Photonic Component and Subsystem Reliability Process

Final Report

Subcontract 0044-SC-20100-0203

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Prepared for
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The Pennsylvania State University Electro-Optics Center hereby certifies that, to the best of its knowledge and belief, the technical data delivered herewith under Contract Number N00421-03-D-0044 is complete, accurate, and complies with all requirements of the contract.

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Executive Summary

This report summarizes the final results of the Photonic Component and Subsystem Reliability Modeling effort that has been performed by Quanterion Solution for the Pennsylvania State University Electro Optics Center (EOC). The report is submitted in accordance with Subcontract 0044-SC-20100-0203. The overall project consisted of four separate tasks, as outlined in Section V. This report covers the results of Task 3.1, 3.2 and 3.3. Task 3.4 encompassed the Communication of the results via a Workshop held at the Patuxent Naval Air Station on Sept. 9, 2008.

Task 3.1 of this effort evaluated existing methodologies that may potentially be used to predict the reliability of photonic components. As a result of that review, it was concluded that no existing methods have the capability to address all of the component types of interest. Some have selected information on relevant technologies, and were used where practical to extract pertinent information towards the goals of this study. Task 3.2 of this effort derived a model development methodology that was used to develop the photonic component models. The methodology is similar to that developed for the derivation of the Reliability Information Analysis Center (RIAC) 217Plus models, but has been tailored for the unique considerations of this project, along with the specific concerns of photonic components. Task 3.3 quantified model parameters by collecting and analyzing reliability data. Models have been developed for the following component types:

- Connectors
- Passive micro-optic components
- Passive fiber-based components
- Isolators
- Variable Optical Attenuators (VOA)
- Fiber
- Splice
- Cable
- Laser diode modules
- Photodiodes
- Transmitters
- Receivers

The goals of these models were to estimate typical failure rates that can be expected for these components when used in various military environments.

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II. Historical Background/Problem Statement

Due to the environments in which they operate, military/aerospace optical communication systems need more assembly flexibility, fault tolerance, and ability to self-heal. Today's typical multimode fiber optic link uses 850nm transceivers over 100/140 micron multimode graded index fiber. This will transition to use of wavelength division multiplexing (WDM) in the near future, with potential use of over 200 wavelengths over single mode fiber.

Component, assembly, and subsystem reliability for electronics used in military platforms has the advantage of extensive past work in standardization and in reliability. At the system level, methods for communicating reliability levels are well understood under the guidance of MIL-HDBK-217, which contains the process for computing and communicating reliability levels for military systems. Little data for photonic hardware can be found in databases meant for computation of reliability levels.

Likewise, photonic components, assemblies, and subsystems used in the telecommunications industry are subject to reliability criteria devised by Telcordia, IEC, and others. Photonic components used in telecommunications are considered mature and stable when deployed for network service. However, the environmental ranges - temperature, humidity, vibration, shock, etc. - are much less harsh than their military counterparts.

Reliability and maintainability experts have stated that "MIL-HDBK-217 is the first step in a reliability program and allows the engineer a first look at predicted reliability of a design, under ideal conditions, based simply on the number of components and their individual failure rates." The MIL-HDBK-217 process for computing system reliability could be improved by inclusion of fiber optic and photonic component failure rate data. The focus of this project is to develop a method for measurement of reliability levels for photonic components and assemblies that is compatible with MIL-HDBK-217, so that system level designers can efficiently evaluate reliability of systems using fiber optics and photonics.

III. Project Chronology

The overall project consisted of four separate tasks, as outlined below:

Task 3.1: Identify Parts and Technologies for Evaluation
Task 3.2: Define the Photonic Device Model Method
Task 3.3: Verify and Enhance
Task 3.4: Communicate

The tasks were being performed over the calendar time period 10 October 2007 through 26 September 2008, as defined in the Project Master Integrated Program Schedule (MIPS).

IV. Project Description

Task 3.1 of this effort evaluated existing methodologies that may potentially be used to predict the reliability of photonic components. Task 3.2 derived a model development methodology that was used to develop the photonic component models. The methodology is similar to that developed for the derivation of the Reliability Information Analysis Center (RIAC) 217Plus models, but has been tailored for the unique considerations of this project along with the specific concerns of photonic components. Task 3.3 quantified model parameters by collecting and analyzing reliability data. Models have been developed for the following component types:

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The goals of these models were to estimate typical failure rates that can be expected for these components when used in various military environments.

V. Technical Approach by Task

The overall project consisted of four separate tasks, as outlined below:

Task 1: Identify Parts and Technologies for Evaluation

Task 2: Define the Photonic Device Model Method

Task 3: Verify and Enhance

Task 4: Communicate

A description of each task is provided below.

V.1 Task 1: Identify Parts and Technologies for Evaluation

This task consisted of an effort to identify representative component types and technologies to be addressed during the study. This was accomplished by:

- Reviewing the design of photonic communication systems
- Identifying part types typically used in their design
- Determining the component types used in Navy designs
- Reviewing potential pertinent documents that may have applicability in predicting the reliability of photonic components

V.2 Task 2: Define the Photonic Device Model Method

This task defined and documented the methodology that was used to develop the photonics device model form.

V.3 Task 3: Verify and Enhance

This task consisted of collecting and analyzing data, and quantifying model parameters in accordance with the methodology defined in Task 3.2.

V.4 Task 4: Communicate

Quanterion presented findings from this work in a one-day Workshop at the Navy facility at Patuxent River on Sept. 9, 2008.

VI. Project Objectives

The objective of this project was to recommend models and methods that can be used to predict the reliability of photonic systems. It was originally envisioned that existing models and methodologies be leveraged to the maximum extent, where possible.

The objective of Task 3.3 of this project was to develop reliability prediction models for selected photonic components in accordance with the methodology developed in Task 3.2. This methodology was based on the RIAC's 217Plus, but has been adapted for the specifics of photonic technologies. This adaptation is detailed within this report.

VII. Technical Activities Performed

VIII. Transition

Not Applicable

IX. Results

This section summarizes the results of the technical activities listed in Section VI that were accomplished in the execution of this project.

IX.1 Task 1: Identify Parts and Technologies for Evaluation

IX.1.1 Review the Design of Photonic Communication Systems

Optical communication systems are often used in long distance telecommunications system when large amounts of data need to be transported long distances. They are also used in local area networks (LANs). Advantages of these systems are:

- Data transfer speeds
- Light weight
- Small size
- Electromagnetic interference immunity

Various photonic systems were reviewed for the purpose of identifying the components with which they are designed. A list of parts/technologies/assemblies typically comprising these systems is provided below:

- Optical fiber
- Cables
- Sources
  - LED
  - Semiconductor Lasers
  - Fiber Lasers
- Fiber Amplifiers
  - Semiconductor Laser Amplifiers
  - Erbium Doped Fiber Amplifiers
  - Raman Amplifiers
- Transmitters
- Attenuators
- Receivers
  - Detectors
    - Photodiodes
    - Phototransistors
- Connectors
  - SC type (single fiber)
  - ST/FC type (Twist on)
  - Duplex
  - Polarizing connectors
  - Multifiber connectors
- Splices
  - Fusion
  - Mechanical
  - Capillary
  - Polished Ferrule

    - Elastomeric
- Couplers
    - 1-to-2
    - 1-to-n
    - Fused fiber
    - Planar waveguide
- Fiber gratings
- Taps
- WDM components
    - Interference filters
    - Arrayed waveguides
    - Fiber gratings
    - Attenuators
    - Band filters
    - Equalizing filters
    - Tunable filters
- Optical isolators
- Dispersion compensators
- Switches
    - Opto-mechanical
    - Cross connect
    - Free space
    - Electro-optical
- Routers

IX.1.2 Identify part types typically used in their design

Addressing all of the above listed components was beyond the scope of this effort. Additionally, many of the above listed items are modules and assemblies comprised of a mix of individual part types. Therefore, an effort was made to pare this list down to a manageable group, yet include the majority of components that comprise optical systems. The result was as follows:

- Connectors
- Passive micro-optic components
- Passive fiber-based components
- Isolators
- VOA
- Fiber
- Splice
- Cable
- Laser diode modules
- Photodiodes
- Transmitters
- Receivers

IX.1.3 Determine the components types used in Navy designs

It was originally envisioned that specific Navy designs would be analyzed so that specific components of interest could be addressed. Limited data was available for this purpose, and, therefore, the project proceeded based on the understanding that the above part types adequately represented the part types used in Navy designs.

IX.1.4 Review potential pertinent documents

An analysis was conducted to determine if existing reliability prediction methodologies have the capability of predicting photonic component reliability. Table 1 summarizes the results of reviewing these various methodologies. It contains a description of the document and a list of component types that may be applicable to this effort.

Table 1: Applicability of Various Existing Reliability Prediction Standards

Document	Description	Potentially Applicable Part Types Addressed
MIL-HDBK-217	MIL-HDBK-217 has been used since the 1960s for the reliability prediction of electronic systems. It contains point estimate failure rates for fiber optic cables and connectors, but no data on any other type of passive photonic components. Also, related active components such as LEDs, opto-isolators, detectors and laser diodes are included. However, the data on these components was obtained in the 1980's and is not necessarily representative of current technologies.	Fiber optic cables (single fiber types only) Single fiber optic connectors LEDs Opto-isolators Detectors Laser diodes
Telcordia	Telcordia GR-332 contains failure rate prediction models on a wide variety of components, including electronic components, fiber, connectors, and selected passive optical components	Fiber Connectors Selected passive optical components
RIAC's Electronic Parts Reliability Data (EPRD) and Nonelectronic Parts Reliability Data (NPRD) Publications	These data sources are not models, but rather contain observed field failure rate information on a variety of part types	LED Photo diode Phototransistor Opto-isolator Fiber optic lamp
RIAC's Failure Mode/Mechanism Distributions (FMD) Publication	Failure mode/mechanism data on a wide variety of part types	Fiber optic cable Splice Opto-coupler Laser diode LEDs Photodiode

Table 1: Applicability of Various Existing Reliability Prediction Standards (continued)

Document	Description	Potentially Applicable Part Types Addressed
217Plus	Contains up-to-date models on a wide variety of parts. No data on passive photonic components.	LED Photo diode Phototransistor Opto-isolator
NSWC 98 (for mechanical predictions)	This document contains a series of reliability prediction models for mechanical components (i.e. seals, bearings, gaskets, fasteners, motors, etc.) It contains no information pertaining to photonic components.	None
CNET	French telecommunication reliability prediction standard	Optocouplers
Italtel	A reliability prediction standard generated by several European telecommunication companies	LEDs Laser Diodes Photodiodes

As a result of this review, it was concluded that no existing methods have the capability to address all of the component types of interest. Some have selected information on relevant technologies, but none addresses photonic component is military environments.

IX.2 Task 3.2: Define the Photonic Device Model Method

IX.2.1 Component Reliability Models Form

This section summarizes the manner in which the photonic models were derived. Traditional methods of reliability prediction model development have relied on the statistical analysis of empirical failure rate data. The statistical methods are multiple linear regression and typically result in a model form that is multiplicative (i.e., the predicted failure rate is the product of a base failure rate and several factors that account for the stresses and component variables that influence reliability). An example of a multiplicative model is as follows:

$$\lambda_p = \lambda_b \pi_e \pi_q \pi_s$$

where,

λ_p = Predicted failure rate

λ_b = Base failure rate
π_e = Environmental factor
π_q = Quality factor
π_s = Stress factor

A primary disadvantage of the multiplicative model form is that the predicted failure rate value can become unrealistically large or small under extreme value conditions (i.e., when all factors are at their lowest or highest values). This is an inherent limitation of this type of model, primarily due to the fact that individual failure mechanisms, or classes of failure mechanisms, are not explicitly accounted for.

The photonic component model form is:

$$\lambda_P = \pi_Q\left(\lambda_{OB}\pi_{DCO}\pi_{TO}\pi_V + \lambda_{EB}\pi_{DCN}\pi_{TE}\pi_{RH} + \lambda_{TCB}\pi_{CR}\pi_{DT} + \lambda_{ind}\right)$$

Where:

λ_P = Predicted failure rate
π_Q = Multiplier for quality
λ_{OB} = Base failure rate from operational stresses
π_{DCO} = Failure rate multiplier for duty cycle

$$\pi_{DCO} = \frac{DC}{DC_{1op}}$$

π_{TO} = Factor for operating temperature

$$\pi_{TO} = e^{\left(\frac{-Ea_{op}}{.00008617}\left(\frac{1}{T_{AO}+T_R+273} - \frac{1}{298}\right)\right)}$$

π_V = Vibration factor

$$\pi_V = \left(\frac{V_a + 1}{V_c}\right)^{n_{vib}}$$

λ_{EB} = Base failure rate from environmental stresses
π_{DCN} = Failure rate multiplier for nonoperating duty cycle

$$\pi_{DCN} = \frac{1 - DC}{1 - DC_{1op}}$$

π_{TE} = Nonoperating temperature factor

$$\pi_{TE} = e^{\left(\frac{-Ea_{nonop}}{.00008617}\left(\frac{1}{T_{AE}+273}-\frac{1}{298}\right)\right)}$$

π_{RH} = Humidity factor

$$\pi_{RH} = \left(\frac{RH_a + 1}{RH_c}\right)^{n_{RH}}$$

λ_{TCB} = Base failure rate from power or temperature cycling stresses
π_{CR} = Cycling rate factor

$$\pi_{CR} = \frac{CR}{CR_1}$$

π_{DT} = Delta Temperature factor

$$\pi_{DT} = \left(\frac{T_{AO} + T_R - T_{AE}}{14}\right)^{n_{PC}}$$

λ_i = Failure rate from induced stresses

The model parameters are defined as follows:

λ_P = Predicted failure rate, failures per million calendar hours
π_Q = Failure rate multiplier for quality
λ_{OB} = Base failure rate, operating
π_{DCO} = Failure rate multiplier for duty cycle, operating
DC = Duty cycle (fraction of calendar time in operation)
$DC1_{op}$ = .25
π_{TO} = Failure rate multiplier, Temperature – operating
Ea_{op} = Activation energy - operating
T_{AO} = ambient operating temperature
T_R = The temperature rise above T_{AO}
π_V = Failure rate multiplier, vibration level
V_A = Max vibration level applied (Grms)
V_C = 1
n_{vib} = Vibration exponent
λ_{EB} = Base failure rate, environment
π_{DCN} = Failure rate multiplier, duty cycle – nonoperating

π_{TE} = Failure rate multiplier, Temperature – environment
Ea_{nonop} = Activation energy, nonoperating
T_{AE} = Ambient environmental temperature
π_{RH} = Failure rate multiplier, relative humidity
RH_a = Relative Humidity (%)
RH_c = 50%
n_{RH} = Relative Humidity exponent
λ_{TCB} = Base failure rate, temperature cycling
π_{CR} = Failure rate multiplier, Cycling rate
CR = Cycling rate (cycles per year)
CR_1 = 1000
π_{DT} = Failure rate multiplier, Delta temperature
n_{PC} = Temperature cycling exponent

By utilizing this model form, factors that account for the application and component-specific variables that affect reliability (Pi-factors) can be applied to the appropriate additive failure rate term. Additional advantages to this approach are that it:

- Addresses operating, nonoperating and cycling related failure rates in an additive/multiplicative model, which are weighted in accordance with the operational profile (duty cycle and cycling rate). The Pi-factors modify only the applicable failure rate term, thereby eliminating many of the extreme value problems that plague multiplicative models.

- Is based on quantitative stresses rather than qualitative environmental categories, but defaults to average stress conditions as a function of environment

- Is industry-independent and predicts average failure rates representing best commercial practices

- Can be tailored with test or field-use data (if available)

The primary difference in the photonic models and the 217Plus models is the manner in which environmental factors are included, as agreed to at the project Kickoff Meeting. The photonic models include environmental factors at the component level, whereas the 217Plus models include environmental influences at the system level. Details regarding the manner in which quality and environment will be accounted for are presented later in the report.

IX.2.2 Model Development Methodology

The modeling methodology that was used in this study is summarized in Figure 1. This methodology is consistent with the 217Plus model development methodology, but has been tailored for the specific needs of photonic components. Each element of this methodology is explained in the following sections.

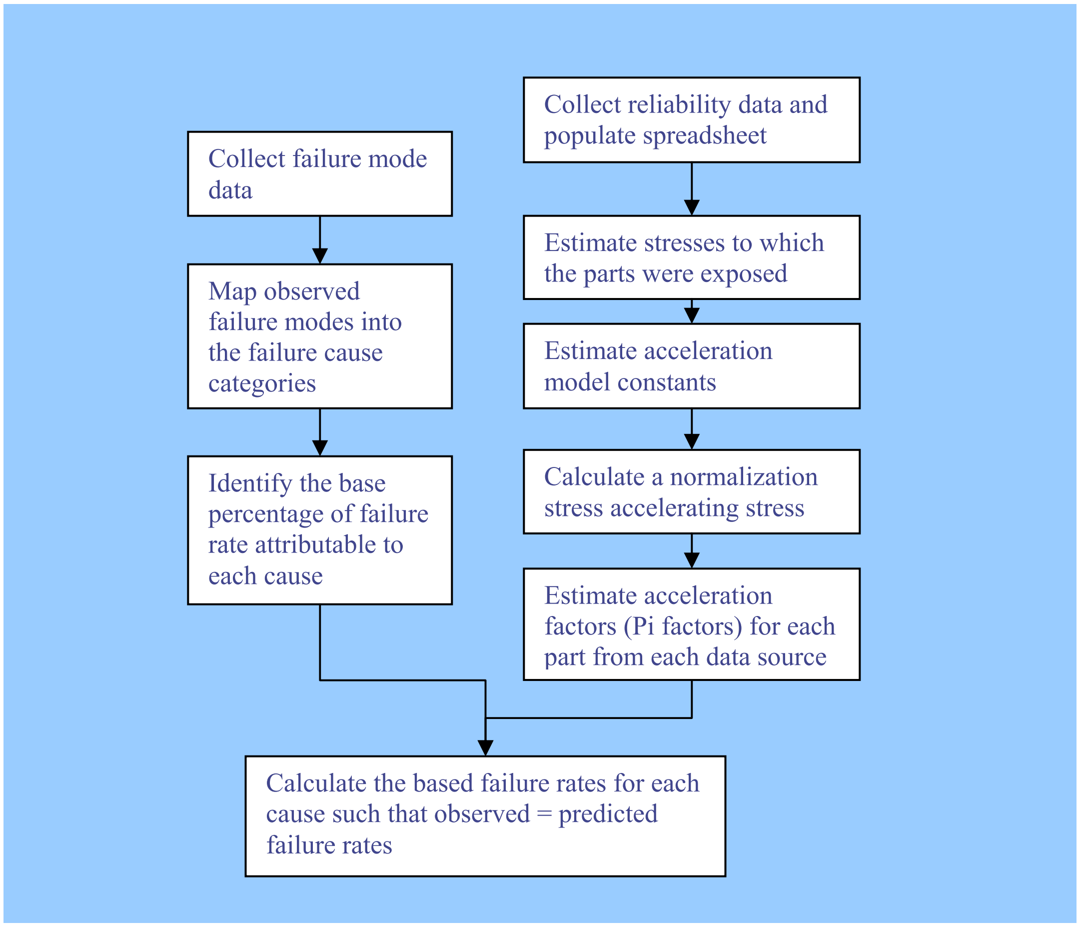

Figure 1: Model Development Methodology Flowchart

IX.3 Task 3: Verify and Enhance

IX.3.1 Model development methodology and results

This section of the report details the model development methodology, and also presents the results of each task in this methodology. Each task in Figure 1 is described in the following sections.

IX.3.1.1 Collect failure mode data

There were two primary types of data upon which the component models were based, failure rate and failure mode. The model development process required that the failure rate data be apportioned into the following five defined failure cause categories:

- Failures from operational stresses
- Failures from environmental stresses
- Failures from power or temperature cycling stresses
- Failures from induced stresses

Originally, it was envisioned that each model would have a factor accounting for the failure rate of the fiber and splice connections for each component. However, it was later decided that the failure rate of the fiber and splice connections would be accounted for with separate failure rate models. In this manner, the specific accelerants of each of these could be modeled without confounding their effect with their associated component.

Since failure mode data is typically not classified according to these categories, it was necessary to transform the failure mode distribution data into the failure cause distribution. This failure mode distribution data was obtained from several sources:

1. Data collected during this study
2. Data obtained from the literature
3. Analysis similar to a Failure Mode and Effects Analysis (FMEA), in which failure causes are hypothesized

The results are summarized in Table 2. In this table, for each component type addressed, the failure causes were hypothesized (2nd column), and then an occurrence rating was given for each cause. This rating is in the 3rd column, and is set equal to 1, 3 or 9, a weighting scheme often used in FMEA analysis. The result was a fractional value for each cause proportional to the weighting. The sum of all of these values for each component type equals one.

Table 2: Failure Mode/Cause Summary

Component Type	Failure Mode/Cause	Occurrence	Fraction of Occurrence
Connector (SC and FC)	Spring failure	3	0.073
	Wear of the connector resulting in misalignment	3	0.073
	Wear of the end face	1	0.024
	Contamination of facet (sand, dust, grease)	9	0.220
	Contamination on outside that wicks in	1	0.024
	Eccentric wear on the ferrule causes misalignment	1	0.024
	Crimping too tight causes pinching	3	0.073
	Crimping too loose causes it to fall apart	1	0.024
	O-ring failure	1	0.024
	Contraction of the outer jacket causes fiber pistoning	3	0.073
	Fracture of the end face	1	0.024
	Misalignment of cable end due to sleeve wear	1	0.024
	Misalignment of cable end due to buckling from tolerance stack up	3	0.073
	Misalignment of cable end due to separation from tolerance stack up	3	0.073
	Insufficient cure of epoxy	3	0.073
	Corrosion, pitting or facets	3	0.073
	Embrittlement of organic materials due to UV exposure	1	0.024
Passive Micro-optic Components	Coating deterioration causes loss (for reflective coatings)	3	0.048
	Mirrors drift out of position (alignment)	9	0.145
	Epoxy index change (if in optical path)	9	0.145
	Wavelength spectrum can change over time (humidity)	1	0.016
	Radial misalignment of (GRIN) collimator	3	0.048
	Lens based collimator misalignment	3	0.048
	Contaminated optical surface from particles	9	0.145
	Contaminated optical surface from outgassing	1	0.016
	Fiber retention failure	3	0.048
	Epoxy embrittlement	1	0.016
	Bulk material of mirror/filter increases attenuation	1	0.016
	Frozen condensation inside package	1	0.016
	Fiber breaks	9	0.145
	Misalignment from external stress from mounting	3	0.048
	Failure (ratio) due to stray light absorption in one path	3	0.048
	Misalignment due to thermal mismatch	3	0.048
Passive Fiber-based Components	Wavelength spectrum can change over time (humidity)	3	0.150
	Fiber retention failure	3	0.150
	Epoxy embrittlement	1	0.050
	Fiber breaks	9	0.450
	Hydrogen diffusion affects the ratio	3	0.150
	Induced bi-refringence from mechanical stress	1	0.050

Table 2: Failure Mode/Cause Summary (continued)

Component Type	Failure Mode/Cause	Occurrence	Fraction of Occurrence
Isolators	Coating deterioration causes loss (for reflective coatings)	3	0.083
	Epoxy index change (if in optical path)	3	0.083
	Radial misalignment of (GRIN) collimator	1	0.028
	Lens based collimator misalignment	3	0.083
	Contaminated optical surface from particles	3	0.083
	Contaminated optical surface from outgassing	3	0.083
	Fiber retention failure	3	0.083
	Epoxy embrittlement	1	0.028
	Bulk material of mirror/filter increases attenuation	1	0.028
	Frozen condensation inside package	1	0.028
	Fiber breaks	3	0.083
	Loss of magnetization	1	0.028
	Deterioration of rotator	1	0.028
	Corrosion	3	0.083
	Polarization change	1	0.028
	Polarizer to polarizer misalignment	1	0.028
	Contamination on outside that wicks in	1	0.028
	Misalignment due to thermal mismatch	3	0.083
VOA (Micro-optic based with Actuator)	Coating deterioration causes loss (for reflective coatings)	1	0.017
	Mirrors drift out of position (alignment)	3	0.052
	Epoxy index change (if in optical path)	3	0.052
	Radial misalignment of (GRIN) collimator	3	0.052
	Lens based collimator misalignment	3	0.052
	Contaminated optical surface from particles	9	0.155
	Contaminated optical surface from outgassing	1	0.017
	Fiber retention failure	9	0.155
	Epoxy embrittlement	1	0.017
	Bulk material of mirror/filter increases attenuation	1	0.017
	Frozen condensation inside package	1	0.017
	Fiber breaks	9	0.155
	Misalignment from external stress from mounting	3	0.052
	Failure (ratio) due to stray light absorption in one path	1	0.017
	Misalignment due to thermal mismatch	1	0.017
	Actuator failure	9	0.155
Fiber	Failure from high power	3	0.136
	Radiation effects	9	0.409
	Hydrogen diffusion	1	0.045
	Crack	9	0.409

Table 2: Failure Mode/Cause Summary (continued)

Component Type	Failure Mode/Cause	Occurrence	Fraction of Occurrence
Splice	Fiber break	9	0.600
	Dirt	3	0.200
	Bad cleve	3	0.200
Cable (Fiber and Cable including Connectors)	Microcracks	3	0.086
	Thermal expansion causes microbending and attenuation	3	0.086
	Microbending	1	0.029
	Pinching	9	0.257
	Twisting	1	0.029
	Fracture	3	0.086
	Wicking of contaminants inside the jacket	3	0.086
	Stress corrosion cracking	1	0.029
	Water freezing inside the jacket	1	0.029
	Radiation	1	0.029
	Outgassing of outer sheathing	1	0.029
	UV embrittlement of outer sheathing	1	0.029
	Thermal overstress of sheathing and jacket	1	0.029
	Thermal overstress of fiber coating due to power leakage at a bend site	3	0.086
	Fiber not tolerant to bending due to cable construsion or loss of the slippery stuff	3	0.086
Laser Diode Module	Solder voids	9	0.161
	Bond wire failure	3	0.054
	Gold-indium intermetallic compound formation	1	0.018
	Diode facet COD	3	0.054
	Solder creep/migration	9	0.161
	Solder de-bonding	1	0.018
	Laser bar material defects	3	0.054
	Cracking of semiconductor from wedge bonds	3	0.054
	Gradual aging manifested by decreasing light output and increased current to maintain operation at a specified output	3	0.054
	Operation at excessive temperature	3	0.054
	Electrical overstress due to an ESD event	3	0.054
	Transient current pulses during operation.	1	0.018
	Thermal induced (overheating)	3	0.054
	Dislocations	3	0.054
	Metal diffusion and alloy reaction that affect the electrode	1	0.018
	Solder instability (reaction and migration) that affect the bonding parts	1	0.018
	Separation of metals in the heat sink bond	1	0.018
	Defects in buried heterostructure devices	1	0.018
	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	1	0.018
	Fiber facet COD	3	0.054
	Fiber break	3	0.054

Table 2: Failure Mode/Cause Summary (continued)

Component Type	Failure Mode/Cause	Occurrence	Fraction of Occurrence
Photodiode	Increase in dark current	3	0.083
	Decrease in breakdown voltage	3	0.083
	Short	1	0.028
	Solder voids	3	0.083
	Bond wire failure	3	0.083
	Diode facet COD	3	0.083
	Solder creep/migration	3	0.083
	Solder de-bonding	1	0.028
	Cracking of semiconductor from wedge bonds	1	0.028
	Electrical overstress due to an ESD event	3	0.083
	Transient current pulses during operation.	3	0.083
	Thermal induced (overheating)	1	0.028
	Solder instability (reaction and migration) that affect the bonding parts	1	0.028
	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	1	0.028
	Fiber break	3	0.083
	Lead failure	3	0.083
Transmitters	Solder voids	9	0.138
	Bond wire failure	3	0.046
	Gold-indium intermetallic compound formation	1	0.015
	Diode facet COD	3	0.046
	Solder creep/migration	9	0.138
	Solder de-bonding	1	0.015
	Laser bar material defects	3	0.046
	Cracking of semiconductor from wedge bonds	3	0.046
	Gradual aging manifested by decreasing light output and increased current to maintain operation at a specified output Operation at excessive temperature	3	0.046
	Electrical overstress due to an ESD event	3	0.046
	Transient current pulses during operation.	1	0.015
	Thermal induced (overheating)	3	0.046
	Dislocations	3	0.046
	Metal diffusion and alloy reaction that affect the electrode	1	0.015
	Solder instability (reaction and migration) that affect the bonding parts	1	0.015
	Separation of metals in the heat sink bond	1	0.015
	Defects in buried heterostructure devices	1	0.015
	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	1	0.015
	Fiber facet COD	3	0.046
	Fiber break	3	0.046
	Integrated circuits failure (amplifier, transistors, etc.)	9	0.138

Table 2: Failure Mode/Cause Summary (continued)

Component Type	Failure Mode/Cause	Occurrence	Fraction of Occurrence
Receiver	Increase in dark current	3	0.067
	Decrease in breakdown voltage	3	0.067
	Short	1	0.022
	Solder voids	3	0.067
	Bond wire failure	3	0.067
	Diode facet COD	3	0.067
	Solder creep/migration	3	0.067
	Solder de-bonding	1	0.022
	Cracking of semiconductor from wedge bonds	1	0.022
	Electrical overstress due to an ESD event	3	0.067
	Transient current pulses during operation.	3	0.067
	Thermal induced (overheating)	1	0.022
	Solder instability (reaction and migration) that affect the bonding parts	1	0.022
	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	1	0.022
	Fiber break	3	0.067
	Lead failure	3	0.067
	Integrated circuits failure (amplifier, demodulator, etc.)	9	0.200
Transceivers	Solder voids	3	0.055
	Bond wire failure	3	0.055
	Gold-indium intermetallic compound formation	3	0.055
	Diode facet COD	3	0.055
	Solder creep/migration	3	0.055
	Solder de-bonding	1	0.018
	Laser bar material defects	3	0.055
	Cracking of semiconductor from wedge bonds	3	0.055
	Gradual aging manifested by decreasing light output and increased current to maintain operation at a specified output Operation at excessive temperature	3	0.055
	Electrical overstress due to an ESD event	3	0.055
	Transient current pulses during operation.	3	0.055
	Thermal induced (overheating)	1	0.018
	Dislocations	1	0.018
	Metal diffusion and alloy reaction that affect the electrode	1	0.018
	Solder instability (reaction and migration) that affect the bonding parts	3	0.055
	Separation of metals in the heat sink bond	1	0.018
	Defects in buried heterostructure devices	3	0.055
	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	1	0.018
	Fiber facet COD	1	0.018
	Fiber break	3	0.055
	Integrated circuits failure (amplifier, demodulator, transistors, etc.)	9	0.164

IX.3.1.2 Map observed failure modes into the failure cause categories

To transform the failure mode distribution data into the failure cause distribution, the following process was used:

- Identify failure modes and their relative percentages (summarized above)
- Identify accelerating factors applicable to each failure cause
- Identify accelerating stresses applicable to each failure cause category (for example, accelerating stresses from device operation applicable to many photonic components will be optical power, temperature, etc.)
- Map the accelerating stress to the appropriate failure modes, identify as being a primary, secondary or no accelerant

The last item was accomplished by assessing whether each stress was a primary accelerant of the failure mode, a secondary accelerant, or was not an accelerant. A 3:1 weighting between primary and secondary accelerant was then used in estimating the percentage of failures that could be attributed to those stresses.

The primary stresses that potentially accelerate operational failure modes are operating temperature, vibration, current/voltage and optical power. The stresses that accelerate environmental failure causes are nonoperating ambient temperature, corrosive stresses (contaminants/heat/humidity), and aging stresses (time). As an example, Table 2 summarizes this process for a connector. Each of the failure modes is listed across the top of the table, and each of the accelerating stresses/causes is listed down the left side. Each combination is identified with a blank (no acceleration from the factor), a "p" (primary) or an "s" (secondary). The associated relative percentage of failures attributable to the accelerating stress/cause is listed down the right columns.

The % column (second from the right) is calculated as follows:

$$\% = \sum_{FM_1}^{n} FM_{\%} \left(\frac{w_i}{\sum_{AC1}^{n} w_i} \right)$$

Where **:**

- $FM_{\%}$ is the percentage associated with the ith failure mode
- w_i is the weight of the specific combination of failure mode and accelerating stress or cause (0 for none, 1 for secondary, and 3 for primary)

For example, the % value for ambient temperature (as part of the environmental failure cause category) is:

$$7.32\%\left(\frac{1}{4}\right)+7.32\%\left(\frac{1}{4}\right)+7.32\%\left(\frac{1}{11}\right)+2.44\%\left(\frac{1}{1}\right)=.07$$

Therefore, an estimate of the percentage of failures accelerated by ambient temperature is 7%.

Tables 3 through 15 present the mapping for each of the components modeled in this study.

Table 3: Failure Mode to Failure Cause Category for Connectors (SC and FC)

Failure Cause Category	Accelerating Stress or Cause	Spring failure	Wear of the connector resulting in misalignment	Wear of the end face	Contamination of facet (sand, dust, grease)	Contamination on outside that wicks in	Eccentric wear on the ferrule causes misalignment	Crimping too tight causes pinching	Crimping too loose causes it to fall apart	O-ring failure	Contraction of the outer jacket causes fiber pistoning	Fracture of the end face	Misalignment of cable end due to sleeve wear	Misalignment of cable end due to buckling from tolerance stack up	Misalignment of cable end due to separation from tolerance stack up	Insufficient cure of epoxy	Corrosion, pitting or facets	Embrittlment of organic materials due to UV exposure	Total	
		7.32%	7.32%	2.44%	21.95%	2.44%	2.44%	7.32%	2.44%	2.44%	7.32%	2.44%	2.44%	7.32%	7.32%	7.32%	7.32%	2.44%	100 %	
Operational Stresses	Op. Temp.																		0.00	0.11
	Vibration	s	p	p			p			s							p		0.10	
	Current/voltage																		0.00	
	Optical power																s		0.01	
Environmental	Amb. Temp.													s	s		s	p	0.07	0.30
	Corrosion	p															p		0.04	
	Ageing	p								p	p		p						0.09	
	Humidity	p	s			s					s		s				p		0.10	
Power Cycling	Power Cycling	s	s							s	s		s	p	p	s			0.23	0.23
Induced/handling	Induced/handling			p	p		p	p	p			p							0.36	0.36
																		TOTAL	1.00	1.00

Table 4: Failure Mode to Failure Cause Category for Passive Micro-optic Components

Failure Cause Category	Accelerating Stress or Cause	Coating deterioration causes loss (for reflective coatings)	Mirrors drift out of position (alignment)	Epoxy index change (if in optical path)	Wavelength spectrum can change over time (humidity)	Radial misalignment of (GRIN) collimator	Lens based collimator misalignment	Contaminated optical surface from particles	Contaminated optical surface from outgassing	Fiber retention failure	Epoxy embrittlement	Bulk material of mirror/filter increases attenuation	Frozen condensation inside package	Fiber breaks	Misalignment from external stress from mounting	Failure (ratio) due to stray light absorption in one path	Misalignment due to thermal mismatch	**Total**	
		4.84%	14.52%	14.52%	1.61%	4.84%	4.84%	14.52%	1.61%	4.84%	1.61%	1.61%	1.61%	14.52%	4.84%	4.84%	4.84%	100 %	
Operational Stresses	Op. Temp.	s		s								p						0.05	0.27
	Vibration		s			s	s											0.06	
	Current/voltage																	0.00	
	Optical power			p												p		0.16	
Environmental	Amb. Temp.	p							p		p							0.04	0.10
	Corrosion																	0.00	
	Ageing										p	p						0.02	
	Humidity	p			p													0.04	
Power Cycling	Power Cycling		p			p	p						p	p			p	0.32	0.32
Induced/handling	Induced/handling							p		p				p	p			0.31	0.31
																	TOTAL	1.00	1.00

Table 5: Failure Mode to Failure Cause Category for Passive Fiber-based Components

Failure Cause Category	**Accelerating Stress or Cause**	Wavelength spectrum can change over time (humidity)	Fiber retention failure	Epoxy embrittlement	Fiber breaks	Hydrogen diffusion affects the ratio	Induced birefringence from mechanical stress	**Total**	
		15.00%	15.00%	5.00%	45.00%	15.00%	5.00%	100 %	
Operational Stresses	Op. Temp.							0.00	0.00
	Vibration							0.00	
	Current/voltage							0.00	
	Optical power							0.00	
Environmental	Amb. Temp.	s		p		p		0.21	0.35
	Corrosion							0.00	
	Ageing			p				0.03	
	Humidity	p						0.11	
Power Cycling	Power Cycling		s		s			0.15	0.15
Induced/handling	Induced/handling		p		p		p	0.50	0.50
							TOTAL	1.00	1.00

Table 6: Failure Mode to Failure Cause Category for Isolators

		Coating deterioration causes loss (for reflective coatings)	Epoxy index change (if in optical path)	Radial misalignment of (GRIN) collimator	Lens based collimator misalignment	Contaminated optical surface from particles	Contaminated optical surface from outgassing	Fiber retention failure	Epoxy embrittlement	Bulk material of mirror/filter increases attenuation	Frozen condensation inside package	Fiber breaks	Loss of magnetization	Deterioration of rotator	Corrosion	Polarization change	Polarizer to polarizer misalignment	Contamination on outside that wicks in	Misalignment due to thermal mismatch	**Total**	
Failure Cause Category	**Accelerating Stress or Cause**	8.33%	8.33%	2.78%	8.33%	8.33%	8.33%	8.33%	2.78%	2.78%	2.78%	8.33%	2.78%	2.78%	8.33%	2.78%	2.78%	2.78%	8.33%	100 %	
Operational Stresses	Op. Temp.	p	p						p	p			p	p		p				0.17	0.37
	Vibration			p	p			s				p					p			0.11	
	Current/voltage																			0.00	
	Optical power	p	p							p										0.09	
Environmental	Amb. Temp.			s			p		p									p		0.07	0.32
	Corrosion					p									p					0.08	
	Ageing																	p		0.01	
	Humidity	s		s		p	p				p				p			p		0.16	
Power Cycling	Power Cycling			s	p			p			p	p		p		s	p	s	p	0.25	0.25
Induced/handling	Induced/handling							p				p								0.06	0.06
																			TOTAL	1.00	1.00

Table 7: Failure Mode to Failure Cause Category for Variable Optical Attenuators (VOAs), (Micro-optic based with Actuator)

Failure Cause Category	Accelerating Stress or Cause	Coating deterioration causes loss (for reflective coatings)	Mirrors drift out of position (alignment)	Epoxy index change (if in optical path)	Radial misalignment of (GRIN) collimator	Lens based collimator misalignment	Contaminated optical surface from particles	Contaminated optical surface from outgassing	Fiber retention failure	Epoxy embrittlement	Bulk material of mirror/filter increases attenuation	Frozen condensation inside package	Fiber breaks	Misalignment from external stress from mounting	Failure (ratio) due to stray light absorption in one path	Misalignment due to thermal mismatch	Actuator failure	Total	
		1.72%	5.17%	5.17%	5.17%	5.17%	15.52%	1.72%	15.52%	1.72%	1.72%	1.72%	15.52%	5.17%	1.72%	1.72%	15.52%	100 %	
Operational Stresses	Op. Temp.			s							p						p	0.10	0.24
	Vibration																	0.00	
	Current/voltage																p	0.08	
	Optical power			p											p			0.06	
Environmental	Amb. Temp.	s						p		p								0.03	0.08
	Corrosion																	0.00	
	Ageing				s	s				p	p							0.04	
	Humidity	p																0.01	
Power Cycling	Power Cycling		p		p	p						p	p			p		0.24	0.24
Induced/handling	Induced/handling						p		p				p	p				0.44	0.44
																	TOTAL	1.00	1.00

Table 8: Failure Mode to Failure Cause Category for Fiber

Failure Cause Category	Accelerating Stress or Cause	Failure from high power	Radiation effects	Hydrogen diffusion	Crack	Total	
		13.64%	40.91%	4.55%	40.91%	100 %	
Operational Stresses	Op. Temp.					0.00	0.13
	Vibration				s	0.06	
	Current/voltage					0.00	
	Optical power	p				0.07	
Environmental	Amb. Temp.			p		0.02	0.63
	Corrosion					0.00	
	Ageing		p	p		0.42	
	Humidity			p	p	0.19	
Power Cycling	Power Cycling					0.00	0.00
Induced/handling	Induced/handling	p			p	0.24	0.24
					TOTAL	1.00	1.00

Table 9: Failure Mode to Failure Cause Category for Splice

Failure Cause Category	Accelerating Stress or Cause	Fiber break	Dirt	Bad cleve	Total	
		60.00%	20.00%	20.00%	100 %	
Operational Stresses	Op. Temp.				0.00	0.07
	Vibration	s			0.07	
	Current/voltage				0.00	
	Optical power				0.00	
Environmental	Amb. Temp.				0.00	0.23
	Corrosion				0.00	
	Ageing				0.00	
	Humidity	p			0.23	
Power Cycling	Power Cycling	s			0.07	0.07
Induced/handling	Induced/handling	p	p	p	0.63	0.63
TOTAL					1.00	1.00

Table 10: Failure Mode to Failure Cause Category for Cable (Fiber and Cable Only, Not Including Connectors)

Failure Cause Category	Accelerating Stress or Cause	Microcracks	Thermal expansion causes microbending and attenuation	Microbending	Pinching	Twisting	Fracture	Wicking of contaminants inside the jacket	Stress corrosion cracking	Water freezing inside the jacket	Radiation	Outgassing of outer sheathing	UV embrittlement of outer sheathing	Thermal overstress of sheathing and jacket	Thermal overstress of fiber coating due to power leakage at a bend site	Fiber not tolerant to bending due to cable construsion or loss of the slippery stuff	**Total**	
		8.57%	8.57%	2.86%	25.71%	2.86%	8.57%	8.57%	2.86%	2.86%	2.86%	2.86%	2.86%	2.86%	8.57%	8.57%	100 %	
Operational Stresses	Op. Temp.													p			0.03	0.09
	Vibration								p	p							0.02	
	Current/voltage																0.00	
	Optical power														p		0.04	
Environmental	Amb. Temp.																0.00	0.21
	Corrosion							s									0.02	
	Ageing										p	p	p				0.09	
	Humidity						p		p							p	0.10	
Power Cycling	Power Cycling		p							p							0.10	0.10
Induced/handling	Induced/handling	p		p	p	p	p	p	p						p	p	0.60	0.60
																TOTAL	1.00	1.00

Table 11: Failure Mode to Failure Cause Category for Laser Diode Module

Failure Cause Category	Accelerating Stress or Cause	Solder voids	Bond wire failure	Gold-indium intermetallic compound formation	Diode facet COD	Solder creep/migration	Solder de-bonding	Laser bar material defects	Cracking of semiconductor from wedge bonds	Gradual aging manifested by decreasing light output and increased current to maintain operation at a specified output Operation at excessive temperature	Electrical overstress due to an ESD event	Transient current pulses during operation.	Thermal induced (overheating)	Dislocations	Metal diffusion and alloy reaction that affect the electrode	Solder instability (reaction and migration) that affect the bonding parts	Separation of metals in the heat sink bond	Defects in buried heterostructure devices	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	Fiber facet COD	Fiber break	Total	
		16.07%	5.36%	1.79%	5.36%	16.07%	1.79%	5.36%	5.36%	5.36%	5.36%	1.79%	5.36%	5.36%	1.79%	1.79%	1.79%	1.79%	1.79%	5.36%	5.36%	100 %	
Operational Stresses	Op. Temp.	s															p					0.05	0.39
	Vibration		s																			0.01	
	Current/voltage	p	p	p						s					p		p					0.20	
	Optical power				p														p	p		0.13	
Environmental	Amb. Temp.																					0.00	0.13
	Corrosion																					0.00	
	Ageing					p	p			p												0.13	
	Humidity																					0.00	
Power Cycling	Power Cycling		p			p	p		p							p						0.18	0.18
Induced/handling	Induced/handling							p			p	p	p	p				p			p	0.30	0.30
																					TOTAL	1.00	1.00

Table 12: Failure Mode to Failure Cause Category for Photodiode

Failure Cause Category	Accelerating Stress or Cause	Increase in dark current	Decrease in breakdown voltage	Short	Solder voids	Bond wire failure	Diode facet COD	Solder creep/migration	Solder de-bonding	Cracking of semiconductor from wedge bonds	Electrical overstress due to an ESD event	Transient current pulses during operation.	Thermal induced (overheating)	Solder instability (reaction and migration) that affects the bonding parts	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	Fiber break	Lead failure	Total	
		8.33%	8.33%	2.78%	8.33%	8.33%	8.33%	8.33%	2.78%	2.78%	8.33%	8.33%	2.78%	2.78%	2.78%	8.33%	8.33%	100 %	
Operational Stresses	Op. Temp.				s													0.02	0.39
	Vibration					s												0.01	
	Current/voltage	p	p	p	p	p												0.25	
	Optical power						p								p			0.11	
Environmental	Amb. Temp.																	0.00	0.10
	Corrosion																	0.00	
	Ageing	s	s					p	p									0.10	
	Humidity																	0.00	
Power Cycling	Power Cycling					p		p	p	p				p				0.15	0.15
Induced/handling	Induced/handling										p	p	p			p	p	0.36	0.36
																	TOTAL	1.00	1.00

Table 13: Failure Mode to Failure Cause Category for Transmitter

Failure Cause Category	Accelerating Stress or Cause	Solder voids	Bond wire failure	Gold-indium intermetallic compound formation	Diode facet COD	Solder creep/migration	Solder de-bonding	Laser bar material defects	Cracking of semiconductor from wedge bonds	Gradual aging manifested by decreasing light output and increased current to maintain operation at a specified output Operation at excessive temperature	Electrical overstress due to an ESD event	Transient current pulses during operation.	Thermal induced (overheating)	Dislocations	Metal diffusion and alloy reaction that affect the electrode	Solder instability (reaction and migration) that affect the bonding parts	Separation of metals in the heat sink bond	Defects in buried heterostructure devices	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	Fiber facet COD	Fiber break	Integrated circuits failure (amplifier, transistors, etc.)	Total	
		13.85%	4.62%	1.54%	4.62%	13.85%	1.54%	4.62%	4.62%	4.62%	4.62%	1.54%	4.62%	4.62%	1.54%	1.54%	1.54%	1.54%	1.54%	4.62%	4.62%	13.85%	100 %	
Operational Stresses	Op. Temp.	s		p											p	p	p					p	0.13	0.52
	Vibration		s																				0.01	
	Current/voltage	p	p	p						p					p	p	p	p				p	0.27	
	Optical power				p														p	p			0.11	
Environmental	Amb. Temp.																						0.00	0.09
	Corrosion																						0.00	
	Ageing					p	p			s													0.09	
	Humidity																						0.00	
Power Cycling	Power Cycling		p			p	p		p														0.14	0.14
Induced/handling	Induced/handling							p			p	p	p	p							p		0.25	0.25
																						TOTAL	1.00	1.00

Table 14: Failure Mode to Failure Cause Category for Receiver

Failure Cause Category	Accelerating Stress or Cause	Increase in dark current	Decrease in breakdown voltage	Short	Solder voids	Bond wire failure	Diode facet COD	Solder creep/migration	Solder de-bonding	Cracking of semiconductor from wedge bonds	Electrical overstress due to an ESD event	Transient current pulses during operation.	Thermal induced (overheating)	Solder instability (reaction and migration) that affect the bonding parts	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	Fiber break	Lead failure	Integrated circuits failure (amplifier, demodulator, etc.)	Total	
		6.67%	6.67%	2.22%	6.67%	6.67%	6.67%	6.67%	2.22%	2.22%	6.67%	6.67%	2.22%	2.22%	2.22%	6.67%	6.67%	20.00%	100 %	
Operational Stresses	Op. Temp.				s													p	0.11	0.51
	Vibration					s													0.01	
	Current/voltage	p	p	p	p	p												p	0.30	
	Optical power						p								p				0.09	
Environmental	Amb. Temp.																		0.00	0.08
	Corrosion																		0.00	
	Ageing	s	s					p	p										0.08	
	Humidity																		0.00	
Power Cycling	Power Cycling					p		p	p	p				p					0.12	0.12
Induced/handling	Induced/handling										p	p	p			p	p		0.29	0.29
																		TOTAL	1.00	1.00

Table 15: Failure Mode to Failure Cause Category for Transceiver

Failure Cause Category	Accelerating Stress or Cause	Solder voids	Bond wire failure	Gold-indium intermetallic compound formation	Diode facet COD	Solder creep/migration	Solder de-bonding	Laser bar material defects	Cracking of semiconductor from wedge bonds	Gradual aging manifested by decreasing light output and increased current	Electrical overstress due to an ESD event	Transient current pulses during operation.	Thermal induced (overheating)	Dislocations	Metal diffusion and alloy reaction that affect the electrode	Solder instability (reaction and migration) that affect the bonding parts	Separation of metals in the heat sink bond	Defects in buried heterostructure devices	Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes	Fiber facet COD	Fiber break	Integrated circuits failure (amplifier, demodulator, transistors, etc.)	**Total**	
		5.45%	5.45%	5.45%	5.45%	5.45%	1.82%	5.45%	5.45%	5.45%	5.45%	5.45%	1.82%	1.82%	1.82%	5.45%	1.82%	5.45%	1.82%	1.82%	5.45%	16.36%	100 %	
Operational Stresses	Op. Temp.	s		p	s			p		p				p	p	p	p	p	s			p	0.28	0.67
	Vibration		s																				0.01	
	Current/voltage	p	p	p				p		p				p	p	p	p	p					0.22	
	Optical power				p			s											p	p		p	0.16	
Environmental	Amb. Temp.																						0.00	0.04
	Corrosion																						0.00	
	Ageing					p	p																0.04	
	Humidity																						0.00	
Power Cycling	Power Cycling		p			p	p		p														0.11	0.11
Induced/handling	Induced/handling										p	p	p								p		0.18	0.18
																						TOTAL	1.00	1.00

IX.3.1.3 Identify the base percentage of failure rate attributable to each cause

The base percentages of failure rate were calculated by summing the accelerating stress/cause percentages associated with each failure cause. For example, for connectors, the four percentages associated with the "operating" accelerating stresses/causes were 11%, or 0.11. These percentages were an estimate of the percent of failures that could be expected for each cause under nominal stress conditions. In this case, nominal stresses were the average stresses to which the models were normalized. Table 16 summarizes the failure cause percentages (in fractional form).

Table 16: Failure Cause Percentages

Model Category	Op.	Env.	Temp Cyc.	Ind.
Connector	0.11	0.30	0.23	0.37
Passive Micro-optic Components	0.27	0.10	0.32	0.31
Passive Fiber-based Components	0.00	0.35	0.15	0.50
Isolators	0.37	0.32	0.24	0.06
VOA	0.23	0.09	0.24	0.44
Fiber	0.13	0.63	0.00	0.24
Splice	0.08	0.23	0.08	0.63
Cable	0.10	0.20	0.10	0.60
Laser Diode Module	0.38	0.13	0.18	0.30
Photodiode	0.39	0.10	0.15	0.36
Transmitters	0.52	0.09	0.14	0.25
Receiver	0.52	0.08	0.12	0.29
Transceiver	0.67	0.04	0.11	0.18

IX.3.1.4 Collect reliability data and populate spreadsheet

As previously summarized, the approach that was taken in this model development methodology relied on the collection of quantitative failure mode and failure rate data. Task 3.3 of this effort encompassed the collection of this data. Literature searches were performed toward the goal of collecting the quantitative data required for model development. Sources searched for applicable data included:

- Optical Society of America (OSA)
- SPIE
- RIAC databases
- TEMS (Database of government-related research from Information Analysis Centers (IACs) and other sources)
- Government-Industry Data Exchange Program (GIDEP)
- Manufacturer data
- Data mined from the Internet

The references provided at the end of this report list the reports and data sources that were reviewed, and from which pertinent data was extracted.

The results of this data collection effort are summarized in Table 17. The first column is the part type; the second is the data type. Data types used in this study include:

- Field data
- Test data
    - Thermal Cycling

  - Vibration
  - Damp heat
  - High temperature storage
  - Low temperature storage
  - Operating life test

Columns three through ten are the estimates of the actual stresses to which the part was exposed in the field or during the test. These stresses are defined as follows:

T_{AO} = Ambient operating temperature
T_{AE} = Ambient environmental temperature
T_R = Temperature rise above T_{AO}
V_A = Maximum applied vibration level (Grms)
DC = Duty cycle (fraction of calendar time in operation)
CR = Cycling rate (cycles per year)
RH_a = Relative Humidity (%)

The right most column lists the reference from which the data was extracted.

Table 17: Data Collected

Part type	Data Type	T_{AO}	T_{AE}	T_R	Delta T	V_A	DC	CR	RH_a	Hours	Failures	Lambda obs.	Ref
Cable	Field	45	23	15	37	1	0.8	368	40	1,002,305.302	1	997.7	57
	Thermal Cycling	85	-20	0	105	0	1	2037		165	0		18
	Thermal Cycling	50	-30	0	80	0	1	4037		65	0		27
	Thermal Cycling	60	-30	0	90	0	1	4037		65	0		28
	Vibration	25	25	0	0	20	1	0		18	0		18
	Vibration	25	25	0	0	13	1	0		32	2		20
	Vibration	25	25	0	0	14	1	0		9	0		27
	Vibration	25	25	0	0	20	1	0		9	0		28
Connector	Field	30	23	5	12	0	0.8	368	40	33,333,333.33	1	30	57
	Damp heat	85	85	0	0	0	0	0	85	20,000	0		35
	Damp heat	60	60	0	0	0	0	0	95	20,160	12		39
	Damp heat	85	85	0	0	0	0	0	85	1,056	0		53
	Damp heat	85	85	0	0	0	0	0	85	22,000	0		79
	Damp heat	85	85	0	0	0	0	0	85	22,000	0		79
	High temperature storage	85	85	0	0	0	0	0	2	20,160	8		38
	High temperature storage	85	85	0	0	0	0	0		1,056	0		53
	Low temperature storage	-40	-40	0	0	0	0	0		1,056	0		53
	Thermal Cycling	85	-40	0	125	0	1	1752		5,000	0		36
	Thermal Cycling	70	-40	0	110	0	1	1752		12,600	16		40
	Thermal Cycling	85	-40	0	125	0	1	1752		50	0		53
	Thermal Cycling	85	-40	0	125	0	1	1752		5,500	0		79
	Vibration	25	25	0	0	20	1	0		33	0		79
Isolators	Field	30	23	5	12	1	0.8	368	40	2.43E+09	4		57

Table 17: Data Collected (continued)

Part type	Data Type	T_{AO}	T_{AE}	T_R	Delta T	V_A	DC	CR	RH_a	Hours	Failures	Lambda obs.	Ref
Laser Diode Module	Field	30	23	15	22	1	0.8	368	40	1,728,314,664	111		57
	Field	30	23	15	22	1	0.8	368	40	1.37E+09	99		65
	Op life test	25		15	40	0	1	0		3,900,000,000	1	0.256	2
	Op life test	25		15	40	0	1	0		2,000,000	1	500	6
	Op life test	50		15	65	0	1	0		117,000	1	8547	7
	Op life test	25		15	40	0	1	0		2,500,000	1	400	9
	Op life test	25		15	40	0	1	0		10,000,000	1	100	9
	Op life test	60		15	75	0	1	0		100,000	1	10000	10
	Op life test	10	10	15	15	0	1	0		166,666,666.7	1	6	33
	Op life test	25	25	15	15	0	1	0		1,111,111.111	1	900	43
	Op life test	85		15	100	0	1	0		30,000	0		45
	Op life test	25		15	40	0	1	0		13,0000	1	7692	48
	Op life test	70		15	85	0	1	0		91,000	0		50
	Op life test	25		15	40	0	1	0		9,009,009.009	1	111	50
	Op life test	100		15	115	0	1	0		2,000,000	1	500	51
	Op life test	25		15	40	0	1	0		500,000	1	2000	52
	Op life test	70		15	85	0	1	0		100,000,000	1	10	51
	Op life test	65		15	80	0	1	0		354,000	1	2825	52
	Op life test	25		15	40	0	1	0		90,909,090.91	1	11	82
Passive Fiber-based Components	Damp heat	85	85	0	0	0	0	0	85	22,000	0		34
	Field	30	23	0	7	0	0.8	368	40	7,128,643,512	21		57
	High temperature storage	85	85	0	0	0	0	0	2	22,000	0		34
	Low temperature storage	-40	-40	0	0	0	0	0	2	22,000	0		34
	Op life test	85		0	85	0	1	0	0.9	20,000,000	1	50	11
	Op life test	85		0	85	0	1	0	0.9	2,000,000	1	500	11
	Op life test	85		0	85	0	1	0	0.9	71,428,571.43	1	14	11
	Op life test	85		0	85	0	1	0	0.9	8,000,000	1	125	11
	Op life test	85		0	85	0	1	0	0.9	2,000,000	1	500	11
	Op life test	85		0	85	0	1	0	0.9	1,000,000	1	1000	11
	Op life test	85		0	85	0	1	0	0.9	50,000,000	1	20	11
	Op life test	85		0	85	0	1	0	0.9	3,508,771.93	1	285	11
	Op life test	10	10	0	0	0	1	0		1,000,000,000	1	1	33
	Thermal Cycling	70	-40	0	110	0	1	1752		5,500	0		34
	Vibration	25	25	0	0	20	1	0		33	0		34

Table 17: Data Collected (continued)

Part type	Data Type	T_{AO}	T_{AE}	T_R	Delta T	V_A	DC	CR	RH_a	Hours	Failures	Lambda obs.	Ref
Passive Micro-optic components	Field	30	23	10	17	0	0.8	368	40	7,128,643,512	21		57
	Field	30	23	10	17	0	0.8	368	40	421,681,080	2		57
Photodiode	Field	30	23	5	12	0	0.8	368	40	1,514,584,464	1		57
	Op life test	25		5	30	0	1	0		1,000,000,000	1	1	3
	Op life test	10	10	5	5	0	1	0		1,000,000,000	1	1	33
	Op life test	85		5	90	0	1	0		33,333,333.33	1	30	49
	Op life test	65		5	70	0	1	0		100,000,000	1	10	52
	Op life test	25		5	30	0	1	0		23,809,523.81	1	42	61
	Op life test	150		5	155	0	1	0		3,174,603			77
	Op life test	85		5	90	0	1	0		95.5			80
Receiver	Damp heat	85		15	100	0	0	0	85	10,000	0		62
	Thermal Cycling	85	-40	15	140	0	1	1752		2500	0		62
	Op life test	85		15		0	1	0	2	2,370,000	1		97
	Op life test	85		15		0	1	0	2	2,250,000	0		97
	Thermal Cycling	125	-55	0		0	0	0		20,550,000	1		97
	Damp heat	85							85	4,360,000	13		97
	High temperature storage	125	125	0						80,000	0		97
	Vibration	25	25	0	0	20	1	0		60	0		97
Splice	Field	30	23	20	27	0	0.8	368	40	1,018,958,424	36		57
Transmitters	Op life test	25		15	40	0	1	0		374,000	1	2673.8	4
	Op life test	25		15	40	0	1	0		1,000,000,000	1	1	5
	Op life test	25		15	40	0	1	0		10,000,000	1	100	5
	Op life test	65		15	80	0	1	0		55,000	1	18182	52
	Op life test	85		15		0	1	0	2	879,500	3		97
	Thermal Cycling	125	-55	0		0	0	0		20,550,000	1		97
	Damp heat	85							85	4,360,000	13		97
	High temperature storage	125	125	0						80,000	0		97
	Vibration	25	25	0	0	20	1	0		60	0		97
VOA	Field	30	23	20	27	0	0.8	368	40	333,670,200	13		57

IX.3.1.5 Estimate stresses to which the parts were exposed

For each source of data that was collected, an estimate of the stresses and operating profiles to which the component was exposed was required so that the failure rates could be normalized to the actual stresses. These stresses were summarized in the previous section.

For test data, these values were generally readily available. For data collected from fielded systems, the actual stress values were not available. Therefore, they had to be estimated. The default values of the environmental and operating profile factors are summarized in Tables 18 and 19. Only field data from telecommunication applications used in a ground, stationary, indoors environment was available for this study and, therefore, only the values pertaining to these conditions were estimated in this manner.

Table 18: Default Environmental Stress Values

Environment	TAO	TAE	Humidity	Vibration (G_{RMS})
Airborne	55	14	40	9
Airborne, Fixed Wing	55	14	40	9
Airborne, Fixed Wing, Inhabited	55	14	40	9
Airborne, Fixed Wing, Uninhabited	71	14	50	9
Airborne, Missile	55	14	40	10
Airborne, Missile, Flight	55	14	40	1.3
Airborne, Missile, Launch	55	14	40	16
Airborne, Rotary Wing	55	14	40	3.3
Airborne, Rotary Wing, Inhabited	55	14	40	3.3
Airborne, Rotary Wing, Uninhabited	71	14	50	3.3
Airborne, Space	55	14	40	0
Ground	35	17	40	0
Ground, Man Pack	55	14	40	1
Ground, Mobile	55	14	40	10
Ground, Mobile, Heavy Wheeled	55	14	40	10
Ground, Mobile, Heavy Wheeled, Chassis Mounted	55	14	40	10
Ground, Mobile, Heavy Wheeled, Engine Compartment	55	14	40	10
Ground, Mobile, Heavy Wheeled, Engine Mounted	55	14	40	10
Ground, Mobile, Heavy Wheeled, Instrument Panel Closed	55	14	40	10
Ground, Mobile, Heavy Wheeled, Instrument Panel Open	55	14	40	10
Ground, Mobile, Heavy Wheeled, Trunk	55	14	40	10
Ground, Mobile, Light Wheeled	55	14	40	4
Ground, Mobile, Light Wheeled, Chassis Mounted	34	14	40	4
Ground, Mobile, Light Wheeled, Engine Compartment	40	14	40	4
Ground, Mobile, Light Wheeled, Engine Mounted	58	14	40	4
Ground, Mobile, Light Wheeled, Instrument Panel Closed	31	14	40	4
Ground, Mobile, Light Wheeled, Instrument Panel Open	24	14	40	4
Ground, Mobile, Light Wheeled, Trunk	17	14	40	4
Ground, Mobile, Tracked	55	14	40	2
Ground, Stationary	35	19	40	0
Ground, Stationary, Indoors	30	23	40	0
Ground, Stationary, Outdoors	40	14	50	0
Naval	55	14	80	0.7
Naval, Shipboard	55	14	80	0.7
Naval, Shipboard, Sheltered	40	20	70	0.7
Naval, Shipboard, Unsheltered	60	14	90	0.7
Naval, Submarine	55	23	50	1

Table 19: Default Operating Profile Values

Equipment type	Operating profile	
	DC	CR (C/yr)
Automotive	5	1000
Commercial Aircraft	25	2982
Computer	80	1491
Consumer	30	368
Emergency Power	10	50
Industrial	80	184
Military Aircraft	25	1008
Military Ground	45	263
Naval	80	50
Telecommunications	80	368

DC = Duty cycle, CR = cycling rate

IX.3.1.6 Estimate acceleration model constants for each part

Acceleration factors (or Pi-factors) are used in the component models to estimate the effects of various stress and component variables on failure rate. The two predominant forms of acceleration factors are the Arrhenius and the power law models.

The Arrhenius model is generally used for modeling temperature effects and is:

$$AF_T = e^{\frac{Ea}{KT}}$$

Where AF_T is the temperature acceleration factor, Ea is the activation energy, K is Boltzman's constant, and T is the temperature in degrees K.

The power law model is:

$$AF = S^n$$

Where S is the stress and n is a constant.

The specific forms of these acceleration factors that were used in the models are summarized below.

π_{TO} = Factor for operating temperature

$$\pi_{TO} = e^{\left(\frac{-Ea_{op}}{.00008617}\left(\frac{1}{T_{AO}+T_R+273}-\frac{1}{298}\right)\right)}$$

π_V = Vibration factor

$$\pi_V = \left(\frac{V_a+1}{V_c}\right)^{n_{vib}}$$

π_{TE} = Nonoperating temperature factor

$$\pi_{TE} = e^{\left(\frac{-Ea_{nonop}}{.00008617}\left(\frac{1}{T_{AE}+273}-\frac{1}{298}\right)\right)}$$

π_{RH} = Humidity factor

$$\pi_{RH} = \left(\frac{RH_a + 1}{RH_c}\right)^{n_{RH}}$$

π_{DT} = Delta Temperature factor

$$\pi_{DT} = \left(\frac{T_{AO} + T_R - T_{AE}}{14}\right)^{n_{PC}}$$

The temperature factors based on the Arrhenius relationship were normalized to 25 degrees C. The acceleration factors for vibration and relative humidity that are based on the power law were normalized to a specific value, i.e. the denominator, and included a value of one in the numerator to ensure that the factor does not go to zero at a stress level of zero.

Each model has a single factor that needs to be estimated: Ea for the Arrhenius and n for the power law. These were estimated in one of the following ways:

1. Values were generated from information that was available in the literature
2. Engineering judgment based on the known behavior of similar failure mechanisms

For the second method, acceleration was categorized from no acceleration to very high acceleration for each specific accelerating stress. Table 20 summarizes the values of the applicable parameters as a function of this relationship.

Table 20: Categories of Acceleration Model Parameters

Dependency	n (PC)	Ea (op)	Ea (nonop)	n (RH)	n (Vibration)
Very High	10	1	1	10	10
High	5	0.7	0.7	5	5
Medium	2	0.5	0.5	2	2
Low	1	0.1	0.1	1	1
None	0	0	0	0	0

Table 21 summarizes the specific parameter values used in the photonic models.

Table 21: Acceleration Model Parameters

Component Type	n (PC)	Ea (op)	Ea (nonop)	n (RH)	n (Vibration)
Connector	2	0.1	0.1	10	5
Passive Micro-optic components	1	0.7	0.7	5	2
Passive Fiber based components	2	0.10	0.1	5	2
Isolators	2	0.10	0.1	5	2
VOA	2	0.50	0.1	2	2
Fiber	0	0.00	0	10	5
Splice	0	0.00	0	10	5
Cable	0	0.00	0	10	5
Laser diode module	2	0.61	0.5	2	2
Photodiode	2	0.65	0.5	2	2
Transmitters	2	0.65	0.5	2	2
Receiver	2	0.65	0.5	2	2
Transceivers	2	0.50	0.5	2	2

IX.3.1.7 Calculate a normalization stress accelerating stress

The Pi factors need to be normalized to a fixed set of conditions. This approach makes it convenient to derive default Pi factors. For example, by normalizing the factors in this manner, the Pi factor is equal to one when the stress is equal to the default stress. Therefore, if an analyst chooses to ignore the effects of a particular stress, the failure rate will be representative of the default stress levels.

The default values for the applicable model Pi factors are summarized in Table 22.

Table 22: Default Model Parameters

Model Category	Default Tr	Default DC	Default CR	Default Vibration	Default RH	Default DT
Connector	0	.25	1000	1	50	20
Passive Micro-Optic Component	10					
Passive Fiber-Based Component	0					
Isolator	5					
VOA	20					
Fiber	0					
Splice	0					
Cable	0					
Laser Diode Module	15					
Photodiode	5					
Transmitter	15					
Receiver	15					
Transceiver	15					

IX.3.1.8 Estimate acceleration factors (Pi factors) for each part from each data source

The acceleration factors used in the models are Pi factors, which represent the acceleration factors normalized to a given stress level. These factors were calculated for each part from each data source. To derive these factors, two pieces of information were required:

1. The estimate of the stress for each data point (in this case, a data point is a single observation of reliability (failures and hours) at a known set of stress conditions). The manner in which these were quantified was previously explained.
2. The default stress level of the data for each stress parameter in the model

The Pi factor is then the acceleration model normalized to the default stress level. An example of this calculation is shown in Table 23. Every data point available from field or test data had an associated Pi factor calculated. Note that some of the Pi factors are zero. This occurs because test data is not applicable to all failure causes. This concept will be further explained in the next section.

Table 23: Example of Pi factor Calculation

		Pi factors							
		Pi DCO	Pi TO	Pi V	Pi DCN	Pi TE	Pi RH	Pi CR	Pi DT
Cable	Field	3.200	1.000	32.000	0.267	1.000	0.137	0.368	1.063
Cable	Thermal Cycling	4.000	1.000	1.000	0.000	1.000	0.000	2.037	1.180
Cable	Thermal Cycling	4.000	1.000	1.000	0.000	1.000	0.000	4.037	1.149
Cable	Thermal Cycling	4.000	1.000	1.000	0.000	1.000	0.000	4.037	1.162
Cable	Vibration	4.000	1.000	4084101	0.000	1.000	0.000	0.000	0.000
Cable	Vibration	4.000	1.000	496874	0.000	1.000	0.000	0.000	0.000
Cable	Vibration	4.000	1.000	785027	0.000	1.000	0.000	0.000	0.000
Cable	Vibration	4.000	1.000	4084101	0.000	1.000	0.000	0.000	0.000
Connector	Field	3.200	1.135	1.000	0.267	0.974	0.137	0.368	0.360
Connector	Damp heat	0.000	1.921	1.000	1.333	1.921	227	0.000	0.000
Connector	Damp heat	0.000	1.506	1.000	1.333	1.506	681	0.000	0.000
Connector	Damp heat	0.000	1.921	1.000	1.333	1.921	227	0.000	0.000
Connector	Damp heat	0.000	1.921	1.000	1.333	1.921	227	0.000	0.000
Connector	Damp heat	0.000	1.921	1.000	1.333	1.921	227	0.000	0.000
Connector	High temperature storage	0.000	1.921	1.000	1.333	1.921	0.000	0.000	0.000
Connector	High temperature storage	0.000	1.921	1.000	1.333	1.921	0.000	0.000	0.000
Connector	Low temperature storage	0.000	0.337	1.000	1.333	0.337	0.000	0.000	0.000

IX.3.1.9 Calculate the base failure rates for each cause such that observed = predicted failure rates

In the case of the 217Plus models, which were based solely on field data, the base failure rates were obtained for each failure cause category, as follows:

$$\lambda_{Bi} = \frac{\sum_{1}^{m} \left(F_{obs} \times \%_{i}\right)_{field}}{\sum_{1}^{m} H_{obs_{field}} \times \prod_{1}^{k} \pi}$$

Where:

F_{obs} is the number of observed field failures
H_{obs} is the number of observed field hours
Π π is the product of the applicable Pi factors applicable to the field environment
“i” is the number of failure causes (4)
“m” is the number of field data sources
“k” represents correction factors
$\%_i$ is the percentage of failure rate attributable to the specific failure causes

The product of the Pi factors converts the actual hours to an equivalent “effective” number of hours normalized to the default stress values.

However, in the case of the photonic models developed during this study, it was necessary to utilize a significant amount of test data since there was not enough field data available. This was due to the fact that there are currently few field data sources for photonic components. Therefore, the modeling methodology needed to be tailored to accommodate the specific data available for the parts addressed in this study. This is accomplished by using a Bayesian technique in which the field data becomes the prior distribution, and the summation of the failure and hours from all data sources forms the basis of the posterior distribution. The failure rate parameter of the exponential distribution is therefore:

$$\lambda_{Bi} = \frac{\sum_{1}^{m} \left(F_{obs} \times \%_{i}\right)_{field} + \sum_{1}^{j} F_{obs_{test}}}{\sum_{1}^{m} H_{obs_{field}} \times \prod_{1}^{k} \pi + \sum_{1}^{j} H_{obs_{test}} \times \prod_{1}^{k} \pi}$$

where there are j test data sources.

Each specific type of test data collected in this study is applicable to only one of the four specific failure causes, as summarized in Table 24. Field data, however, encompasses all four failure causes.

Table 24: Applicability of Test Data

Data Type	**Failure Cause Category**			
	Operating	**Environmental**	**Cycling**	**Induced**
Field	X	X	X	X
Operating Life Test	X			
High Temperature Storage		X		
Low Temperature Storage		X		
Damp Heat		X		
Vibration	X			
Thermal Cycling			X	

One of the advantages to the model structure is this ability to modify the base failure rates of specific failure causes with test data applicable to only the failure cause.

There were several part types that did not have any field data on which to base the calculation of the base failure rate. These parts included:

- Connectors
- Cables
- Receivers
- Transmitters
- Transceivers

The options considered to address this problem were:

1. Use field data from similar part types as a baseline, and use test data from actual parts to modify the appropriate failure causes. In this case, this "seed value" becomes the Bayesian prior
2. Construct a "hybrid" model from portions of other models, where applicable

The first option was chosen due to the fact that there were some generic failure rates applicable to each of these part types. The seed values used for this analysis for these part types are summarized in Table 25.

Table 25: Seed Values

Part Type	Seed Failure Rate (Failures per million hours)	Data Source
Connector	0.030	Ref. 98
Cable	0.9977	Ref. 57
Receiver	0.064	Ref. 57
Transmitter	0.064	Ref. 57

Transceivers yielded no field or test data and, therefore, a reliability model could not be developed.

The base failure rates resulting from this analysis are listed in Table 26.

Table 26: Base Failure Rates (Failures per Million Calendar Hours)

Component	Base Failure Rate (failures per million calendar hours)			
Connector	0.0002	0.3053	2.7952	0.0110
Passive Micro-optic Components	0.0001	0.0036	0.0031	0.0010
Passive Fiber-based Components	0.0003	0.0107	0.0098	0.0015
Isolators	0.0000	0.0055	0.0030	0.0001
VOA	0.0006	0.0192	0.0140	0.0171
Fiber	0.0008	0.2169	0.0070	0.0221
Splice	0.0008	0.2169	0.0070	0.0221
Cable	0.0033	5.5089	0.2543	0.6010
Laser Diode Module	0.0004	0.0558	0.0280	0.0206
Photodiode	0.0001	0.0004	0.0007	0.0002
Transmitter	0.0005	2.4489	0.1648	0.0158
Receiver	0.0004	2.4438	0.1563	0.0186

IX.3.1.10 Adjust the base failure rates

The last step in the process was to adjust the base failure rates to ensure that the predicted number of failures was equal to the observed number. The manner in which this is accomplished was to scale the base failure rates in a manner that ensured that the cumulative predicted number of failures of the entire population of observed data points was equal to the observed number of failures. This was accomplished by using the Microsoft EXCEL® "Goal Seek" function, which finds the value of a "correction factor" that satisfies this boundary condition. This approach is conceptually similar to a maximum likelihood estimate (MLE) method.

The correction factor, and the resulting base failure rates. are shown in Table 27.

Table 27: Correction Factor and Base Failure Rates

Component	**Correction Factor**	**Base Failure Rate (failures per million calendar hours)**			
Connector	1.000	0.0002	0.3052	2.7951	0.0110
Passive Micro-optic Components	1.000	0.0001	0.0036	0.0031	0.0010
Passive Fiber-based Components	0.946	0.0003	0.0101	0.0093	0.0014
Isolator	1.000	0.0000	0.0055	0.0030	0.0001
VOA	1.000	0.0006	0.0192	0.0140	0.0171
Fiber	1.000	0.0008	0.2169	0.0070	0.0221
Splice	1.000	0.0008	0.2169	0.0070	0.0221
Cable	1.000	0.0033	5.5089	0.2543	0.6010
Laser Diode Module	0.718	0.0003	0.0401	0.0201	0.0148
Photodiode	0.921	0.0001	0.0004	0.0007	0.0002
Transmitter	0.573	0.0003	1.4036	0.0945	0.0091
Receiver	1.300	0.0005	3.1766	0.2032	0.0241

IX.3.1.11 Treatment of Quality and Environmental Stresses

There were several options for modeling the effects of environmental stresses. Early in this study, it was decided that the effects of quality and environment would be treated such that the photonic component models would be "stand-alone". This approach differs from the form of the 217Plus methodology, in that quality and environment are treated as "system" level effects. This concept is based on the premise that quality and environmental effects are manifested more at the assembly or system level than they are at the component level. The proposed photonic component models include the effects of their pertinent environmental stresses in the component models, instead of applying the environment factor in the assembly or system model, as is the case with 217Plus. The primary environmental stresses included in the photonic component models are temperature, humidity and vibration.

The quality factor (Π_Q) is calculated in a manner similar to the 217Plus methodology, but tailored to the unique concerns of photonic components. This factor is calculated as follows:

$$\pi_Q = \alpha_i \left(-\ln\left(R_i\right)\right)^{\frac{1}{\beta_i}}$$

where α_i and β_i are Weibull parameters representing the distribution of the percentage of failures attributable to components (parts). The quality factor is scaled within this distribution based on how good the parts control program is. The variable R_i is the rating of the parts control program and is given as:

$$R_i = \frac{\sum_{j=1}^{n_i} G_{ij} W_{ij}}{\sum_{j=1}^{n_i} W_{ij}}$$

Where,

R_i = rating of the process for the ith failure cause, from 0 to 1

G_{ij} = the grade for the jth item of the ith failure cause. This grade is the rating between 0.0 and 1.0 (worst to best).

W_{ij} = the weight of the jth item of the ith failure cause

n_i = number of grading criteria associated with the ith failure cause

The 217Plus grading criteria are provided in Table 28. These were modified for photonic components as part of Task 3 of this project.

Table 28: Part Quality Process Grade Factor Questions

Parts Contribution to Reliability	**Rating**	**Input Range**	**User Input**	**Highest Possible Score**	**Actual Score**
Is there a documented part selection and **part management process**?	yes = 5 no = 0	Y,N	N	5	0.0
Are **part evaluation and qualification processes** established to add parts to the PPL?	yes = 3 no = 0	Y,N	N	3	0.0
Does a cross functional development team (**CFDT)** review and approve new candidate parts for addition to the PPL?	yes = 3 no = 0	Y,N	N	3	0.0
Is this a commercial off-the-shelf **(COTS)** purchased assembly with a **good history** of operational reliability?	yes = 6 no = 0	Y,N	N	6	0.0
Will **new parts** be added to the PPL to design this FRU?	yes = 4 no = 0	Y,N	N	4	0.0
Are procedures in place to **detect part problems** in both manufacturing and the field?	yes = 10 no = 0	Y,N	N	10	0.0
Are quality and **reliability data tracked on parts** and fed back to suppliers so they know their performance on this product?	yes = 10 no = 0	Y,N	N	10	0.0
Is there a **design compliance checklist** to ensure that all parts are properly applied, operating at sufficient margin with respect to environmental and operational stresses, and take into account lessons learned?	yes = 10 no = 0	Y,N	N	10	0.0
Are **teaming** relationships established with all critical component suppliers?	yes = 7 no = 0	Y,N	N	7	0.0
Will all suppliers provide timely failure reporting and corrective action support (**FRACAS**) for both critical and custom parts? (Timely reporting implies a 2 week turnaround with faster response on priority demand.)	yes = 7 no = 0	Y,N	N	7	0.0
Have supplier **identified the likely failure modes** on critical and custom parts, and does the design take these failure modes into account?	yes = 10 no = 0	Y,N	N	10	0.0
Are **operational failure rate and failure mode data** provided by the suppliers of critical and custom parts being used?	yes = 7 no = 0	Y,N	N	7	0.0
Is there a **device specification** for all critical and custom parts?	yes = 5 no = 0	Y,N	N	5	0.0
Has the **supplier reviewed the part application** for all critical and custom parts?	yes = 7 no = 0	Y,N	N	7	0.0
Will critical suppliers **provide timely notice of impending part changes** to allow the developer to assess the impact?	yes = 7 no = 0	Y,N	N	7	0.0
Is a **change history log** maintained to provide traceability of engineering change actions and their associated rationale for critical and custom parts?	yes = 7 no = 0	Y,N	N	7	0.0
Will part identification (**revision numbers**) be shown on the part to identify the particular part configuration, including the level of the part's firmware?	yes = 7 no = 0	Y,N	N	7	0.0

Table 28: Part Quality Process Grade Factor Questions (continued)

Parts Contribution to Reliability	Rating	Input Range	User Input	Highest Possible Score	Actual Score
Is there a **first article inspection** and acceptance test planned?	yes = 7 no = 0	Y,N	N	7	0.0
Have key suppliers **identified their part failure mechanisms**?	yes = 10 no = 0	Y,N	N	10	0.0
Have the sources and the extent of **part variation been identified**?	yes = 7 no = 0	Y,N	N	7	0.0
Have **mitigations** been identified to handle the effects of part's variations?	yes = 8 no = 0	Y,N	N	8	0.0
Will a **design of experiments part evaluation**, considering variations, as well as manufacturing variations, be conducted?	yes = 7 no = 0	Y,N	N	7	0.0
Will developers' **quality organization audit** the supplier's processes and facility capabilities?	yes = 6 no = 0	Y,N	N	6	0.0
Is an **optical path adhesive (OPA)** used in the component	A. No OPA = 10 B. yes, MFD <2um = 0 C. yes, MFD = 2 - 5 um = 4 D. yes, MFD = 5 - 10 um = 6 E. yes, MFD > 10 um = 8	A,B,C,D,E	B	10	0.0
Are there **thin films (AR coatings, filter elements)** in the light path?	A. No Thin film = 0 B. yes, and surface is prepared by sputtering = 2 C. yes, and surface is not prepared by sputtering = 3	A,B,C	A	3	0.0
Does the component contain **fused fiber**?	yes = 5 no = 0	Y,N	N	5	0.0
Does the component contain **fiber**?	yes = 5 no = 0	Y,N	N	5	0.0
Was the package **thermally designed to safely dissipate heat** by understanding and modeling the thermal characteristics?	yes = 3 no = 0	Y,N	N	3	0.0
Has the **manufacturer characterized the power handling capability** of the component?	yes = 5 no = 0	Y,N	N	5	0.0
Have **acceleration factors for power and temperature been quantified** and are they used to determine the derating requirements?	yes = 5 no = 0	Y,N	N	5	0.0
Does the **component contain absorbers** at wavelengths for which the component will be exposed (i.e. garnet, shutter, etc.)	yes = 4 no = 0	Y,N	N	4	0.0
How is **dissipated power** intended to be dumped?	A. with a heat sink = 4 B. dissipation not actively managed = 0	A,B	B	4	0.0
Does the component rely on **alignment of free space components attached with organics**	yes = 3 no = 0	Y,N	N	3	0.0
Cleanliness precautions	A. stringent cleaning procedures = 3 B. some cleaning procedures = 2 C. no cleaning procedures = 0	A,B,C	C	3	0.0
For components that have a fiber/epoxy interface, is the **fiber tip inspected** to ensure it is free of defects and contamination?	yes = 3 no = 0	Y,N	N	3	0.0

IX.4 Model Summary

A summary of the complete set of models is provided below. Model parameters are provided in Table 29.

$$\lambda_P = \pi_Q\left(\lambda_{OB}\pi_{DCO}\pi_{TO}\pi_V + \lambda_{EB}\pi_{DCN}\pi_{TE}\pi_{RH} + \lambda_{TCB}\pi_{CR}\pi_{DT} + \lambda_{ind}\right)$$

$$\pi_{DCO} = \frac{DC}{DC_{1op}}$$

$$\pi_{TO} = e^{\left(\frac{-Ea_{op}}{.00008617}\left(\frac{1}{T_{AO}+T_R+273}-\frac{1}{298}\right)\right)}$$

$$\pi_V = \left(\frac{V_a+1}{V_c}\right)^{n_{vib}}$$

$$\pi_{DCN} = \frac{1-DC}{1-DC_{1op}}$$

$$\pi_{TE} = e^{\left(\frac{-Ea_{nonop}}{.00008617}\left(\frac{1}{T_{AE}+273}-\frac{1}{298}\right)\right)}$$

$$\pi_{RH} = \left(\frac{RH_a+1}{RH_c}\right)^{n_{RH}}$$

$$\pi_{CR} = \frac{CR}{CR_1}$$

$$\pi_{DT} = \left(\frac{T_{AO}+T_R-T_{AE}}{14}\right)^{n_{PC}}$$

Where:

λ_P = Predicted failure rate, failures per million calendar hours
π_Q = Failure rate multiplier for quality
λ_{OB} = Base failure rate, operating
π_{DCO} = Failure rate multiplier for duty cycle, operating
DC = Duty cycle (fraction of calendar time in operation)
$DC1_{op}$ = 0.25
π_{TO} = Failure rate multiplier, Temperature – operating
Ea_{op} = Activation energy - operating
T_{AO} = Ambient operating temperature
T_R = Temperature rise above T_{AO}
π_V = Failure rate multiplier, vibration level

V_A = Max vibration level applied (Grms)
V_C = 1
n_{vib} = Vibration exponent
λ_{EB} = Base failure rate, environment
π_{DCN} = Failure rate multiplier, duty cycle – nonoperating
π_{TE} = Failure rate multiplier, Temperature – environment
Ea_{nonop} = Activation energy, nonoperating
T_{AE} = Ambient environmental temperature
π_{RH} = Failure rate multiplier, relative humidity
RH_a = Relative Humidity (%) - actual
RH_c = 50%
n_{RH} = Relative Humidity exponent
λ_{TCB} = Base failure rate, temperature cycling
π_{CR} = Failure rate multiplier, Cycling rate
CR = Cycling rate (cycles per year)
CR_1 = 1000
π_{DT} = Failure rate multiplier, Delta temperature
n_{PC} = Temperature cycling exponent
λ_{ind} = Base failure rate, induced

Table 29: Model Parameters

Model category	**Default Tr**	**n (PC)**	**Ea (op)**	**Ea (nonop)**	**n (RH)**	**n (Vib)**	λ_{OB}	λ_{EB}	λ_{TCB}	λ_{ind}
Connector	0	2	0.1	0.1	10	5	0.0002	0.3052	2.7951	0.0110
Passive Micro-optic components	10	1	0.7	0.7	5	2	0.0001	0.0036	0.0031	0.0010
Passive Fiber based components	0	2	0.1	0.1	5	2	0.0003	0.0101	0.0093	0.0014
Isolators	5	2	0.1	0.1	5	2	0.0000	0.0055	0.0030	0.0001
VOA	20	2	0.5	0.1	2	2	0.0006	0.0192	0.0140	0.0171
Fiber	0	0.1	0	0	10	5	0.0008	0.2169	0.0070	0.0221
Splice	0	0.1	0	0	10	5	0.0008	0.2169	0.0070	0.0221
Cable	0	0.1	0	0	10	5	0.0033	5.5089	0.2543	0.6010
Laser diode module	15	2	0.606	0.5	2	2	0.0003	0.0401	0.0201	0.0148
Photodiode	5	2	0.654	0.5	2	2	0.0001	0.0004	0.0007	0.0002
Transmitters	15	2	0.654	0.5	2	2	0.0003	1.4036	0.0945	0.0091
Receiver	15	2	0.654	0.5	2	2	0.0005	3.1766	0.2032	0.0241

IX.5 Example Calculations

Table 30 summarizes predicted failure rates for a variety of application environments and operating profiles. The input parameters used in these examples are listed in the top of the table, and the resulting failure rates, for each component, are shown in the bottom of the table.

Table 30: Example Calculations

Input Parameter	GB - Telecom	GB - Consumer	GM - Chassis	AU - Uninhabited
Tao	30	30	34	71
Tae	23	23	14	14
Tr	15	15	15	15
Delta T	22	22	35	72
Vibration Level	0	0	1	9
Duty Cycle	0.8	0.3	0.05	0.25
Cycling Rate	368	368	1000	1008
Humidity	40	40	40	40
Component	**Failure Rate (failures per million calendar hours)**			
Cable	0.908	1.406	1.850	331.307
Connector	0.393	0.420	4.425	55.604
Isolator	0.001	0.002	0.007	0.039
Laser Diode Module	0.034	0.047	0.094	1.813
Passive Fiber-based Components	0.004	0.006	0.015	0.130
Passive Micro-optic Components	0.003	0.003	0.006	0.529
Photodiode	0.001	0.001	0.002	0.292
Receiver	0.622	1.865	1.932	7.346
Splice	0.035	0.053	0.072	82.865
Transmitter	0.276	0.825	0.867	3.828
VOA	0.039	0.042	0.090	2.381

IX.6 MIL-HDBK-217-Like format models

The models summarized above are similar in form to the 217Plus models, but differ in form to the models within MIL-HDBK-217. The primary difference (in addition to the inherently different model form) is the fact that the failure rate units are failures per million calendar hours for the models developed in this study, versus failures per million operating hours, which is the traditional failure rate unit for the MIL-HDBK-217 models. Therefore, it was desirable to develop a set of photonic component models that are similar in form and units to the MIL-HDBK-217 models. This was accomplished by utilizing the detailed models developed in this study to derive a simplified version of the models, as shown below:

$$\lambda_P = \lambda_B \pi_E \pi_{OP} \pi_Q$$

Where:

λ_P = Predicted failure rate (failures per million operating hours)

λ_B = Base failure rate (failures per million operating hours)

π_E = Environment factor

π_{OP} = Operating profile factor

π_Q = Quality factor

To convert the failure rates from failures per million calendar hours to failures per million operating hours, the failure rate in failures per million calendar hours is divided by the duty cycle.

The base failure rates were derived by calculating the predicted failure rate under the normalizing conditions of:

1. An environment of "Ground, Stationary, Indoors"
2. An operating profile of "Consumer"

These conditions were previously defined in the section describing default stresses. The models were then used to calculate the failure rate under all environments, while the operating profile was fixed as "Consumer." The ratio of failure rates, relative to the "Ground, Stationary, Indoors" were then calculated and used as the environmental Pi factor. Likewise, the models were used to calculate the failure rate under all operating profiles while the environment was fixed as "Ground, Stationary, Indoors". The ratio of failure rates, relative to the "Consumer" operating profile were then calculated and used as the operating profile Pi factor.

Table 31 lists the base failure rates, Table 32 lists the environmental Pi factors, Table 33 lists the operating profile Pi factors, and Table 34 lists the quality factor.

The quality factor was derived by using the quality factor criteria previously presented, and selecting the grading criteria consistent with several different "classes" of quality. These classes were:

1. Commercial quality - no special design for reliability practices used
2. Best commercial practices – nominally good practices that utilize some design for reliability (DFR) processes
3. Full use of design for reliability practices - all DFR practices are applied

Table 34 details the specific grading criteria used for each of these classes.

Table 31: Base Failure Rates (λ_B)

	Part Type										
	Cable	Connector	Isolators	Laser diode module	Passive Fiber based components	Passive Micro-optic components	Photodiode	Receiver	Splice	Transmitters	VOA
Base Failure Rate	4.69	1.40	0.008	0.158	0.019	0.011	0.002	6.22	0.177	2.75	0.139

Table 32: Environment Pi Factor (π_E)

		Part Type										
		Cable	Connector	Isolators	Laser diode module	Passive Fiber based components	Passive Micro-optic components	Photodiode	Receiver	Splice	Transmitters	VOA
Environment	Airborne	282.3	82.5	6.3	17.3	12.4	65.2	172.9	1.7	1868.3	2.0	31.5
	Airborne, Fixed Wing	282.3	82.5	6.3	17.3	12.4	65.2	172.9	1.7	1868.3	2.0	31.5
	Airborne, Fixed Wing, Inhabited	282.3	82.5	6.3	17.3	12.4	65.2	172.9	1.7	1868.3	2.0	31.5
	Airborne, Fixed Wing, Uninhabited	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Airborne, Missile	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Airborne, Missile, Flight	1.2	13.1	3.3	2.6	3.8	4.7	11.4	0.9	2.2	0.9	3.4
	Airborne, Missile, Launch	3995.5	998.7	12.1	46.6	29.5	185.9	495.4	3.4	26514.5	4.2	87.5
	Airborne, Rotary Wing	5.1	14.1	3.7	4.7	5.0	13.1	33.9	1.0	28.4	1.1	7.3
	Airborne, Rotary Wing, Inhabited	5.1	14.1	3.7	4.7	5.0	13.1	33.9	1.0	28.4	1.1	7.3
	Airborne, Rotary Wing, Uninhabited	9.1	25.5	7.2	9.9	8.8	36.9	93.6	1.8	32.6	1.9	14.0
	Airborne, Space	1.0	13.1	3.2	1.9	3.4	2.0	4.0	0.8	1.0	0.9	2.1
	Ground	1.0	3.4	1.4	1.1	1.4	1.1	1.4	0.7	1.0	0.8	1.2
	Ground, Man Pack	1.1	13.1	3.3	2.4	3.7	3.9	9.2	0.9	1.6	0.9	3.0
	Ground, Mobile	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Ground, Mobile, Heavy Wheeled	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Ground, Mobile, Heavy Wheeled, Chassis Mounted	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7

Table 32: Environment Pi Factor (π_E), continued

		Part Type										
		Cable	Connector	Isolators	Laser diode module	Passive Fiber based components	Passive Micro-optic components	Photodiode	Receiver	Splice	Transmitters	VOA
Environment	Ground, Mobile, Heavy Wheeled, Engine Compartment	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Ground, Mobile, Heavy Wheeled, Engine Mounted	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Ground, Mobile, Heavy Wheeled, Instrument Panel Closed	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Ground, Mobile, Heavy Wheeled, Instrument Panel Open	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Ground, Mobile, Heavy Wheeled, Trunk	454.1	124.9	6.9	20.6	14.3	78.6	208.8	1.9	3008.4	2.3	37.7
	Ground, Mobile, Light Wheeled	9.8	15.2	3.9	5.7	5.6	17.3	45.0	1.1	59.3	1.1	9.2
	Ground, Mobile, Light Wheeled, Chassis Mounted	9.8	5.7	2.1	2.1	3.2	4.2	10.2	0.7	59.3	0.7	3.7
	Ground, Mobile, Light Wheeled, Engine Compartment	9.8	7.8	2.5	2.7	3.7	6.3	15.9	0.8	59.3	0.8	4.8
	Ground, Mobile, Light Wheeled, Engine Mounted	9.8	17.1	4.3	6.6	6.1	21.1	54.9	1.1	59.3	1.2	10.5
	Ground, Mobile, Light Wheeled, Instrument Panel Closed	9.8	4.7	1.9	1.8	2.9	3.4	8.2	0.7	59.3	0.7	3.2
	Ground, Mobile, Light Wheeled, Instrument Panel Open	9.8	3.0	1.5	1.3	2.5	2.2	4.8	0.6	59.3	0.6	2.4
	Ground, Mobile, Light Wheeled, Trunk	9.8	1.9	1.3	1.0	2.2	1.4	2.8	0.6	59.3	0.6	1.8
	Ground, Mobile, Tracked	1.7	13.2	3.4	3.2	4.2	7.1	17.7	0.9	5.5	1.0	4.5
	Ground, Stationary	1.0	2.8	1.3	1.1	1.3	1.1	1.3	0.8	1.0	0.8	1.2
	Ground, Stationary, Indoors	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Ground, Stationary, Outdoors	5.0	6.6	3.2	1.4	3.0	1.5	2.0	1.0	5.1	1.0	1.6

Table 32: Environment Pi Factor (π_E), continued

		Part Type										
		Cable	Connector	Isolators	Laser diode module	Passive Fiber based components	Passive Micro-optic components	Photodiode	Receiver	Splice	Transmitters	VOA
Environment	Naval	455.8	85.8	23.0	3.0	19.3	7.1	7.7	2.3	474.3	2.4	3.4
	Naval, Shipboard	455.8	85.8	23.0	3.0	19.3	7.1	7.7	2.3	474.3	2.4	3.4
	Naval, Shipboard, Sheltered	122.4	25.0	12.3	2.1	10.2	5.2	3.3	2.4	127.5	2.4	2.1
	Naval, Shipboard, Unsheltered	1458.6	249.2	39.7	3.6	32.8	11.1	10.3	2.9	1517.6	2.9	4.1
	Naval, Submarine	5.0	9.2	4.0	2.5	4.0	4.5	8.8	1.7	5.7	1.7	2.9

Table 33: Operating Profile Pi Factor (π_{OP})

		Part Type										
		Cable	Connector	Isolators	Laser diode module	Passive Fiber based components	Passive Micro-optic components	Photodiode	Receiver	Splice	Transmitters	VOA
Operating Profile	Automotive	7.8	15.3	9.2	8.8	7.7	9.3	6.6	8.5	7.5	8.5	8.5
	Commercial Aircraft	1.8	8.7	2.7	2.8	1.9	3.7	2.3	1.7	1.6	1.7	3.1
	Computer	0.3	1.4	0.4	0.5	0.3	0.7	0.6	0.2	0.3	0.2	0.6
	Consumer	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Emergency Power	3.3	0.8	3.2	2.8	3.2	2.3	2.4	3.7	3.3	3.7	2.5
	Industrial	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.1	0.2	0.1	0.3
	Military Aircraft	1.4	3.0	1.6	1.6	1.4	1.8	1.4	1.4	1.3	1.4	1.7
	Military Ground	0.6	0.5	0.5	0.6	0.6	0.6	0.7	0.5	0.6	0.5	0.6
	Naval	0.2	0.1	0.1	0.2	0.2	0.3	0.4	0.1	0.2	0.1	0.3
	Telecommunications	0.2	0.4	0.2	0.3	0.3	0.3	0.5	0.1	0.2	0.1	0.4

Table 33: Quality Factor (π_Q)

Quality	**π_Q = Quality factor**
Commercial, no special design for reliability practices applied	6.1
Best commercial practices	1.2
Full design for reliability practices applied	0.2

Table 34: Quality Criteria Used in π_Q Calculations

Parts Contribution to Reliability	**Rating**	**Input Range**	**Commercial Quality Score**	**Best Commercial Practices Score**	**Full Design For Reliability**	**Highest Possible Score**
Is there a documented part selection and **part management process**?	yes = 5 no = 0	Y,N	N	Y	Y	5
Are **part evaluation and qualification processes** established to add parts to the PPL?	yes = 3 no = 0	Y,N	N	Y	Y	3
Does a cross functional development team (**CFDT**) review and approve new candidate parts for addition to the PPL?	yes = 3 no = 0	Y,N	N	Y	Y	3
Is this a commercial off-the-shelf **(COTS)** purchased assembly with a **good history** of operational reliability?	yes = 6 no = 0	Y,N	N	Y	Y	6
Will **new parts** be added to the PPL to design this FRU?	yes = 4 no = 0	Y,N	N	Y	Y	4
Are procedures in place to **detect part problems** in both manufacturing and the field?	yes = 10 no = 0	Y,N	N	Y	Y	10
Are quality and **reliability data tracked on parts** and fed back to suppliers so they know their performance on this product?	yes = 10 no = 0	Y,N	N	Y	Y	10
Is there a **design compliance checklist** to ensure that all parts are properly applied, operating at sufficient margin with respect to environmental and operational stresses, and take into account lessons learned?	yes = 10 no = 0	Y,N	N	Y	Y	10
Are **teaming** relationships established with all critical component suppliers?	yes = 7 no = 0	Y,N	N	Y	Y	7
Will all suppliers provide timely failure reporting and corrective action support (**FRACAS**) for both critical and custom parts? (Timely reporting implies a 2 week turnaround with faster response on priority demand.)	yes = 7 no = 0	Y,N	N	N	Y	7

Table 34: Quality Criteria Used in π_Q Calculations, continued

Parts Contribution to Reliability	**Rating**	**Input Range**	**Com-mercial Quality Score**	**Best Com-mercial Practices Score**	**Full Design for Reliability**	**Highest Possible Score**
Have supplier **identified the likely failure modes** on critical and custom parts, and does the design take these failure modes into account?	yes = 10 no = 0	Y,N	N	Y	Y	10
Are **operational failure rate and failure mode data** provided by the suppliers of critical and custom parts being used?	yes = 7 no = 0	Y,N	N	Y	Y	7
Is there a **device specification** for all critical and custom parts?	yes = 5 no = 0	Y,N	N	Y	Y	5
Has the **supplier reviewed the part application** for all critical and custom parts?	yes = 7 no = 0	Y,N	N	N	Y	7
Will critical suppliers **provide timely notice of impending part changes** to allow the developer to assess the impact?	yes = 7 no = 0	Y,N	N	Y	Y	7
Is a **change history log** maintained to provide traceability of engineering change actions and their associated rationale for critical and custom parts?	yes = 7 no = 0	Y,N	N	Y	Y	7
Will part identification (**revision numbers**) be shown on the part to identify the particular part configuration, including the level of the part's firmware?	yes = 7 no = 0	Y,N	N	N	Y	7
Is there a **first article inspection** and acceptance test planned?	yes = 7 no = 0	Y,N	N	Y	Y	7
Have key suppliers **identified their part failure mechanisms**?	yes = 10 no = 0	Y,N	N	Y	Y	10
Have the sources and the extent of **part variation been identified**?	yes = 7 no = 0	Y,N	N	N	Y	7
Have **mitigations** been identified to handle the effects of part's variations?	yes = 8 no = 0	Y,N	N	N	Y	8
Will a **design of experiments part evaluation**, considering variations, as well as manufacturing variations, be conducted?	yes = 7 no = 0	Y,N	N	N	Y	7
Will developers' **quality organization audit** the supplier's processes and facility capabilities?	yes = 6 no = 0	Y,N	N	Y	Y	6
Is an **optical path adhesive (OPA)** used in the component	A. No OPA = 10 B. yes, MFD <2um = 0 C. yes, MFD = 2 - 5 um = 4 D. yes, MFD = 5 - 10 um = 6 E. yes, MFD > 10 um = 8	A,B,C,D,E	B	D	A	10
Are there **thin films (AR coatings, filter elements)** in the light path?	A. No Thin film = 0 B. yes, and surface is prepared by sputtering = 2 C. yes, and surface is not prepared by sputtering = 3	A,B,C	A	A	A	3

Table 34: Quality Criteria Used in π_Q Calculations, continued

Parts Contribution to Reliability	**Rating**	**Input Range**	**Com-mercial Quality Score**	**Best Com-mercial Practices score**	**Full Design for Reliability**	**Highest Possible Score**
Does the component contain **fused fiber**?	yes = 5 no = 0	Y,N	N	N	Y	5
Does the component contain **fiber**?	yes = 5 no = 0	Y,N	N	N	Y	5
Was the package **thermally designed to safely dissipate heat** by understanding and modeling the thermal characteristics?	yes = 3 no = 0	Y,N	N	N	Y	3
Has the **manufacturer characterized the power handling capability** of the component?	yes = 5 no = 0	Y,N	N	N	Y	5
Have **acceleration factors for power and temperature been quantified** and are they used to determine the derating requirements?	yes = 5 no = 0	Y,N	N	Y	Y	5
Does the **component contain absorbers** at wavelengths for which the component will be exposed (i.e. garnet, shutter, etc.)	yes = 4 no = 0	Y,N	N	N	Y	4
How is **dissipated power** intended to be dumped?	A. with a heat sink = 4 B. dissipation not actively managed = 0	A,B	B	B	A	4
Does the component rely on **alignment of free space components attached with organics?**	yes = 3 no = 0	Y,N	N	N	Y	3
Cleanliness precautions	A. stringent cleaning procedures = 3 B. some cleaning procedures = 2 C. no cleaning procedures = 0	A,B,C	C	B	A	3
For components that have a fiber/epoxy interface, is the **fiber tip inspected** to ensure it is free of defects and contamination?	yes = 3 no = 0	Y,N	N	N	N	3

IX.7 Uncertainty Analysis

An analysis was performed to quantify the degree of uncertainty in the predicted failure rates. This was accomplished by calculating the predicted failure rate and comparing it to the observed failure rate. The metric that was used for this analysis was the $\log_{10}$ of the value: (predicted failure rate/observed failure rate). The value of this metric should cluster around zero if the prediction models are approximating the observed data. Calculation of the standard deviation of this metric also provides a quantification of the uncertainty levels present in the predictions made with these models. Table 35 summarizes the mean and standard deviation of this metric for all of the data, and for only the field data.

Table 35: Summary of Uncertainty Metrics

	All Data	Field Data
Mean	-0.68	0.20
Standard deviation	1.07	0.44

Figures 2 and 3 illustrate the distribution of this metric for all data and for field data, respectively. For this analysis, only data for which failures occurred were included, since data with no observed failures only have a single-sided bound on the failure rate and, therefore, cannot be compared to the predicted value. The result of not including zero failure data is that the metric is biased. As can be seen in these figures, the distribution of all failures is significantly wider than the distribution of only field failure rates. This is due to the fact that the non-field data, i.e. test data, is typically at extreme conditions, and, therefore, the uncertainty in these extreme cases is typically larger than nominal conditions.

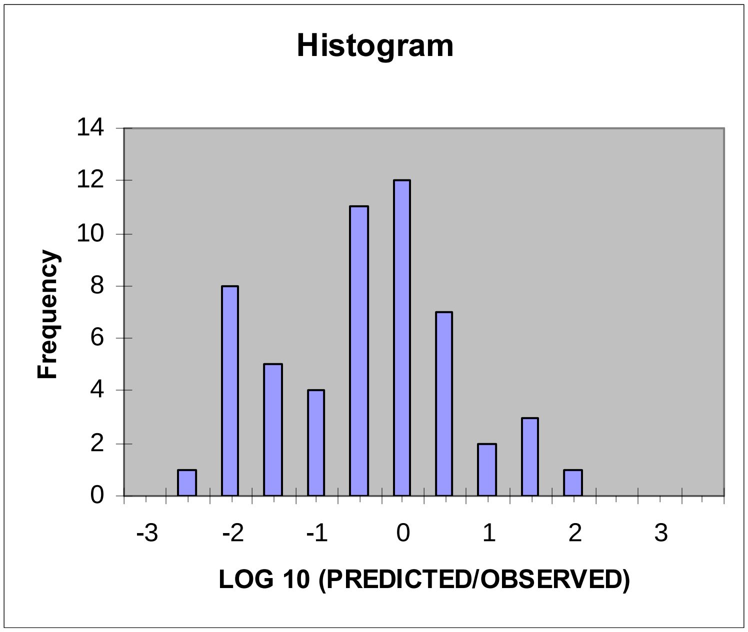

Figure 2: Distribution of Log_{10} (Predicted/Observed) for all Data

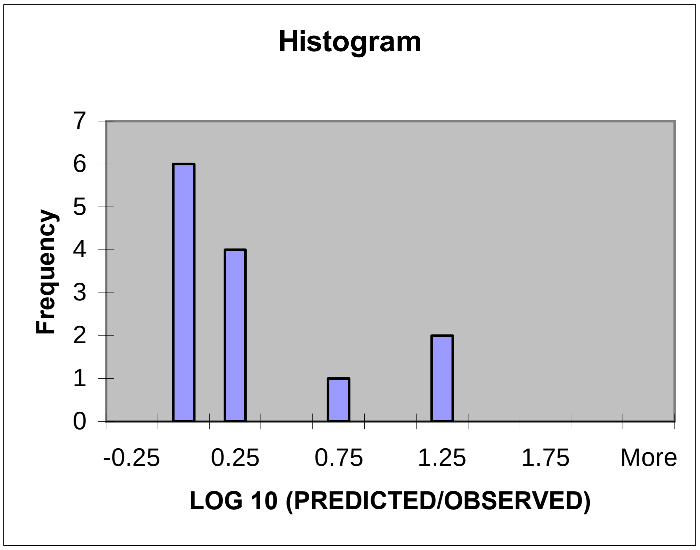

Figure 3: Distribution of Log_{10} (Predicted/Observed) for Field Data

The distributions of the Predicted/Observed failure rate ratio are illustrated in Figure 4. With this metric, the value should be centered about one, since the log of this ratio has not been taken.

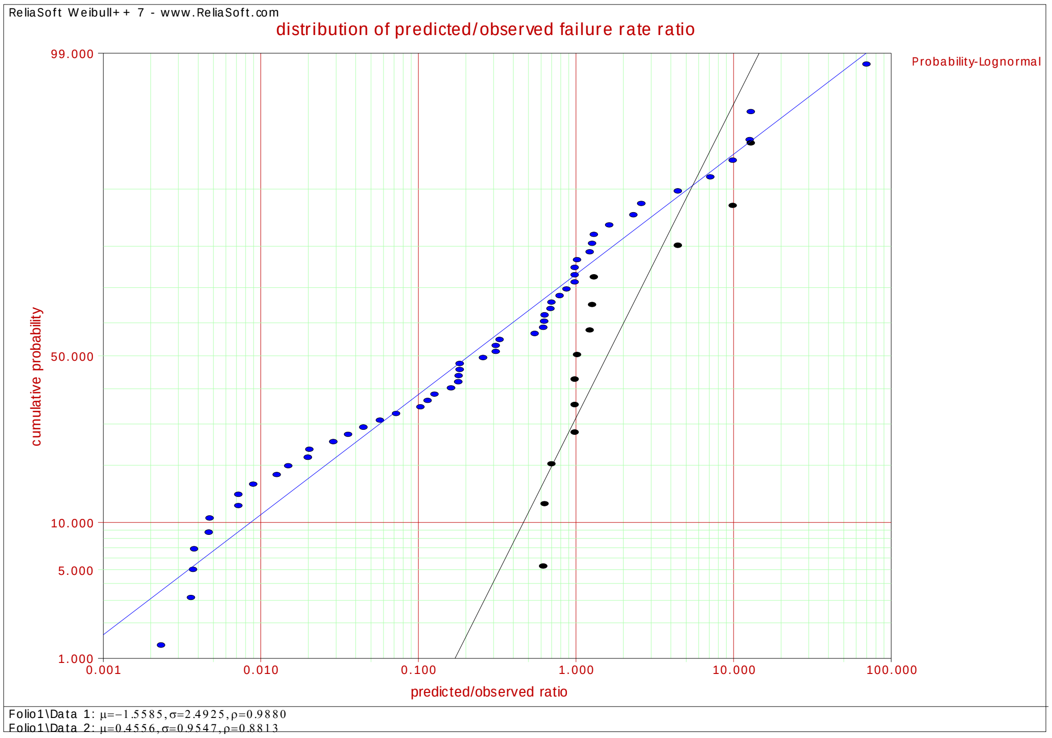

Figure 4: Distributions of the Predicted/Observed Failure Rate Ratio for All Data (Folio1/Data1) and For Only Field Data (Folio1/Data2)

IX.8 Rationale

The rationale for the model development approach used in this study is that:

- It was customizable to the specific failure modes/causes of photonic components
- It could utilize any form of quantitative reliability data:
  - Test data
  - Field data
- Factors that account for the application and component-specific variables that affect reliability (Pi factors) could be applied to the appropriate additive failure rate term
- It addresses operating, non-operating and cycling-related failure rates, in an additive/multiplicative model, that were weighted in accordance with the operational profile (duty cycle and cycling rate)
  - The Pi factors modified only the applicable failure rate term, thereby eliminating many of the extreme value problems that plague multiplicative models
- It was based on failure mode distributions, so that observed component failure causes were empirically modeled

- It was based on quantitative stresses rather than qualitative environmental categories
- It was industry independent and predicts the average failure rates of best commercial practices
- It can be tailored with test data (if available), via Bayesian methods
- Extrinsic and intrinsic failure causes were separated, allowing the user to address them or not, depending on the purpose of the analysis

X. Benefits Analysis

Not Applicable

XI. Implementation Report (Transition/Deployment Progress/Status)

Not Applicable

XII. Conclusions and Recommendations

This report details the results of a project to develop reliability prediction capabilities for photonic components and systems. Task 3.1 of this effort evaluated existing methodologies that could have been potentially used to predict the reliability of photonic components. As a result of that review, however, it was concluded that none have the capability to address all of the component types of interest. Some of the existing methodologies had selected information on relevant technologies, and were used to extract pertinent information towards the goals of this study. Task 3.2 of this effort derived a model development methodology that was used to develop the photonic models. The methodology was similar to that developed for the derivation of the RIAC 217Plus models, but was tailored for the unique considerations of this project, along with the specific concerns of photonic components. Task 3.3 quantified the model parameters through the collection and analysis of reliability data. The derivation of these models was described in detail in this report. Additionally, a simplified version of the model form has been derived for compatibility with traditional MIL-HDBK-217 model forms.

XIII. Backup Material

Not Applicable

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XV. Appendices

Not Applicable

XVI. List of Abbreviations

EPRD	Electronic Parts Reliability Data
FMD	Failure Mode/Mechanism Distributions
GIDEP	Government-Industry Data Exchange Program
LED	Light Emitting Diode
MIPS	Master Integrated Program Schedule
NPRD	Nonelectronic Parts Reliability Data
NSWC	Naval Surface Warfare Center
RIAC	Reliability Information Analysis Center
VOA	Variable Optical Attenuator
WDM	Wavelength Division Multiplexer

XVII. Distribution List

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