	S,G,MD	3.0/1.0	HIGH
SINGLE MODE	1300,1550	S	1.0	HIGH
DISPERSION SHIFTED	1550	US	1.0	LOW
DISPERSION FLATTENED	1300-1550	US	1.0	LOW
POLARIZATION MAINTAINING	1300-1550	US	1.0	LOW

* S= STEP G= GRADED US= UNIQUE/SPECIALITY MD= MODAL DISPERSION

FIBER CHARACTERISTICS

TABLE 6

CABLE TYPE	UTILIZATION					PROPERTIES				
	AERIAL	DUCT	DIRECT BURIED	SUBMARINE	TACTICAL	FIBER FREE TO MOVE	CRUSH RESISTANCE	FLEXIBILITY	IMPACT RESISTANCE	EASE OF CONNECTION
LOOSE CABLE	I	I	I	I	I	YES	LOW	MED	MED	MED
STAR CORE	I	I	I			YES	MED	LOW	MED	MED
PLENUM		I				NO	HIGH	HIGH	HIGH	MED
TIGHT TUBE					I	NO	HIGH	HIGH	HIGH	HIGH
RIBBON	I	I	I	I		NO	MED	MED	LOW	LOW

CABLE CHARACTERISTICS
TABLE 7

Table 8 depicts the prevalent failure causes and prevention measures associated with Fiber Optic Cables.

MODE	CAUSE	PREVENTION
FRACTURE	STRESS CORROSION OR FATIGUE DUE TO MICROCRACKS	RESIDUAL OR TRESHOLD TENSION LESS THAN 33% OF THE RATED PROOF TESTED TENSILE STRENGTH
HYDROGEN DIFFUSION	HYDROGEN MIGRATES INTO THE CORE OF THE FIBER	DESIGN CABLES WITH MATERIALS THAT DO NOT GENERATE HYDROGEN
CABLE JACKET INTEGRITY	TEMPERATURE CYCLING, ULTRAVIOLET EXPOSURE, WATER & FLUID IMMERSION	DESIGN A JACKET THAT CAN PREVENT SHRINKING, CRACKING, SWELLING OR SPLITTING
NUCLEAR RADIATION	MAY BECOME OPAQUE FOR A SHORT TIME, POSSIBLE PERMANENT DISCOLORATION	DESIGN TO BE RADIATION HARDENED

COMMON FAILURE MECHANISMS (FIBER & CABLE)
TABLE 8

Based on the analysis (reliability numerics), Table 9 depicts the failure rates associated with these device types.

COMPONENT TYPE	FAILURE RATE (10 ⁴) HRS	MTBF (10 ⁵) HRS		
		I	II	III
FIBER	4.35 - 5.26	.18	.21	.26
CABLE	1.15 - 1.81	.4	.75	.84

COMPONENT FAILURE RATES
TABLE 9

CONNECTORS AND SPLICES

Linkage or connection is a requirement because fiber optic cables are not of infinite length and due to the ease of pulling short sections. Of the two types of linkage available, connector linkage gives the ability to mate and unmate repetitively while splicing is more or less permanent. In linking optical fibers care must be taken to ensure long life, ease of assembly and operation. Each fiber ends must be positioned and aligned to avoid loss of signal as shown in Figure 5. A good connector should provide no more than 1dB of loss.

The insertion losses common to each connection method are intrinsic and extrinsic losses. Intrinsic loss is contingent upon fiber parameters while extrinsic loss happens because of numerical aperture and variation in core diameters. In general, extrinsic losses can be attributed to alignment problems which may be lateral, angular, or a gap generated. All of these alignment difficulties will affect optical loss and degrade system performance. Figure 5 depicts those extrinsic losses.

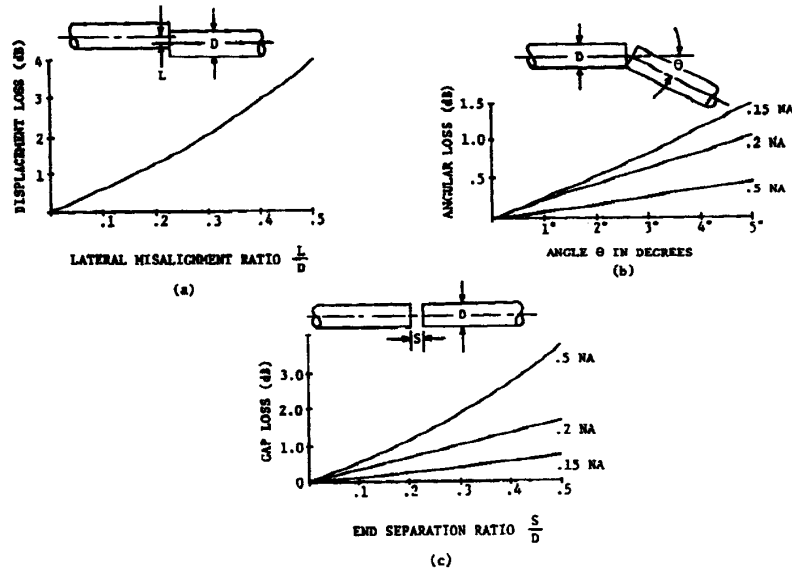


FIGURE 5

Extrinsic Losses

It should be mentioned that gaps are used in fiber connections to prevent them from being scratched or cracked during mating/unmating. To avoid Fresnel loss (reflection coefficients) an index matching fluid is deposited between the fiber ends. This index matching fluid decreases fiber separation loss by reducing the beam

divergence. Care has to be taken in applying this fluid to avoid dust and dirt. In addition, over time the fluid breaks down (cloudy, viscosity, etc.) due to continuous mating/unmating and temperature changes. Tables 10 and 11 provide splice and connector criteria which can be used in the part selection decision process,

STYLE	NOMINAL ATTENUATION - FIRST USE (dB)	NOMINAL ATTENUATION AFTER 1,000 MATINGS (dB)
CYLINDRICAL SLEEVE WITH CYLINDRICAL FERRULES	0.2 - 2.0	0.2 - 2.5
BICONIC SLEEVE WITH CONICAL FERRULES	0.5 - 0.7	0.6 - 1.0
CYLINDRICAL SLEEVE WITH LENSES	0.6 - 1.5	0.6 - 1.7

CONNECTOR LOSS CRITERIA

TABLE 10

SPlice TYPE	TYPICAL LOSS (dB)		OPERATING TEMPERATURE (C) ¹	AVERAGE ASSEMBLY TIME (MIN)
	MULTI MODE	SINGLE MODE		
HOLLOW TUBE	0.2	0.2	-40 TO 70	5 - 7
THREE ROD	0.2	0.2	-40 TO 70	5
ELASTOMERIC	0.2	0.2	-40 TO 70	3 - 5
ROTARY	0.035	0.035	-40 TO 70	10 - 19
RAPID RIBBON	0.25	0.3	-40 TO 70	20 - 30
SILICON CHIP ARRAY	0.15	0.3	-40 TO 70	10
FUSION SPlice	0.1	0.1	LIMITED BY THE FIBER OR THE PROTECTION SLEEVE	5 - 40

SPLICE CRITERIA

TABLE 11

Based on the analysis (reliability numerics), Table 12 depicts the failure rates associated with these devices types. Connectors were based on the number of matings.

COMPONENT TYPE	FAILURE RATE (10 ⁴) HRS	MTBF (10 ⁴) HRS		
		A	M	B
SPICES	.022 - .64	14	27	54
CONNECTORS	# OF MATINGS	N/A		
MIL - T - 29504	1000			
MIL - C- 28876	500			
MIL - C-38999	500			
MIL - C-83522	500			
MIL - C-83526	1000			
FC- STYLE	1000			

COMPONENT FAILURE RATES

TABLE 12

CONCLUSION

This paper resulted in the identification of reliability issues relating to photonic needs. Specific failure modes and mechanisms have been identified for transmitters, receivers and cables. Design and manufacturing techniques for avoiding or reducing the risk of failure for each mode have been developed. The tables that include this information are prepared for ease of use and understanding and should be included as a quality checklist for design and manufacturing personnel. Continued work is needed to establish a deeper database for estimating life expectancy as the data collected is limited in size and scope. To accomplish this, Rome Laboratory is continuously collecting part failure rate data and historical operational data on fiber optic systems.

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