Beyond 85°C: Thermal Aging Impact on Optical Fiber with Corning® CPC® Coatings

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Introduction

Corning® CPC® coatings are the coating system used by Corning to provide advanced optical performance and robust mechanical protection for optical fibers. The industry-leading microbend attenuation resistance has been demonstrated in standard lab testing conditions from -60°C to +85°C. While -60°C to +85°C is considered to be the operating temperature range for the majority of optical cables, some customer specific processes and/or applications may expose optical fibers to high temperatures[1] beyond 85°C. As part of Corning's commitment to provide industry-leading technical support for our products, we present herein a comprehensive study of the thermal aging impact on Corning® optical fiber with CPC coatings[2]. In this white paper, both single-mode and multimode optical fibers were subjected to aging conditions from 85°C to 300°C. For each set of single-mode and multimode fibers, natural, black, blue, and orange fibers were selected for testing[3]. We discuss the thermal aging impact on transmission performance, fiber geometry, coating mechanical properties, and fiber identification.

Impact on Attenuation

As the most important parameter determining the transmission performance of optical fibers, attenuation is the focus of this study. Two kilometers of each fiber was wound in the form of 8" diameter loose coil. The loose coils were then placed in chambers and exposed to dry-heat conditions at 85°C, 100°C, 150°C, 200°C, and 300°C, as well as humid-heat condition at 85°C/85% RH (relative humidity). Attenuation was monitored periodically by removing the loose coils from the chambers to carry out the measurement at ambient condition of 23°C/50% RH. We compare the attenuation change to understand the impact of thermal aging on optical fibers. In-situ attenuation measurement at 150°C dry-heat was also conducted to examine if the data collected from the out-of-chamber ambient condition is representative for the attenuation at elevated temperatures.

1. Single-mode fiber

The single-mode fiber used in this study was Corning® SMF-28® Ultra optical fiber. As shown in Figure 1, for the entire aging period at 85°C for 2040 hours (85 days), the induced attenuation was less than 0.02 dB/km for all four single-mode fibers, which is well within the standard product specification (≤0.05 dB/km at 1310 nm, 1550 nm, and 1625 nm). When aging at 85°C with 85% RH (relative humidity) for 2016 hours (84 days), there was still less than 0.02 dB/km for all four single-mode fibers, as shown in Figure 2. The two conditions, 85°C and 85°C/85%RH, represent the upper limit of Corning's standard fiber operating range. It can be concluded that 85°C aging up to 2000 hours has no significant impact on attenuation performance.

[1] Corning offers specialty fibers that are designed for deployment in high temperature environment. We encourage our customers to evaluate these specialty fibers for their high temperature applications.
[2] It should be noted that all the results presented herein are only characterzations based on the present state of our best scientific and practical knowledge, and should not be deemed as a warranty for product's suitability for a particular use or application.
[3] All color-coded Corning® optical fibers are coated with Corning® ColorPro™ identification technology.

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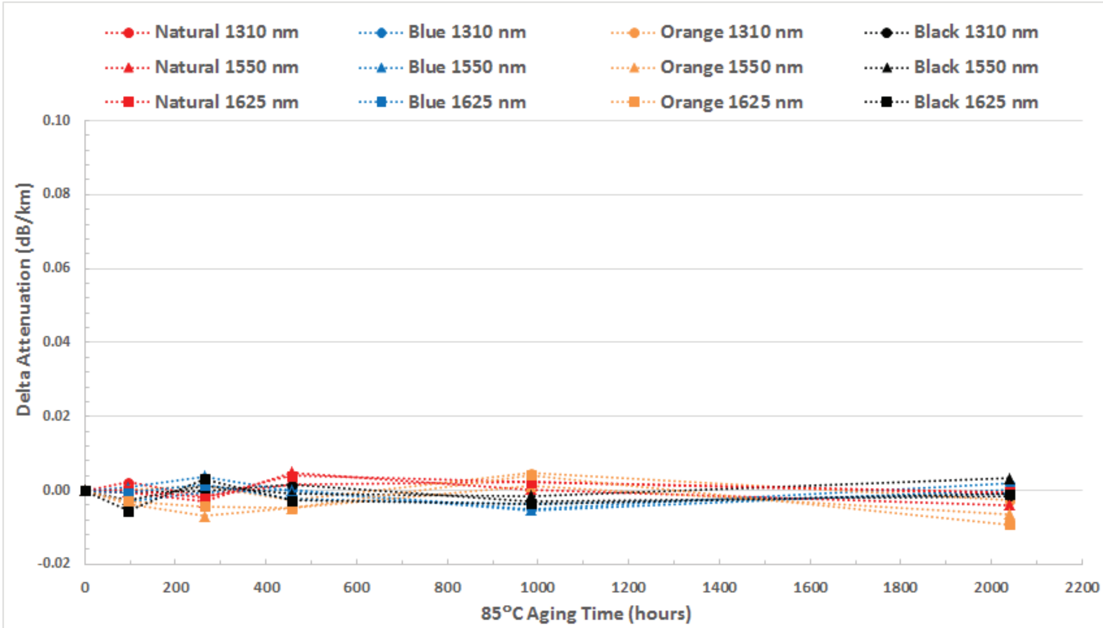


Figure 1. Attenuation change of single-mode fibers exposed at 85°C.

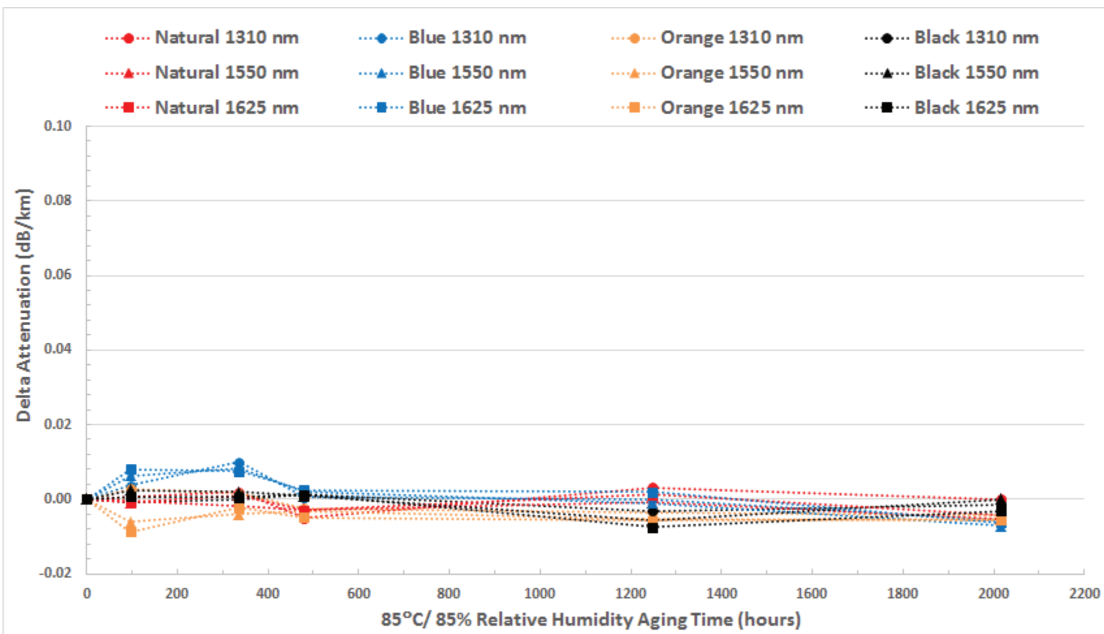


Figure 2. Attenuation change of single-mode fibers exposed at 85°C and 85% RH.

Beyond 85°C, we first tested the fibers at the temperature of 100°C up to 2040 hours (85 days). Figure 3 shows that all four single-mode fibers had less than 0.02 dB/km induced attenuation. This result indicates that the single-mode fibers maintain satisfactory transmission performance after 2000 hours of 100°C aging.

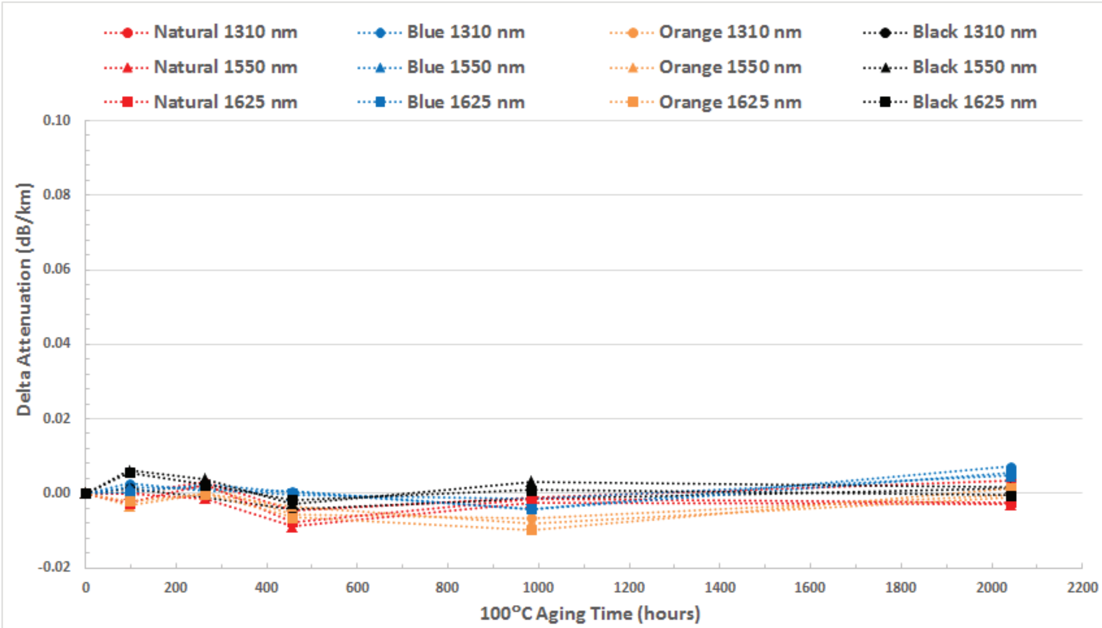


Figure 3. Attenuation change of single-mode fibers exposed at 100°C.

When single-mode fibers are exposed to 150°C, slightly higher attenuation increases were recorded compared to the results from 85°C and 100°C aging. However, as shown in Figure 4, during the 1200 hours (50 days) of 150°C exposure, all four single-mode fibers maintain satisfactory performance as the attenuation changes are ≤0.02 dB/km. The slight increase in attenuation can be attributed to the slow degradation of coatings, which will be discussed in the later sections.

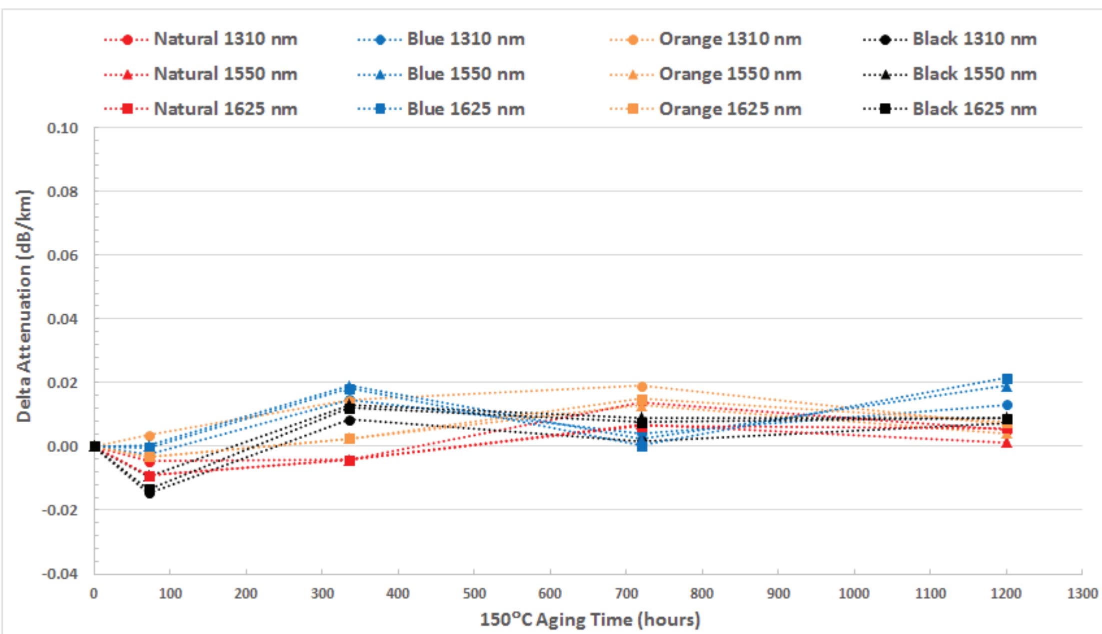


Figure 4. Attenuation change of single-mode fibers exposed at 150°C.

At 200°C, induced attenuation started to exceed 0.05 dB/km as early as 72 hours of aging (blue fiber), as shown in Figure 5. All four fibers have attenuation increases over 0.05 dB/km after 150 hours exposure. This indicates that coatings exhibit a significantly faster degradation rate at 200°C and can demonstrate significant degradation in performance in less than 72 hours. Inked fibers (black, blue and orange) demonstrate faster degradation in attenuation compared to natural fiber. This is due to the ink layer degradation that caused the adjacent fibers to stick randomly in the loose coil.

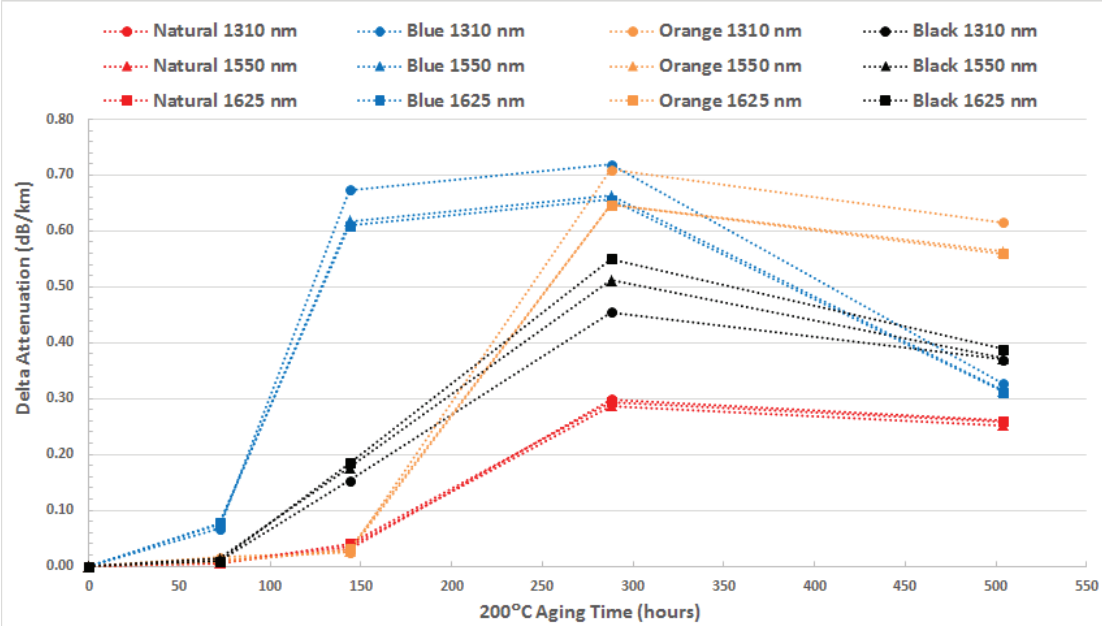


Figure 5. Attenuation change of single-mode fibers exposed at 200°C.

When single-mode fibers were exposed to 300°C, the degradation and decomposition of coatings became so severe that within minutes, thick smoke appeared and we stopped the experiment due to fire hazard concern. We strongly recommend not to expose standard optical fiber at 300°C for safety and performance reasons.

We also performed an in-situ measurement of single-mode natural fiber attenuation at 150°C to determine if the removal of fiber to ambient conditions for measurement affected the results. In this test, we first measured the initial attenuation at 23°C/50% RH, then periodically took measurements while the fiber was in chamber at 150°C dry-heat for up to 672 hours (28 days), and then took the final measurement at 23°C/50% RH again. As shown in Figure 6, the induced attenuations remain ≤0.023 dB/km. This result is well aligned with Figure 4, where the measurements were taken when fibers were cooled to ambient condition. The results from Figure 4 and Figure 6 together confirm that satisfactory performance is maintained at 150°C exposure up to 1200 hours.

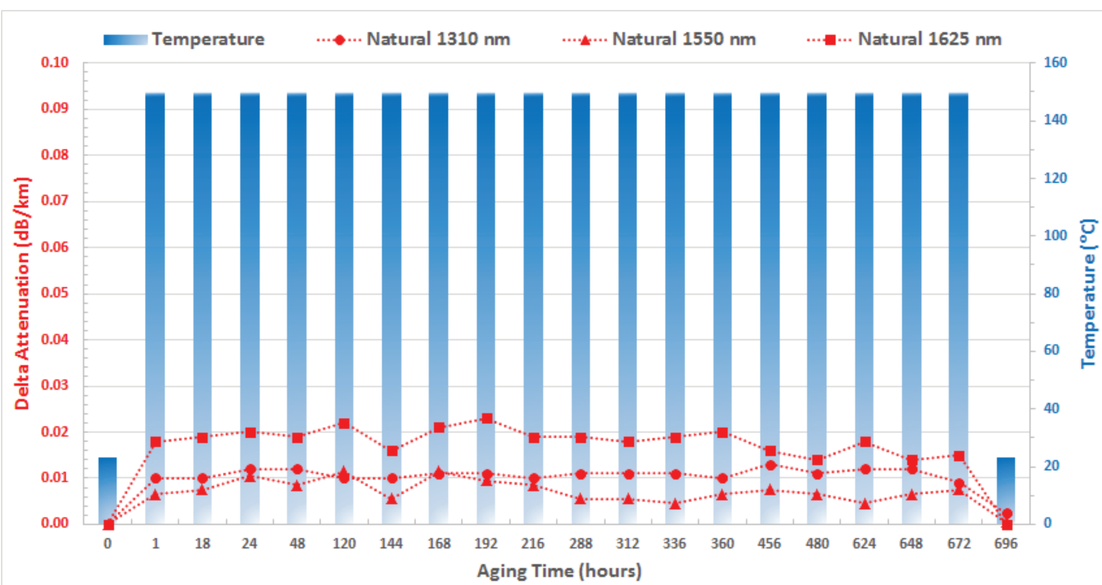


Figure 6. In-situ attenuation change of single-mode fibers exposed at 150°C.

2. Multimode fiber

The multimode used in this study were Corning® ClearCurve® multimode optical fibers. Multimode fibers show ≤ 0.02 dB/km response to the exposure of 85°C, 85°C/85% RH, and 100°C aging, as shown in Figure 7, 8, 9, respectively.

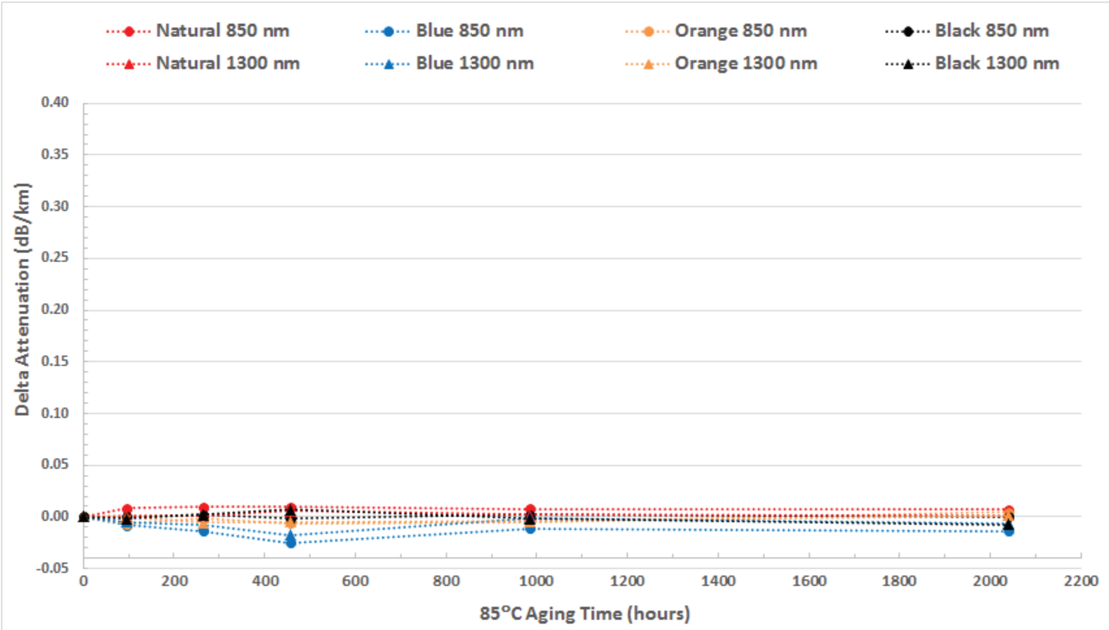


Figure 7. Attenuation change of multimode fibers exposed at 85°C.

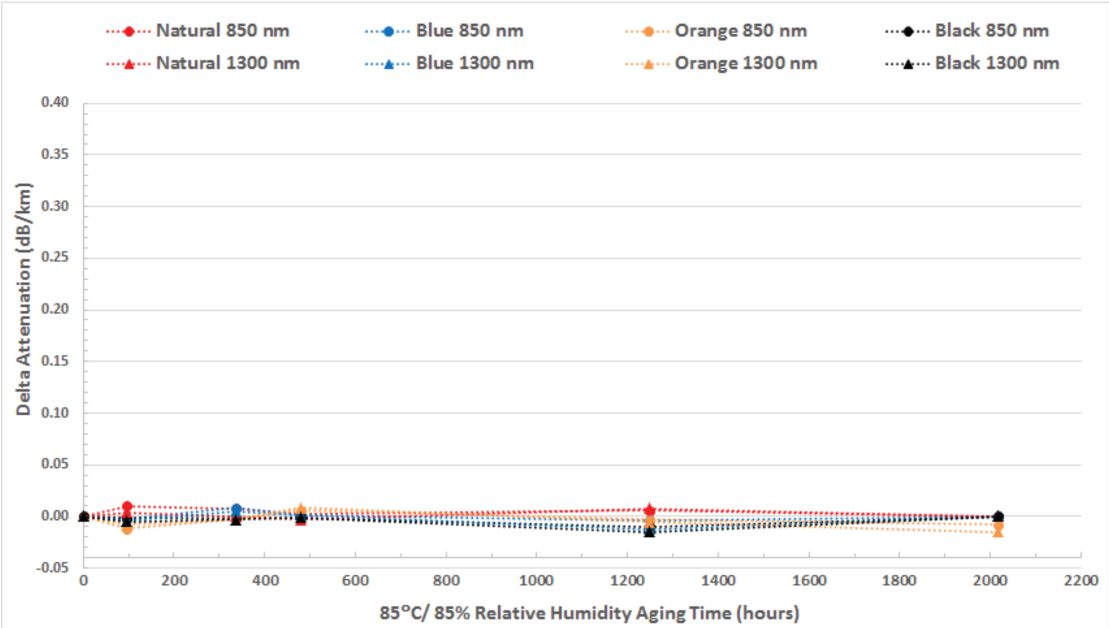


Figure 8. Attenuation change of multimode fibers exposed at 85°C and 85% RH.

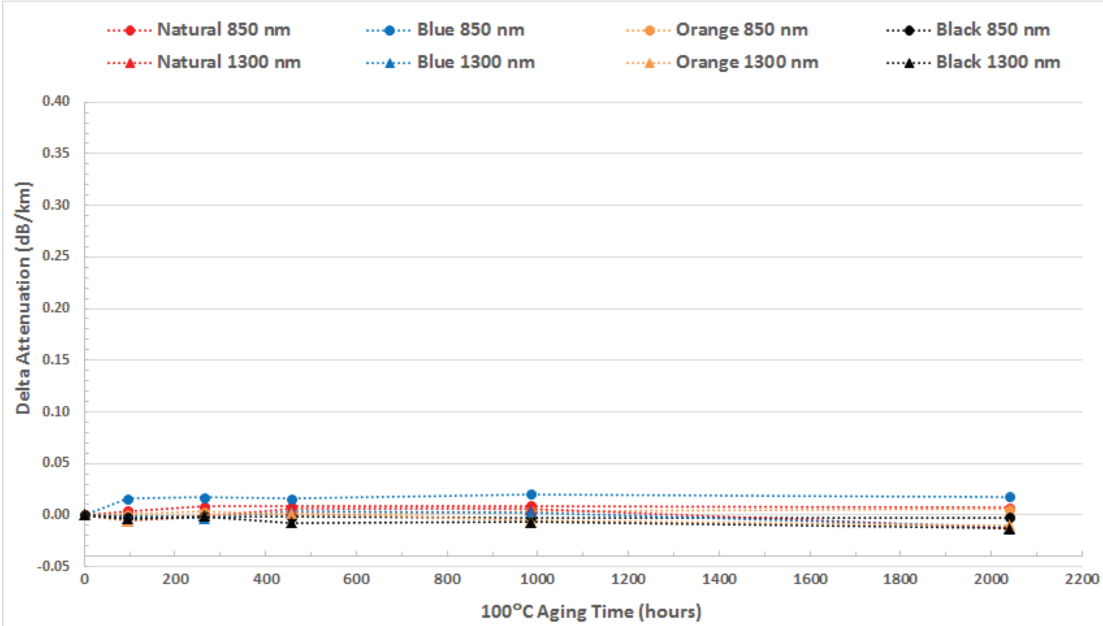


Figure 9. Attenuation change of multimode fibers exposed at 100°C.

When the multimode fibers are exposed to 150°C aging, the attenuation response becomes variable. Figure 10 shows the attenuation change from multimode fibers aged in 150°C for up to 1200 hours (50 days). Natural multimode fiber maintains ≤0.03 dB/km change in attenuation. However, the inked fibers, show more significant attenuation increases with the highest being 0.21 dB/km at 1300 nm from black multimode fiber after 1200 hours aging. The plausible cause for the inked fibers having higher attenuation is that the ink layers are more susceptible to becoming tacky at 150°C and therefore more microbending occurred as fibers adhered to adjacent fibers in the loose coil deployment.

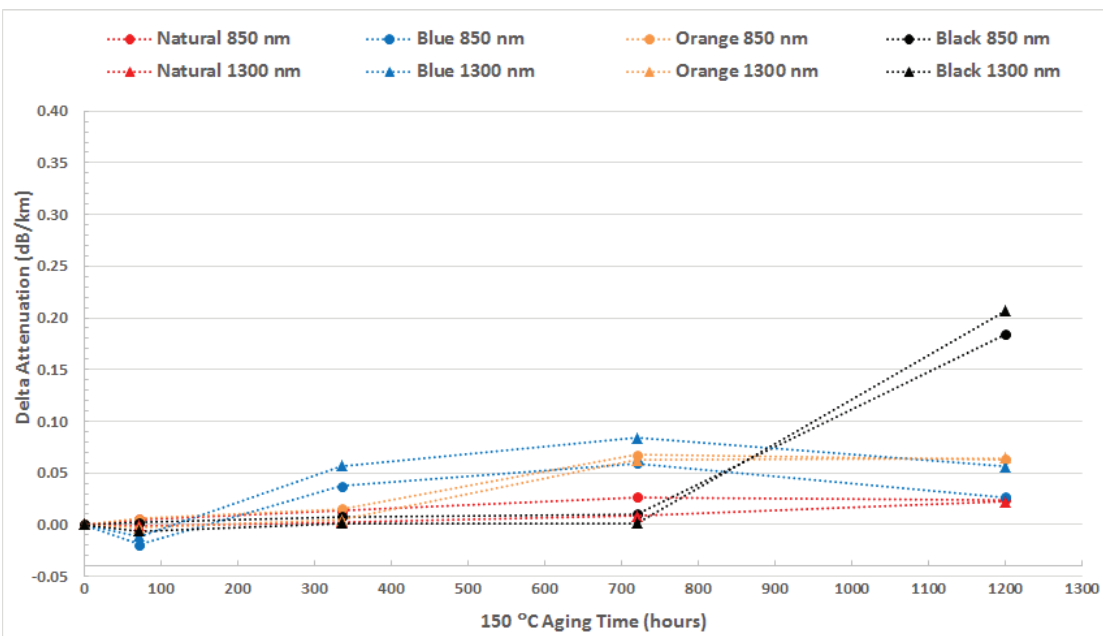


Figure 10. Attenuation change of multimode fibers exposed at 150°C.

The difference between natural and inked multimode fibers is even more pronounced at 200°C, as shown in Figure 11. Only the natural multimode fiber maintains low attenuation response, all inked fibers show high attenuation over 0.20 dB/km at as early as 72 hours. Interestingly, black multimode fiber again has the worse attenuation among the ink fibers. It is postulated that some color inks, such as black, are more fragile when exposed to heat aging.

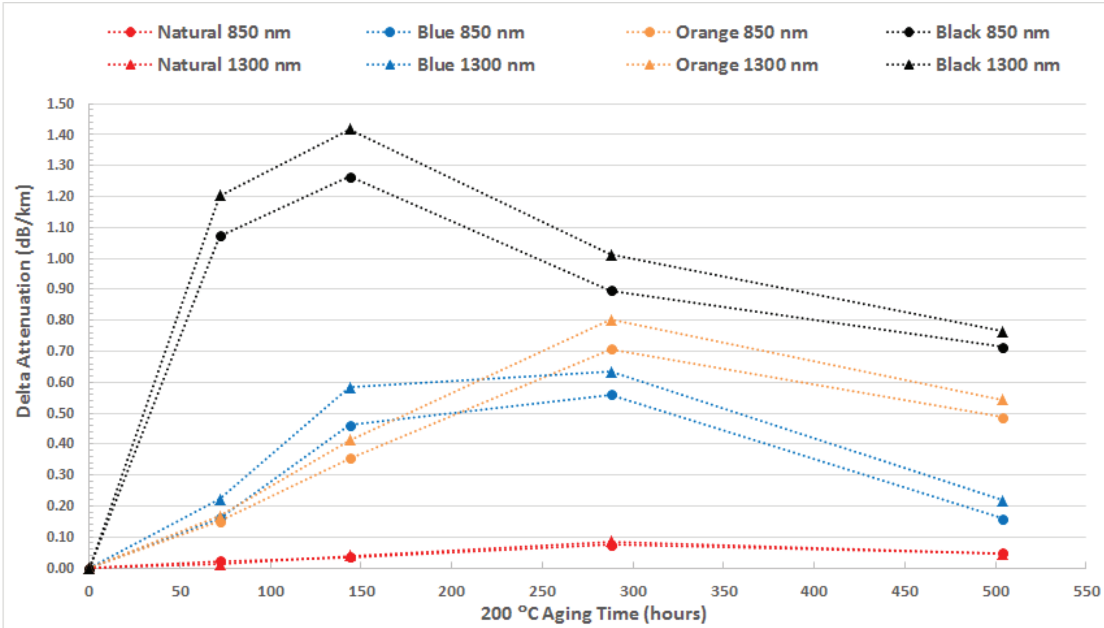


Figure 11. Attenuation change of multimode fibers exposed at 200°C.

At 300°C aging, within minutes we observed the same severe degradation and decomposition accompanied with smoke generation for multimode fiber as for single-mode fiber. Therefore, no measurement was performed due to fire hazard concern. We again strongly recommend not to expose standard optical fiber at 300°C for safety and performance reasons.

Impact on Fiber Geometry

Heat aging can also lead to changes in fiber geometry. To investigate this matter, we monitored the change in outer coating diameter (OD) as a response to heat aging. The fiber OD change is due only to the coating volume change, as the glass structure does not respond to temperature increases from 85°C to 200°C. We present the fiber coating volume change in Figure 12. Both 85°C and 100°C exposure cause only a small decrease in coating volume after 1800 hours (75 days) aging, only 3.8% for 85°C and 7.1% for 100°C. The outgassing of absorbed moisture can be expected in these two heating conditions and thus cause the small reduction in coating volume. The loss in coating volume accelerates when the single-mode fiber is subjected to 150°C aging, with 22% decrease after 1200 hours (50 days). Such volume loss is more than can be accounted for by just the outgassing of volatiles. Here, degradation of coating is the major effect. As mentioned in the attenuation impact section, we attributed the slight increment in attenuation from 150°C aging to coating degradation. The result from Figure 12 provides support for this postulation. 200°C aging obviously accelerates the coating degradation, as evidenced by the rapid loss of 27% coating volume within 24 hours and the significant 60% loss by the end of 576-hour (24 days) exposure.

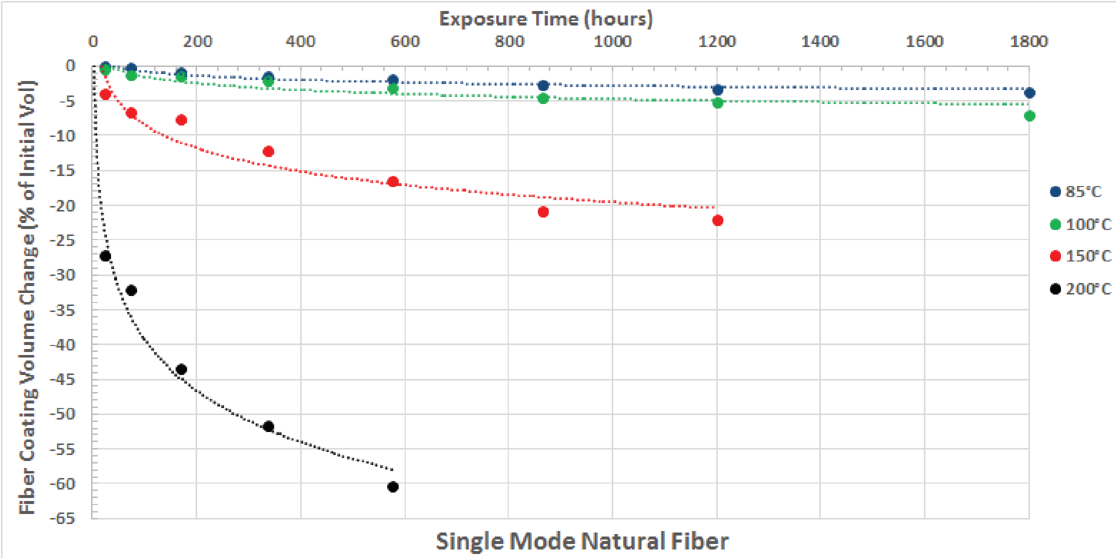


Figure 12. Volume change of single-mode natural fibers exposed in air.

The mechanism for the degradation of coating at elevated temperatures can be attributed to the oxidation reaction with O_2 in air. We will elucidate our reasoning for such mechanism in the next section.

Impact on Coating Mechanical Properties

CPC coatings are a dual layer acrylate coating system that consists of a soft primary coating (inner layer surrounding the glass core) and a hard secondary coating (outer layer forming the fiber enclosure). Rods of CPC secondary coating were prepared by injecting the liquid coating into Teflon tubing having an inner diameter of about 0.025 inch and then the aforementioned coating filled Teflon tubing was exposed to 2.4 J/cm^2 dose of UV irradiation with Fusion D bulb. Cured coating rods were then obtained by removing the Teflon tubing and rods were conditioned at 23°C and 50% relative humidity for 18-24 hours before tensile testing. We exposed the secondary coating rods at temperatures from 23°C to 285°C for 2.5 hours, and then measured the Young's modulus and elongation at break to compare how temperature affected the mechanical properties. At each temperature, one set of coating sample was exposed in air and another set was exposed in nitrogen. Figure 13 shows the Young's modulus change and Figure 14 shows the elongation at break change. For coatings exposed in the inert atmosphere of nitrogen from 23°C to 285°C, both the Young's modulus and the elongation at break show very little change, even above 250°C For coatings exposed in air, very little change occurs up to 180°C. From 180°C to 240°C, the oxidation reaction starts to take moderate effect, which can be seen as the elongation at break starts to drop. When exposed in air from 240°C to 285°C, the secondary coatings become much harder and brittle as the Young's modulus increases significantly and the elongation at break deteriorates sharply. These results indicate that oxidation is the strongest contributor to the degradation of secondary coating mechanical properties.

It should be noted that in many deployment conditions, optical fibers are enclosed in cables. Within the cable jacket, there is limited air or O_2 to cause oxidative degradation. However, the individual components in the cable may also impact the fiber performance upon thermal aging. The subject of cable materials impact on optical fiber is beyond the scope of this white paper.

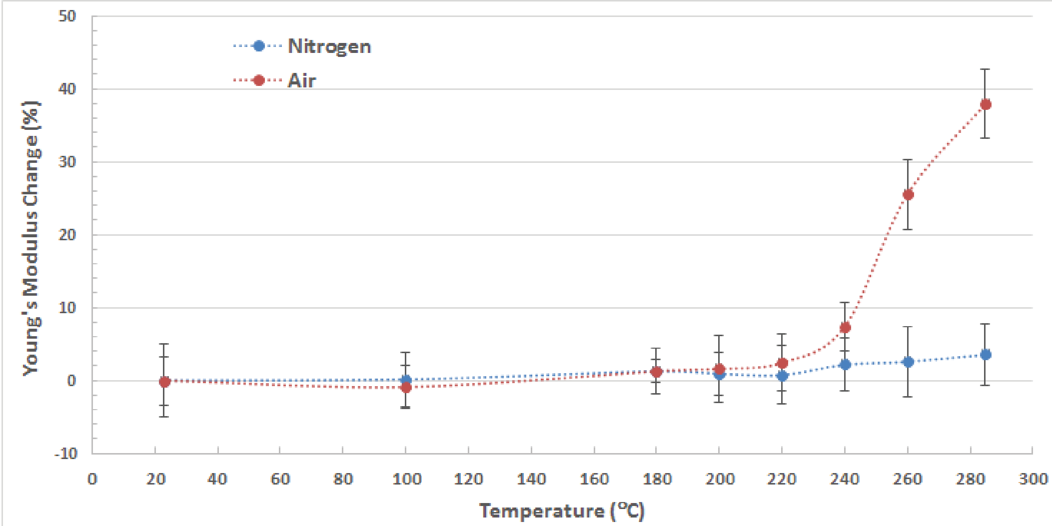


Figure 13. Young's modulus change of secondary coating after 2.5 h exposure.

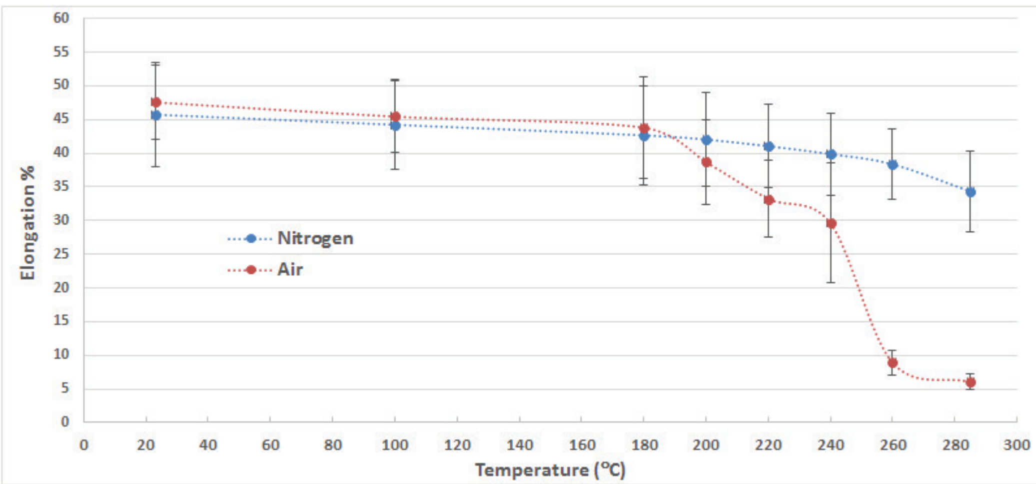


Figure 14. Elongation at break of secondary coating after 2.5 h exposure.

Impact on Fiber Identification

Optical fibers are inked in different colors for identification purpose. All color-coded Corning® optical fibers in this paper are coated with Corning® ColorPro™ identification technology. To evaluate the thermal impact on fiber identification, we exposed 13 different optical fibers, namely 12 colors plus one natural, at elevated temperatures from 85°C to 200°C in dry air. The thermal aged fibers were visually checked every 24 hours until severe discoloration appeared or the exposure time reached 1800 hours (75 days), whichever came first. Photographs of fibers before and after thermal aging were also taken for visual comparison.

Figure 15 (a) shows the fibers before thermal aging. Figure 15 (b) shows the fibers after 1800 hours (75 days) of 85°C in air. All fibers are still easily distinguishable from each other and visually there is no appreciable change from their original colors.

b

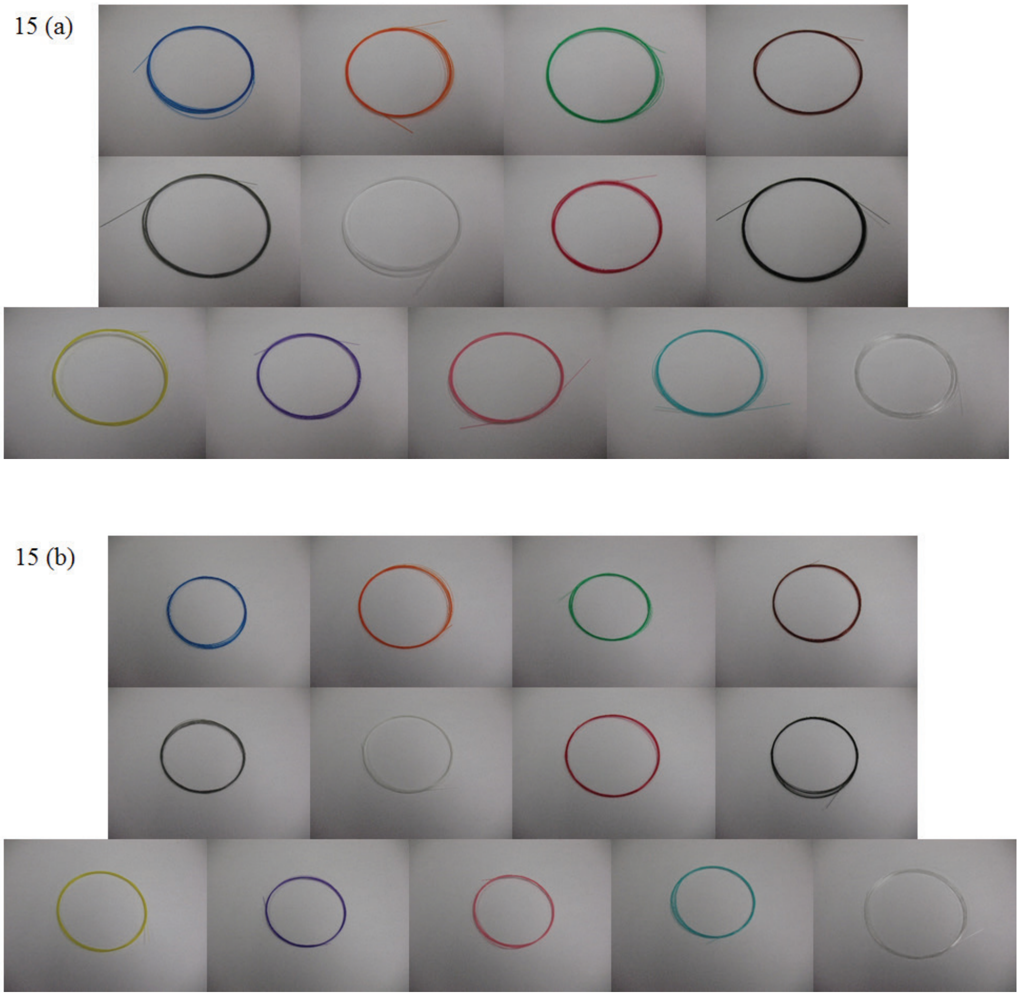
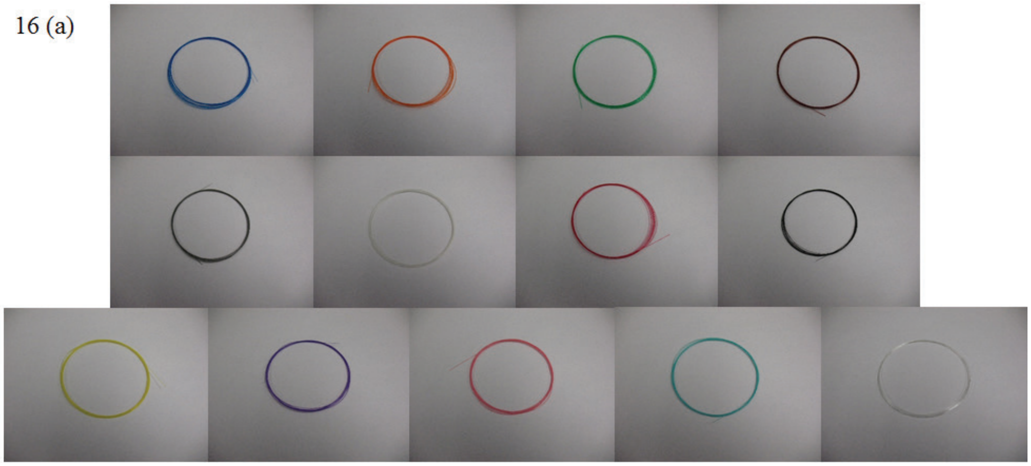


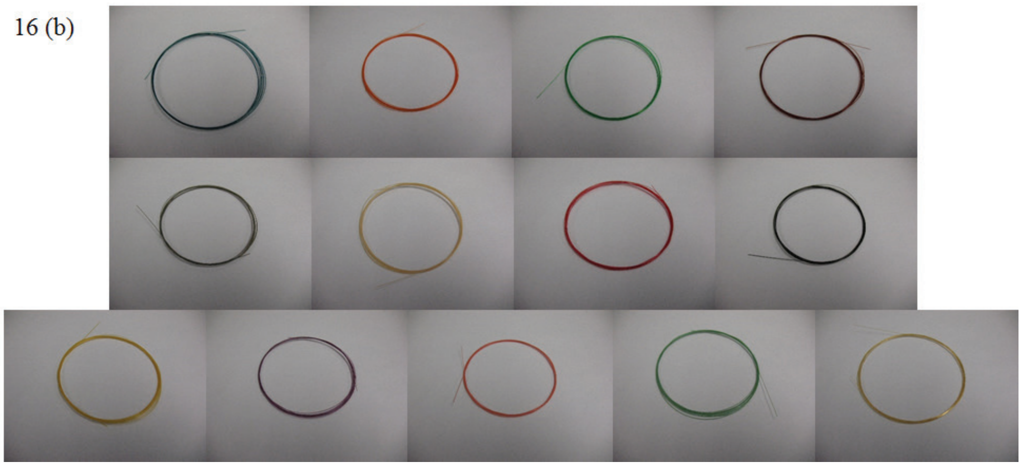
Figure 15. Images of optical fibers. From left to right, top row: blue, orange, green, brown; middle row: slate, white, red, black; bottom row: yellow, violet, rose, aqua, natural.
(a) Fibers before thermal aging.
(b) Fibers after 1800 hours (75 days) of 85°C aging in air.

100°C aging does not seem to have any impact on the fiber identification, as shown in Figure 16 (a). None of the fibers show any noticeable change from their original colors after 1800 hours (75 days) of 100°C exposure in air. However, when the temperature reaches 150°C, the fibers experience much faster discoloration, as illustrated in figure 16 (b). The impact of 150°C exposure takes a significant effect at 14 days. Some colors degrade beyond the limit where they can be reliably distinguished, i.e. blue, white, violet, aqua and natural.

16 (a)



16 (b)



16 (c)

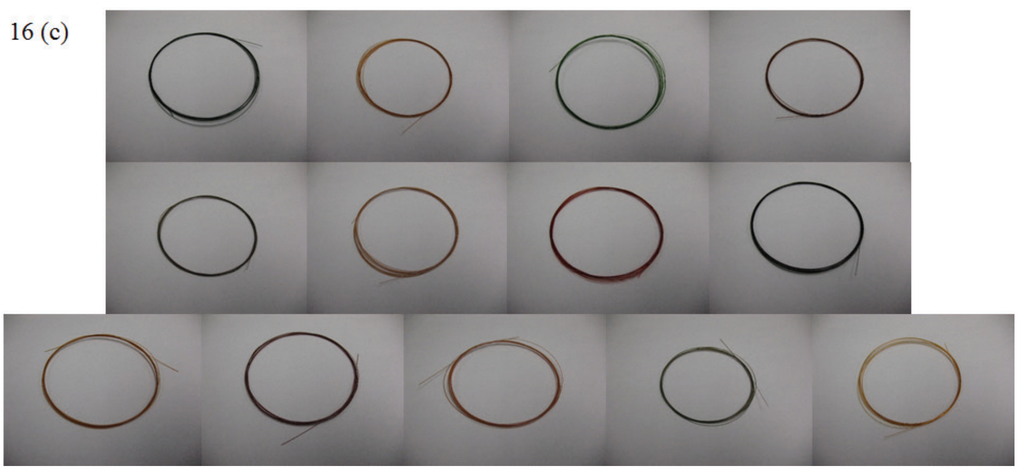


Figure 16. Images of optical fibers. From left to right, top row: blue, orange, green, brown; middle row: slate, white, red, black; bottom row: yellow, violet, rose, aqua, natural.
(a) Fibers after 1800 hours (75 days) of 100°C aging in air.
(b) Fibers after 336 hours (14 days) of 150°C aging in air.
(c) Fibers after 24 hours of 200°C aging in air.

The color deterioration of the fibers is so severe at 200°C that after 24 hours exposure, most fibers become unrecognizable, as shown in figure 16 (c). It can be concluded that thermal exposure up to 75 days at 100°C or below will not have any negative impact on the identification of inked optical fibers, while conditions at 150°C and beyond will rapidly deteriorate the inks and make it difficult to distinguish fibers according to their original color codes.

Summary

This thermal aging study has demonstrated that at 85°C and 85°C/85% RH, Corning® optical fibers with the CPC coatings show excellent transmission performance. When the aging temperatures are between 100°C and 150°C, optical fibers with CPC coatings can still maintain good optical performance within the 85°C specification limits, for at least 50 days. When exposed in air at 150°C and beyond, optical fibers suffer from coating degradation and high attenuation loss. Fiber geometry shows very little change upon 85-100°C aging, while temperatures above 150°C lead to significant coating volume loss. The O_2 from air is the major factor causing the coating oxidative degradation, as in inert atmosphere (N_2) secondary coating does not show appreciable mechanical deterioration responding to high temperatures. Inked optical fibers are able to sustain at least 75 days of 100°C in air exposure and maintain their colors. Temperatures of 150°C and above are detrimental to the inked layer and it becomes very challenging to identify such exposed fibers according to their original color codes. As a rule of thumb from these results, natural optical fibers with CPC coatings are capable of performing within product specifications at elevated temperatures up to 100°C, and 150°C appears to be the operation limit where cautions should be taken.

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