IEEE 1682-2011 IEEE Standard for Qualifying Fiber Optic Cables, Connections, and Optical Fiber Splices for Use in Safety Systems in Nuclear Power Generating Stations

White Paper

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Executive Summary

IEEE Standard 1682 was developed as a daughter standard to IEEE Std. 323. and modeled after IEEE Std. 383 and IEEE Std. 572. As the standard's first version, this white paper will examine significant topics that were discussed during the writing process, including some included and those deferred for subsequent revisions.

Fiber optic cables have been deployed in nuclear power plants since at least 1979 for non-safety related systems. Since then, usage has expanded throughout the plant, including into safety related systems.

During the writing of the 2011 standard and subsequently, advances in optical fiber and other materials continued at a fast pace. Highly radiation resistant optical fibers have been developed and usage in harsh environments may now be possible.

The topics discussed in this white paper include:

Section I – Differences between Fiber Optic and Electrical Cable Qualification

Section II - Unresolved Topics

Section III – Families of Fiber Optic Cables

Section IV – Bend Radius

Section V – Basis for Specimen Size Selection

Section VI – Fiber Optic Cable Failure Mechanisms

Section VII – Radiation Induced Attenuation

Section VIII – DBE Test Sequence

Section IX – Design Extension Conditions

Section I – Differences between Fiber Optic and Electrical Cable Qualification

While the principles of qualification are identical for both types of cables, there are significant differences in the application to fiber optic cable as compared to electrical cable.

Most significantly, the effects of aging on fiber optic cable performance can be monitored directly, for instance, by measuring attenuation, while electrical cables rely upon indirect measurements, for example, by correlating tensile and/or elongation of the insulation and jacket materials to an endpoint. Whereby the endpoint is chosen so that it includes sufficient margin for the degradation that will occur as a result of radiation exposure and DBE simulation. The typical critical characteristic measured for fiber optic cable is optical attenuation (power loss). Attenuation can be monitored directly, using power meters or optical time domain reflectometry (OTDR). Electrical cable typically uses measurements of dielectric strength as the pass/fail criteria. Insulation resistance and leakage current are also measured when qualifying electrical cable.

Both fiber optic and electrical cables may use Arrhenius methods as the basis for accelerated aging and establishing thermally qualified life and post-accident operating time. Because optical fibers carry only limited power, which is a small fraction of that for electrical cables, internal heating is insignificant. Therefore, thermal aging may be based on lower service temperatures than for electrical cables. However, consideration should be given to external heat sources when applicable.

The optical fiber is coated with a single or composite nonconductive, thin, polymerized layer(s) that function to protect the fiber from mechanical damage and moisture ingress. The protective coating(s) acts to cushion the glass fiber from mechanical forces which could create micro bends in the fiber, thereby minimizing optical signal loss. The coatings also act as a moisture barrier, thereby preventing micro-crack propagation. Since the fiber coating(s) are critical to the safety function of the fiber, the Arrhenius method may be used to establish a qualified life for the coating(s)

Radiation exposure may cause an unacceptable increase in power loss, often described as Radiation Induced Attenuation (RIA). Depending on the fiber, partial recovery from RIA may occur following radiation exposure. RIA is not applicable to electrical cables. However, after radiation exposure some electrical cable materials may have an increase in properties when the radiation exposure causes additional cross-link curing to occur. By contrast, radiation exposure of electrical cables degrades only the mechanical properties of the polymer compounds of the cable, and not the current carrying conductor.

After age conditioning and, if required, a DBE exposure can be performed. The change in performance of the optical fiber cable can be measured directly to establish power loss, which is used to determine acceptability. For electrical cables, the change in performance is measured indirectly by correlating tensile and/or elongation of the insulation and jacket materials to an end of life.

Both standards require bending the cable prior to performing the aged cable testing. While electrical cables stipulate a specific bend radius, IEEE Std. 1682 does not have a specific bend radius criterion. At the time the standard was written, there was no consensus on bend radius requirements.

Section II – Unresolved Topics

During the writing of the standard, other topics were considered. The working group was not able to achieve full consensus of many of these topics and therefore they were not included in the final document. These topics include:

Hybrid and Composite Cable

Hybrid cable combines electrical conductors and optical fiber units under a common jacket. Composite cable combines multiple optical fiber types, e.g. 50/125, 62.5/125 and/or single mode fiber, under a common jacket. IEEE Std. 1682 is applicable to composite cable.

The working group decided that at this time, hybrid cable would not be considered at this time, for the following reasons:

- The use of hybrid cable in nuclear power plants is very limited
- Fiber optic cable qualification was already breaking new ground, and the inclusion of electrical conductors could significantly complicate the standard. The types of electrical conductors, including power, instrumentation and control cables, have a variety of parameters that would be difficult to address.
- Electrical cable qualification is a well-developed protocol described in IEEE 383. While certain properties, for instance flame resistance, could be easily handled, other requirements such as temperature effects could not.
- The failure modes are different. For an electrical cable, the failure mode is typically electrical insulation breakdown. The failure mode in optical fiber cable is typically a decrease of the optical fiber's transmittance or a fiber break.
- If there is a need to qualify a hybrid cable, there is sufficient guidance in IEEE Standards 323, 383 and 1682 for the qualifier to develop their own plan and methods.

Connectors

IEEE Std.1682 also addresses connector qualification, while electrical connectors are specifically excluded from IEEE Std. 383 and are handled in a separate standard, IEEE Std. 572. The expansion to include hybrid cables might necessarily have led to a completely new section on this topic.

IEEE Std. 572 can be used to amplify points which are lacking from IEEE 1682 such as moisture barriers, vibration, design extension conditions, etc.

Penetrations

Penetrations are covered in IEEE Std. 317 and the working group felt that there was enough latitude in this standard to sufficiently address fiber optic elements in them. This is also consistent with IEEE Std. 383.

Section III – Families of Fiber Optic Cables

There is consensus that qualification of product families is possible and thus should be allowed, but there is also concern that qualification of families which are too broadly defined could inadvertently subvert the intent of safety related equipment qualification. Also, there is an expectation that the safety function of fiber optic cable and connection assemblies could vary widely. For instance, in some situations, the requirement may simply be to retard fire spread along the length of the cable. In other cases, the requirement of the cable could be to ensure that the optical circuit stays within the optical loss budget associated with the optoelectronic transmission equipment.

The working group's solution to this concern was to avoid being proscriptive in defining product families, but instead to provide qualifiers, users, and regulators with sufficient knowledge regarding differences in cable design and optical fiber design that might affect optical power loss, considering the potential environmental stressors in a nuclear generating station. Representatives of cable manufacturers in the working group provided guidance that similar cable designs can perform very differently in mechanical and environmental stress tests when different brands of fiber, different types of fiber, different fiber coatings and different coating thicknesses are used.

One common practice, acknowledged as valid in general fiber optic industry standards, is to qualify cable designs using single mode fibers and/or 50/125 multi-mode fibers with optical measurements made only at the highest potential operating wavelength (1550nm for single mode fiber, and 1300nm for multimode fibers). If qualification with these "stress sensitive" fibers at the highest operating wavelength (where cable macro-bend losses typically have the greatest effect) is successful, then the use of less "stress sensitive" fibers is often considered to be justified by the qualification.

In some cases, this approach may also be valid in a nuclear power plant application, but it cannot simply be assumed to be valid. In the case of gamma radiation exposure, it has generally been shown that radiation induced attenuation is much higher for lower wavelengths, than for higher wavelength transmission. Even fibers made using a similar manufacturing process with the same glass, dopant and coating materials, but having a different core size or radial dopant profile, may have different radiation induced attenuation profiles.

More recent studies have observed that the radiation effect on optical fibers produced by the same manufacturing methods exhibit very similar results whether testing bare, buffered fiber or in cables. It may be valid to test a specific family (distribution, breakout or loose tube constructions) and then substitute the radiation induced attenuation for alternate fiber types.

It was the working group's goal to highlight some of these "pitfalls" without precluding the use of broader families when the environmental conditions do not require their consideration. For instance, in some cases, a cable may not be used in spaces with high radiation resulting from a DBE, but only high temperature, steam or submergence.

Flame retardance is a common requirement for all cables in a nuclear generating station and may be the only requirement for some FO cables. The working group researched the qualification of FO cables for flame spread with different fiber types and core sizes and with the same fiber coating materials and core material. The consensus of this research was that the flame retardance of the FO cable is independent of fiber type but depends upon the other materials used in the FO cable, particularly buffer and jacket materials.

The working group decided a listing of typical fiber optic cable types and the various fiber coating/buffer types that are used within these cable types provided value to the user. The listings are provided in an annex with a detailed example of how a cable product family could be qualified, along with a wide variety of situations where changes to cable elements would not be likewise qualified without additional testing. This fits with the working group's intention to arm users with knowledge of valid family qualifications but was put in the Annex to avoid being proscriptive with respect to any specific cable design that could be qualified.

Section IV – Bend Radius

There are several references to bend radius in IEEE Std. 1682. At the time of writing, there was no agreement among manufacturers as to the proper value to be used. Discussion related to fiber bend radius included various values: from 7X to 10X radius for installed or permanent bending, and 15X to 20X OD bend radii during installation. In general, the standard was written to be non-proscriptive. That allows for innovation and improvements in technology and knowledge. The consensus of the working group was this was the best course for a new standard for a relatively new class of devices. The working group decided that the cable manufacturer should be contacted for specific bend radii.

Section V – Basis for Specimen Size Selection

Specimen size means the length of device under test and does not mean statistical sampling for acceptance testing. Testing with OTDR's, for instance, may require longer sample lengths, as OTDRs are not sensitive (resolution in Attenuation in dB/m) for shorter test lengths. Consideration of longer sample lengths such as 100 meters was debated by the working group. Future revisions will consider longer fiber lengths or consider splices lengths. Splices, when tested, should be spaced to allow light dispersion to the incident fiber.

The intent of the working group is to emphasize that the burden is on the user of the standard to justify the (minimum) length used. That is, the minimum length should be such that (1) any degradation due to the age conditioning will be representative of changes in the bulk properties of the material, and (2) it will facilitate testing after the age conditioning. Accurate measurement of loss on short samples is very difficult.

The basis for a minimum specimen length of 3 continuous meters (10 feet) was drawn directly from the requirements of IEEE Std. 383. It is generally accepted that the minimum 3 continuous meters (10 feet) of a cable sample along with the limited sample set that undergoes a type test is not statistically representative of all variations which may occur during the manufacturing process. The limited sample set and minimum sample length allows for representative samples to qualify a broader range of cables while limiting the number of type tests. IEEE Std. 323-1974 and its later revisions and 10 CFR 50.49 (d) (8) account for this uncertainty by incorporating requirements for margin into the type test.

The basis for margin is best described in 10 CFR 50.49 (d) (8) in "that margins must be applied to account for unquantified uncertainty, such as the effects of production variations and the inaccuracies in test instruments." Margin is applied to a variety of stressors that a cable sample is exposed to during a type test such as time (or qualified life), temperature, pressure, and radiation. In addition to the margin, additional conservativism is provided to address other possible uncertainties. The mandrel bend tests are a primary example. This conservatism was incorporated to ensure that the cable sample was not at its complete end of life condition following a type test

Section VI – Fiber Optic Cable Failure Mechanisms

Fiber optic cable failure modes are mechanical damage and signal degradation. Causes include

- Microbending
- Improper handling during installation
- Radiation exposure
- Fire
- Chemical exposure
- Humidity
- Moisture Ingress

Section VII – Radiation Induced Attenuation

Optical fibers are especially sensitive to increased attenuation when exposed to radiation. Performance varies greatly with the construction and processing of the optical fiber. Performance is affected by dose rate, total dose and temperature. This phenomenon makes environmental qualification of optical fibers fundamentally different than electric cables. Electrical cables are tested to correlate long term performance with change in physical properties (i.e. tensile strength or elongation) of the insulation material. Fiber optic cables are evaluated by directly monitoring the signal loss in the fiber, usually expressed as Radiation Induced Attenuation (RIA), which is the difference in attenuation prior to radiation exposure and the attenuation during and/or immediately after exposure.

In the years while the standard was being written and since the standard was published, significant progress has been made in understanding this topic, and that work continues. However, certain principles are established.

- Increasing dose rate and increasing total dose increases RIA
- Increasing temperature decreases RIA
- Recovery of RIA ("annealing") may occur after the radiation stressor is removed.

The ability to simultaneously expose optical fiber or optical fiber cables to radiation and temperature are rare or non-existent. Therefore, sequential aging is usually performed. Because of annealing and the decrease in RIA with temperature, as accelerated aging temperatures are generally much higher than service temperature, reducing the induced attenuation and producing a greater annealing effect, we generally recommend a sequence of thermal aging followed by radiation exposure. The working group also suggested the annealing be handled by a correction factor to add the annealing effect back to the tested loss. This is meant to provide the maximum radiation induced attenuation, and therefore the most conservative estimate.

Because low dose rate exposures produce lower RIA, studies to determine the long term effect of low dose rates are difficult to analyze. Models have been developed for this phenomenon, but caution should be used in evaluating this phenomenon. The working group is unaware of any studies that indicate low dose rates are a problem, specifically for fibers that are specifically designed to withstand radiation.

In a nuclear power plant, high radiation usually occurs simultaneously with high temperature associated with a DBE. Since the high temperatures tend to reduce RIA and radiation pre-aging occurs at about room temperature, the sequence of thermal aging followed by radiation is more conservative.

Section VIII – DBE Test Sequence

When the standard was written, extremely limited data concerning age conditioning sequence – temperature then radiation vs. radiation then temperature – was available. Hence, the working group suggested that aging may be done in both sequences and the results compared. The lack of available test facilities that can perform simultaneous thermal and radiation exposure dictates the use of sequential conditioning.

However, as noted in Section VII, the annealing phenomena would seem to favor the temperature – radiation sequence as being more conservative. However, either sequence could be used but the chosen method should be identified and justified. The next revision of the standard may recommend the thermal -radiation sequence.

Section IX Design Extension Conditions

Design Extension Conditions (DEC) were not considered in the original standard. It will be discussed for possible inclusion in the next revision of the standard.

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