Fiber Optic Cable Assemblies for Space Flight Applications III: Characterization of Commercial Cables for Thermal Effects

Melanie N. Ott
Advanced Component Technologies and Radiation Effects Branch
Sigma Research and Engineering/ Goddard Space Flight Center
301-286-0127
melanie.ott@gsfc.nasa.gov
misspiggy.gsfc.nasa.gov/tva/photonics.html
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Introduction
This is the third paper in a series of white papers addressing the issues associated with the usage of optical fiber cables in space flight applications.[1-2] These experiments to characterize commercially available optical fiber cables are crucial to deciding which cables are appropriate for which space flight mission based on their environmental performance. The objective of this project has always been to distinguish which commercially available cables will perform adequately in different space flight environments and to end up with a selection of different cable assemblies for a selection of different space flight environments. In addition to determining which cables are best for space flight applications the methods and parameters by which these cables are "preconditioned" is also under study such that the problem of thermally induced cable component shrinkage can be alleviated. This problem of cable component shrinkage has become an issue associated with all optical fiber cable on the market today and presents a calibration and reliability problem.[1] This paper addresses the issue of thermal effects and preconditioning of optical fiber cables with the goal of making these cables more readily available to all space flight missions.

Optical Fiber Cable Candidates Under Test
For this thermal characterization, five fiber optic cable configurations were tested. One from W.L.Gore, two from Brand Rex, and two from RIFOCS (manufacturer Northern Lights). All cables chosen for this testing were chosen based on the intention of these cables to be used for space flight applications. These cables were designed to be commercially available (all but the OC1614 which was made for space station) but also space flight ruggedized cable configurations. One of the Brand Rex cables included in this study the OC1008 is actually a discontinued item but was included for comparison purposes since this cable was used for both the TRMM and XTE missions. The W.L. Gore cable was designed to be used in the -55 to +125°C thermal environment and the Brand Rex space station cable OC1614 was designed for the -100°C to +75°C but most of the other candidates have a smaller thermal range for performance. Another aspect to note about the OC1614 is that based on the configuration described below which includes a polyimide coated fiber, it is very likely that the cable could be operated all the way to 200°C. Brand Rex does confirm that although the OC1614 was made to the SSQ-21654 specification it could be capable of temperatures well beyond the upper limit required by Space Station of +75°C. Table 1 describes the configurations of the cables tested with some details about their dimensions and specified thermal environments. The cables listed in Table 1 with the exception of the OC1008 are in fact available or will be available if not already, with other types of optical fiber. Brand Rex, W.L.Gore and Rifocs have communicated the intention of using these configurations to manufacture for various different applications that require other fiber diameters that are the standard outer diameter of 125 microns or the 140 micron non standard fiber with acrylate and polyimide coatings. Therefore, the products listed here are only an example of the family of cables that are available using these configurations and these cables were chosen based on availability at the time of this testing.

Table 1: Cable Candidate Configuration Summary

Vendor Cable Part #	Cable Configuration	Fiber Type	Secondary Buffer	Strength Members	Outside Jacket	Outer diameter	Thermal rating
W.L. Gore FON1004	Tight Tube with Metal braid over GoreTex buffer	Single mode, 1310/1550 nm acrylate buffer	Gore Tex Expanded PFA	Kevlar	FEP Fluoropolymer	2.5 mm	-55°C to +125°C
Brand Rex OC1614 (SSQ-21654 Rev. B)	Tight tube	Multimode 100/140/170 hermetic seal/ polyimide buffer	FEP Teflon	Teflon impregnated fiber glass	FEP Teflon	2.1 mm	-100°C to +75°C
Brand Rex OC1008	Loose tube	Multimode 100/140/500 acrylate buffer from corning now discontinued	Hytrel	Teflon impregnated fiber glass	ETFE Tefzel	2.77 mm	- 55°C to +85°C
RIFOCS H06	Tight tube	Multimode 62.5/125/250	Hytrel	Kevlar	Tefzel	2.4 mm	-40°C to +95°C
RIFOCS HL1	Tight tube	Single mode, 1310/1550 nm acrylate buffer	Hytrel	Kevlar	Tefzel	2.4 mm	-40°C to +95°C

Thermal testing environmental parameters:

Although most of the tested cables are not rated for the extremes of -55°C to +125°C, that is usually due to the rating of the acrylate coating on the fiber itself that is usually only rated to +85 C. However this test was conducted to determine the amount of thermally induced shrinkage of the cable components and the optical performance as a result so the limits were extended to the -55°C to +125°C range for all cables tested. Because of this, it is important to note that all the optical cable candidates with the exception of the W.L. Gore FON1004 were taken beyond their thermal specifications. The ramp rates for all of the thermal testing was 2°C/min with dwells of 28 minutes per temperature extreme.

The thermal testing was conducted in two parts. During part one of the testing all cables were cycled and measured post each 8 cycle session for dimensional shrinkage in the longitudinal direction only and some optical measurements were made. Part two of this testing was focused on the optical performance of these cables (with most of them being taken well outside of their thermal specifications) both during cycling and after. The overall optical fluctuations that occur during the cycling are used as a characterization of the thermal expansions and contractions due to the CTE of materials used in the configuration. The after thermal cycling optical measurements should be indicative of how the static shrinkage of materials in the cable configuration have affected the optical performance permanently.

Table 2: Test Plan and Measured Parameters

Candidate	Color	Length	# of Samples	Fiber Type	Outer diam	Test Temp Range	Test	Termination connector/ test wavelength
W.L.Gore Prototype II FON1004 (8.4 m)	yellow	3 m	3	SM (7.0/125)	2.53 mm	-55 to +125	- 2 samples length test only, - 1 sample optical test	ST, SM 125 micron
Brand Rex Space Station OC-1614 (9.85 m)	dark purple	3 m	3	MM (100/140)	2.23 mm	-55 to +125	- 2 samples length test only, - 1 sample optical test	ST, MM 1300 nm
Brand Rex OC-1008** (leftover on spool)	purple	3 m	3	MM (100/140)	2.62 mm	-55 to +125	- 2 samples length test only, - 1 sample optical test	ST, MM 140 micron 1300 nm
Northern Lights HL1 (Rifocs) (50 m)	plum	3 m	3	SM (8.8/125)	2.36 mm	-55 to +125	- 2 samples length test only, - 1 sample optical test	ST, SM 125 micron 1300 nm
		10 m	4			-55 to +125	- 2 samples length testing, - 2 samples optical test	
Northern Lights H06 (Rifocs) (50 m)	plum	3 m	3	MM (62.5/125)	2.33 mm	-55 to +125	- 2 samples length test only, - 1 sample optical test	ST, MM 125 micron 1300 nm
		10 m	4			-55 to +125	- 2 samples length testing, - 2 samples optical test	

Table 2 lists the cables being tested and specifies the measured outer diameter of the cable configurations prior to testing. Also listed is the actual amount of cable available for this testing. The last column lists the connector type used as well as the testing wavelength. It was not ideal to use ST connectors (instead of FC's) for this evaluation but for the purposes of compatibility between existing test equipment and available patch cables, these connectors were chosen.
The cables were measured in length prior to any testing and remeasured after each 8 thermal cycle session. The total number of cycles for thermal testing part one was 72 cycles total. Therefore, 9 sessions were conducted and 10 measurements per cable were made.

Test Results Part I: Cable Component Shrinkage as a Result of Thermal Cycling

The test results of the length shrinkage thermal testing are in tables 3 and 4. The data in Table 3 is graphed in figure 1. The length measurements were made post each 8 cycle session and compared to the length value that was measured previous to the session. The numbers in bold in each column represent the point at which the dimensional length shrinkage remained below .1%. The largest amount of cable jacket shrinkage was seen with the W.L.Gore FON1004 and the smallest amount of jacket shrinkage was seen with the Brand Rex OC1614. By the end of the 48th cycle it appears that most of the cables with the exception of the OC1008, had begun shrinking less than .1%. This result is similar to the results from the study published last year in reference 2. It also appears that by the end of the 24th cycle a good deal of the total shrinkage has been accomplished (see Figure 1). Since the values from sample set 2 are similar to that of sample set 1 only the data from sample set 1 is represented in Figure 1.

Table 3: Summary % shrinkage results per cycle session from thermal testing of sample set 1

Total Thermal Cycles	**W.L Gore FON1004**	**Brand Rex OC1614**	**Brand Rex OC1008**	**RIFOCS H06**	**RIFOCS HL1**
8	1.98	**0.05**	0.77	1.42	1.82
16	0.60	0.00	0.30	0.22	0.10
24	0.09	0.03	0.24	0.14	**0.07**
32	0.09	0.00	0.17	0.00	0.03
40	0.22	0.00	0.14	0.10	0.03
48	**0.04**	0.00	0.10	**0.00**	0.03
56	0.00	0.03	0.10	0.03	0.00
64	0.00	0.00	**0.03**	0.00	0.00
72	0.00	0.00	0.07	0.00	0.03
Total % shrinkage	**2.99**	**0.12**	**1.90**	**1.90**	**2.12**

Table 4: Summary % shrinkage results per cycle session from thermal testing of sample set 2

Total Thermal Cycles	**W.L Gore FON1004**	**Brand Rex OC1614**	**Brand Rex OC1008**	**RIFOCS H06**	**RIFOCS HL1**
8	1.14	**0.07**	0.77	1.28	1.82
16	0.47	0.00	0.27	0.25	0.12
24	0.37	0.03	0.24	0.10	0.03
32	0.24	0.03	0.10	**0.07**	0.00
40	0.34	0.00	0.17	0.07	0.14
48	0.10	0.00	0.07	0.00	**0.00**
56	0.21	0.00	0.10	0.00	0.00
64	**0.07**	0.00	**0.07**	0.03	0.00
72	0.03	0.00	0.03	0.07	0.03
Total % shrinkage	**2.94**	**0.13**	**1.80**	**1.87**	**2.13**

There was no visible damage that occured as a result of taking most of the cables outside of there respective thermal specifications. It is interesting to note that the FON1004 and both RIFOCS cables had jacket shrinkage but the kevlar and other buffer materials did not shrink back. In the thermal tests conducted and reported in reference 2, this was not the case. All cable components would shrink back exposing only the coated optical fiber.

RIFOCS has outlined a preconditioning proceedure for their cables as 8 thermal cycles with 60 minute dwell at +90°C and 15 minutes at +10°C and ramp rates of less than 10°C/minute. However they do not state as to what amount of shrinkage can be expected after this preconditioning has been performed. RIFOCS also offers this preconditioning as part of the product for an additional charge. As evidenced here the majority of the cable jacketing shrinkage does in fact occur as a result of the first 8 cycles. For HL1 85% of the shrinkage occurred in the first 8 cycles and for H06, sample 1 decreased in length 75% in the first 8 cycles and sample 2 had decreased by 69% of the total shrinkage amount determined here after a total of 72 cycles. However, these tests do not confirm the preconditioning procedure used by RIFOCS since the parameters used are not the same. Tests to confirm the RIFOCS preconditioning procedure will be verified during the next session of testing scheduled for the year fiscal 2000. The inclusion of the OC1008 was to simply make a reference comparison to a flight cable used on space flight missions of the past. The effect that the thermally induced jacket shrinkage has on the optical performance of these cables is presented in part two of this paper.

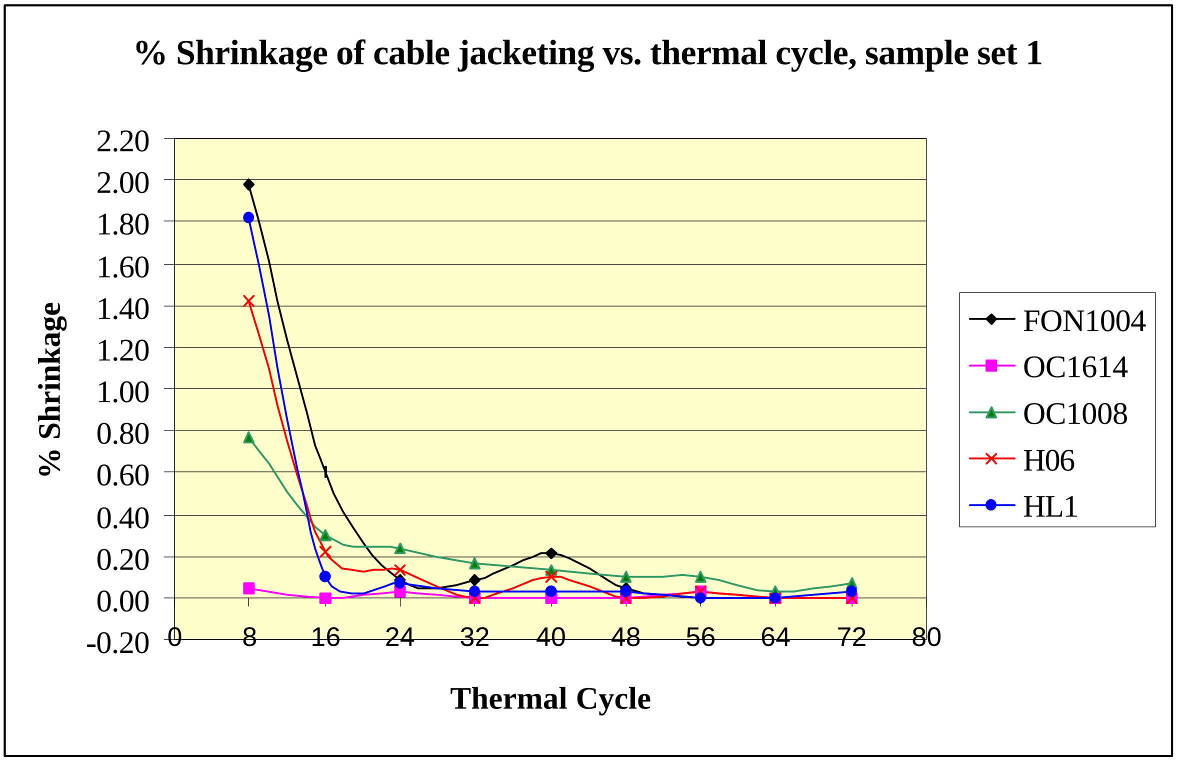

Figure 1

Test Results Part II: Optical Performance During and After Thermal Cycling.

To better characterize the thermal stability of the candidate cables a second round of testing was conducted to measure optical changes as a result of thermally induced configuration shrinkage and the CTE mismatch induced microbending. The assumption for the insitu testing was that the greatest amount of thermally induced attenuation would occur at the lower thermal extremes. Also, at the higher temperature extremes it was expected that the optical power transmission would exceed the ambient optical power transmission levels. This testing was designed to give a sense of what to expect from the cable candidates but was in no way meant to be statistically significant.

Experimental Set Up

The thermal environment was the same as discussed in Part 1 of this report. The thermal cycling environment was from -55°C to +125°C with a soak at each extreme for 20 minutes and a ramp rate of 2°C/min. Each cable was placed inside the chamber with terminated ST connectors just outside the feed-through hole to the oven. There were reference cables connected to the sources and detectors with the cable under test in between the two sets. Insertion loss of the cable assembly was not the issue of concern here. Instead it was the change in transmitted optical power during the thermal cycling. Launch conditions were not controlled such that thermal stability testing could mimic the conditions being used in space flight.

The sources used for launching optical power through the cables were the RIFOCS 252A and the RIFOCS 752L both used at 1300 nm. LED sources were used as opposed to laser sources due to the noise generated near the thermal chamber. The laser sources were found to be too sensitive to this noise to be used during the thermal cycling testing. The detector used to convert the optical signal to an electrical signal was the HP8153A with HP81532A power sensor modules. For the insitu testing a Labview program was written to acquire data and store it in a text file. One cable of each type was tested for optical transmittance changes before, during and after thermal cycling to a total of 48 cycles.

Experimental Data and Results

After each 8 cycle session the cables were measured for changes in optical transmission as a result of thermal cycling for up to 48 cycles total. These measurements were made once the cable was held at room temperature for several hours. The insitu data was used to calculate the amount of optical power transmission changes during the thermal cycling. The data for both tests are presented below.

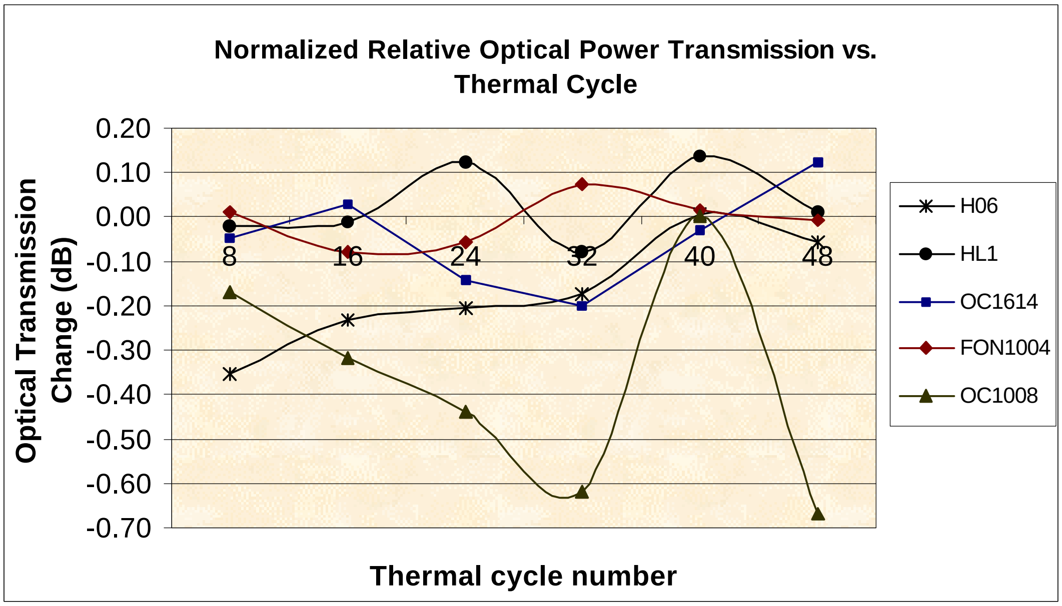

Figure 2: Relative optical power transmission through the cable under test. Measured before and after thermal cycling.

The lengths of the cables were measured after termination but prior to testing and are in table 5. The values in Figure 2 are scaled by the absolute cable lengths and then multiplied by 3, such that the presented cable data is scaled to exactly 3 meters in length.

Cable Configuration	Length for Optical Testing (meters)
H06	2.965
HL1	2.714
OC1614	3.719
FON1004	2.78
OC1008	2.935

Table 5: Cables under test, lengths prior to thermal cycling

Due to the repeatability uncertainty associated with the use of ST connectors, the values in Figure 2 have an uncertainty of +/- .06 dB according to experimental repeatability testing of the ST connectors on the test cables and the cables under test. Taking the repeatability uncertainty into consideration it is probably safe to conclude that the loss variations recorded for the FON1004 are small enough to be considered below the noise floor. The HL1 configuration seemed to be very close as well at being below the noise floor for possible recorded losses with this set up. The losses recorded for the OC1008 (vintage space flight cable) are clearly the highest in terms of after cycling losses and are well above the noise floor. For the H06 configuration it appears that the losses for this cable decrease as the cable is thermal cycled. The OC1614 did not perform that different than the other cables tested, with only a few measurements noted above those of the HL1. None of the data presented here is statistically significant since only one cable of each type was tested. However, the data does give a picture of how typical cables currently available compare to the NASA qualified vintage cable OC1008. It was expected that the OC1008 would have higher microbend losses as a result of the linear component shrinkage. This cable has a loose tube configuration and as the materials shrink linearly the fiber bends in a helical fashion, inside of the loose tube. This being the case the losses from microbending should be larger than they would be in tight tube configuration of similar materials. This would also be true of the OC1614 if the materials inside of the configuration were to shrink as much as the OC1008. However, of all the cables tested the OC1614 had the lowest thermally induced cable component length shrinkage.

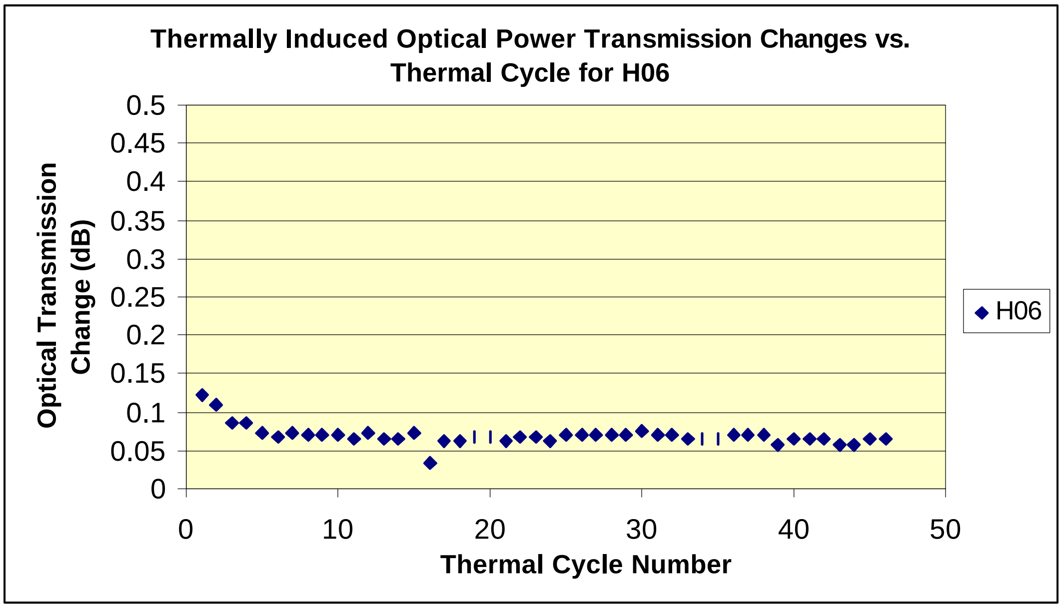

Figure 3: Thermally induced optical power transmission changes during thermal cycling for the H06 cable configuration, normalized to 3 meters exactly.

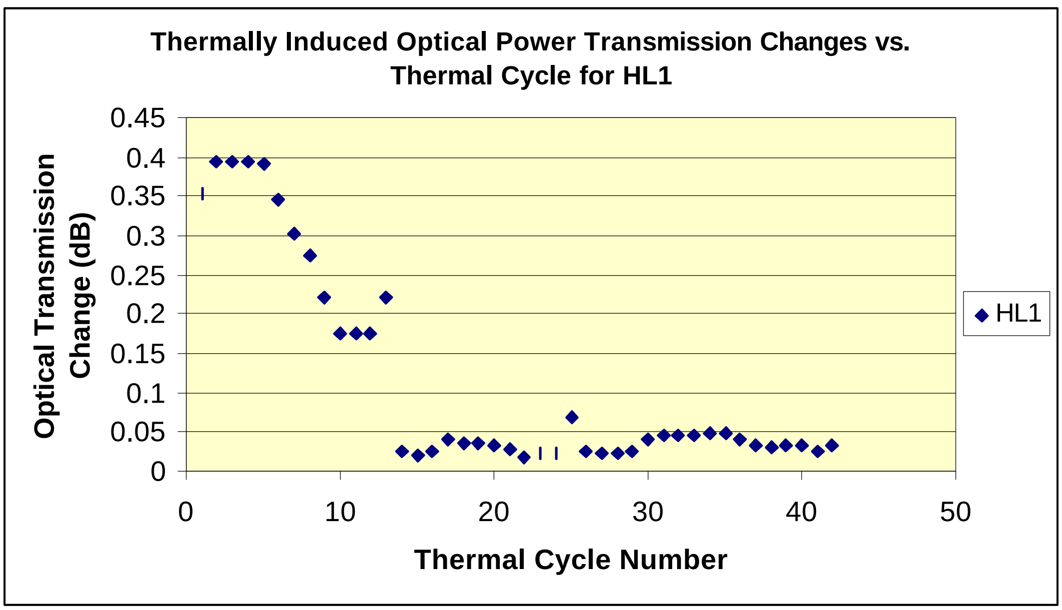

Figure 4: Thermally induced optical power transmission changes during thermal cycling for the HL1 cable configuration, normalized to 3 meters exactly.

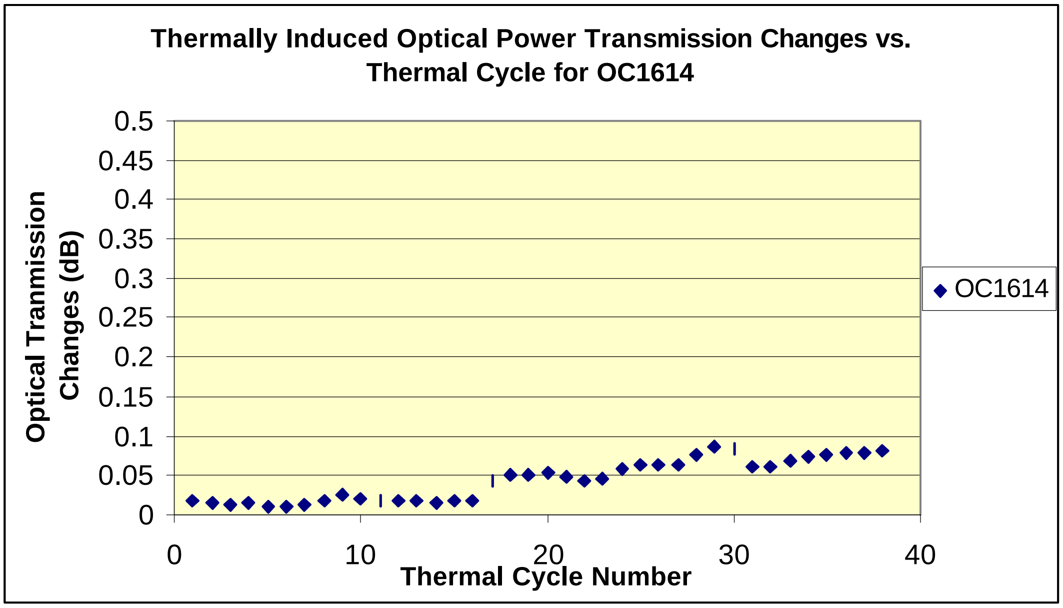

Figure 5: Thermally induced optical power transmission changes during thermal cycling for the OC1614 cable configuration, normalized to 3 meters exactly.

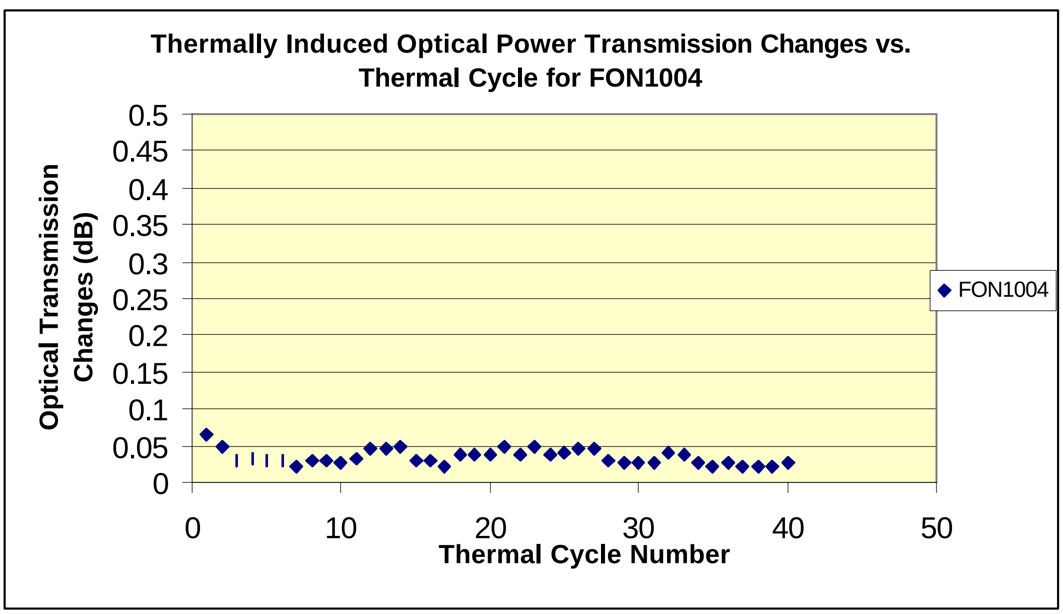

Figure 6: Thermally induced optical power transmission changes during thermal cycling for the FON1004 cable configuration, normalized to 3 meters exactly.

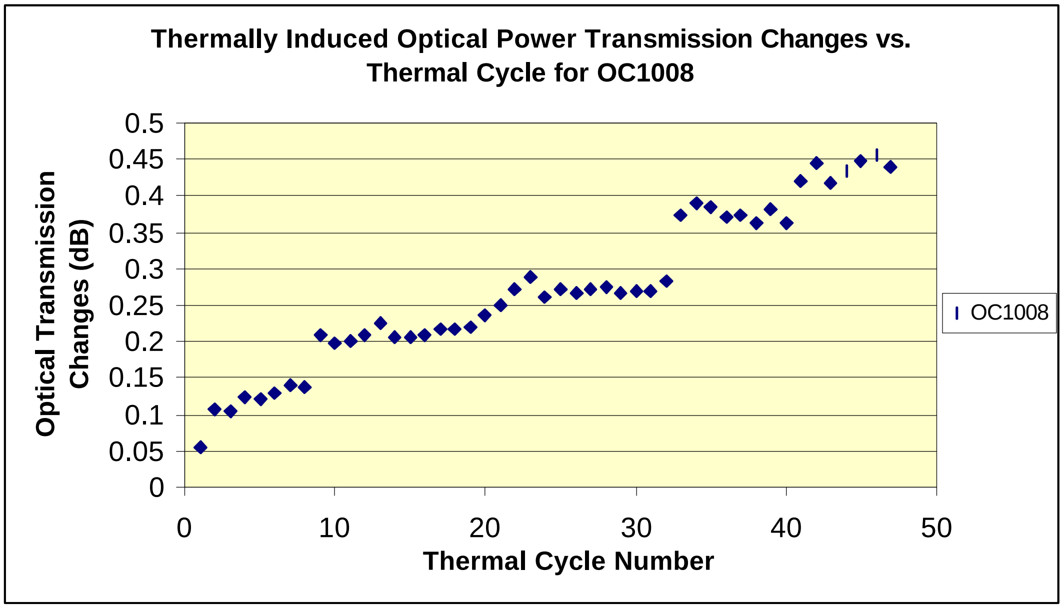

Figure 7: Thermally induced optical power transmission changes during thermal cycling for the OC1008 cable configuration, normalized to 3 meters exactly.

Figures 3 through 7 show the data from insitu testing of all the cable candidates. This data has been normalized to cable lengths of 3 meters each, such that the values may be compared. The optical power transmission transients were calculated by comparing adjacent optical power peaks and losses within a thermally induced cycle. In this way the LED output power drift was eliminated. The total optical power transmission change, which is presented in these figures, is calculated by comparing the optical power maximum to the optical power minimum in a given cycle. Although the intention was to collect data for 48 thermal cycles total, in some cases not all data was captured due to operation error.

The optical transmission changes for the H06 (Figure 3) were less than .1 dB for the duration of the testing on a length of cable approximately 3 meters long (actual lengths for the cables under test are in table 5). The optical transmission changes for HL1 (Figure 4) decrease considerably after 13 thermal cycles down to less than .05 dB. The FON1004, for the duration of the testing had fluctuations less than .05 dB (Figure 6). The OC1614 and the OC1008 (Figures 5 and 7 respectively) both had increased power fluctuations during thermal cycling as the cycling progressed. This was most likely due to the fact that both cables have a loose tube construction. It would make sense that shrinking cable would force the fiber into a tighter helix and make the fiber more sensitive to the expansion and contraction caused by the materials CTE. The OC1614 shrinks very little and even though there is a slight increase in the thermally induced transmission transients, the total swing never reach more than .1 dB.

During this testing it was expected that the single mode cables would perform better than the multimode cables in terms of stability due to the short lengths used and that indeed was the case. Launch conditions were not regulated such that the multimode fiber would reach its equilibrium point for power distribution across the traveling modes. In typical space flight applications launch conditions are not always controlled or at optimal levels and therefore they were not regulated here.

It was expected that during insitu testing that when the temperature was at a maximum, the optical power transmission of the cable under test would be at a maximum as well and that during a low thermal extreme that the power would reach its minimum value. In most cases this was true except for the OC1614. Just the opposite appeared to occur. Two more addition tests were conducted on cables from another source to confirm that indeed for the cable OC1614, the optical maximum would be reached during the soak at -55°C and that during the +125°C soak, the optical transmission would reach a minimum.

Summary and Conclusions

The overall rankings of how the cable candidates performed are in table 6. The ranking is somewhat subjective for the optical tests in that multimode cables are being compared to single mode cables. It is expected that the highest ranking cables for optical performance should be the FON1004 and the HL1. For the most part these do appear to be more optically stable than the multimode cables. Comparing the HL1 and the FON1004 to each other the FON1004 slightly outperforms the HL1 for the optical testing. The difference here could be that the HL1 was being cycled at a temperature +30°C above and -15°C below the temperatures for which it is rated. The HL1 did have large thermally induced transmission transients during the first 13 cycles but decreased after the 13th cycle and remained at a level less than .05 dB. This again may be due to fact that the cable is being taken well above its rated thermal limit. In addition it is also interesting to note where the majority of the linear cable component shrinkage becomes less than .1 %, and that it is after the 16th thermal cycle. It may be that the reduction in shrinkage actually occurred after the 13th cycle but that during this testing the thermal effects were only measured after 8 cycle sessions. The data here indicates the H06 is a good performer once the 13th cycles have been completed. This gives an indication of how much "preconditioning" the HL1 requires to reach a thermal stability, given these thermal cycle extremes of -55 to +125 degrees C. There is in fact a RIFOCS preconditioning procedure (mentioned previously) that after being performed, would allow the cable to remain thermally stable. Verification of the preconditioning procedure is scheduled for later this year.

The FON1004 cable ranks the lowest in the total amount of thermally induced shrinkage although the shrinkage did stabilize somewhere after 48-56 cycles. Optically, this cable performed very well even with the large amount of cable component shrinkage. Again, we see that preconditioning for this cable is absolutely necessary for up to 50 cycles.

Test	Total Length Shrinkage	Cycles to less than .1% Shrinkage	Post 8 cycle session loss	Insitu transmission stability
Rank 1	OC1614	OC1614	FON1004	FON1004
Rank 2	H06	HL1	HL1	OC1614
Rank 3	OC1008	H06	OC1614	H06
Rank 4	HL1	FON1004	H06	HL1
Rank 5	FON1004	OC1008	OC1008	OC1008

Table 6: Ranking summary of cables in terms of best performance, 1 being the best and 5 being the worst of the total.

Of the multimode cables the OC1614 is by far the best performer for all testing conducted when compared to the multimode cables. The H06 appears to be second when compared to the OC1614. However, where a preconditioning procedure may not be necessary for the OC1614 it is absolutely necessary for the H06 where the bulk of the linear shrinkage occurs in the first 32-40 thermal cycles. It may or may not be the case that the configuration materials in the HL1 and the H06 are identical. If the assumption is that they are in fact the same, then the variability from lot to lot with respect to the lengthwise component shrinkage could be a factor of 2. This could explain why for the HL1 the bulk of the length shrinkage occurred around 13-16 cycles and for the H06 the bulk of the shrinkage occurred after 32-40 cycles. Without a large enough number of cable samples from different lots this can not be verified.

For most of the testing conducted, the available cables perform better than the vintage OC1008 optical fiber cable currently used in space flight. Since the thermal induced transients becoming larger as the loose tube configuration cables, OC1008 and OC1614, are cycled, preconditioning to eliminate the bulk of the shrinkage must be conducted prior to termination of the optical connectors. In fact, in all cases preconditioning should be performed prior to termination to avoid reliability hazards from the fiber being pulled out of the ferrule from the stress or leaving exposed fiber between the cable components and the connector itself.

The OC1614 was the superior performer throughout the testing and was taken well beyond its specification level. Just as this testing was completed, the International Space Station Mission reported failures on their space flight cable, which is the OC1614. For more information on this failure please see the report currently being written on the root cause of the failure on the ISS optical fiber cable due out later this year.

Based on the ISS failures, it is likely that the OC1614 will not be considered for use in future space flight missions in its current form. The ISS investigation team is currently writing a new specification for optical fiber cable. A new cable configuration should be available sometime in the next year.

Presented here are the latest test results from the testing conducted during the fiscal years 1999 and the first two quarters of fiscal year 2000. Both OC1008 and the OC1614 will not be used for space flight, in that OC1008 is obsolete and the OC1614 is soon to be as well. Further testing later this year will verify the preconditioning procedure mentioned previously for the HL1 and the H06. These cables may provide a promising alternative for an environment from -40C to +95C. Future versions of the W.L.Gore prototype will be tested as they become available.

References:

1. Melanie N. Ott, Jeannette Plante, Jack Shaw, M. Ann Garrison-Darrin, "Fiber Optic Cable Assemblies for Space Flight Applications: *Issues and Remedies,*" Paper 975592 SAE/AIAA 1997 World Aviation Congress, October 13-16, Anaheim, CA.

2. Melanie N. Ott, "Fiber Optic Cable Assemblies for Space Flight II: Thermal and Radiation Effects," Photonics For Space Environments VI, Proceedings of SPIE Vol. 3440, 1998.