

Unusual Attenuation Recovery Process After Fiber Optic Cable Irradiation

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Abstract. At present, the number of optical cables in nuclear power plants has been increasing. Fiber optic cables are commonly used at nuclear power plants in instrumentation and control systems but they are usually used in environments without radiation. Nevertheless, currently, the number of applications in NPP containment with radiation is increasing.

One of the most prevalent effects of radiation exposure is an increase of signal attenuation (signal loss). This is the result of fiber darkening due to radiation exposure and it is the main limitation factor in application of fiber optics in radiation environment. However, after the irradiation, the fiber optics go through a “recovery process” during which the optical properties improve again; i.e. attenuation decreases. However, we have found cable, where the expected healing process after few days changed its trend and the attenuation increased again to a value well above the attenuation just after the irradiation. This paper describes experiments that were carried out to explain this unusual recovery behaviour.

1. Introduction

Application of safety related fiber optic cables in harsh environments of nuclear power plants (NPPs) requires their qualification. The international standard for qualification IEEE 1682: Standard for Qualifying Fiber Optic Cables, Connections, and Optical Fiber Splices for Use in Safety Systems in Nuclear Power Generating Stations [1] has existed since 2011. This standard supplements more general qualification standard IEC/IEEE 60780-323 [2].

In nuclear research institute ÚJV Řež laboratory, we tested and qualified fiber optic cables for NPP applications via simulation of degradation factors of optical cables by accelerated ageing.

Main degradation factors are:

- Temperature
- Mechanical stress
- Humidity
- Radiation

All these factors have a negative influence on polymer materials used in jackets and tubes, which are studied and known thanks to metallic cables. Less information exists about ageing of fiber optic glass and the importance of individual stressors above mentioned. Long term effect of temperature and humidity may lead to embrittlement of glass, cause microcracks and diffusion of OH ions into glass structure.



The most important stressor in NPP is ionizing radiation, which causes fiber darkening, i.e. dramatically attenuation increase and loss of functionality. Need to be mentioned, that the total dose causing glass to be “blind” is much lower than the dose, which would cause other fiber optic cable polymer materials degradation.

The influence of ionizing radiation initiates significant changes in glass matrix. Photons of gamma-radiation infiltrate deep into the glass structure and in the simplest case cause oxidation-reduction chemical processes [4], but most serious effects of high-energy gamma radiation include a number of changes in chemical, mechanical and optical, properties of glass. Electrons, released by ionization, can be trapped in grid structure creating defects that change temporarily or permanently the glass structure.

Deflections resulting from the displacement of atoms (atoms or ions are moved from their equilibrium into interstitial positions) are accompanied by energetic level changes of their electrons. If the ion leaves its equilibrium position, the vacancy acts as positive charged. The electrons released from the glass due to the radiation, are captured here and create a color centers with typical absorption in the visible area of the spectrum [5]. The direct consequence is the change in the absorption characteristics leading to the coloration of the fiber (glass goes through the darkening process) and hence attenuation increases. This is so significant that it can lead to the “blinding” of optical fiber with attenuations in tens of dB per km of its length. Such a value can affect proper function of fiber optic cables in NPP safety systems.

Qualification according to the standard IEEE 1682 [1] requires following steps: functionality testing, accelerated thermal ageing, accelerated radiation ageing using irradiation of cables with gamma rays, coiling the cables around mandrel to simulate mechanical stress encountering from the operation and checking the functionality during the recovery process after irradiation, finally accident condition simulation with functionality testing.

A new installed cable shall meet all the requirements described in its technical specifications and/or requirements established in the respective NPP design. Nevertheless, during the service ageing the cable may change some of its properties but it shall not be damaged to the extent which might compromise its proper function. Following radiation exposure the light transfer function of optical cable fibers will be ensured if the change of attenuation is smaller than 10dB/100m. For telecommunication applications, this value would be not acceptable. But for NPP safety systems, where the total length is typically bellow 100 m this value can be used as an end-point acceptance criterion.

2. Influence of Gamma-irradiation on Fiber Optic Cable

As mentioned above, increasing attenuation and especially the “recovery process”, are the most important factors that limits fiber operability. The extent of recovery can be affected among the others by time and temperature after the irradiation [6]. But it will never come back to the initial value. This process and description how to take it into account during qualification for nuclear power plant application are described in the IEEE 1682 standard [1].

2.1. Recovery Process - Relaxation

We started our activities in NPP fiber optic qualification with simplex and multicore fiber optic cables. The used fibers were multi-mode (MM) fibers with graded index, consisting of a fiber optic core covered with a buffer layer. The used fiber was: MM 62.5/125 radiation hardened fiber. The buffer was surrounded by aramid yarn and a final jacket. Cables were irradiated with gamma rays from ⁶⁰Co source to the total dose 1.7 kGy at the dose rate 40 Gy/h. After the end of the irradiation, the cable was placed in a room with controlled temperature for the period up to 30 days to check attenuation recovery. Results are plotted in Figure 1 and Figure 2. The first figure shows the attenuation increase during the irradiation, while Figure 2 represents a 10 days recovery process at room temperature. It is a typical and expected behavior [3]; attenuation increases during irradiation with partial recovery after the irradiation.

Quite different was the situation for jelly filled loose tube single-mode (SM) cable. Cable was during the qualification irradiated with the dose 15 kGy at the dose rate 0.3 kGy/h. The attenuation increased to quite high value. When the irradiation was stopped, the attenuation as expected decreased (recovered).

Nevertheless, the recovery took only 3 days. After this short period, the trend changed and attenuation increased to a value well above the attenuation just after the irradiation; well above the acceptance criterion for NPP application. For comparison see expected (model) vs. real conditions in Figure 3. We have called this unusual behavior as “inverse recovery process”.

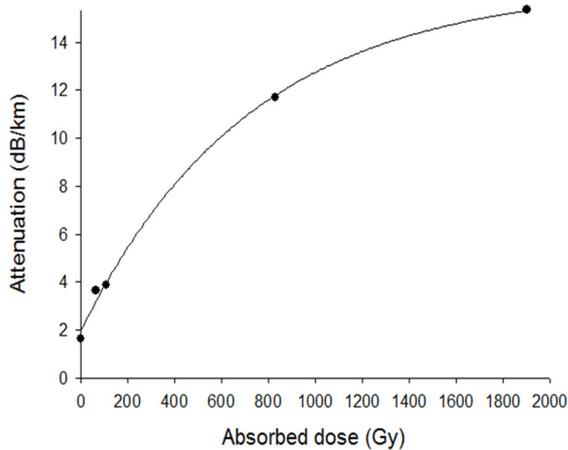


Figure 1. Attenuation increases during irradiation measured on MM simplex cable. Measuring was performed on wavelength 1300 nm in radiation interruptions.

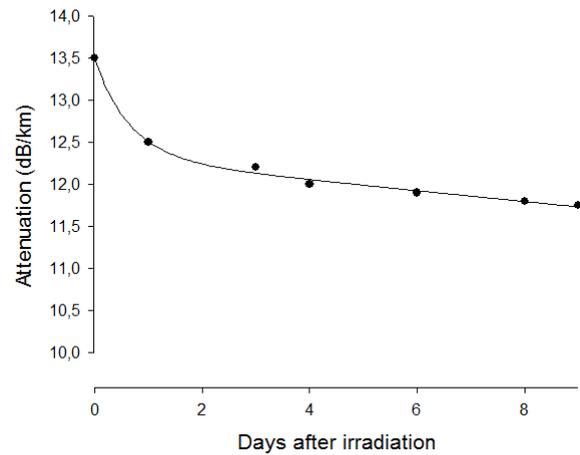


Figure 2. Recovery process initiation measured on MM simplex cable mentioned in Figure 1. Measured at 1300 nm. Measurement started 2 hours after irradiation.

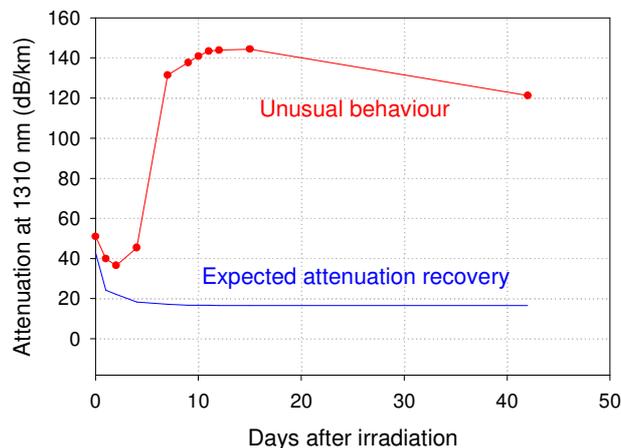


Figure 3. Attenuation recovery after fiber optic cable irradiation measured at 1310 nm. Expected is attenuation decrease, i.e. improvement of optical properties. Some types of fiber optic cables exhibits an unusual attenuation increase after few days of recovery time.

2.2. Reason of Observed Phenomenon

There are at least two main processes, attenuation recovery process, which is typical for irradiated Si glass and some process, quite slow at the beginning but that tends to dominate after few days. Possible explanations and reasons can be following:

1. Problem is in connectors and not in the cable itself.
2. Ge dopant in the SM fiber.
3. Thermal ageing that was carried out before irradiation
4. Mechanical stress. After irradiation, the cables must be, in accordance with the standard [1], straightened and coiled around a cylinder with a diameter similar to maximal allowed bending radius.
5. Dose rate of irradiation. During the operation, the cables are irradiated at very low dose rates, while irradiation in laboratory uses much higher ones. Is there any dose rate effect?
6. Total dose. MM cable was irradiated with ten times lower dose.
7. Different cable construction, used materials, fibers (MM vs. SM), tubes, jelly etc.
8. Some stress encountering during the manufacturing process.
9. Other.

3. Methodology of Experiment

3.1. Attenuation Measurement

As measuring method for transparence fiber glass detection, measuring of attenuation was chosen. MM cables were measured on wavelengths 850 nm and 1300 nm and SM cables on 1310 nm and 1550 nm (in few cases on 1625 nm).

During experiments, we used two attenuation – measuring methods:

- LSPM – Light Source and Power Meter (EN/IEC 60793-1-40 – method B Insertion Loss)
- OTDR – Optical Time Domain Reflectometer (EN/IEC 60793-1-40 – method C Backscattering)

It needs to be noticed, that all these experiments require quite long cable samples. The measuring devices need to be connected to the tested samples during 30 days of the recovery process and cannot be easily used for another experiment. Therefore, it was performed only limited amount of experiments and some of our conclusions were not proved on more samples. The most important was for us to find what causes the “inverse recovery process”.

Attenuation measurement was performed discretely in the time for trend monitoring or continuously.

3.2. Irradiation

To measure attenuation with a reasonable uncertainty, cables need to be at least 100 m long. To increase the optical length of the cable, individual fibers within the cable can be connected to series by fusion. Nevertheless, it must be ensured, that these fusions and connections do not influence the results.

Sample is attached to a perforated stainless steel cylinder with the diameter of 0.4-0.8 m, while the cobalt source is in the middle of the cylinder. Cable ends with connections and protective boxes are placed to a position with much lower dose rate or they are shielded. After irradiation, cables are straightened and bent around a mandrel to minimal allowed bending radius for installations, which was for the tested cables $20 \times$ cable diameter (20D), such a mechanical stress is required by the standard [1]. Samples are kept at room temperature. Attenuation is measured during the recovery period.

4. Results and Discussion

We have performed a lot of experiments with the aim to explain this inverse recovery process. Firstly, we checked individual steps of the qualification process. In the first step, we focused on explanation of possible cable connection effect, fiber itself, thermal ageing which had to be applied before irradiation, mechanical stress and irradiation process. Table 1 summarizes experiments carried out to explain inverse recovery process.

Table 1. Experiments overview.

Experiment	Sample type	Note
Connector and fusions irradiation	Whole cables	
Fiber dopants	Fibers	Two types of used dopants
Thermal ageing prior to irradiation	Whole cables	
Mechanical Stress after Irradiation	Fibers and cables	Influence of recoiling after irradiation exposure
Dose Rate Effect	Fibers and cables	

4.1. Connector and fusions irradiation

To check the possible influence of connectors and fusions, same samples were irradiated in such a way, that the cables ends were shielded and/or pulled out of the irradiation facility. There was no difference between the ends with connectors that were pulled out (i.e. not irradiated) or were slightly irradiated which was the case of previous testing.

4.2. Fiber dopants

To check if the germanium (Ge) plays a role in attenuation increase after irradiation, fibers with two different dopants were tested: fiber with Ge dopant, Single mode Fiber SM (G652D); and Single mode Fiber SM, radiation hardened fiber, unknown dopants (but no Ge).

Both fibers were irradiated with the dose 15.7 kGy at the dose rate 1.7 kGy/h. Samples were attached to a cylinder with the diameter 40 cm. Attenuation after the irradiation is in Figure 4.

These experiments gave very important results:

- There is no attenuation increase during recovery process if only fiber alone is irradiated. Compare Figure 3 and 4: in both experiments the same Ge fiber was irradiated. Figure 3 – whole cable; Figure 4 – only fiber alone.
- No effect of the used dopant (Figure 4).

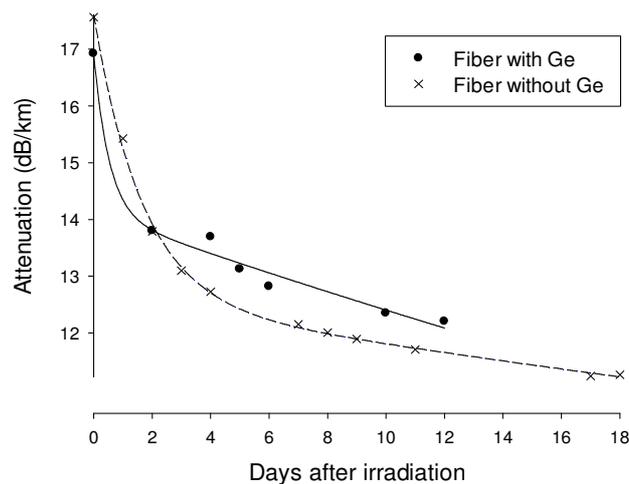


Figure 4. Monitored influence of used dopants in fiber structure. Fiber with Ge is optic fiber with germanium dopant. Fiber without Ge is optical fiber with another unknown dopant.

4.3. Thermal ageing

First step of qualification is simulation of long term thermal ageing. In accordance with the standard [1], thermal ageing is simulated using Arrhenius approach, which assumes that a short-term simulation of thermal ageing at higher temperature causes the same degradation as long-term ageing at lower temperatures. Cable was aged at 100 °C for the period of 110 days before it was irradiated. To check the influence of possible influence of thermal ageing, cable was irradiated also without any thermal treatment. Both cables, thermally aged as well as without thermal treatment exhibited the same inverse recovery process.

4.4. Mechanical Stress after Irradiation

Mechanical stress has the origin in sample straightening and bending immediately after the irradiation. Such a procedure is required by the standard and simulates possible mechanical stresses encountering in the NPP operation and during some accidents.

Therefore, cables coiled around a mandrel after irradiation as well as samples without mechanical stress were measured during the recovery process. There was no difference; i.e. the mechanical stress is not the reason for inverse recovery behavior.

Additionally, two samples of only SM fiber were irradiated together on a drum of 40 cm diameter. After the irradiation one fiber was kept on the drum without any manipulation, while the second one was very carefully straightened and recoiled on a smaller drum with the diameter 10 cm. Attenuation on both samples was measured during the recovery time. Results are displayed in Figure 5. Mechanically treated has little bit higher attenuation. Nevertheless, the effect is small, there is almost negligible difference between both samples.

Summary of the mechanical stress:

- Mechanical stress caused by the cable straightening and subsequent bending on small radius does not influence the process of the recovery and its inverse behavior after the irradiation.
- We eliminated mechanical stress as a cause of induced microbendings. We checked the OTDR traces and there is not such a big difference between attenuation measured at 1310 nm and 1550 nm, even 1625 nm. Microbending losses shall decrease at longer wavelengths [6], but we did not observe this trend.

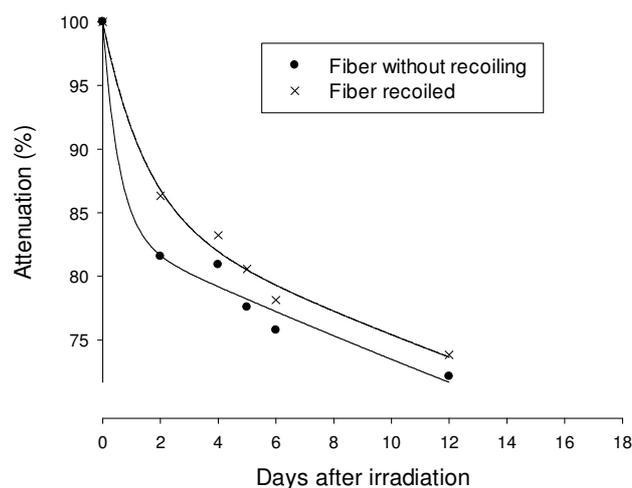


Figure 5. On y-axis is relative change of attenuation (100 % is value immediately after irradiation). Fiber recoiling was left on the drum with diameter of 40 cm without any manipulation while the second sample was recoiled on a smaller drum with the diameter of 10 cm.

4.5. Dose Rate Effect

A loose tube SM jelly filled loose tube single-mode (SM) cable was irradiated at the dose rate 1.45 kGy/h and compared with the same cable irradiated at 0.0173 kGy/h, i.e. approx. 100 times lower dose rate. Total dose was around 15 kGy. Difference in the recovery process is quite visible. Even the attenuation just after the irradiation at both dose rates was similar, at low dose rate irradiation is the inverse recovery process much less important, see Figure 6.

To check the attenuation increase after irradiation at different dose rates on fibers used in the cable, only fibers alone were irradiated at the same conditions as mentioned above.

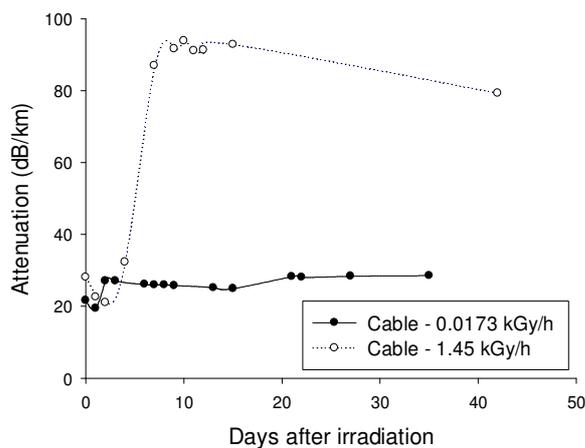


Figure 6. Influence of dose rate irradiation of whole cable on the attenuation and recovery process. Total dose was 15 kGy.

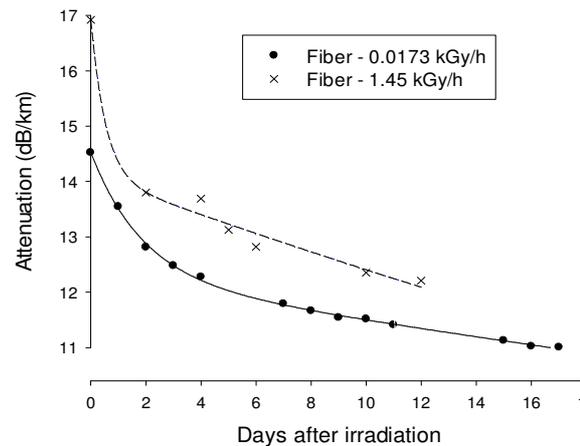


Figure 7. Influence of dose rate on recovery of fiber samples, that were irradiated alone.

The attenuation increase due to the irradiation, was not influenced by the applied dose rate significantly; i.e. the attenuation immediately after the irradiation was almost the same when irradiated fast at 1.45 kGy/h or slowly at .0173 kGy/h (see Figures 6 and 7). However, important fact is, that the attenuation values after irradiation were higher for cable samples than for fibers. At higher dose rate, it was approx. two times, at small dose rate only one and half times.

Summary of the dose rate experiments:

- The applied dose rate is not important for final attenuation increase during and immediately after irradiation.
- Inverse recovery effect was much higher when irradiated at higher dose rate.
- Attenuation increase during and after irradiation was approx. two times higher when irradiated whole cable comparing to irradiation only fiber alone.

5. Conclusion

While we tested fiber optic cable for the use in NPPs, we discovered unusual phenomenon “inverse recovery process”. Expected behavior of fiber optic cable after irradiation expose is improving of optical properties; i.e. glass fiber become darker while irradiated but during the recovery process without radiation, the optical properties improve. However, for some cables, improving of their properties after irradiation stopped after short period and attenuation started to increase to a value well above the values measured just after the irradiation. We performed a lot of experiments to explain this unusual phenomena. At first, we tested the possible influence of individual steps of the fiber optic cable qualification process. Results of our experiments could, as the reason for inverse recovery process,

exclude the influence of thermal ageing before irradiation, mechanical stress encountering from the bending of irradiated cable around mandrel as well as the applied dose rate. Moreover, attached connectors and fusions on qualified cable were excluded as well. Another set of experiments checked possible effect of dopants in the glass fiber. They showed, that there is no effect of the fiber dopant.

Interesting results appeared when we compared the recovery process of whole irradiated cable with only fiber. There was no attenuation increase (inverse recovery process) when only fibers alone were irradiated. The root cause of the inverse recovery process phenomenon is not known yet. However, we suppose that this effect is limited to the cable construction. Thus we are planning experiments with other materials of tubes, analyzing role of coating, jelly, influence of fiber amount in tube etc.

Acknowledgments

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