Validation of Commercial Fiber Optic Components for Aerospace Environments

Melanie N. Ott*, NASA Goddard Space Flight Center Greenbelt MD, 20771

ABSTRACT

Full qualification for commercial photonic parts as defined by the Military specification system in the past, is not feasible. Due to changes in the photonic components industry and the Military specification system that NASA had relied upon so heavily in the past, an approach to technology validation of commercial off the shelf parts had to be devised. This approach involves knowledge of system requirements, environmental requirements and failure modes of the particular components under consideration. Synthesizing the criteria together with the major known failure modes to formulate a test plan is an effective way of establishing knowledge based "qualification". Although this does not provide the type of reliability assurance that the Military specification system did in the past, it is an approach that allows for increased risk mitigation.

The information presented will introduce the audience to the technology validation approach that is currently applied at NASA for the usage of commercial-off-the-shelf (COTS) fiber optic components for space flight environments. The focus will be on how to establish technology validation criteria for commercial fiber products such that continued reliable performance is assured under the harsh environmental conditions of typical missions. The goal of this presentation is to provide the audience with an approach to formulating a COTS qualification test plan for these devices. Examples from past NASA missions will be discussed.

Keywords: components, environmental, space, flight, qualification, photonic, fiber, optic, radiation

1. INTRODUCTION

In order to construct a reliable space flight sensor system to meet program specifications, a design engineer must first consider the performance requirements for the system as requested by the program. This means that the project system engineer must supply a list of performance specifications for the sensor system. The design engineer will then build a system to meet these requirements as a concept demonstration in a "bench" type form or prototype. Let us assume that this prototype is constructed with commercial fiber components where available and bulk components where fiber components are not available on this prototype To take this system to the next phase, a development engineer with the design engineer will need to formulate a plan for making the prototype into a rugged system that can withstand the environmental specifications of the program. This is usually a great challenge since in order to meet state of the art performance requirements for a system, component choices are many times in conflict with what is considered "reliable". Couple that dilemma with the fact that some components are no longer readily available as they once were during the telecommunications market surge and now the engineer is faced with few options for component selection. Such is the case many of us are facing when designing state-of-the-art systems to for space and other harsh environments. In order to meet this challenge, the development and the design engineer need the assistance of a component engineer who is knowledgeable on the subject of application, reliability and testing of commercial components for harsh environments. This engineer based on a changing market has to be aware of the materials and processes used for fabrication of these components as well as the physics of failure on a variety of materials and components. By incorporation of this knowledge into the final hardware, the program now has a chance of providing a highly reliable system for a harsh environment based on commercial components. NASA Goddard Space Flight Center components engineers call this approach "Technology Validation Assurance", where research on materials and packaging and knowledge based testing can mitigate the risk of environmental related failures under harsh environmental conditions.

* 301-286-0127, Melanie.ott@gsfc.nasa.gov, misspiggy.gsfc.nasa.gov/photonics

In general, it is always a benefit to provide as many fiber optic links as possible as opposed to assembling a system of bulk optic interfaces due to alignment issues in a vacuum and contamination issues with optical interfaces. When it comes to component selection, many times the device itself is reliable but the packaging can induce failures that are not considered until too late in the development process. Interconnection or any type of mechanical coupling can create other issues that need to be examined for potential failure mechanisms. When it comes to device and packaging configuration, design and reliability can go well together if the research for component selection is done during the prototype study of the system. This enables additional design options to be considered. Certain devices are perfect for the performance needs of an application but the packaging makes it difficult for practical use in a harsh environment. You do not want to discover too late in the process that too much development would be required to enable a design because a component that can meet the performance and environmental conditions simultaneously, does not exist. With short deadlines and small budgets its even more imperative to assess quickly, in the early stages of design, if a component that can meet the specifications can also withstand the environment. A photonic components engineer with knowledge of potential failure mechanisms of commercial components will be vital to making these assessments. Outlined here is an approach to assess photonic commercial components and to assure the reliability of these components for harsh environments.

Once the performance requirements are supplied, the critical parameters for each component in the system can be established. Some parameters are less sensitive to environmental conditions than others. Therefore, once the critical parameters are established per component, then the deviation of those parameters will need to be addressed. For example, how much can you allow your sensor output wavelength to shift as a result of thermal changes during the mission and still provide the information necessary? Then the environmental requirements are established that allow you to compare what you have chosen as a reasonable tolerance for your critical parameters against environmental induced changes. The major environmental issues are: contamination or non metallic materials issues associated with vacuum exposure and operation, launch vibration, thermal changes as a result of orbit parameters, and radiation exposure. Also from knowledge of the failure modes or physics of failure on each of the components themselves some critical tests can be formulated to bring out a majority of the failure modes. Incorporating, the environmental testing necessary with innovative test methods that bring out the known failure modes, a qualification or characterization plan for each commercial component can be formulated. Will this mitigate all risk against failure? No, but it's a reasonable start at providing knowledge based assessments and providing the most reliable system possible given the situation of COTS usage. Even in cases of components that are part of the military qualification process, failures still occur. So there is never a way to completely eliminate the possibility of failures but the probability can be reduced.

2. ENVIRONMENTAL DISCUSSION

2.1 Materials Analysis and Vacuum Environmental Considerations

When making a component selection or working with a manufacturer to supply a specialized component, it is not often possible to specify how a component shall be manufactured and with what materials. NASA utilizes small numbers of very specialized components and this makes it non economical for commercial vendors to provide a product that can not be sold in large quantity. However, it is often possible to effect small changes during manufacturing that can greatly affect the overall space flight reliability of a commercial component. Materials identification is the first step in the process of effecting the reliability of a commercial part in a space flight environment. If information can not be shared from vendor to user, a destructive physical analysis (DPA) can be performed in which all materials can be identified as well as the location of the material in the package. In this way, an analysis can provide reliability information of the packaging configuration as well as provide information about which materials are non-metallic for contamination related concerns.

In all cases, where the materials are identified by the vendor or if identified by another method, the non metallic materials should always be characterized for their outgassing properties in a vacuum environment. Even if the immediate system would not be effected by stray materials outgassing and then re-depositing on surfaces, other systems nearby may be effected by the contamination. The information about which systems nearby are susceptible to the outgassing of materials is supplied by the lead contamination expert on the project.

For characterization of materials NASA typically uses the ASTM-E595 procedure for thermal vacuum exposure and analysis of materials.[1] This test method is entitled "Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment". This method is used to screening test for materials that could provide a contamination issue as a result of large volatile content, which can include trapped solvents, unreacted materials and water. The test is conducted at 125ºC usually for 24 hours at less than 10^{-6} Torr. The criteria for this test are for the Total Mass Loss (TML) to be less than 1.0% and the Total Collected Volatile Condensable Materials (CVCM) to be less than 0.1%. This screening test does not provide definitive information about contamination but as an initial screening can provide the contamination engineer enough information to assess whether or not to prohibit certain materials, require preprocessing of materials, or to require additional measures to guard against the potential threat of contamination. Knowing that contamination is such a large failure mode of high power laser systems, this issue is extremely important to space flight laser development engineers.

In cases where a material TML is higher than the screening criteria but the CVCM is very low and less than the screening criteria it can still be usable depending on the levels of contamination allowable. The Epotek 353ND epoxy is a good example of this where even using a very high temperature cure schedule, the TML is still above the acceptance criteria but the CVCM is well enough below. Having a low CVCM indicates that the material is less likely to deposit on nearby optics once released. In cases where materials do not pass ASTM E595 such as with the material Hytrel, a "preconditioning" vacuum exposure procedure can be conducted, where upon completion of this procedure, the material will then pass the ASTM-E595 test. When all else fails and the system has been assembled with outgassing materials regardless of every effort to avoid it, post manufacturing decontamination can be used to drive off any volatile materials. This is especially necessary in the case where the fabricated hardware will be placed nearby to other optics such as mirrors and bulk telescope optics. Since this test is costly and requires a much larger vacuum chamber to accomplish, performing this type of decontamination would be considered more of "last resort" option and not a recommended regular practice. It is however a common practice to perform this level of decontamination at the box or instrument level to better alleviate the possibility of contamination as a result of vacuum exposure once already in flight.

Materials analysis can also uncover potential long term reliability issues such as packaging induced failures. During the GLAS mission it was found that indium solder was used too close in proximity to the tiny gold wires in the packaging configuration.[2] Due to indium creep, the wires became an intermetallic and disintegrated as a result of being driven at high currents for long pulse duration. Destructive physical analysis of this packaging design showed that many of the wires were in various stages of becoming an intermetallic from "indium attack" of the gold. This allowed designers to suggest changes to the packaging configuration to avoid this reliability hazard for future missions. This is one example of how upfront materials analysis on commercial components can be very instrumental in avoidance of packaging related failure modes. In all cases, it should be the first step performed when checking for potential problems with flying commercial components.

2.2 Vibration Environment Considerations

For characterization of any component the random vibration test is a requirement for all projects. The parameters of the random vibration test are generated based on the vibration conditions expected as a result of the launch vehicle. NASA's space flight vibration parameters are usually much less stringent than those for the Military. A typical profile for testing at the box or instrument level usually totals no more than 10 grms. For component testing, the profile parameters are doubled and the overall vibration (acceleration) level totals 14.1 grms as a result of integrating the acceleration parameters over the entire spectral frequency range. The spectral frequency range for space flight is usually between 20 and 2000 Hz. The random vibration test is typically conducted for 3 minutes for each axis of orientation. The overall total prototype level is higher than the actual qualification level. The following profile is published in the General Environmental Verification Specification for STS and ELV Payloads, Subsystems and Components for payloads of 50 pounds or less.[3] This is what would be expected at the box or instrument level for protoflight.

Table 1: GEVS Protoflight Generalized Vibration Levels for Random Vibration Testing.

Frequency (Hz)	Acceleration Spectral Density Levels
20	.026 g^2/Hz
20-50	+6 dB/octave
50-800	.16 g^2/Hz
800-2000	-6 dB/octave
2000	.026 g^2/Hz
Overall	14.1 grms

The term "protoflight" here indicates that qualification of a large amount of test objects to produce real statistical analysis is not possible. The same idea is applied to commercial devices where most likely due to the budgetary concerns testing large numbers of each component under consideration is not possible. Therefore, the rule of thumb in cases where the "qualification" is on very few samples or engineering models, is to use the profile of Table 1 with the acceleration spectral density levels doubled at the ends of the range. Table 2 shows the profile that would be used for "protoflight" qualification of a small commercial part or component.

Table 2 : Random Vibration Levels for Small Parts and Components Based on GEVS Protoflight Levels.

Frequency (Hz)	Acceleration Spectral Density Levels
20	.052 g^2/Hz
20-50	+6 dB/octave
50-800	.32 g^2/Hz
800-2000	-6 dB/octave
2000	.052 g^2/Hz
Overall	20.0 grms

Using the levels outlined in Table 2 commercial components can be tested at the part level to ensure reliability after space flight launch. It is also the case that vibration testing can bring out known failure modes especially associated with packaging. Again, this profile is used when testing for 3 minutes in each axis of orientation. Functional performance testing to ensure the part still meets the specification given the margin values assigned should be performed after the testing is completed. Where possible in-situ testing is used especially for testing of assembly interconnecting devices. This would be significant if the system is expected to be operational during launch or re-entry, such as a system on the shuttle used for health monitoring.

2.3 Thermal Environmental Considerations

For thermal requirements there is no strict "standard" because each project will establish a thermal environment for operation and for survival at the system or instrument level. Here again, the performance specification for each component during thermal variations established at the system level will need to be established prior to testing as criteria for "qualification". It is crucial to understand the limitations of the component of interest (under test) such that the parameters of the test are set based on system constraints (how hard it would be to adjust the system thermal limits on your subsystem) or on the limitations of the component itself. Many commercial parts are limited to the basic standard of –25ºC to +85ºC (which could be acceptable for GEO and LEO orbits) and others that are Telecordia certified or qualified are rated for –45ºC to +85ºC for storage and operational between -40ºC to +85ºC. The project will specify the operational and survival thermal range based on the expectations of orbit and orientation with respect to the sun, from there the component levels for testing should be set at 10 degrees above and below each extreme of the thermal range. If the instrument operational requirement is 0ºC to +50ºC (which is considered benign as compared to some missions that require –200ºC to +100ºC) than the component testing range should be set for –10ºC to +60ºC and should be monitored in-situ during testing. Telecordia standards require 2000 hours minimum for accelerated aging testing. For long term reliability information it is always best to choose a Telecordia certified component that has been tested over long duration. Then as a user, and depending on the part type, perform 100 to 60 cycles to provide enough information during qualification to either bring out known failure modes or assure that the part will survive the mission as procured.

2.4 Radiation Environmental Considerations

Background radiation can be specified as anywhere from 15 Krads to 100 Krads total dose for a typical mission, although the Military may specify much higher values in the Mrads. These numbers are generated based on the type of orbit, mission, shielding expected and mission years. If we focus mostly on earth orbiting type space craft, the lower earth orbit (LEO) missions can see background radiation anywhere in the range 5 to 10 Krads and most of this dose is accumulated during passes through the South Atlantic Anomaly (SAA).

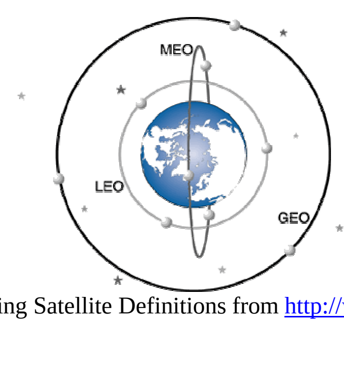


Figure 1: Earth Orbiting Satellite Definitions from http://www.inetdaemon.com/

The Middle Earth Orbit (MEO) path passes through the Van Allen Belts and the total dose accumulation can be anywhere from 10 to 100 Krads. For Geosynchronous orbits (GEO) the majority of the dose is accumulated from cosmic rays and is typically around 50 Krads with a travel path above the Van Allen Belts. The radiation total dose amounts here are based on typical spacecraft shielding and a 7 year mission. In some cases where the hardware is not shielded by the spacecraft, the levels even for background radiation can reach Mrads for expected total ionizing dose. Many electronic parts are tested based on total dose alone but optical fiber has other dependencies such as the dose rate, temperature during exposure, and the wavelength of operation. Laser diodes are most susceptible to displacement damage effects which are best stimulated by proton testing as opposed to gamma ray radiation exposure. To get a sense of how protons equate in total ionizing dose, the conversion from protons to total dose for 60 MeV protons is 10^{10} protons = 1 Krad total dose.

For optical fiber, since total dose as well as dose rate is important, viewing the details of typical missions can help give perspective about testing parameters or at least environmental parameters for extrapolation of the testing data. Table 3 summarizes the total dose, mission duration and calculated average dose rate for several GSFC missions.

Table 3: Summary of Missions and Dose Rates

Program	Total Dose	Mission Length	Dose Rate
GLAS	100 Krads	5 years	0.04 rads/min
MLA	30 Krads	8 years	0.011 rads/min
EO-1	15 Krads	10 years	0.04 rads/min

GLAS is the Geoscience Laser Altimeter System [5-6], MLA is the Mercury Laser Altimeter [7], and EO-1 is Earth Orbiter 1. Usually the total dose is divided by the mission duration to calculate an average dose rate. However, to calculate the average dose rate for MLA, the duration of dose was changed to 5 years for the 8 year mission, as a conservative estimate of when the majority of the dose would be accumulated. Usually the radiation physicist on the project will be the one to supply the mission expected radiation environmental parameters and from there a test plan can be devised that focuses on the best known failure mode expected for that component.

2.4.1 Test Conditions for Optical Fiber Based Components

A majority of optical fiber used in past missions and most susceptible to radiation, was usually multimode for communications and large core multimode for some LIDAR applications. For testing of these fibers, the two dose rate extrapolation model developed by E. Joe Friebele at NRL was used.[8] This model allows for two total dose tests to be performed with all parameters kept the same except for the dose rate. From the data an expression for the attenuation at any dose and total dose can be formulated. When using this model its best to stay at low dose rates as compared to the actual expected dose rate. For example we typically test less than 100 rads/min to collect data for GSFC missions. The other parameters that are key to producing a conservative result are temperature and wavelength. If the operation wavelength for the instrument can not be used during testing for monitoring of the fibers under test, than its best to use a shorter wavelength as close as possible to the operational wavelength. This is because fiber is typically more sensitive at shorter wavelengths therefore providing a more conservative data set. When using a source to monitor the optical fiber during testing, a total average power of less than 1 microwatt will keep the photobleaching effects from correcting the radiation induced darkening. For temperature, its best to know the thermal environment very well. If there is denoted a period of time when the temperature will remain cold, or a temperature range is given for operation without details as to how long at cold temperatures the instrument will remain, the rule of thumb is to use the coldest operation temperature for testing. In summary the idea is to provide the parameters for testing that are representative of the harshest conditions for the optical fiber; dark, cold and of short wavelength. For further study reference [9] provides a summary of optical fiber radiation data. This study reference allows the engineer to make comparisons among a variety of types and vendors.

2.4.2 Other Components

Although all components have radiation susceptibility, the way in which they are tested for validation purposes can be different. As mentioned previously for laser diodes the test would involve using protons to test for displacement damage based on the fluence and the energies expected, and for fiber gamma exposure will do for simulating the darkening effects. When deciding on a test for optical fiber, gamma not only simulates the environment for dose rate and total dose it does so as well as protons would during testing. For devices such as isolators and modulators, tests in the past have shown them less susceptible to radiation effects since they are short path length devices as compared to a long length of fiber (1 m to 100 m) in a communications system.[10,11] The most susceptible to radiation induced darkening will be components that are heavily doped such as special bulk components or fiber amplifier fiber.

3. DISCUSSION EXAMPLES

To provide more instruction and perspective, several examples will be discussed to illustrate technology validation practices for COTS. These cover a few different environmental and performance requirements and components. Although some of these examples may not be directly related to sensing systems, they are still similar enough to components that comprise a sensing system to make the information useful in formulating testing plans for sensing system components.

3. 1 Shuttle Assembly Materials Analysis and Issues

Conducting a materials analysis can alert the engineer to potential contamination hazards therefore allowing outgassing materials to be replaced by non-outgassing materials. As part of a Shuttle inspection system, a collimator assembly manufactured by the vendor Lightpath was used. This collimator assembly, as is sold off the shelf, had a few non-quantified materials in the packaging. The collimator shell is metal but there are several adhesives and epoxies that came into question for lack of outgassing information or that had known characteristics not compatible with vacuum environments. From the list of materials, one material was known for its low outgassing properties and therefore was going to be used to replace another adhesive that is well known as an outgassing noncompliant material. However, upon making this small change to the adhesive that holds one of the lenses in place, the lenses cracked during prescreening thermal testing. The final solution needed to include a non outgassing material such that no contaminants would be sticking to the lenses but still provide the thermal compatibility with the lenses. GSFC materials expert Fred Gross suggested a polyurethane adhesive called Arathane made by Huntsman Advanced Materials America. This material passes outgas testing and has a very low glass transition temperature. The lower glass transition temperature allows for less additional stress to be passed along by the adhesive to the glass during external thermal changes. It is also a good rule for practice to use a cure temperature for adhesives that is closest to the actual expected operation temperature to avoid inducing further stresses.

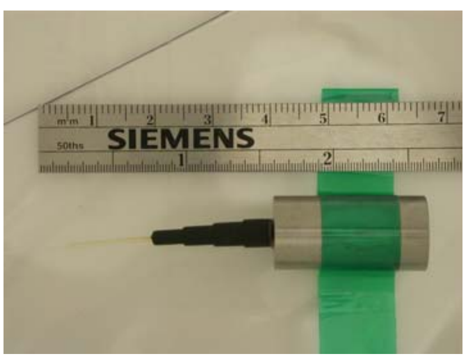


Figure 1: Collimator Assembly Lens Shell

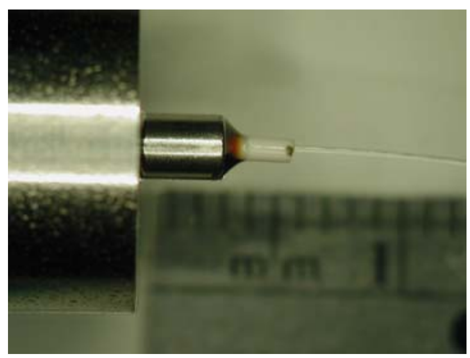
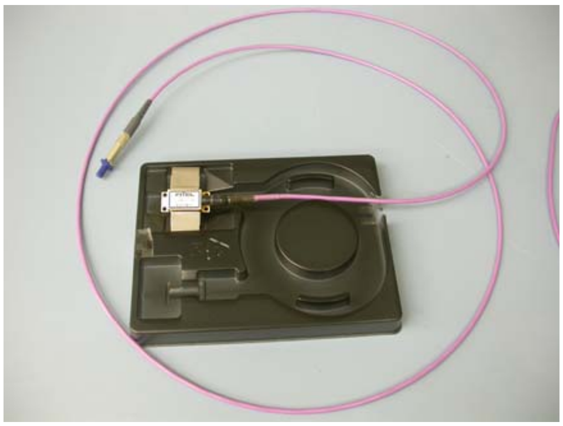


Figure 2: Close Up on Exit of Collimator Shell

Performing a material analysis can allow the engineer to make decisions about how to use the existing materials that are already used in a commercial off the shelf product but with a few additional procedures that can make the packaging of the component more reliable for the long term. In another part of the assembly a Hytrel tube was used for bonding the fiber to the exit of the collimator cylindrical shell casing. In general Hytrel is known for its thermal induced shrinkage. Length shrinkage of the Hytrel in this case can result in a connection failure by pulling on the fiber that it is bonded to and forcing it to dislodge from its internal connection in the lens tube. In general, prior to using any type of fluoropolymer cable or furcation tubing, its best to conduct a thermal preconditioning procedure to eliminate the internal stresses of the material that were induced during processing. Lightpath did not precondition the Hytrel tubing for their commercial off the shelf devices. Therefore, the Hytrel tubing prior to installation on the collimators was thermal preconditioned at GSFC. The thermal preconditioning process involved 30 thermal cycles from –20ºC to +85ºC with dwells at –20ºC for 30 min and 60 min at +85ºC. The ramp rate was 2ºC/min. To be sure that the Hytrel tubing would pass outgass testing, the material was also put through a thermal vacuum (also called a vacuum bakeout) exposure for 24

hours at less than 1 Torr and a temperature of +145ºC. The tubing was then outgas tested to verify that it would then pass the criteria for ASTM-E595.
The shuttle inspection system also required commercial laser diode assemblies to be upjacketed and prepared for space flight. The part used comes from Fitel and has a silicone boot as strain relief for the fiber pigtail attached to the device. These parts were originally intended for prototype use and were from in house stock. Since the parts were already fabricated and costly, it was not feasible to go back through the preprocessing of the boot and have them re-manufactured. The devices were upjacketed and then put through a vacuum bake-out process used for larger finished components and small instrumentation. This enabled a majority of the non compliant by-products to be driven off while a verification was performed simultaneously to insure that no more than 0.1% of the materials were coming out during exposure prior to the procedure ending. As mentioned previously this is not a recommended procedure for small components but used only when preprocessing is not an option and as also mentioned previously, it is a very expensive procedure.



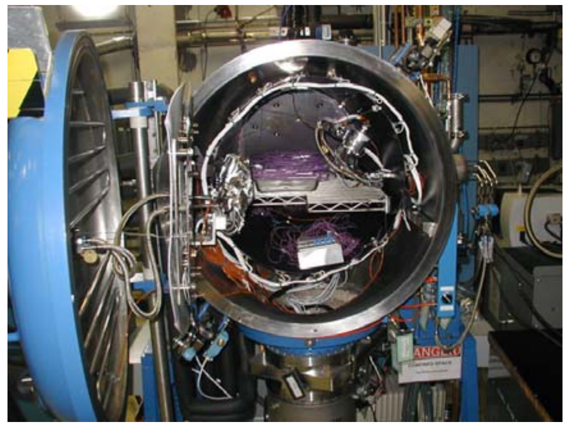


Figure 4: Upjacketed Laser Diode Assembly, Figure 5: Laser Diode Assemblies in Vacuum Chamber Ready for Decontamination

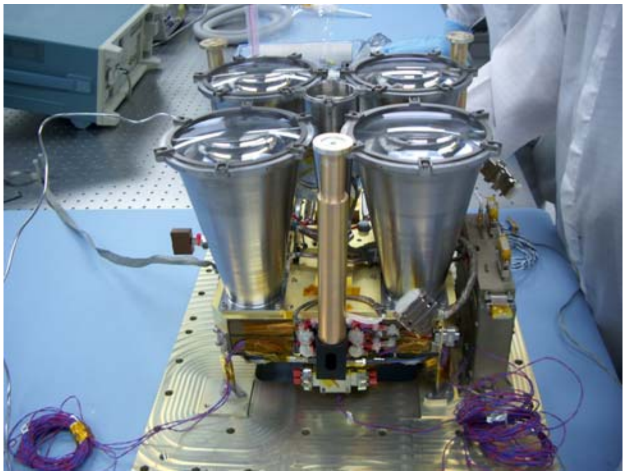
3.1.1 Adhesive Substitutions

When materials changes are necessary because of poor outgassing qualities of a material caution is advised. Be sure when a substitution is made it does not add other failure modes. There are cases where it seems one non-outgassing epoxy can be easily substituted for another one. Sometimes this works but other times especially with terminations or lens mounting as examples, the substitution can result in cracking of the glass. The key to making a packaging configuration that will be reliable is to limit the induced stresses for bonding processes. One way of doing that is to limit the difference between the cure temperature of the material and the usage temperature for the application.   This will avoid cracking occurring in either glass or fiber during thermal cycling as the material fatigues and become embrittled. Although other options usually exist for materials that by making these changes, the new packaging configuration will pass ASTM-E595, thermal validation (cycling) testing should be conducted. Thermal cycling can be used to ensure that the new material is compatible with the rest of the component materials if it is not obvious by reviewing the material characteristics on the materials data sheet. For Lightpath this is a common practice to validate the procedure and screen out the infant mortality prone parts.

3.2 Mercury Laser Altimeter Assemblies

For the MESSENGER Mercury Laser Altimeter (MLA) the performance requirements were a challenge in that the assemblies needed to maintain less than 0.4 dB of insertion loss throughout validation testing. The fiber needed to have a large core size so that both 200 and 300 micron core fiber was investigated. The lengths had to be tightly controlled and had to be within +/- 0.1 inch, the assembly had to be constructed of non-outgassing materials since the optics would be nearby and no failures could be tolerated since all four assemblies had to be functional for the instrument to operate. These assemblies needed to retain stability while withstanding harsh environmental conditions and continue performing reliably for a minimum of 10 years. [12]
In this case, the opportunity existed to choose flight heritage components (components that had been used on space flight instrumentation previously). The Diamond AVIMS optical fiber connector was chosen for use with the W.L. Gore FLEX-LITE™ cable configuration. Both the connector and the cable had been tested for harsh environments and had been used for the Geoscience Laser Altimeter (GLAS) aboard ICESAT. The fiber itself did not have heritage usage,

although it was expected that the radiation performance would be the largest issue to consider. However, the vendor (Polymicro Technologies) manufacturing the fiber had a very good reputation for the radiation performance of other optical fiber products.



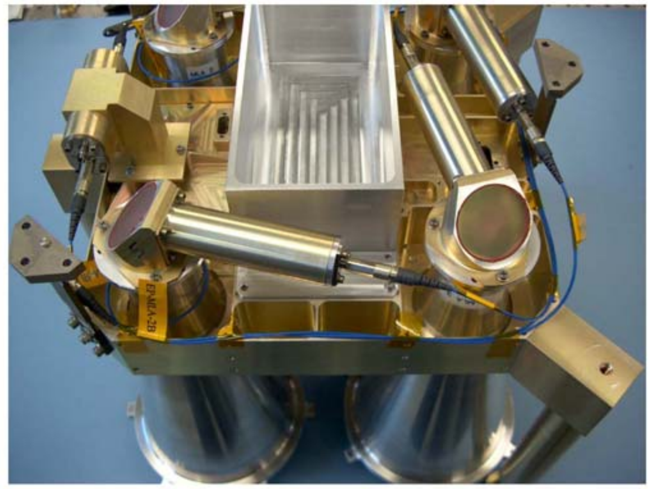


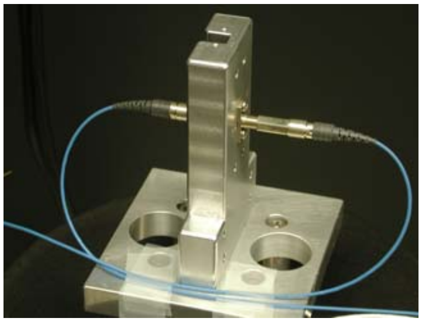
Figure 6: Side View of Mercury Laser Altimeter Figure 7: Bottom View of MLA Mock-Up with Actual Assemblies

3.2.1 Materials Issues and Analysis

Materials preprocessing was conducted on the non-metallic materials. The Hytrel boots used for the AVIMS connector strain relief were put through vacuum bake-out for 24 hours at 140ºC and at less than 1 Torr. The cable was thermally preconditioned using eight cycles from –20ºC to +60ºC with a dwell at 60ºC for 60 min and at -20ºC for 25 min using a ramp rate of less than 2ºC/min. Of the commercial and military cables available, this cable is well known for its thermal stability.[16-17] The Epotek 353ND is approved for space flight use and has a very low CVCM which makes it an acceptable epoxy for use around optics that are sensitive to contamination. However, even after taking all necessary precautions to be sure all materials are degassed such that they pass the vacuum environmental criteria of ASTM-E595 the contamination engineers put the final assemblies through a decontamination vacuum bake-out prior to integration on the space flight instrument. This procedure was performed at less than 50ºC. It is important to note that when performing a vacuum bake-out for decontamination purposes, the higher the temperature used during vacuum exposure the shorter the procedure will take. During these procedures, the thermal specification of the component under exposure should never be exceeded and it is best to give a 10 to 15 degree margin. Therefore if the specification states an operation temperature of 85ºC, be sure to conduct testing below 75ºC.

3.2.2 Environmental Validation Testing

For random vibration validation the test was conducted at 14.1 grms as recommended by the project for qualification purposes using the profile shown in Table 1. The actual box level vibration requirement was less than 10 grms total. A thermal validation test was conducted for three mated pairs, with in situ monitoring of the assemblies for 90 thermal cycles. The temperature range was from –30ºC to +50ºC with 25 minute dwells at each thermal extreme and a ramp rate of 2ºC/min. The range for this testing was set by the mission operation and survival range requirements of –20ºC to +40ºC. Usually the survival range will be larger or different from the operational range. Such was the case here, and the survival range was used to determine the testing parameters for this thermal test to provide a conservative estimation of performance.



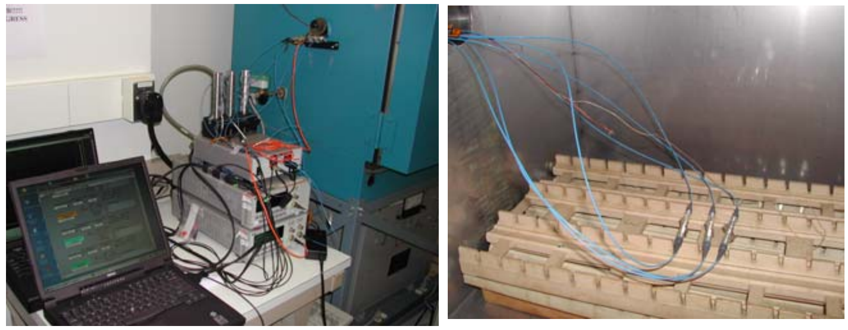


Figure 8: AVIMS Vibration Fixture, Figure 9 a) Thermal Testing outside of Chamber, b) Inside of Thermal Chamber

Each assembly was monitored using 850 nm light through out the vibration testing and the 90 thermal cycles and no losses were registered after all testing was completed. In fact, small power increases were noted ~ 0.04 dB.
Radiation testing was performed on the 200 micron core optical fiber FLEX-LITE™ cables at 850 nm. The temperature was supposed to be at –20ºC throughout testing but varied above and below such that the two dose rate model could be used due to lack of sufficient thermal control. However, the results still showed that under the condition of testing at 22 rads/min (MLA actual dose rate from Table 3 .011 rads/min), at –18ºC, 30 Krads total dose, and at a shorter wavelength of 850 nm, the darkening was less than 0.07 dB per assembly. The reason the losses were so low was because the lengths were short at 26.1 inches long. The result at 10 meters was a radiation induced attenuation of ~ 1.0 dB at the total dose of 30 Krads.

3.3 Geoscience Laser Altimeter System Fiber, Assemblies and Diodes

The Geoscience Laser Altimeter System (GLAS) instrument was built to provide science data as part of ICESAT. The way components and parts for this project were chosen and investigated illustrates the technology validation approach and also shows in one particular case, the problems that occurred when the approach was not followed closely. To keep costs down the approach of quality by similarity was used for fiber choices, cable and interconnection.

3.3.1 Quality: Similarity and Testing.

Radiation analysis was performed on a variety of single mode and multimode fiber based on available published data. Fiber candidates for different parts of the altimeter where chosen based on expected performance. Using the expected total dose of 100 Krads over five years and the average dose rate of .038 rads/min expected performance for a typical optical fiber, a small database of performance analysis was drafted. The results of this data was later incorporated into a NASA Electronic Parts and Packaging program funded document entitled "Radiation Effects on Commercially Available Optical Fiber" [9]. Choices for the GLAS fiber were made based on the available data and were not followed up by radiation testing, since the margin for radiation induced darkening was large enough to allow for possible differences in performance due to lot to lot variability. Therefore, the fibers were accepted based on quality by similarity for radiation effects. The only unanswered question or "tall tent pole" for long term reliability and functionality during the mission was whether or not there would be particle radiation issues or scintillation resulting from electrons. There was a concern that the light returning to the instrument would at such low levels, that any radiation induced scintillation could interfere with the science data. A study was conducted to study a variety of candidates from the original database which contained both single and multimode type fibers at 532 and 1064 nm. It was found that using the energies and flux levels in Table 4, no scintillation was detectable above the detector system noise floor of 50 photons/sec [13].

Table 4: Summary of Energies used for Scintillation Testing on Optical Fiber Candidates for GLAS from Reference 13.

Electron Energy MeV	Expected Ave Flux (e/cm^2/s)	Expected SEE Flux (e/cm^2/s)	Actual Accelerator Test Flux (e/cm^2/s)
0.10	$7.9*10^5$	$7*10^6$	$1*10^7$
0.50	$6.4*10^4$	$2*10^5$	$2*10^5$ - $8*10^5$
1.00	$1.6*10^4$	$5*10^4$	$2*10^5$ - $4*10^5$

The connectors and cable used for the GLAS assemblies were tested previously by Lockheed Martin in the mid 1990's {14-15]. This data was accepted to prove that the Diamond AVIMS connectors themselves would function adequately for the duration of the mission. In addition the W..L Gore FLEX-LITE™ cable had been tested under a NASA Electronic Parts and Packaging funded program and this data was also readily available to be used for quality by similarity.[16-17].

3.3.2 Construction Analysis

One important issue that proved the importance of a materials construction analysis was the failures of the high power laser diodes while the GLAS instrument was in operation on ICESAT. Had the construction analysis been conducted prior to the actual integration of the devices in to the Nd:YAG lasers it would have been apparent that the solder applied for connection of the repeating units on these components, had set the stage for a potential failure mode. For commercial systems on the ground, a failure, although inconvenient, is repairable to some degree. Unless this is anticipated ahead of time based on a known condition prior to flight, most repairs in flight are not considered an option. The exception of this was on International Space Station. For US Lab aboard Space Station spare cables were added, in case a known failure mode caused the signal on those cables to discontinue. Knowing prior to launch but after integration, that the failure probability is high and knowing far enough in advance to produce a repair plan, is not the case usually for space flight. Therefore, some commercial practices are unacceptable for the long term reliability of space bound components. This is one of those cases. Indium solder that is commonly used for commercial photonic packaging was used in abundance on the laser diode bar array packaging for GLAS. Indium is also known for its creep characteristics [18] and therefore great care needs to be executed when this material is used in a packaging configuration that also involves other metals that will react with indium, such as gold. The results of indium creep and metallic interaction on the laser diode array packages were indium attack of the gold wires due to the creeping onto the gold wires and the subsequent interaction between the two metals which resulted in an intermetallic of AuIn2. Figures 10a and 10b illustrate the creeping mechanism of indium. In this case the indium squeezed out of the sides of the packaging when it was bolted down and created a shorting situation from the top of the package to the bottom.[19]

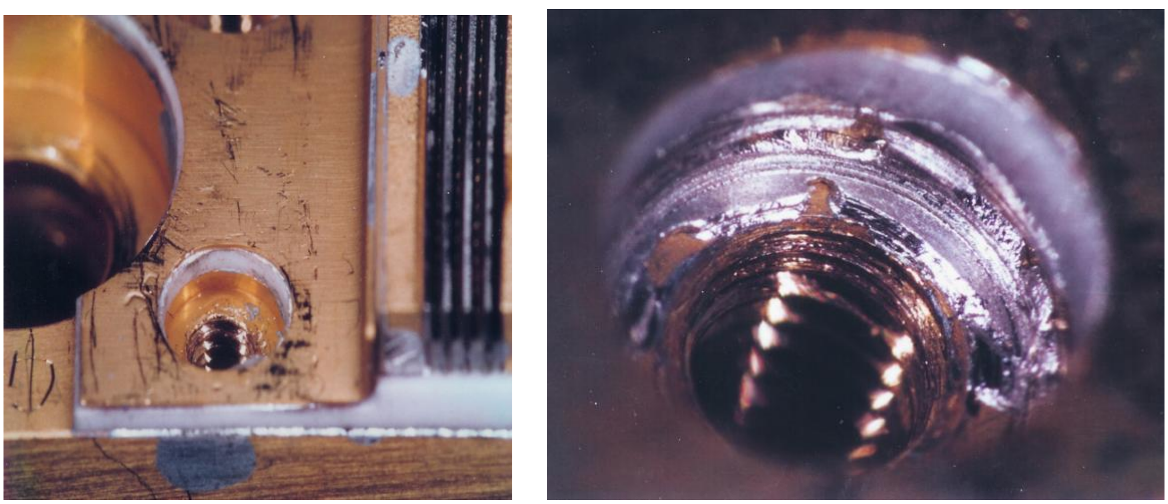


Figure 10 a) Indium creep into bolt hole of package that caused device shorting, b) high magnification of bolt hole.

The resulting intermetallic is very brittle and forms blocky crystals and this intermetallic takes up more space than the reactants. If no additional stresses are applied, the intermetallic continues to be a good conductor. However, in the case of the laser diode bar arrays, the pulsed operation created a situation in which the in indium attacked gold wires were constantly under current/thermal induced stresses. Eventually the wires broke.

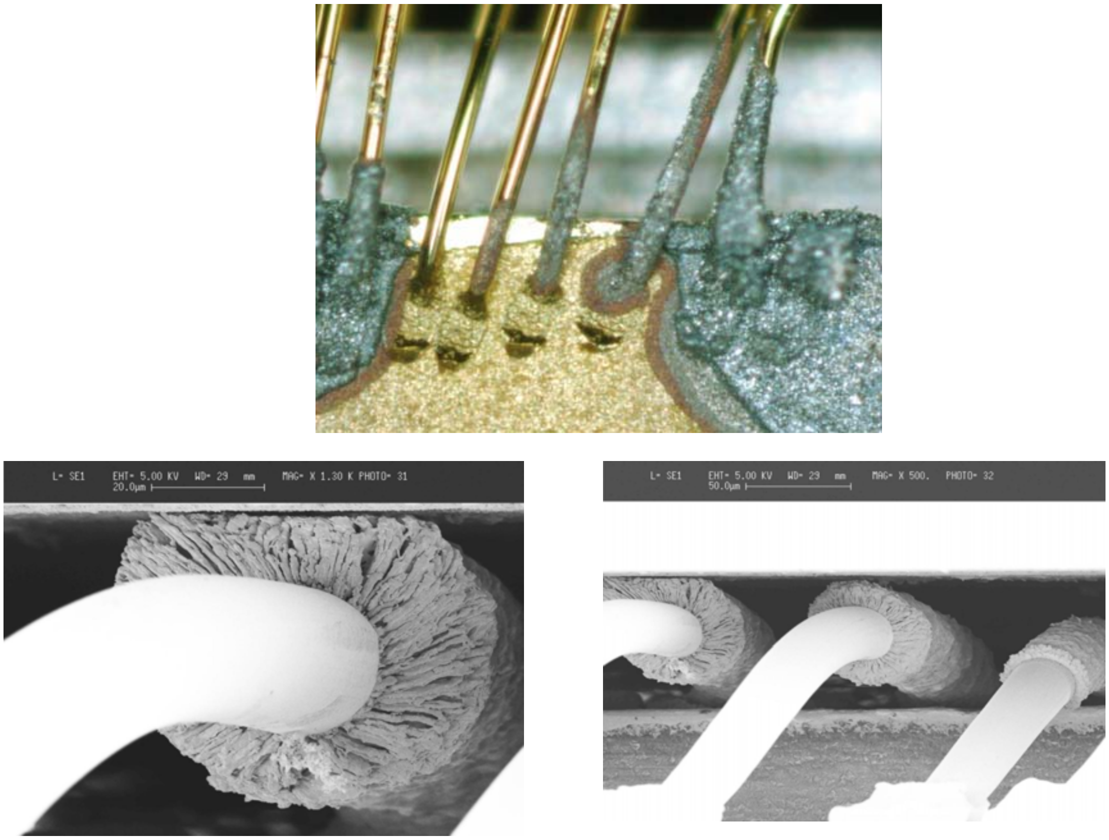


Figure 11a) Indium attack of gold wires,
b) & c) SEM images of gold wires with AuIn2 sheath as a result of Indium creep.[19]

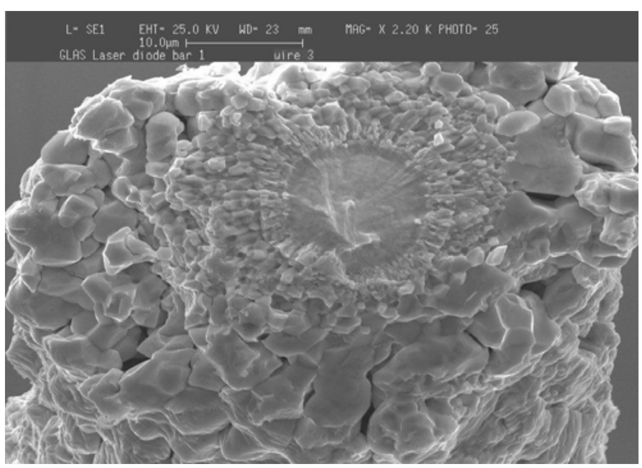


Figure 12. SEM image of cross section of Gold/Indium intermetallic wire.

The key to this packaging configuration working without major failure during the Mars Orbiter Laser Altimeter (MOLA) mission [20] was that the stresses on the AuIn2 wires were less than for the GLAS mission. Below is a table in which the stresses on the gold wires of the laser diode arrays are summarized for a variety of missions.

Table 5: Summary of Projects and Operation Parameters for the Pump Laser Diode Arrays and Resulting Stresses on the Gold Wires.

Project	Pulse width	Rep. Rate	Peak Current	Stress ~(I^2*PW)	Damage/Pulse ~($Stress^8$)	Damage Rate ~(D/P * RR)
MOLA	150 µs	10 Hz	60 Amp	$5.4*10^5$	$7.23*10^{45}$	$7.23*10^{46}$
GLAS	200 µs	40 Hz	100 Amp	$2.0*10^6$	$2.56*10^{50}$	$1.02*10^{52}$
Calipso	150 µs	20 Hz	60 Amp	$5.4*10^5$	$7.23*10^{45}$	$1.45*10^{47}$
MLA	160 µs	8 Hz	100 Amp	$1.6*10^6$	$4.30*10^{49}$	$3.44*10^{50}$

From looking at the damage rate numbers for the gold wires on the laser diode bar arrays in Table 5, the damage rate levels for GLAS were higher than all the other programs using these pump diodes in a pulsed manner. Due to the fact that the GLAS diodes were driven harder than the others for previous and current missions, it is now clear why on GLAS the failure occurred where it did not on MOLA. Since this discovery it has become a policy for many programs to insist on a Destructive Physical Analysis (DPA) for all laser diodes as part of the construction/materials analysis process.

CONCLUSION

An approach to characterizing and development of commercial photonic components for space flight was discussed here. The method always begins with a construction and materials analysis especially of the packaging configuration. In many cases performing this step alone results in a huge impact on the reliability of the device in a harsh environment. In addition the four major characterization tests were discussed; vacuum, vibration, thermal and radiation, that bring out a majority of the failure modes for components. The most important aspect of this testing is a knowledge of a components failure modes. Knowledge of a part's vulnerabilities will not only reduce the cost of testing but also make for accurate studies. The best example of this was given for radiation effects where gamma exposure is the best way of simulating radiation induced attenuation in optical fiber. This is not the case for devices that are susceptible to displacement damage where particulate radiation is of greatest interest for permanent damage mechanisms. Knowing this distinction of how to test which part, allows for a test to be designed that deals directly with the damage mechanism and eliminates costly over-testing. For each component the testing parameters must be adjusted to bring out the known failure modes of the device and its packaging as well as simulate the actual environment or worst case expected. Where possible insitu testing is always recommended to gather as much information as possible. When making component selections is it also recommended that telecordia qualified components and vendors be considered first. Most important to keep in mind for future procurements and development is to remember that no amount of documentation is a good enough substitute for engineering expertise and involvement. If an instrument or component is being built, the development engineer needs to stay very involved in the processes that the vendor uses, not in an auditing capacity but in a consulting type role as another member to the development team.

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