

Fiber optic cable assemblies for space flight II: thermal and radiation effects

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ABSTRACT

Goddard Space Flight Center is conducting a search for space flight worthy fiber optic cable assemblies that will benefit all projects at all of the NASA centers. This paper is number two in a series of papers being issued as a result of this task to define and qualify space grade fiber optic cable assemblies. Though to qualify and use a fiber optic cable in space requires treatment of the cable assembly as a system, it is very important to understand the design and behavior of its parts. This paper addresses that need, providing information on cable components shrinkage testing and radiation testing results from recent experiments at Goddard Space Flight Center. This work is an extension of the "lessons learned" reported in the first paper of this series entitled "Fiber Optic Cable Assemblies for Space Flight: Issues and Remedies," published and presented at the AIAA World Congress in Anaheim CA, on October 15, 1997.¹

Keywords: fiber optic, cable, radiation effects, thermal effects, shrinkage, jacketing, space flight, cable assemblies, multimode, preconditioning

1. THERMAL EFFECTS AND TESTING

1.1 INTRODUCTION

As part of the NASA Advanced Interconnect Program, GSFC has been investigating alternatives for fiber optic communication applications. In particular the MIL-STD-1773 is being implemented more readily in space flight than ever, possibly due to several successful missions using the communications bus. Previously this communications system used 100/140 micron multimode fiber from Corning with a cable made by Brand Rex. Due to the discontinuation of this fiber by Corning, it became necessary to acquire a new space flight grade fiber optic cable and conduct qualification testing and analysis to determine its stability during missions of different duration. Therefore, the goal of this program has been to determine which commercially available fiber optic cable assemblies could be best suited for general space flight missions of approximately 10 years in duration. This paper discusses the recent findings on cable related issues and experiments that have been used to better quantify the performance of commercially available fiber and cable. Two issues in particular, the shrinking of the materials used in cable components and the radiation effects on available fiber, left many unanswered questions in the first paper issued on this topic.¹ As a follow on to that investigation, these two subjects have been examined more closely for clarification. Several different cables are examined here for shrinkage characteristics and one type of available multimode hermetic acrylate fiber from Spectran is examined for radiation hardness.

1.2 BACKGROUND

Shrinking of Cable Components: In the first paper giving status on this investigation¹ it was established that fiber optic cable components experience an overall permanent shrinkage as a result of thermal cycling. This effect is different from the tendency of these materials to contract and expand in temperature extremes. The dimensional transient effect in a changing thermal environment is characterized by a materials thermal coefficient of expansion. The type of shrinkage being discussed here is permanent. Once the cable components have shrunk in size, post thermal cycling, they do not return to the previous state.

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There are several theories for why the permanent shrinkage occurs with one being that the extrusion process for depositing these materials on top of an optical fiber induces stresses that tend to relax and result in shrinkage at high temperature extremes. In wire cable this does not greatly effect performance although it can create a reliability hazard, whereas in optical fiber constructions it has large effects on signal transmission integrity as well as reliability.

Both thermal effects mentioned (transient and permanent) have an attenuation effect on the performance of the cable. In addition to attenuating an optical transmission, the permanent shrinkage will also impact the reliability of a termination by pulling away from the connector that it is bonded to or by pulling the connector away from the fiber. In either case the permanent shrinkage is a concern and limiting that shrinkage is a goal for manufacturers of fiber optic cable for harsh environments. For single mode applications the transient effects of thermal shrinkage can have destabilizing effects on the transmitted phase of the signal and the power, whereas the permanent effect will cause a static phase shift and a greater permanent attenuation. Due to this effect it is necessary to mitigate the expansion and contraction transient thermal effects in a single mode application by choosing a suitable cable configuration. This "suitable" cable configuration should have a loose or "looser" tube buffer, as opposed to the tight tube configuration more common to slower optical communication systems that can utilize multimode fiber. However, for multimode applications the overall shrinkage is the issue of concern here for tight tube and loose tube buffer configurations.

Although projects and manufacturers have used preconditioning procedures to limit the shrinkage of fluoropolymers it has been found that in some cases these procedures can be inadequate to limiting the shrinkage when preconditioned for the usual eight cycles. In other words, the shrinkage of a cable's components is specific to each cable type. Thermal preconditioning may limit very little of the shrinkage, and the cable may continue to shrink by the large amounts after a preconditioning procedure has been used.

1.3 DISCUSSION

Five different types of cable candidates were measured for overall cable component shrinkage: W.L. Gore Prototype 1, Spectran Flight Guide, Brand Rex OC-1008, and Northern Lights Hytel jacketed single mode cable and multimode cable. Of those five cables, the Northern Lights multimode cable was measured for static optical change attenuation, as was the W.L. Gore FON 1008 multimode cable. The W.L. Gore 8388 Prototype 1, is called such for the reason that this cable in its exact configuration was improved during this testing and another version is soon to be released. Therefore, the results of this cable can be used for information purposes or as a reference but do not reflect the performance of the final space flight version of the new prototype being developed by W. L. Gore currently.

The Brand Rex OC-1008 has been used in past space flight projects at Goddard Space Flight Center but contains the multimode optical fiber that has since been discontinued by Corning. Brand Rex now makes this same cable configuration with polyimide coated optical fiber from Spectran in place of the acrylate multimode from Corning used in the OC-1008.

The W.L. Gore 8388 Prototype 1, the Brand Rex cable and the Spectran Flight Guide were tested up to 60 thermal cycles from -30°C to 140°C at 1°C/min with a 5 min dwell at both temperature extremes. This rate was decided by EIA standards that state to limit thermal shock, cables should be heated at a rate less than 40°C/hour. This test was run at the lowest rate possible for the thermal chamber being used in this experiment. It is also worth noting that this thermal chamber is used frequently for thermal reconditioning of space flight cable assemblies. The Hytel jacketed cable by Northern Lights and the W.L. Gore FON 1008 were tested to 36 thermal cycles.

Each cable that was not optically monitored, was cut to approximately a 3 meter piece and measured for overall length. Each cable that was unterminated had all cable components cut to the same length. Those that were terminated were measured for output power. The FON 1008 cable was terminated with ST connectors and 100 meters for each of the two samples were used. One sample of the Hytel jacketed cable from Northern Lights was terminated for optical measurements and was a length of approximately 4 m. The summary table below describes the parameters of importance for the cables and some results from the thermal cycle testing.

Manufacturer	W. L. Gore	Spectran	Brand Rex	Northern Lights Microcable	Northern Lights Microcable	W. L. Gore
Part Number	8388 Prototype 1	Flightguide	OC 1008	1-HY-MC-62CFD	1-HY-MC-10C	FON 1008
Total samples tested	4	6	4	3	3	2
Length of samples	~ 3 m	~ 3 m	~ 3 m	~ 3, 4 m	~ 3 m	100 m
Measurement	Length	Length	Length	Length, Optical	Length	Optical
Jacket Material	Fluoropolymer	Tefzel	Tefzel	Hytrel	Hytrel	Fluoropolymer
Outer Diameter	2.5 mm	.9 mm	2.75 mm	.9 mm	.9 mm	1.16 mm
Total Number of cycles	60	60	60	36	36	36
Ave Total % shrinkage	3	1.58	2.43	1.14	2.25	
Total attenuation (28 cycles)	--	--	--	--	--	.25 dB/100m
Total Attenuation (36)	--	--	--	3.6 dB/4 m	--	.084 dB/100m

Table 1: Summary of Cables Tested with Shrinkage and Attenuation Results

Cable Component Shrinkage vs. Thermal Cycle

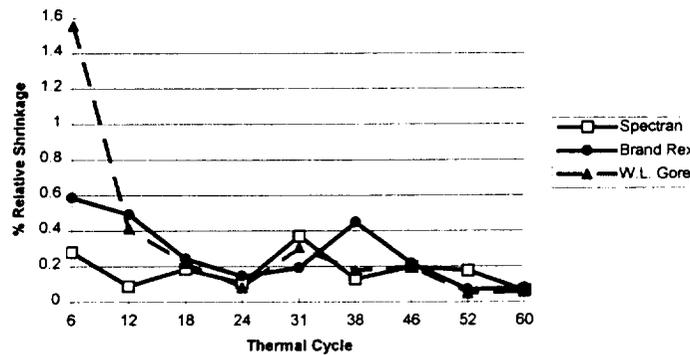


Figure 1

Results of cable component shrinkage of spectran flightguide, Brand Rex OC-1008 and W.L. Gore 8388 Prototype 1

Cable Component Shrinkage of Northern Lights Hytrel Jacketed Optical Fiber Cable

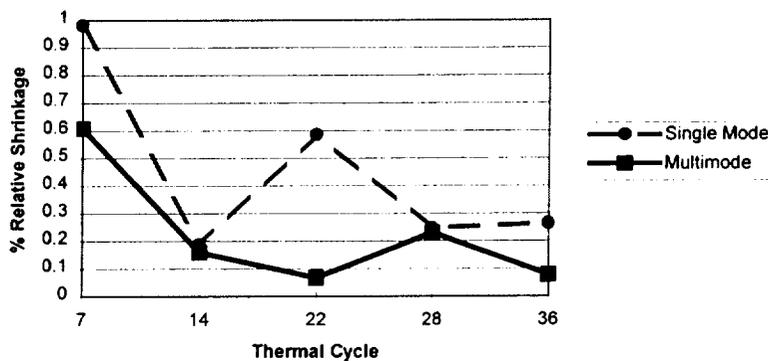


Figure 2

Shrinkage Results of Northern Lights Hytrel Coated Optical Fiber Cable

1.4 SUMMARY

From viewing Table 1, Figure 1 and Figure 2 it is apparent that the cables that had the most amount of cable component shrinkage were of the largest outer diameter. In third place for the greatest amount of overall shrinkage was the Hytrel coated single mode cable from Northern Lights which was only cycled 36 times and shrunk by a large amount. Had the cycling continued for this Northern Lights cable it may have ended up shrinking more than the larger diameter cables.

It was previously stated in paper one of this investigation¹ that a typical preconditioning procedure consisted of 8 thermal cycles and that this procedure would alleviate further materials shrinkage. In some senses it is true, especially with cables such as the W.L. Gore Prototype and the Brand Rex cables. However, by looking at Figure 1 it is obvious that while 8 cycles could limit the amount of shrinkage over temperature cycling after this preconditioning, 18 cycles makes more of an impact. The Spectran Flight Guide appears to shrink by almost the same amount each cycle session. In reference 1, it is stated that after 50 cycles the shrinkage would cease. Although it seems to continue shrinking after the 52nd thermal cycle all cables have shrunk by less than .1% relatively by the 60th thermal cycle. It is apparent that each cable behaves slightly different from the others, which is not surprising since each cable uses slightly different materials and fabrication processes. While preconditioning makes a dramatic difference to the shrinkage of the W.L. Gore prototype after the 18 cycle or even after the 12th cycle, the Spectran seems to be less affected in that it continues to shrink each session by nearly the same amount but slowly decreases relative to the previous cycling session. There is also a large difference in the way both cables from Northern Lights perform under thermal transients. Figure 3 plots the shrinkage of all cables tested for comparison purposes. Although there is a line connecting the % shrinkage of the Hytrel cables from cycle 24 to cycle 31, the cables were put in the oven just after cycle 24, so this part of the plot deserves no attention.

% Relative Shrinkage for Cable Components vs. Thermal Cycles

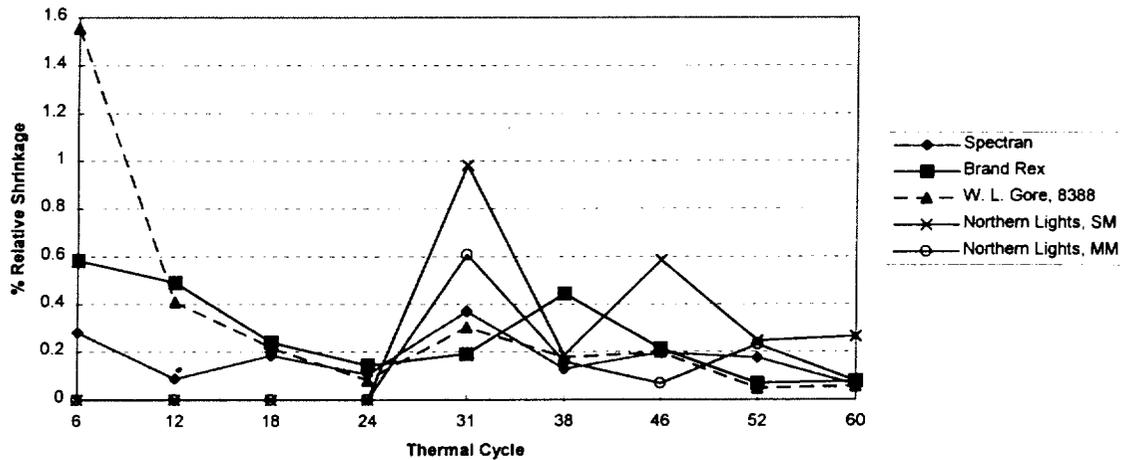


Figure 3
Shrinkage Results of all Cables Tested

In Figure 4 the shrinkage of cable components is characterized by the power output of the optical fiber. The assumption is that as the cable components shrink microbend attenuation will cause a power loss of the transmission signal. This effect is most obvious in the Northern Lights Hytrel jacketed multimode cable. The power drops from 8.6 μ watts to 3.7 μ watts and then rises again to 5.3 μ watts after the 22nd cycle. This is also true for the W.L. Gore FON 1008. Although it loses very little power over the thermal cycling process due to very little shrinkage of this cable it also begins to rise again in power after cycle 28 for sample one and cycle 14 for sample two. A logical reason for this could be that the connector being bonded so well to the cable components begins to pull back from the fiber that does not shrink, and in doing so pushes the fiber farther through the ferrule causing a protrusion, allowing more light to be coupled through the gap that is usually between the connector ferrules. It is apparent from this more sensitive test, that the W.L. Gore FON 1008 shrinks very little in comparison with some of the other candidates and loses optical power of less than .25 dB/100 meters. (Table 1). In summary, it appears

that the cables that performed the best over thermal cycling was the W. L. Gore FON 1008 due to the very low induced attenuation and the non detectable length changes. Even though this 100 meter cable was not measured for detection of length changes, it was evident that very little shrinkage was occurring by viewing the area bonded to the connector. This type of stress from the cable pulling back from the connector was detectable in the Hytrel jacketed Northern Lights multimode cable which by actual length measurements shrunk less than the unterminated Northern lights single mode microcable.

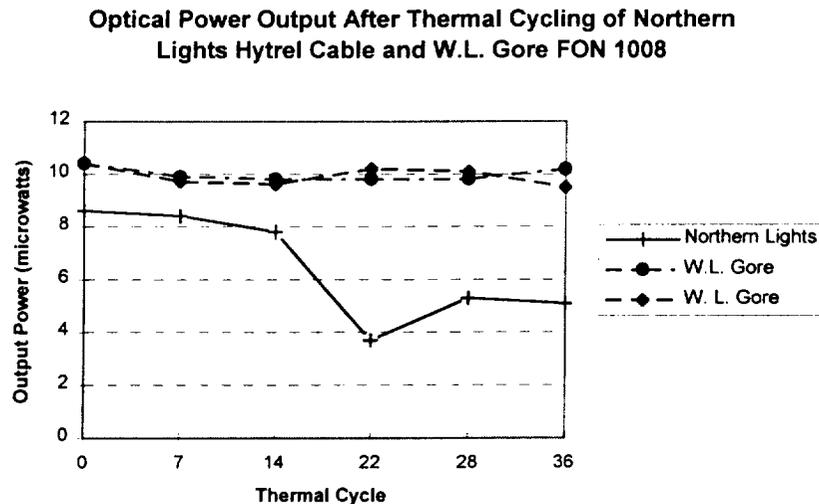


Figure 4
Optical Attenuation as a Result of Cable Component Shrinkage

2. RADIATION EFFECTS AND TESTING

2.1 BACKGROUND

It is a well known fact that an optical signal can attenuate when transmitted through an optical fiber in a radiation environment. The question with each optical fiber is: by how much does the signal attenuate? Many parameters affect an optical fiber's ability to withstand a harsh radiation environment including: operating wavelength, materials used for doping, temperature of operation, fabrication impurities, coatings, draw speed, draw tension, dose rate and total dose.

Attenuation occurs in optical fiber as a result of ionizing radiation generating color centers in the material. The color centers are areas in the material that appear opaque to some wavelengths of light and transparent to others. The color centers have high absorption of light wavelengths in the UV portion of the electromagnetic spectrum and less absorption at longer wavelengths in the infrared portion of the spectrum. A fiber's tendency to attenuate is sometimes suppressed by its self healing abilities.

Optical fiber can thermally anneal and therefore "recover" from the effect. This annealing is thermally activated and can offset the color center generation better at higher temperatures than a lower temperatures if the core dopant used in the fiber is not phosphorous or boron. However, the dose rate must be slow enough for a fiber to reach an equilibrium. This equilibrium is achieved when the competition between the annealing properties and the generation of the color centers evens out to a steady state attenuation. This behavior is called "saturation". Fibers doped with germanium or simply optical fibers that are pure silica are most prone to a saturation behavior with pure silica core fiber being faster to saturate. Pure silica fiber is used in single mode applications. Multimode applications that demand greater bandwidths require graded index fiber which must be doped with some type of material.

The ability of a fiber to self heal or anneal is aided by the light that transmits down the fiber while in a radiation environment and this is called "photobleaching". Continuous signal power over 5 to 10 microwatts will stimulate this photobleaching

effect thereby limiting the attenuation caused by radiation. In the past, researchers were stating that greater OH (hydroxyl) content in the fiber would desensitize the fiber to radiation, but OH has a high absorption around 1390 nm. It is also true the previously multimode optical communications were operating at a wavelength around 850 nm and now systems are using 1300 nm making the elevation of OH content not an option for systems that operate at this longer wavelength. Manufacturers are well aware of the fact that impurities introduced during the fiber drawing process will make a fiber sensitive to radiation by allowing more opportunities for color centers to form. Most maintain a clean environment to assure that no impurities enter into the drawing fiber.

Coatings, as well, have an affect on a fibers performance in a radiation environment. In some cases hermetic coatings themselves help the performance by disallowing the migration of impurities from the external coatings and materials into the fiber itself. Polyimide coating has been preferred over acrylate coating for the radiation hardness properties it provides, however it has more to do with the process with which the coating is fabricated. During the polyimide coating process the fiber is heated to 400 - 500 °C and coating the fiber with acrylate requires a UV cure that could actually create a residual damage. For space flight applications Goddard Space Flight Center prohibits any mechanical stripping of the fiber coating and uses chemical stripping only. This causes problems with the usage of chemicals because to strip the polyimide, hot sulfuric acid is required and to strip acrylate a methylene chloride solution similar to paint stripper is required and is safer for everyday use. Therefore, part of the study here is dedicated to determining the radiation hardness of hermetic acrylate coated 100/140 micron fiber that can be easily and safely chemically stripped.

Typical data results for radiation hardened graded index multimode fiber from Spectran state that at a dose rate of 1300 rads/min the induced attenuation reaches between 2 to 4 dB/Km for 10 Krads total ionizing dose (TID) but after an hour of “dark” recovery (meaning no photobleaching stimulation by the optical source) drops to 1 to 3 dB/km. Space environments usually have a much slower dose rate for ionizing radiation so better performance could be expected under a slower dose rate and with photobleaching effects if a greater power source is used.

Extrapolation Method: For this set of experiments two dose rate tests were conducted such that the extrapolation method developed at NRL by Friebele, Gingerich and Griscom could be utilized.[2] The method states that radiation induced attenuation can be extrapolated using the expression

$$A(D) = CD^f .$$

Where A(D) is the expected induced attenuation, C is a constant determined by dose rate, D is the total dose and f is a constant independent of dose rate. The expression for C is described by

$$C \propto \Phi^{(1-f)/n} ,$$

where Φ is the dose rate and n is the kinetic order of recovery. With this information, the entire expression should take the form

$$A(D) = C_0 \Phi^{(1-f)/n} D^f , \tag{1}$$

where C_0 and f are constant for all dose rates and total dose. If a value is assumed for n, kinetic order (usually 1 or 2) and a minimum two sets of data have been accumulated at two distinct dose rates, then the equation can be solved and used to extrapolate for all total dose and dose rates. Solving for f given two distinct data points of (A_1, Φ_1, D_1) and (A_2, Φ_2, D_2) and knowing that C_0 is the same for all data points the solution is

$$f = \frac{\log(A_1 / A_2) + \frac{1}{n} \log(\Phi_2 / \Phi_1)}{\log(D_1 / D_2) + \frac{1}{n} \log(\Phi_2 / \Phi_1)} . \tag{2}$$

Equation 2 can be solved by using several data points from the actual data which are values of attenuation, dose rate and a total dose. Averaging these values a suitable f can be determined once a value is chosen for n.

2.2 DISCUSSION

The data presented here is based on two total dose radiation tests; one conducted approximately at 50 rads/min, and one conducted approximately at 34 rads/min. Choosing two dose rates so close together was not by choice but by necessity since the ⁶⁰CO chamber’s maximum dose rate was no higher than 65 rads/min. The fiber tested in this experiment was an acrylate

hermetic coated 100/140 micron graded index fiber from Spectran, part number BF0544. For each of the two tests over 100 meters of optical fiber was irradiated in a wound spool with a diameter larger than 6 inches. Due to the geometry of the spool and the radiation distribution of the ⁶⁰CO chamber, the dose rate on the spool was not uniform and therefore had to be taken in to consideration. The geometry calculations approximated the two radiation dose rates mentioned above.

A source from RIFOCS 252A dual source at the 1300 nm setting was used which was rated for 10 microwatts but actually transmitted more power than the rating. For converting the output power into a voltage, an optical to electrical converter P6703A for 1300nm was used from Tektronix and data was recorded using a digital oscilloscope HP54201D, (due to lack of equipment compatible with available lab data acquisition software). The power was monitored as well with a nanovolt meter HP34420A. The test lasted several days and each dose rate test was conducted separately due to constraints of the radiation chamber. During the first hour of the testing, data was recording from the nanovolt meter and throughout the duration of the testing was recorded with the digital oscilloscope. The test for each dose rate was run undisturbed for the first 100 Krads and after this TID was reached the chamber was opened and shut to include other experiments not associated with this one. The test conducted at 34 rads/min was disturbed several times between the total dose of 100 Krad to 200 Krad. However, each time the chamber shutter was lowered it wasn't for more than 5 to 10 minutes. These disturbances were detectable by viewing the recorded data. Optical power output measurements were recorded prior to irradiation to provide a reference. Therefore, all increases in attenuation could be considered induced attenuation due to radiation. During the first hour, output power was monitored to illustrate the linear reaction of the attenuation at low total dose. Unfortunately, this data was not logged by computer throughout the testing and had to be taken by observation.

The results of the 50 rads/min test are in Figure 4 showing a linear decline in power. Average change in power for the first hour from the data points graphed in Figure 4 were calculated at -2.35 nW/minute at 50 rads/min, -47 nW/Krad or .019 dB/Krad induced attenuation.

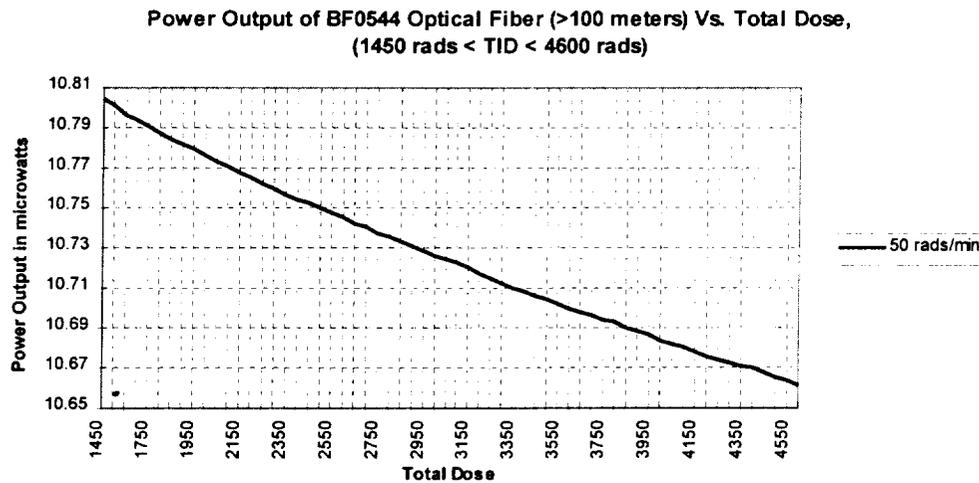


Figure 5
Power Output During First Hour of Radiation Testing at 50 rads/min

2.3 SUMMARY

All the data captured was processed after the testing was complete and the results of the actual data capture is graphed in Figure 6. The extrapolation method was used via equation 2 and the results of the calculated attenuation are graphed in Figure 6 as well. For these calculations the best fit to the actual data was determined to have a value of n=1 making f = .5345. These calculations were made by using both the data from the 50 rads/min test and the 34 rads/min test shown in Figure 7. The expression used for the extrapolation of this data is

$$A(D) = .003\Phi^{-.4655} D^{.5345} \quad (3)$$

where the units are dB/Km. Although the slower dose rate test did not saturate at a lower total dose, with the test of 50 rads/min showing a faster saturation, the slower rate test at 34 rads/min does show less attenuation once it did reach saturation. The 50 rads/min test sample saturated at a value of attenuation 12.21 dB/km at a total dose of 150 Krads. The 34 rads/min test sample saturated at 9.18 dB/Km at approximately a total dose of 160 Krads. It is most likely the case that frequent opening and lowering of the gamma ray chamber shutter during testing may have delayed the saturation of the 34 rads/min test sample. However, in most cases 100 Krads total dose is more than sufficient for testing of parts for space flight and at that total dose the 50 rad/min test sample had experienced an induced attenuation of 9.60 dB/Km and the 34 rads/min had experienced an induced attenuation of 6.45 dB/kKm at 100 Krads total dose.

To illustrate how this fiber performed when compared to the Spectran specification: at 10 Krads the 50 rads/min sample had an induced attenuation of 1.67 dB/km and the 34 rads/min sample had 1.05 dB/Km induced attenuation. Both of these attenuations are below that of the rating Spectran specifies (values approximately between 2 to 4 dB/Km at a dose rate of 1300 rads/min). This of course makes sense due to the slower dose rates used in this experiment and the photobleaching effects that were small, but present.

Extrapolating using Equation (3) the result of a total dose of 10 Krads at a dose rate of 1300 rads/min yields an attenuation of 11.6 dB/Km. This result is much higher than what Spectran has published in the specification. This could be because the extrapolation method sometimes does not predict well at very low total doses and at very high total doses. This is evident in both Figures 6 and 7 by the over estimate of the extrapolation curve in both tests at high dose rates after the fiber has reached a saturation point and the over estimate at the lower total doses in the 34 rad/min test. It is possible that by conducting two tests both at low dose rate has caused faulty results at higher dose rates but for space flight the lower dose rate information is more realistic for planning purposes. It also appears that the extrapolation curve fits the 50 rads/min test data better than the 34 rads/min test data. The values for f and n were chosen based on the best fit of the available data and it may have been quite different with two dose rates much farther apart. It is also the case that due to the experimental setup available the data collected can not be considered exact but should be considered approximations. This is another reason that the extrapolation method does not provide the correct data to predict attenuation accurately for all dose rates and total doses. It does however, show the trend and may be able to be used for other low dose rates.

It was somewhat difficult to solve for f for this experiment, possibly due to the slow dose rates used. The best choice had to be sorted out from the available data instead of a simple averaging of all the data point calculations. Some results were obviously incorrect and would not work for extrapolation purposes.

After 24 hours the permanent induced attenuation for the 50 rad/min test was 7.7 dB/Km. The attenuation for the 34 rad/min test was higher than the saturation value of the induced attenuation during the radiation testing; therefore, it most likely had to do with the connector or termination becoming damaged during removal from the radiation chamber.

**Induced Attenuation and Extrapolated Induced Attenuation for Spectran
BF0544 Acrylate Hermetic 100/140 Graded Index Multimode Fiber
vs. Total Dose, dose rate = 50 rads/min**

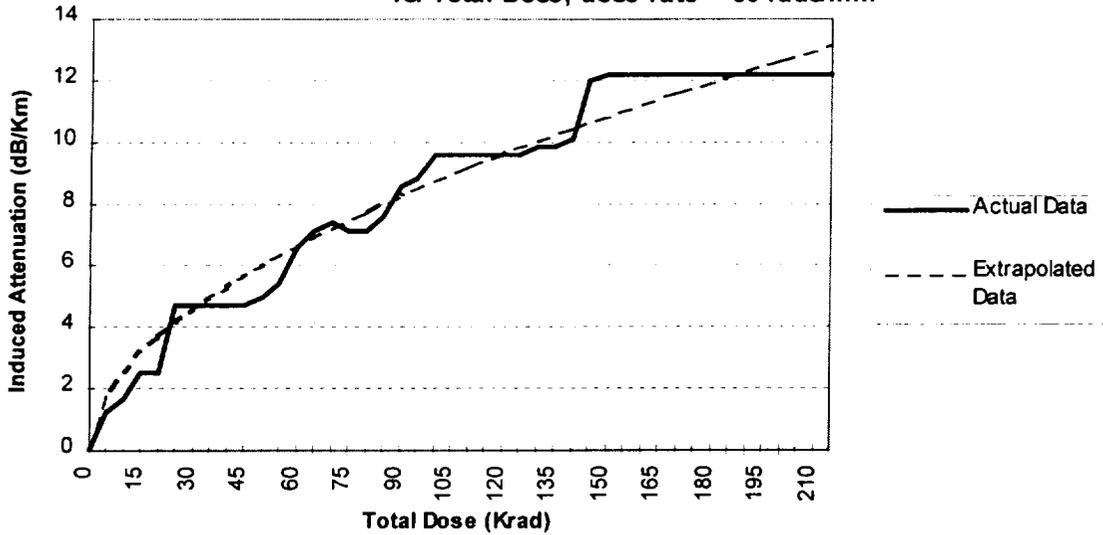


Figure 6

**Induced Attenuation Data and Extrapolated Attenuation for 50 rads/min on BF0544 Spectran Multimode Acrylate
Hermetic Optical Fiber**

**Induced Attenuation and Extrapolated Induced Attenuation for the
Spectran BF0544 Hermetic Acrylate 100/140 Graded Index Multimode Fiber
vs. Total Dose for 34 rads/min**

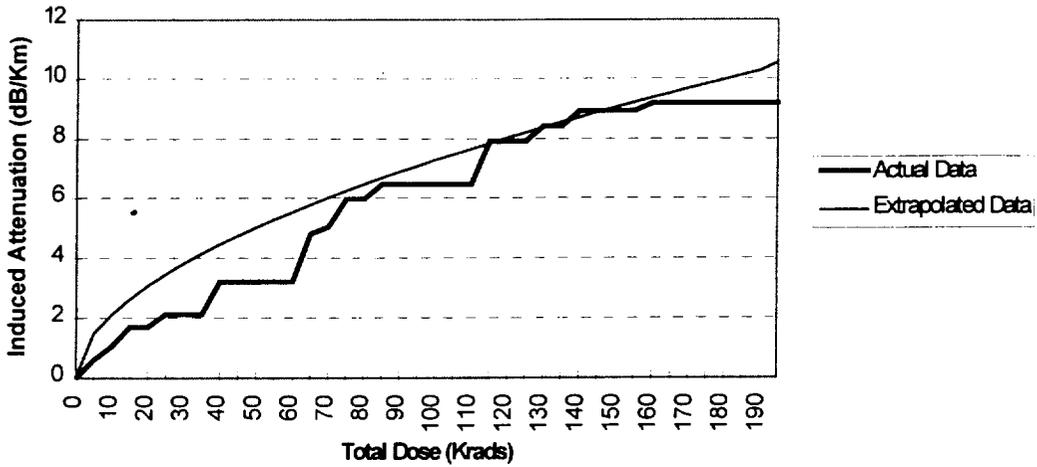


Figure 7

**Induced Attenuation Data and Extrapolated Attenuation for 34 rads/min on BF0544 Spectran Multimode Acrylate
Hermetic Optical Fiber**

3. CONCLUSIONS: THERMAL AND RADIATION TESTING RESULTS

The shrinkage testing of cable components illustrated how a preconditioning procedure for fiber optic cable assemblies should be tailored to fit the type of cable being used. In some cases there is no need for a preconditioning procedure. In other cases 8 cycles provides some protection against further shrinkage but 18 cycles provides enough to consider further shrinkage much less of an issue. The Spectran Flight Guide seemed to shrink continuously but by an amount much less than the other types tested. The W.L. Gore FON 1008 that was optically tested as well as inspected for stress from shrinkage around the connector did quite well by causing very little loss in comparison to the Hytrel jacketed multimode cable. It is probably important to once again point out that the cable components may pull the connector back from the fiber after a certain amount of shrinkage is attained and that a result of this could be the fiber protruding out of the ferrule. This is only one of the reasons that preconditioning should be accomplished prior to terminating the cable to a connector. Overall, it is apparent that many types of fiber optic cable components should be examined for shrinkage before use and possibly preconditioned before termination such that further shrinkage may be suppressed but not eliminated. As shown, it takes many cycles to eliminate the shrinkage entirely and all possible steps should be taken to be sure that during extrusion fabrication stresses should be avoided as much as possible. Although preconditioning procedures may not entirely remove the possibility of further shrinkage, in some cases it can be limited by a large amount.

The radiation results presented here on the Spectran BF0544 hermetic acrylate coated 100/140 fiber show that in the low dose rate environment of space this fiber would experience less than 10 dB/Km for a total dose of 100 Krads (taken from the 50 rads/min data). The BF0544 experienced less than 7 dB/Km for a total dose of 100 Krads at a dose rate of 34 rads/min. It is also important to keep in mind that in most space flight applications the lengths of fiber optic cable used are approximately 10 meters and in very few applications are lengths as long as 100m used. Another advantage of this optical fiber is that it did reach a saturation point of induced attenuation. This implies that at a low enough dose rate, like those used here, a maximum amount of attenuation can be expected for any total dose.

One of the reasons that this optical fiber was chosen for investigation, is that it does have the advantage of a coating that is strippable in a methylene chloride solution. It was verified during these experiments that the acrylate coating did strip off of the fiber easily in chemical solution after 2 minutes of being immersed.

4. ACKNOWLEDGEMENTS

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