TID Radiation Induced Attenuation Testing at 1300 nm Using ISS Requirements on Three Optical Fibers Manufactured by Lucent SFT

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Objective

The testing of Lucent SFT optical fiber was conducted to characterize several types of the Lucent SFT 100/140/172 carbon coated product for use in a harsh space flight environment. The environmental parameters used in this testing were extracted from the new International Space Station (ISS) specification 21657 Revision N/C.[1] The environmental parameters include a constant temperature of -121°C for a maximum of six days during which the fiber is exposed to total ionizing radiation exposure as a result of solar flare events, orbital passes through the South Atlantic Anomaly, and background radiation. The ISS specification requirement includes testing of cable to three different levels of the expected total ionizing dose (TID) in a cold environment. The objective of this testing was to simulate the worst of the actual conditions during a six day cold temperature exposure without over testing. In order to accomplish this, two dose rates were to be used for estimating the radiation induced attenuation performance of the cable, 42 rads/min for two hours to simulate the solar flare activity and .5 rads/min to simulate passes through the South Atlantic Anomaly, SAA and background radiation. The specification requires a TID radiation exposure on the optical fiber cable for a total of six days at a constant temperature of -121°C +/- 4°C. This test was to continue at the second dose rate of exposure, but at room temperature for an additional 48 hours or once a saturation level had been reached for radiation induced attenuation.

Background

In order to use the TID cobalt 60 chamber at NASA Goddard Space Flight Center with a thermal chamber and necessary shielding, the highest dose rate attainable for exposure on an optical fiber reel was 28.3 rads/min. Therefore, two tests had to be conducted at different dose rates. It was expected that the highest radiation induced attenuation would occur after an exposure to 5.1 krads at 42 rads/min. That being the case, it was considered adequate to use two different dose rates for testing and extrapolate to obtain the actual required radiation induced attenuation values.

The optical fibers under test (DUTs) are described in Table 1. Optical fiber F3 is the "rad hard" fiber most space flight projects have used when a 100/140/172 micron hermetic fiber was required. F2 is the same fiber as F3, but manufactured a different way using a synthetic silica deposition tube. Both F2 and F3 are doped with germanium and boron. F1 is a commercially available non "rad hard" optical fiber that is doped with germanium and phosphorous. F1 was included in this study to determine if in fact, a non radiation hardened optical fiber could be used in a harsh space flight environment such as the ISS specification illustrates.

Table 1: Lucent SFT optical fiber DUTs.

Fiber ID for Test	Part Number	Lot Number Test 1 (96 meters)	Lot Number Test 2 (100 meters)	Description
F3	BF05202	CD0712XA	CD0712XB	SL BASE Prem, Flightguide 100/140/172 micron, Ge- B- doped, natural silica deposition tube, carbon coated
F2	BF05202	CD0892XC	CD0892XC	New Flight guide, Ge- B- doped, synthetic silica deposition tube, carbon coated
F1	CF04530-04	CD0266XA	CD0266XA	SL TCU-MC100H, standard fiber, carbon coated Ge- P- doped, synthetic silica deposition tube)

Experimental Setup

The Cobalt 60 chamber housed the nitrogen tanks and thermal chamber operating at -121°C, with the spool holding approximately 100 m of each type of fiber F1, F2, and F3 inside the thermal chamber. The fiber spool was shielded by a 62.5 milli-inches lead box and a 62.5 milli-inches aluminum plate to limit secondary X-rays and reflections that could lead to other types of radiation damage not included in this study. The terminated FC connector ends of each fiber DUTs (devices under test) were fed through the thermal chamber feed-through hole. The fiber DUTs were mated to 25 meter lead out cables that were fed through the chamber feed through conduit and led to the source and detector setups outside of the chamber.

A light emitting diode (LED) source was connected to a reference cable, which was mated to a mandrel wrap and then to an attenuator. In the first test the 1300 nm LED source was the EXFO FLS-2100 which included an attenuator and in this case the mandrel wrap was connected between the output of the source and the input coupler. For Test 2, the RIFOCS 752L dual wavelength source was used with the JDS FITEL HA9 optical variable attenuator and in this case the mandrel wrap was connected between the source and the attenuator. The purpose of the attenuator was to reduce the power to the DUTs such that the input optical power was equal to or less than 1 microwatt at 1300 nm. The input coupler was connected to the output of the attenuator for Test 2. The input coupler was connected to the input "lead-in" cables that were fed through the radiation chamber feed through wall conduit. The input lead-in cables were then connected to the fiber DUTs and mounted to the top of the thermal chamber. The fiber spooled onto the reel, was very closely spooled on one side of the reel and filled a space of less than 1 inch along the reel width. This was to insure that each fiber was getting the same radiation exposure. All fiber on the spool was unjacketed and spooled such that the leads in and out were not considered part of the 100 m.

The chamber lead-out cables were connected to HP8153A power meters with HP81532A power sensor modules. The system was operated at 1300 nm. Labview software via a Dell laptop computer controlled the data acquisition from the HP detectors. Data was logged once per minute, time stamped and stored in a text file with the first data point recorded prior to radiation exposure. All lead and reference cables contained 100/140 micron optical fiber.

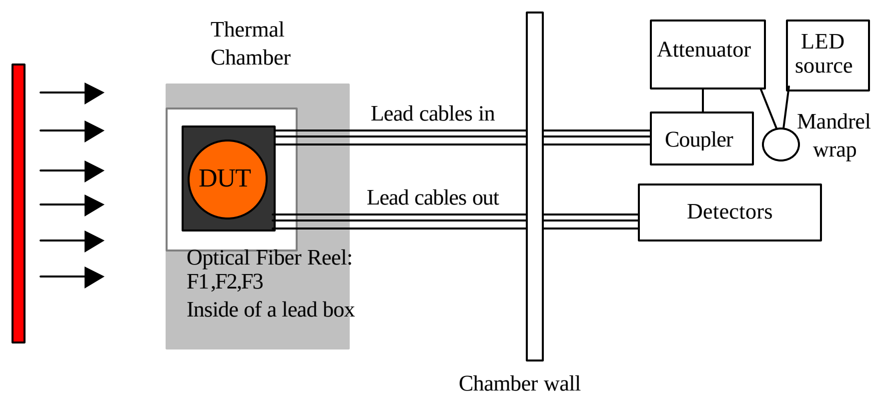

Figure 1: Block diagram of experimental set-up for radiation testing of Lucent SFT optical fiber F1, F2, and F3.

Test Discussion

Two tests were conducted for the purpose of data extrapolation to 42 rads/min for two hours and .5 rads/min for a total of six days (including the two hours) at a constant temperature of -121°C. The thermal chamber was positioned in front of the radiation source shutter to achieve the maximum radiation dose rate at the location of the fiber spool. The largest dose rate achieved was 28.3 rads/min. Therefore, the second dose rate was scaled proportionally from the actual lower dose rate to .34 rads/min. The first test involved exposing the fiber, while at -121°C, to 28.3 rads/min for three hours, which was approximately a total dose of 5.1 Krads. Following the high dose rate exposure, a low dose rate exposure of .34 rads/min was used for the rest of the six-day duration. The dose rate for Test 2 was scaled by a factor of two and therefore a dose rate of 14.2 rads/min was used for the initial 5.1 Krads (six hours). This was followed by a six-day exposure of .17 rads/min at -121°C after which the exposure continued at room temperature, 25°C for two additional days.

In order to maintain a constant temperature of -121°C for six days, several 230 ml nitrogen tanks needed to be on hand for changing of the tank every 21 hours. Several times the tanks were changed prior to reaching 21 hours between tanks to maintain a schedule that allowed this to occur during normal working hours. Whenever a tank substitution occurred, the shutter had to be brought down, but the duration lasted no more than five minutes. It is also the case that for 10 minutes during the change of dose rates from the higher dose rate to the lower dose rate of each test, that the shutter had to be lowered.

There were several "false starts" while trying to conduct testing due to equipment malfunction. The total number of tests conducted was actually four. The last two tests provided the only useful data since the prescribed conditions were met throughout testing.

During Test 1, the EXFO source with internal attenuator was used and found after completion of the test to have large high frequency noise content. It is surmised that during the attenuation calibration the internal modulation was turned on in error. To avoid this error during the calibration for Test 2, the RIFOCS 752L dual wavelength source (certified to +/- .03 dB stability) was substituted with the JDS variable attenuator. There were not enough detector channels to monitor the source power during testing. The sources with the input cables were examined for the launch conditions of the light entering the fiber DUTs. The RIFOCS 752L sets up a standard overfill condition in the 100/140 optical fiber and used with a mandrel wrap ensures that launch conditions are adequate for not over or under estimating the results of the environmental effects on the optical performance of the fiber.[2] Therefore the 752L with mandrel wrap and cables was used as the "model" launch condition. Using the RIFOCS launch condition analyzer, Figure 2 shows the results of analyzing the conditions for 1) the 752L with mandrel wrap after 25 m of cable, 2) 752L with JDS attenuator, mandrel wrap and 25 m of cable, 3) the EXFO, mandrel wrap and 25 meters of cable. This test was used just to verify that the source/attenuator/lead-in cables combination had similar launch conditions to the 752L with mandrel wrap.

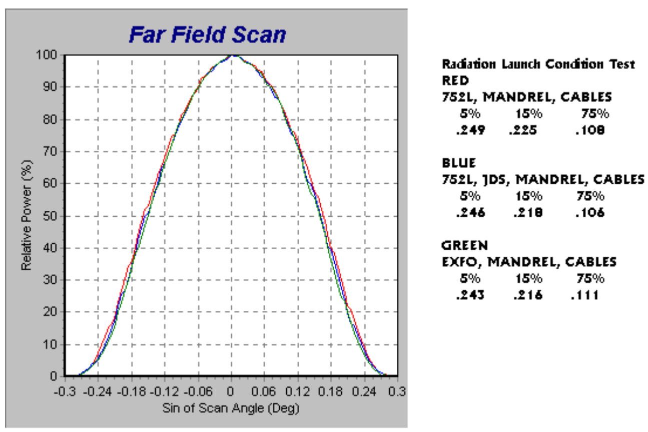

Figure 2: Launch condition analysis of the RIFOCS 752L/JDS HA9 attenuator and the EXFO FLS-2100.

The attenuators on both test set-ups were used to limit the input power to the DUTs to either 1 microwatt or less. This was done as a precaution to avoid most of the photobleaching effects of the source on the radiation performance of the optical fiber. Typically, the higher the optical power is, the more a fiber is capable of annealing due to this effect known as photobleaching, although germanium doped DUTs show little dependence on the amount of optical power injected.[3] Regardless, the optical power was limited to between .5 and 1 microwatt.

Throughout testing the temperature of the thermal chamber was monitored and logged into a text file.

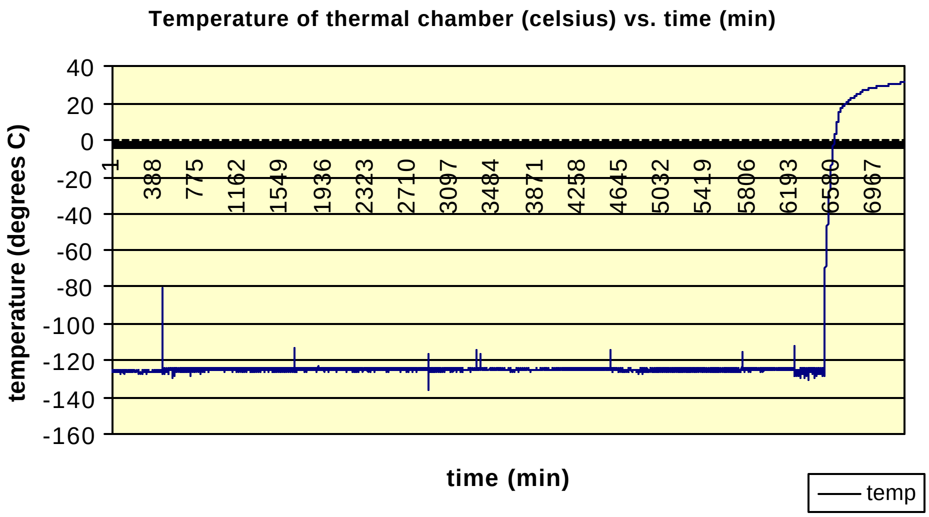

Figure 3: Temperature monitoring of thermal chamber during radiation testing, Test 2.

Figure 3 shows the thermal chamber temperature monitored during Test 2. The "spikes" are events where the nitrogen tanks were substituted. The thermal monitoring detector indicated that the temperature was averaging -125 °C which was a little colder than necessary. For testing of optical fiber, the worst case is usually a colder temperature so the difference will by no means make the data appear optimistic and the deviation is not large enough to simulate over testing.

Table 2: Radiation Test Conditions

Test	High dose rate condition (5.1 Krads)	Low dose rate condition (~6.3 Krads)
1	28.3 rads/min, 3 hours	.34 rads/min, 141 hours
2	14.2 rads/min, 6 hours	.17 rads/min, 138 hours

The radiation exposure test conditions for total dose and dose rates of each test are represented in table 2.

Data and Results

For the data set of Test 1 for all fibers tested, the high frequency modulation content of the EXFO had to be filtered out using a mathematical filter in MATLAB, such that the signal could be analyzed and used for extrapolation. The data was low pass filtered under the assumption that the "darkening" of the optical fiber would be a low frequency change and not a high frequency shift. Data from Test 2 did not contain high frequency modulation and did not require filtering.

Optical Fiber F1

The radiation induced attenuation data from the high dose rate segment of Test 1 & 2 of F1 is shown in Figure 4A. For this segment of the testing the conditions of Test 1 were 28.3 rads/min and for Test 2 were 14.2 rads/min. The plot in blue is from Test 1, and the plot in red is data from Test 2. Although the sampling rate for Test 2 was actually one data point per minute, the data here is represented as one point per every two minutes. This was so that the Test 2 data could be compared to the data from Test 1 which differs in dose rate by a factor of two from the dose rate of Test 2. The data set from Test 1 for all fibers F1, F2 and F3 was normalized to match an exact length of 100 m since the length of the DUTs for Test 1 were actually 96 meters long.

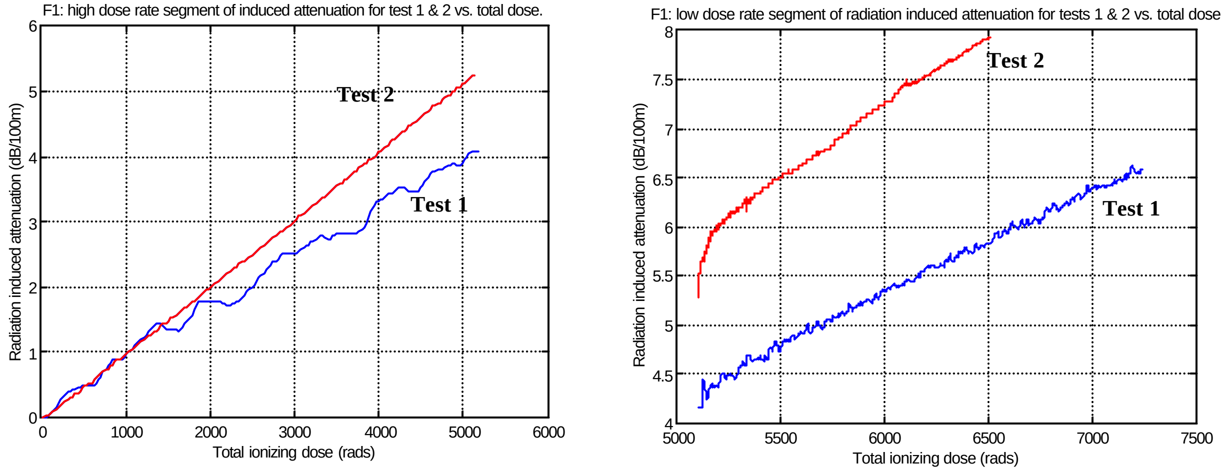

Figure 4: Data of optical fiber F1, A) High dose rate segment of radiation induced attenuation for Test 1 (blue) and 2 (red) at -125 °C with a total dose of 5.1 Krads. B) Low dose rate segment of radiation induced attenuation for Test 1 (blue) and 2 (red) at -125 °C to a total dose of 6.5 Krads for Test 2 and 7.25 Krads for Test 1.

Test 1 actually ended prematurely due to a power outage, but enough data was gathered to conclude what does happen at increasing dose using the higher dose rates of 28.3 rads/min and .34 rads/min. What is missing from the Test 1 data is the radiation induced attenuation values during exposure but after the return to a temperature of ~25 °C. For Test 2 the data set included the effects of a return to room temperature during exposure but is not included in Figure 4B. Figure 5 shows the complete data set of radiation induced attenuation for F1 during test conditions of Test 2.

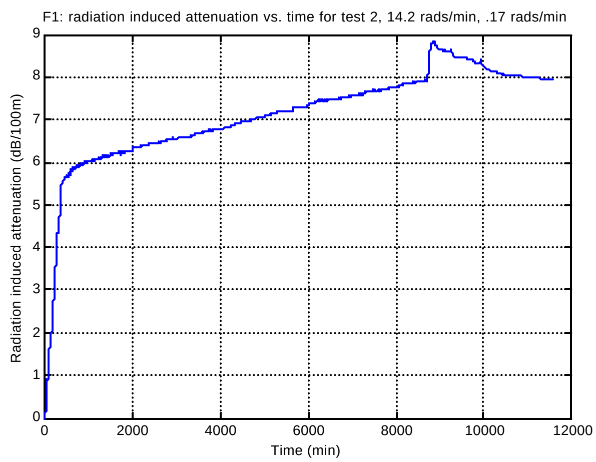

Figure 5: Optical fiber F1, Test 2, complete data set for radiation induced attenuation.

In Figure 5, the data shows that as the thermal chamber returned to 25 °C, the radiation induced attenuation became even larger (at ~8640 min). This was the opposite of the way a typical radiation hardened optical fiber performs. [4] Typically radiation hardened fiber will attenuate more with decreasing temperature and higher dose rate, but in the case of F1, which no doubt is due to the phosphorous dopants used for manufacturing, the attenuation is larger for decreased dose rates at low temperature.[5]

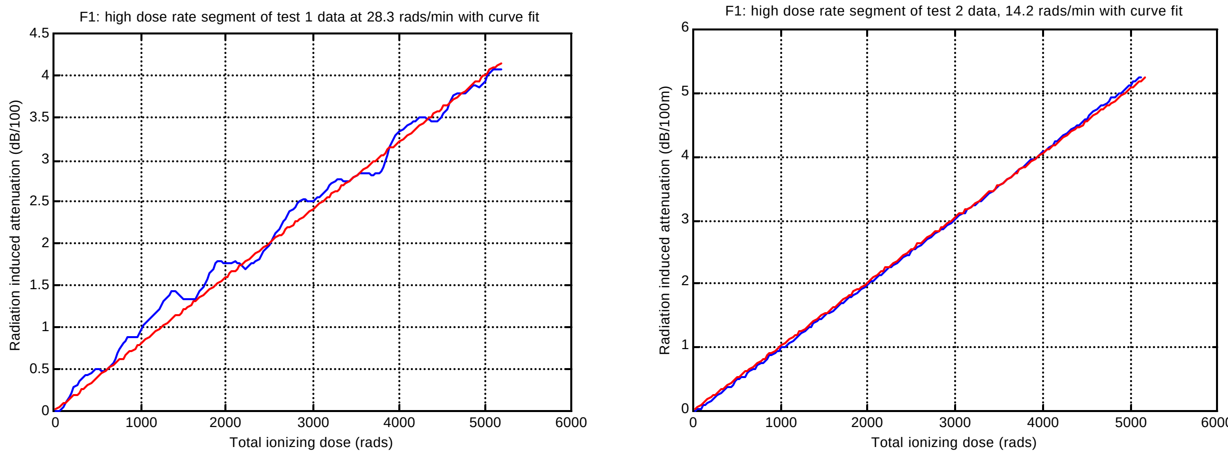

Figure 6: Optical fiber F1, A) Data (blue) with curve fit (red) for high dose rate segment of Test 1, B) Data (blue) with curve fit (red) for high dose rate segment of Test 2.

Using the extrapolation method described in Reference 6, the equation for radiation induced attenuation in optical fiber takes the form $A=CD^f$, where A is the radiation induced attenuation, C is a constant dependent on the radiation dose rate and f is a constant less than one. For Figure 6A, Test 1 with a dose rate of 28.3 rads/min the equation of the curve fit is $A=8.1*10^{-4}D^{.999}$(dB/100m) and for Figure 6B, Test 2 at 14.2 rads/min, the equation is $A=1.02*10^{-3}D^{.999}$ (dB/100m). Using these curves one can use the model to extrapolate to larger dose rates and total doses assuming the model is relevant to this type of optical fiber. Figure 7 shows the data curves for 14.2 rads/min, 28.3 rads/min and an extrapolation curve for the dose rate of interest 42 rads/min. Also in Figure 7, there is an extrapolation to a much higher total dose of approximately 16 Krads using the extrapolation curves for all three dose rates and assuming that the temperature would remain constant at -125°C.

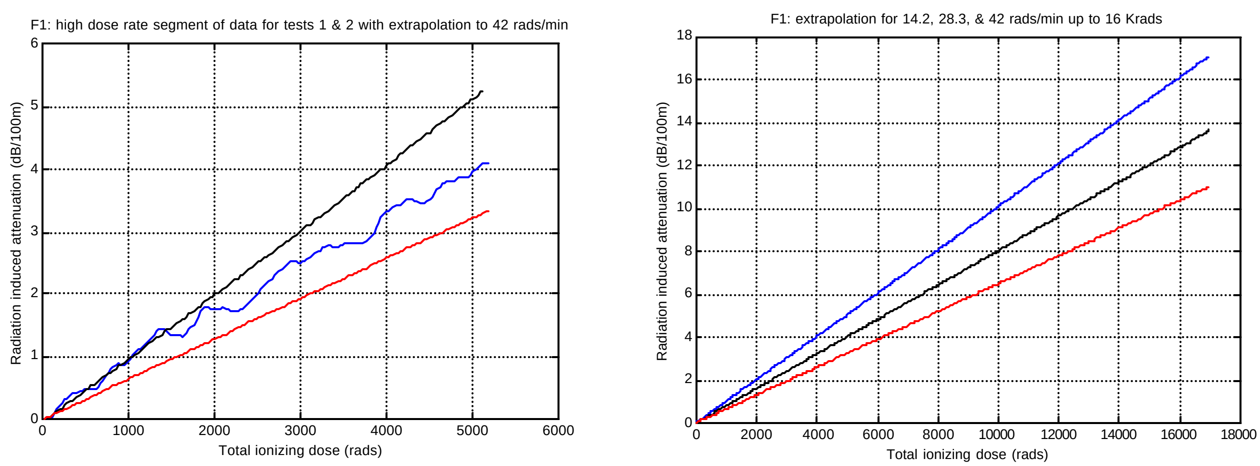

Figure 7: Optical fiber F1, A) High dose rate segments of data from Tests 1 (blue) & 2 (black) with extrapolation curve to 42 rads/min (red), B) Extrapolation curves for 14.2 rads/min (black), 28.3 rads/min (blue) and 42 rads/min (red)to 16 Krads TID.

For extrapolating to 42 rads/min, it was assumed that the larger dose rate, would decrease the radiation induced attenuation based on the test results of Test 1 and 2. The equation that governs the radiation induced attenuation at 42 rads/min at -125°C is $A=6.5*10^{-4}D^{.999}$ (dB/100m). The extrapolation curves indicate a nearly linear relationship between total dose and radiation induced attenuation.

Optical Fiber F2

The results of the radiation testing of F2 are in Figure 8. It is evident in Figure 8A that the attenuation curves for Test 1 & 2 differ by very little and that as expected the higher dose rate data curve shows a slightly higher radiation induced attenuation as expected for germanium doped optical fiber. In Figure 8B, the two different tests match exactly showing that at the lower dose rates of .17 rads/min and .34 rads/min, there is no difference in the behavior. It also indicates a saturation behavior of the fiber at the lower dose rates.

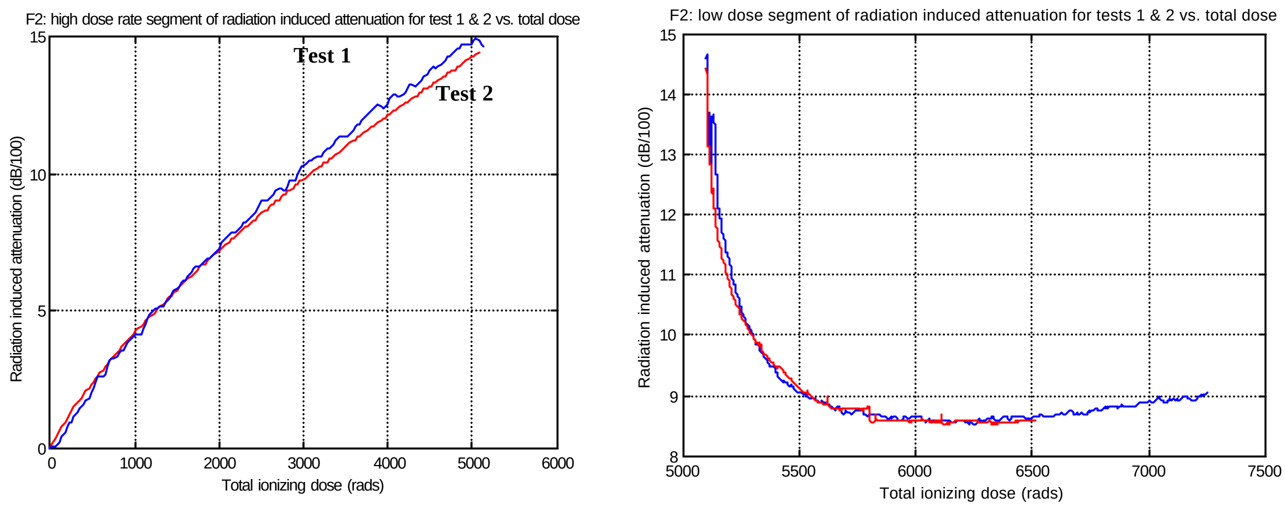

Figure 8: Optical fiber F2 radiation induced attenuation data plots, A) High dose rate segment of Tests 1 (blue) and 2 (red), B) low dose rate segment of Tests 1 (blue) & 2 (red).

Figure 9 shows the entire data set for radiation induced attenuation for Test 2.

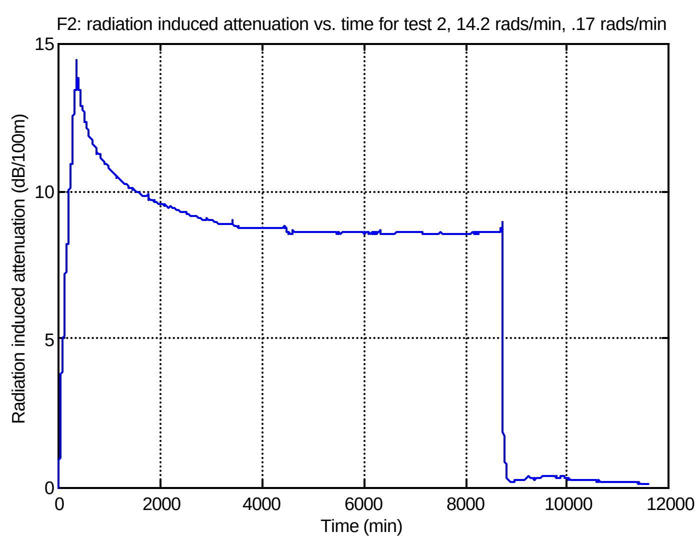

Figure 9: Optical fiber F2, Test 2, complete data set for radiation induced attenuation.

Here in Figure 9, the data shows the expected behavior of a germanium-doped optical fiber. The sharp increase in attenuation for the first six hours (360 minutes) is consistent with a high dose rate of 14.2 rads/min. The curve that appears as though the fiber is "recovering" continues and begins to saturate by the time the six days (~8640 min) at -125°C is completed. The attenuation then appears to be nearly nonexistent while the fiber continues being exposed to .17 rads/min at room temperature for another two days. This represents typical performance for a germanium doped optical fiber. Figure 10 shows the extrapolation curves for the high dose rate segment of both tests for F2 at -125°C.

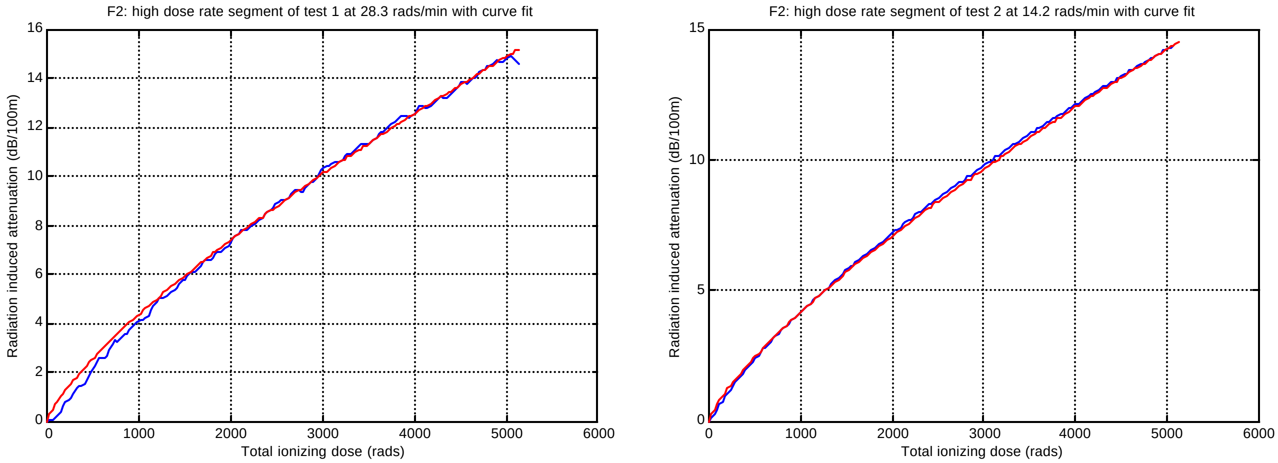

Figure 10: Optical Fiber F2, high dose rate radiation induced attenuation data from A) Tests 1 at 28.3 rads/min exposure (blue) with curve fit in red and B) Test 2 at 14.2 rads/min exposure (blue) with curve fit in red.

In Figure 10A the extrapolation curve is represented by $A=23*10^{-3}D^{.76}$ (dB/100m) and this curve fits the data for Test 1 at 28.3 rads/min. For the data represented in Figure 10B, the equation that governs the fitted curve is represented as $A=22*10^{-3}D^{.76}$ dB/100m for the data of Test 2 at 14.2 rads/min. The extrapolation curve that represents a model for radiation induced attenuation at 42 rads/min is shown in Figure 11.

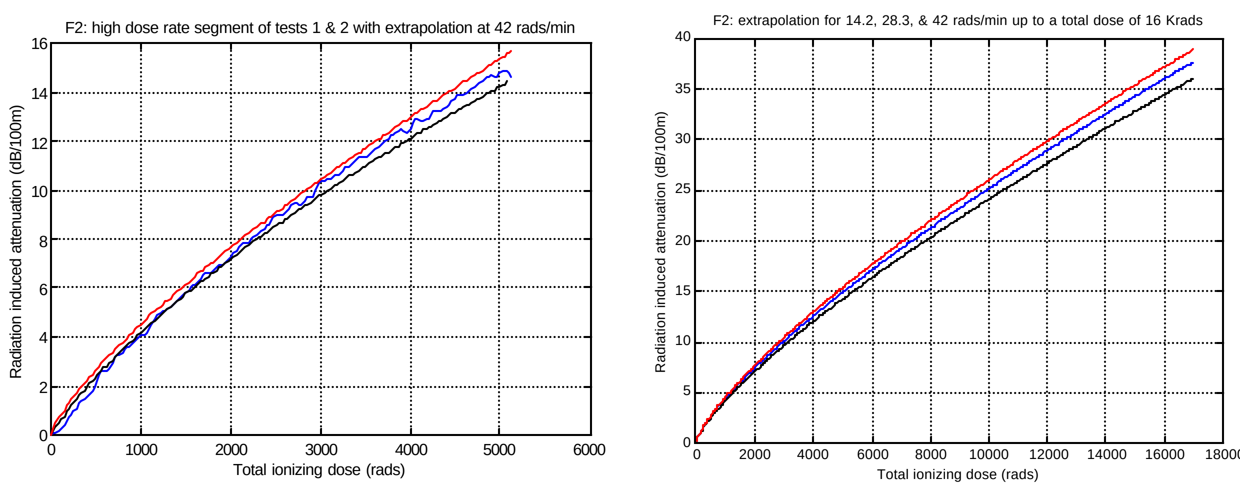

Figure 11: Optical fiber F2, A) radiation induced attenuation data plotted for Test 1 (blue) at 28.3 rads/min and 2 (black) 14.2 rads/min with the extrapolation curve for 42 rads/min (red); B) Extrapolation curves for 14.2 (black), 28.3 (blue) and 42 (red) rads/min to a total dose of 16 Krads at -125 C.

Optical fiber F2 performs predictably and has an extrapolation curve for 42 rads/min that meets expectations of having a greater induced attenuation for a larger dose rate at the same total dose as the lower radiation dose rate data. The equation that governs the extrapolated data for 42 rads/min is $A=23.75*10^{-3}D^{.76}$ dB/100m. Figure 11B represents the radiation induced attenuation (in dB/100m) for all the extrapolation curves up to a total dose of 16 Krads assuming a constant temperature of -125 °C.

Optical Fiber F3
The results of both segments (high and low dose rate) of the radiation testing for fiber F3 is shown in Figure 12A and 12B.

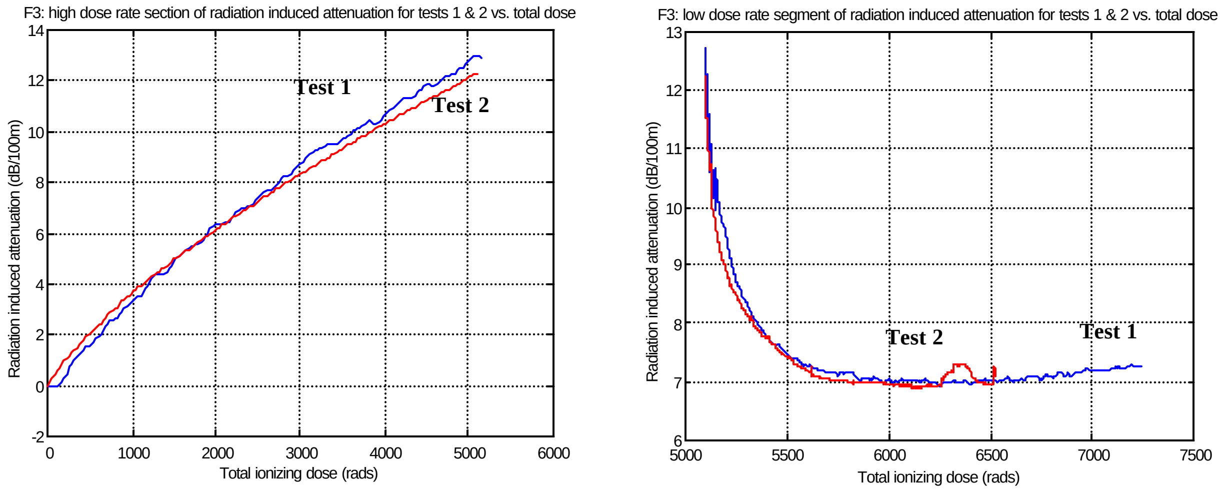

Figure 12: Optical fiber F3 A) high dose rate segment of the radiation induced attenuation data for Test 1 (blue) at 28.3 rads/min and Test 2 (red) at 14.2 rads/min; B) low dose rate segment of the radiation induced attenuation data for Test 1 (blue) .34 rads/min and Test 2 (red) at .17 rads/min to total dose of 5.1 Krads at -125 C.

Again as with fiber F2, the radiation susceptibility of F3 at two different dose rates that differ by a factor of two, appears only slightly different for a total dose of 5.1 Krads. This is seen in Figure 12A at the higher dose rates, but at the lower dose rates illustrated in Figure 12B the performance at both .17 rads/min, and .34 rads/min is nearly identical. There is a slight "dip" in the data for Test 2 on the plot of Figure 12B. It is not likely that this increase in attenuation is due to optical fiber performance and is more likely due to power transients from the equipment or a disturbance of the lead in or lead out test cables.

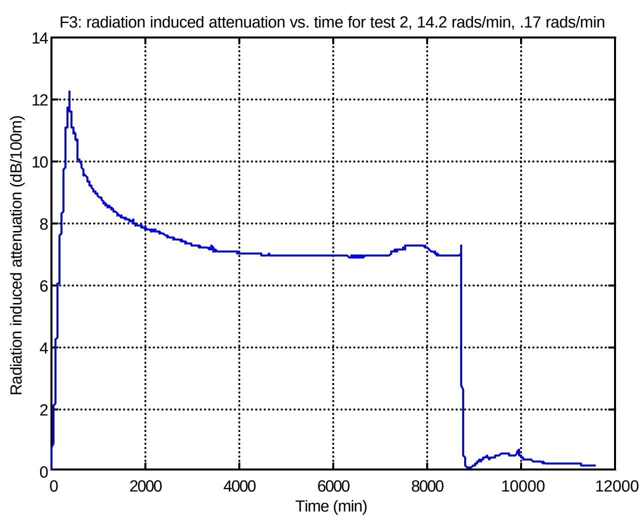

Figure 13: Optical fiber F3, entire data set for Test 2, radiation induced attenuation for dose rate of 14.2 rads/min to a total dose of 5.1 Krads and then a dose rate of .17 rads/min at -125°C to a total dose of 8.64 Krads.

Figure 13 shows the entire data set of radiation induced attenuation for fiber F3 at 14.2 rads/min for the first 360 min and then at .17 rads/min for the remainder of the test. The temperature remains at -125°C up until a time of 8640 min and then the temperature returns to 25°C while still being exposed to the .17 rads/min dose rate. This fiber behaves similar to the fiber F2, with the radiation induced losses of F2 only slightly larger.

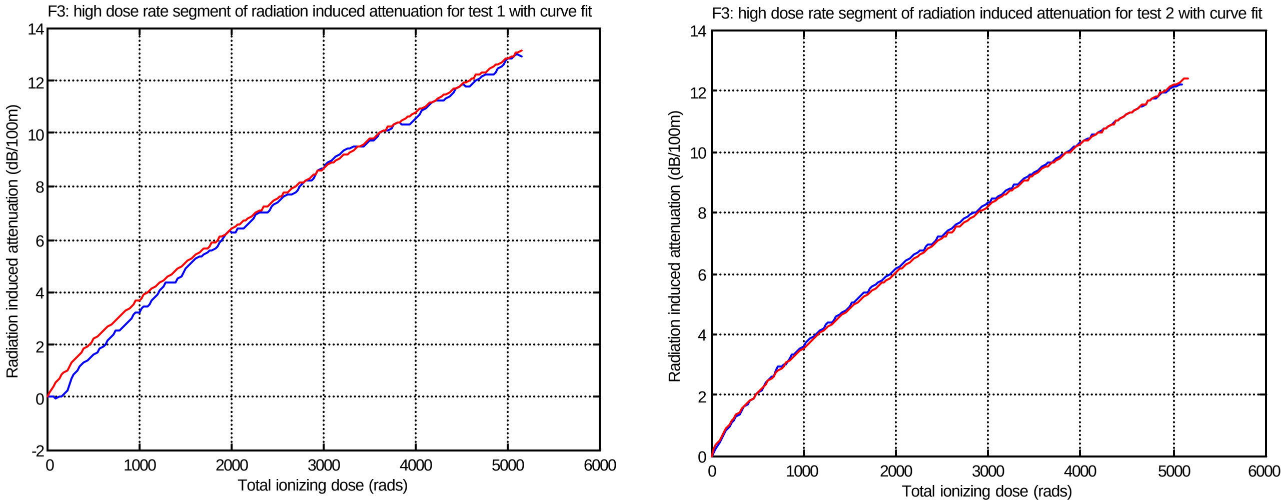

Figure 14: Optical Fiber F3, high dose rate radiation induced attenuation data from A) Tests 1 at 28.3 rads/min exposure (blue) with curve fit in red and B) Test 2 at 14.2 rads/min exposure (blue) with curve fit in red.

In Figure 14A the extrapolation curve is represented by $A=19*10^{-3}D^{.765}$ (dB/100m) and this curve fits the data for Test 1 at 28.3 rads/min for optical fiber F3. For the data represented in Figure 14B, the equation that governs the fitted curve is represented as $A=18*10^{-3}D^{.765}$ (dB/100m) for the data of Test 2 at 14.2 rads/min. The extrapolation curve that represents a model for radiation induced attenuation at 42 rads/min is shown in Figure 15 for optical fiber F3.

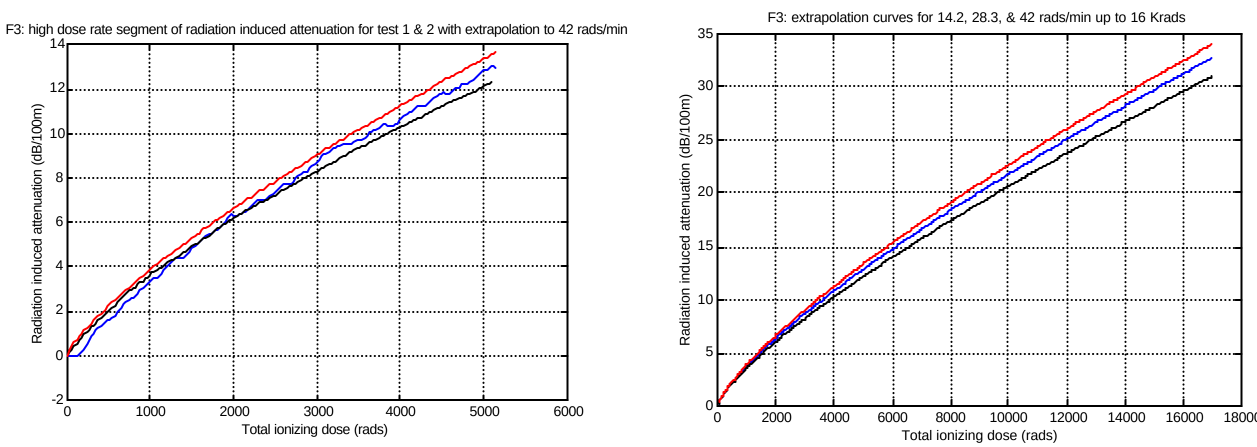

Figure 15: Optical fiber F3, A) high dose rate segment of radiation induced attenuation data for 14.2 rads/min (black), 28.3 rads/min (blue) with extraplation at 42 rads/min (red) to a total dose of 5.1 Krads; B) High dose rate extrapolation to 16 Krads for dose rates 14.2 rads/min (black), 28.3 rads/min (blue) and 42 rads/min (red).

Optical fiber F3 performs predictably and has an extrapolation curve for 42 rads/min that meets expectations of having a greater induced attenuation for a larger dose rate at the same total dose as the lower radiation dose rate data (Figure 15A). The equation that governs the extrapolated data for 42 rads/min is $A=19.75*10^{-3}D^{.765}$ (dB/100m). Figure 15B represents the calculated radiation induced attenuation (in dB/100 m) for all three dose rates (14.2, 28.3, and 42 rads/min) extrapolated up to a total dose of 16 Krads assuming a constant temperature of -125 °C.

Summary and Discussion

The results in terms of radiation induced attenuation are summarized in Table 3.

Table 3: Summary of radiation induced attenuation data from Test 1 and 2.

Test Condition During Exposure	Radiation Induced Attenuation Optical Fiber F1	Radiation Induced Attenuation Optical Fiber F2	Radiation Induced Attenuation Optical Fiber F3
28.3 rads/min 5.1 Krads, - 125°C	4.1 dB/100m	14.9 dB/100m	12.9 dB/100m
14.2 rads/min 5.1 Krads, -125°C	5.3 dB/100m	14.4 dB/100m	12.3 dB/100m
.34 rads/min (Test 1) 6.5 Krads -125°C	5.8 dB/100m	8.6 dB/100m	7.0 dB/100m
.17 rads/min (Test 2) 6.5 Krads -125°C	7.9 dB/100m	8.6 dB/100m	7.0 dB/100m
After 6.5 Krads 25°C, Test 2 (.17 rads/min)	8.0 dB/100m	0.15 dB/100m	0.15 dB/100m

Table 3 is based on available data only and not extrapolated or calculated numbers. Examining the results presented in Table 3, it is evident that fiber F1 performs quite differently from the behavior of both F2 and F3 which behave similarly. Radiation induced attenuation for fiber F1, as was evident in the previous results analysis, actually increased as the fiber was tested at a lower dose rate. This is contrary to how F2 and F3 perform. In both tests for the fibers F2 and F3 as the dose rate decreased, so did the amount of radiation induced attenuation. For F1 at 28.3 rads/min to a total dose of 5.1 Krads at -125 °C, the total attenuation at the completion of this segment of the test was 4.1 dB/100m. To clarify, this implies that at a dose of 5.1 Krads and a dose rate 28.3 rads/min, the signal at the output of the optical fiber was down by 4.1 dB from the pre-irradiated measured optical transmission. Under the same conditions but with a lower dose rate of 14.2 rads/min, this attenuation increased to 5.3 dB/100m. So by decreasing the dose rate by a factor of 2, the attenuation increased by 1.2 dB/100m from the previous attenuation at the higher dose rate. This result was unexpected.

The radiation induced attenuation of optical fiber F2 decreased with decreasing dose rate. At the dose rate 28.3 rads/min to a total dose of 5.1 Krads, the induced attenuation was 14.9 dB/100m. By reducing the dose rate by a factor of two to 14.2 rads/min (to a TID of 5.1 Krads), the induced attenuation decreases by .5 dB/100m; from 14.9 dB/100m to -14.4 dB/100m. The same is true for F3 where after reducing the dose rate by a factor of two the radiation induced losses decrease by .6 dB/100m. These fibers perform as expected for typical germanium doped silica. Fibers F2 and F3 perform similarly and only differ by 2 dB in performance under exposure. Where F2 is only slightly more sensitive than F3 to radiation effects.

Both fibers F2 and F3 saturate after a long exposure to both lower dose rates. They saturate at attenuation values that differ by almost 2dB as noticed in the high dose rate data. The lower dose rates used in the second segment of this testing, differ by a factor of two (.34 rads/min for Test 1 and .17 rads/min for Test 2) but have no difference in effect on fibers F2 and F3. For F2, both low dose rate data sets show that the fiber saturates at 8.6 dB/100m and for F3 the saturation point for both low dose rate tests is at 7.0 dB/100m. In contrast, the attenuation continues to increase on fiber F1 showing no effects related to lowering the dose rate. It is also interesting that even when the temperature returns to 25°C after six days prior at -125°C, where the transmission for most optical fibers would return to a nearly nonexistent attenuation, F1 continues to attenuate as if the conditions of temperature had not changed. It is possibly the case that after a few days F1 would begin to recover such that it would be evident it would eventually reach a much lower attenuation value but that was not yet evident from the 48 hours that it was monitored at room temperature. When F2 and F3 return to 25°C the losses decrease to less than 0.2 dB/100m and would probably decrease even further over a long period of time at this exposure. From viewing the data more closely during the last two days it does in fact appear that fibers F2 and F3 would have continued the downward trend even while being exposed to .17 rads/min.

Overall, the losses for F1 for the high dose rate segment of the testing are much less than that of both F2 and F3. The losses for F1, after the first 5.1 Krads, is more than 10 dB less than the induced attenuation for F2. After the low dose rate testing, even then, F1 is still registering lower losses than F2 and F3 in the case of the higher low dose rate exposure. At the .17 rads/min dose rate exposure F1 is rating between the performance of F2 and F3. This in itself would be promising for the usage of this non rad hard fiber in a space environment. The only unknown is what the fiber F1 will do after constant exposure of .17 rads/min at room temperature. Would it continue to attenuate until it reached values for radiation induced attenuation much larger than those of the high dose rate segment of F2 and F3 or would it eventually saturate and then recover to a much smaller attenuation value? Because this fiber behaves so differently than typical germanium doped optical fiber it is impossible to make any conclusions without conducting more testing. Additional testing would answer the question of whether there is a predictable pattern to the radiation induced attenuation, and whether the fiber would eventually have recovered or continued to attenuate over prolonged low dose radiation exposure.

Table 4 is a summary of the extrapolated data as a result of the analysis discussed previously. The extrapolated data contains the answer to the question "how will this fiber perform in the ISS environment?". In Table 4 the results of extrapolation are shown where the extrapolation high dose rate is 42 rads/min with a low dose rate value of .5 rads/min for all fibers. The largest radiation induced attenuation is seen from fiber F2 at 15.7 dB/100m, and the lowest for F1 at 6.1 dB/100m assuming that the fiber F1 has lower losses for a greater dose rate. The data for F1 indicated this was so under the same -125 °C thermal conditions.

The data was extrapolated to assume that instead of stopping at 5.1 Krads, the exposure would continue until all fibers experienced a total dose of 16 Krads. The data for the 2nd through 4th rows of Table 4 is graphed in Figures 7B, 11B and 15B. It is just interesting to note what the trend would become over a longer total dose. This extrapolation to a larger total dose of 16 Krads is not part of the ISS requirement.

It is safe to assume that both F2 and F3 will perform similarly at a low dose rate of .5 rads/min (ISS environmental requirement) to the way they performed during this testing. Therefore, a conclusion can be made based on this available data that the values for attenuation after this low dose rate exposure of .5 rads/min are the same for both the fibers as shown in Table 3. More data would need to be available to make conclusions on how F1 would perform under the .5 rads/min dose rate following a high dose rate exposure of 42 rads/min. The only assumption that can be made based on available data is that the radiation induced attenuation would linearly increase regardless of the decrease in radiation dose rate.

Table 4: Extrapolated values for radiation induced attenuation

Test Condition During Exposure	**Radiation Induced Attenuation Extrapolation** Optical Fiber **F1**	**Radiation Induced Attenuation Extrapolation** Optical Fiber **F2**	**Radiation Induced Attenuation Extrapolation** Optical Fiber **F3**
42 rads/min 5.1 Krads, - 125°C	6.1 dB/100m	15.7 dB/100m	13.4 dB/100m
42 rads/min 16 Krads, -125°C	10.4 dB/100m	37.2 dB/100m	32.5 dB/100m
28.3 rads/min 16 Krads, -125°C	12.8 dB/100m	36.0 dB/100m	31.2 dB/100m
14.2 rads/min 16 Krads, -125°C	16.1 dB/100m	34.5 dB/100m	29.6 dB/100m
.5 rads/min 6.5 Krads -125°C	ND	8.6 dB/100m	7.0 dB/100m
After 6 Days at -125°C .5 rads/min (while at 25 °C)	ND	~ 0.2 dB/100m ↑	~0.2 dB/100m ↑

ND: not enough data to make conclusion.

Conclusions

Three types of Lucent SFT optical fiber were tested for radiation effects using two different sets of conditions towards the goal of extrapolating to the ISS radiation requirements. For both Test 1 and Test 2 the temperature remained at -125°C for a total of six days and at 25°C for two days following. The two dose rate combinations used were chosen to make the extrapolation to a higher dose rate combination, simpler. In both tests, the first dose rate of exposure was approximately two orders of magnitude higher than the second dose rate, to match the radiation environmental requirement of the ISS specification for space flight cable. The collected data for radiation induced attenuation using two dose rate combinations of 28.3 rads/min and .34 rads/min for Test 1, and 14.2 rads/min and .17 rads/min for Test 2, was used to extrapolate to a dose rate combination of 42 rads/min and .5 rads/min. Under the conditions of 42 rads/min to a total dose of 5.1 Krads at -125°C, the fiber F1 would reach an attenuation of 6.1 dB/100m, F2 would reach an attenuation of 15.7 dB/100m, and F3 would experience radiation induced losses of 13.4 dB/100m. After a total dose exposure of 5.1 Krads at 42 rads/min, it was concluded based on available data that the induced loss for F1 could not be predicted but the losses for F2 and F3 would be 8.6 dB/100m, and 7.0 dB/100m respectively. After completion of the six days at -125°C, it is expected that both F2 and F3 would return to less than 0.2 dB/100m during low dose rate exposure of .5 rads/min over a prolonged amount of time. The ISS requirement states that the total dose should be 50.4 Krads at the lower dose exposure and requires a low dose rate of .24 rads/min. It is expected that even up to a total dose of 50.4 Krads that the losses for F2 and F3 would still be less than 0.2 dB/100m. The low dose extrapolation was performed for a dose rate of .5 rads/min but by available data the results show that the effects are the same regardless of a factor of 2 decrease in dose rate (Table 4). This conclusion was made based on the low dose rate data for both F2 and F3. It was not apparent that a recovery would occur for F1 and for now it can only be assumed that the radiation induced attenuation for F1 would only continue to increase even at a low dose rate of .5 rads/min while at 25°C.

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