

Fiber optics communication failure modes

Jonathan Rosenqvist

**Department of Fire Safety Engineering
Lund University, Sweden**

**Brandteknik
Lunds tekniska högskola
Lunds universitet**

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Felsignal i fiberoptiska kablar

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Sökord

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Abstract

This report examines fiber optic cables and their ability to transmit data when exposed to fire conditions. By performing various experiments the study aims to widen the knowledge base in an area that at the moment is scarce in information. Literary studies of standards connected to fiber optic cables and their application in nuclear power plants are studied as well as previous work done in the field. By comparing experimental results, previous work and standards conclusions are drawn about the use of fiber optic cables in facilities dealing with nuclear radiation.

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Brandteknik, Lunds tekniska högskola
Lunds universitet
Box 118, 221 00 Lund
Sverige

brand@brand.lth.se
<http://www.brand.lth.se>
Telefon: 046 - 222 73 60

Department of Fire Safety Engineering
Faculty of Engineering, Lund University
P.O. Box 118, SE-221 00 Lund
Sweden

brand@brand.lth.se
<http://www.brand.lth.se>
Telephone: +46 46 222 73 60

Foreword

I would like to extend my deepest appreciation and a thank you to all the people that somehow have given me advice and support through the course of this thesis. I would especially like to thank the following people for their contribution to this report.

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For invaluable support, advice and guidance during the course of this thesis.

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For invaluable support, advice and guidance during the course of this report and for always being available when I needed help. You were also of big help in finding all the appropriate standards and other quality documentation during the literary studies.

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For educating me about fiber optic cables and to enhancing the quality of this report by lending your expertise in this area as well as inviting me to join your visit with the fiber manufacture OFS in Copenhagen.

Kim Lundqvist, *NILAN Engineering AB*

For helping me during and after the experiments with questions that I have had.

Summary

This thesis has been developed in collaboration with ESS, European Spallation Source, as a step in their process to justify that their new facilities will meet necessary requirements on fire safety. For this project, ESS needs to evaluate functionality of fiber optic cables when they are exposed to elevated temperatures and open flames. The aim was to get a better understanding of fiber optic cables and communication failure modes when they are exposed to fire. The objectives were to study and conduct experiment on how fiber optic cables handle fire conditions and based on the results give recommendations for the usage in facilities that require a high level of safety.

After extensive literary studies, of previous work and standards connected to the use of fiber optics in nuclear facilities, experiments were conducted. The experimental setup was designed after studying standards such as SS-EN 50200 and IEC 60331. Five different experimental setups were designed and two different fiber optic cables were tested in the experiments. Some of the experiments were performed with a cone calorimeter and some with a free burning fire. The cables used in the experiments were singlemode (SM) 10/125 and multimode (MM) 62.5/125. In chapter 5.3 a summary of the experimental results are presented.

By comparing experimental results, previous work and standards conclusions could be drawn about the use of fiber optic cables in facilities dealing with nuclear radiation. The key information that was obtained from the experiments was the difference in fragility of the fiber when exposed to fire conditions compared to normal conditions. The fiber becomes very susceptible to external forces as well as mechanical and thermal stresses when it is heated or after it has cooled down. It was found that the fiber was especially susceptible to crushing or twisting forces. These findings correspond well with conclusions that are drawn in previous work in this field. Some other conclusion that could be drawn is that as long as the cables:

- Are not directly exposed to fire
- Simultaneously not subjected to crushing or twisting force
- And the mechanical and thermal stresses are handled in an appropriate way
- As well as installed according to the guidelines recommended in standards.

there should be no large risk for the use of fiber optic cables in nuclear power plants or other facilities that are dealing with nuclear radiation. However this is based on the information obtained in this thesis.

Sammanfattning

Det här examensarbetet har tagits fram tillsammans med ESS, European Spallation Source, som ett steg i deras process att säkerställa att nuvarande standarder uppfylls under byggnationen av deras nya anläggningar med avseende på brandsäkerhet. I det här projektet vill ESS utvärdera av fiberoptiska kablers funktionalitet när de utsätts för höga temperaturer och flammor. Syftet är att få en bättre förståelse om hur fel uppstår i signalöverföringen när fiber optiska kablar utsätts för brand. Målet är att studera och utföra experiment på fiberoptiska kablar när de utsätts för brand och utifrån resultaten ge rekommendationer på användning inom verksamheter som har höga säkerhetskrav.

Efter omfattande litteraturstudier av tidigare utförda arbeten och standarder kopplade till användningen av fiberoptiska kablar i kärnkraftsanläggningar utfördes experiment. Experimentuppställningen utformades utifrån tillgängliga standarder för såsom SS-EN 50200 och IEC 60331. Fem olika experimentuppställningar togs fram och två olika typer av kablar testades i experimenten. Vissa av experimenten utfördes med en konkalorimeter och andra där kablarna placerades över ett etanolbål. Kablarna som användes i experimenten var singlemode (SM) 10/125 och multimode (MM) 62.5/125. I kapitel 5.3 presenteras en sammanfattning av resultaten från experimenten.

Genom att jämföra resultaten från experimenten, tidigare gjorda arbeten och standarder så kunde slutsatser dras om fiberoptiska kablers lämplighet vid användning i kärnkraftsanläggningar. Den viktigaste informationen som erhöles från experimenten var skillnaden i skörhet av fibern när den var brandutsatt jämfört med under normala förhållanden. När fibern är uppvärmd eller efter att den har svalnat så är den väldigt känslig för externa krafter samt mekaniska och termiska spänningar. Det visade sig att fibern var särskilt känslig för krossande eller vridande krafter. Dessa slutsatser stämmer väl överens med de slutsatser som dragits i tidigare arbeten inom området. Några andra slutsatser som kunde dras var att så länge kablarna:

- Inte är direktexponerade för brand
- Samtidigt som de inte utsätts för krossande eller vridande krafter
- Och de mekaniska och termiska spänningarna hanteras på ett lämpligt sätt
- Samt att de installeras enligt riktlinjer angivna i standarder

så borde det inte vara någon stor risk att använda fiberoptiska kablar i kärnkraftsanläggningar eller anläggningar som hanterar kärnstrålning. Detta är dock baserat på information som erhöles genom denna studie.

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1. Introduction

1.1 Background

This report is a result of the work that have been done in the course *VBRM01 – Examensarbete i brandteknik (eng. Thesis in fire safety engineering)*, provided by the department of Fire Safety Engineering at Lund University.

This report has been developed in collaboration with ESS, European Spallation Source, as a step in their process to justify that their new facilities will meet necessary requirements on fire safety. European Spallation Source AB is a public company owned by the Swedish and Danish governments. For this project, ESS needs to evaluate functionality of fiber optic cables when they are exposed to elevated temperatures and open flames. Besides ESS, Ringhals AB is also an interested party in this report.

1.2 Aim and Objective

The aim is to get a better understanding of fiber optic cables and communication failure modes when they are exposed to fire. The objectives were to study and conduct experiment on how fiber optic cables handle fire conditions and based on the results give recommendations for the usage in facilities that require a high level of safety.

1.3 Research questions

The following research questions will be studied:

- Can data transfer in fiber optic cables be ensured when they are exposed to fire conditions? If not, after how long will data transfer stop?
- In SS-EN 60709 it says that fiber optic cables are an effective way off achieving electrical isolation. Does this mean that there will be no communication failure modes when the cables are exposed to fire conditions?
- Are there any other standards that mention the use of fiber optic cables and if so, what do they recommend?
- Is conventional fiber optic cable good enough when exposed to fire or are fire-classified cables needed to ensure that the data transfer is not affected?

1.4 Limitations

This research dealing with fiber optics communication failure modes focuses on data transfer when the cables are exposed to fire. To make the work manageable some limitations have to be made.

- This thesis will not investigate fire loads of fiber optic cables or smoke production during pyrolysis of the cables.
- The report will focus on fiber optic cables that do not have any fire safety classification.
- In the experiments no standardized method will be used to test the cables, though standards has been taken into account when designing the experimental setup.
- The runtime in the experiments is limited to a shorter time than recommended in standards.

1.5 Method

The project started off with gathering information about fiber optic cables or other similar cables (Höst, et al., 2011, pp. 36-39). Due to the lack of reports regarding fiber optic cables functionality when exposed to fire conditions, reports with other types of cables were also of interest. The focus was also on finding other standards than SS-EN 50200 and SS-EN 60709 that mentions fiber optic cables and how it should be used in facilities that requires a high level of safety.

When the literary study was done and the information about previously performed experiments was gathered, it was time to formulate an experimental setup. Based on available standards an experimental setup that suits real life applications was designed. After the experimental setup was formulated, the experiments were conducted (Höst, et al., 2011, pp. 36-39).

After the experiments were done the results was analyzed, error sources in the experiments was discussed, and recommendations about the use of fiber optic cables were also discussed. Based on this conclusions were drawn. Finally, there will also be a chapter about future research project within this field.

The overall workflow during this thesis is illustrated in Figure 1, the writing of the report is done continuously during this thesis.

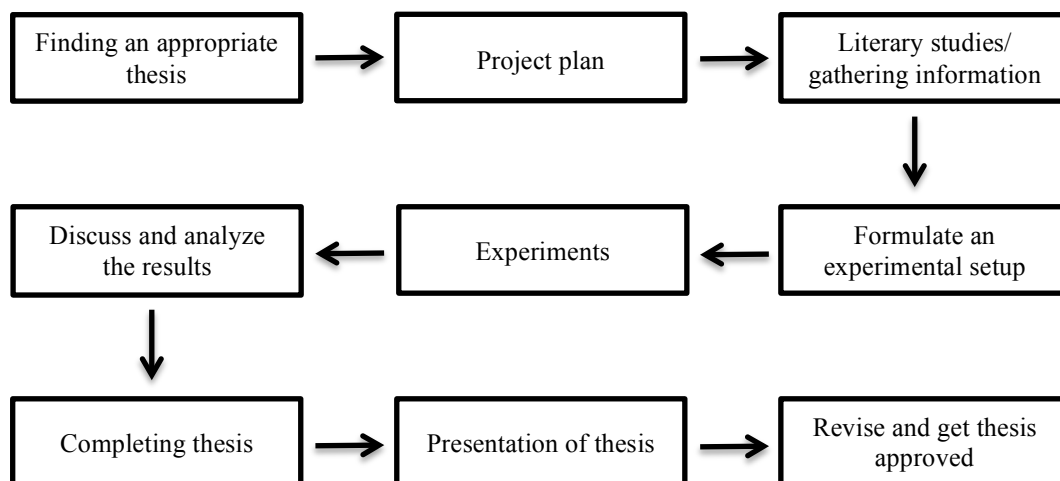


Figure 1 - Sketch of workflow.

2. Fiber optic cables and measuring devices

This chapter contains information about the structure and functionality of fiber optic cables. The chapter also contains descriptions of the measuring devices that are used in the experiments.

2.1 Fiber optic cables

There are two types of fibers available on the market today; they are called singlemode (SM) and multimode (MM). Singlemode is an optical wavelength in which light travels in one mode. In multimode it travels in multiple modes. The singlemode has a higher bandwidth than the multimode, thereby allowing larger amounts of data to be sent and over longer distances. The fiber core used in singlemode fibers has a very small diameter, usually only 8-10 μm and is made of glass. Laser light is used to counteract the chromatic desparation that occurs due to the small core in the singlemode fibers, if laser light is not used it would not be possible to send data over long distances. Two of the more common singlemode fibers are called OS1 and OS2, the most common sizes are 8/125 or 10/125. The first number represents the diameter of the core in μm and the second number represents the diameter of the cladding in μm (Wallmark & Linzander, 2014) (IEEE, 2005).

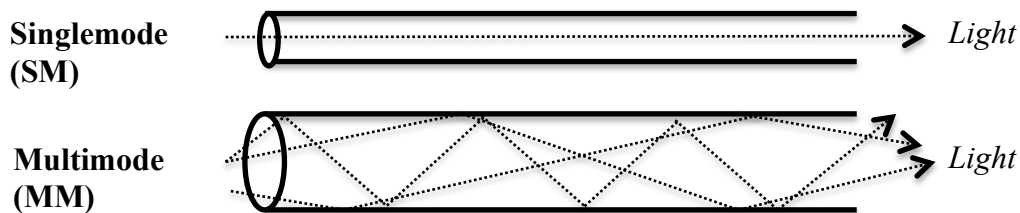


Figure 2 - Illustration of light travelling through SM and MM fibers, reproduced from (Wallmark & Linzander, 2014).

The common multimode fibers are called OM1, OM2, OM3 and OM4, the most common sizes are 50/125, 62.5/125, 100/140 and so on. The OM1 and OM2 use LED-light, OM3 and OM4 use laser light. The OM4 fiber that uses laser light can carry as much data as 40 GB/s, that is much more than LED-light and because of the increasing demand for high transfer speeds fibers using LED-light will soon only be a memory. Multimode fibers have a larger core diameter than the singlemode fibers and because of that there will not be any problems with chromatic desparation (Wallmark & Linzander, 2014) (IEEE, 2005).

When sending light through a core made out of glass, light is sent through several “windows”. In this case a window is a wavelength that in a sense makes the core transparent and suitable for transmitting signals. Common wavelengths that are used are 850 nm, 1310 nm and 1550 nm (Wallmark & Linzander, 2014) (IEEE, 2005).

A fiber optic cable can be designed in a verity of different ways to suit the customer’s need but a standard configuration is illustrated in Figure 3. Starting from the outside with a cladding of some type of material that protects the core from mechanical stress and moisture. Inside the cladding there is often some kind of insulation to reduce the

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temperatures impact on the fibers performance. Within the insulation lies the core. It can be one core or there can be many cores, common configurations are 1, 2, 4, 6, 12, 18 and 24 cores (IEEE, 2005).

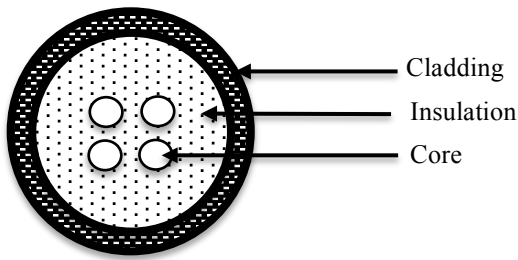


Figure 3 - Standard configuration of a fiber optic cable.

Outside the core there usually is another very thin layer of cladding. The melting point for fiberglass is 2000 °C. The fiber core consists of two glass staves that have been melted together, one put inside of the other. The outer staff creates a layer of different refractive indices that prevents the light, which travels in the inner staff, from scattering (Wallmark & Linzander, 2014).

Fiber optic cables are very sensitive to rapid temperature changes and the recommended operating temperatures often are in the interval of -30 to +70 °C. It is not the fiber or the cladding that is sensitive it is the other layers that are put into the cable that are sensitive to temperature changes. Other problems with the usage of fiber is the presence of water, the moisture could darken the fiber, which would lead to attenuation and when the water freezes it could result in microbending and fracturing of the fiber. Fiber optic cables can withstand a lot of pull tension, several hundred kilos, but they are very fragile when it comes to crushing or twisting forces under normal conditions. The bend radius should not be lesser than 20 times the cable diameter when exposed to tension. If no tension is applied the bend radius can be 10 times the cable diameter (IEEE, 2005).

2.2 OTDR device

OTDR stands for optical time-domain reflectometer; it is the most sophisticated way of measuring a fibers performance status at this moment. The OTDR device sends out light that reflects back to the device by hitting impurities in the glass or components connected to the fiber optic cable. The amount of reflected light that returns to the OTDR are then plotted as a function of length. Some of the things that can be measured with the device are attenuation, point attenuation, length, fault location and continuity (IEEE, 2005). In Figure 4 the measuring setup is illustrated.

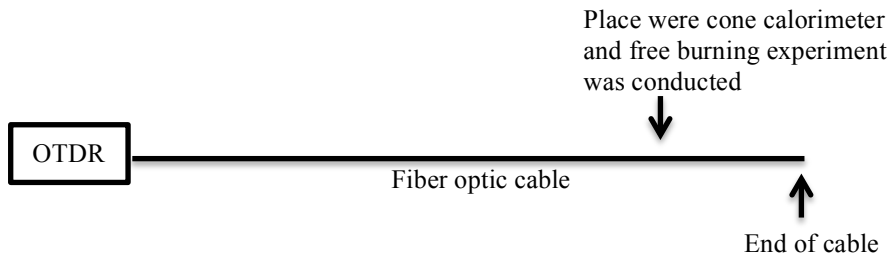


Figure 4 - Measuring setup OTDR device.

The OTDR device used in the experiments is called EXFO FTB 200 Compact platform and the measuring plug FTB-7400E-0234B Metro/CWDM (only singlemode); see Figure 5. Laser light was used as light source in all experiments in this report.



Figure 5 - In the left picture is the OTDR device and in the right picture is the OPM devices.

2.3 OPM device

OPM stands for optical power meter; the device consists of a transmitter and a receiver and is often referred to as an optical loss test set. The transmitter sends out light and the receiver measures the amount of light exiting the fiber at the other end. It is a very accurate way of measuring circuit attenuation but it gives no information about how the loss is distributed in the fiber (IEEE, 2005). The receiver used in the experiments is called EXFO EPM-50 Power Meter and transmitter is called ELS-50 Light Source, see Figure 5. Laser light was used as light source in all experiments in this report. In Figure 6 the measuring setup is illustrated.

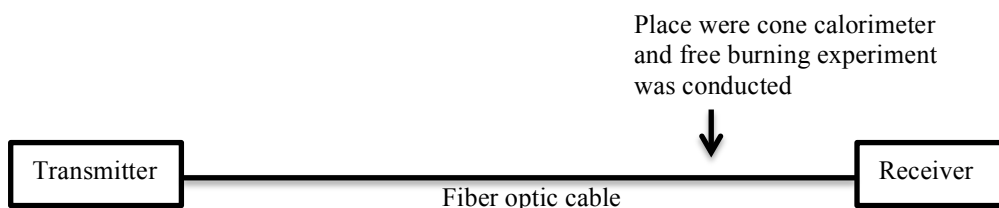


Figure 6 - Measuring setup OPM device.

3. Standards connected to fiber optics and fire testing

Short summaries of the more prominent standards connected to fiber optics and fire testing are presented in this chapter. There are American as well as international, Swedish and European standards presented.

3.1 IEEE 1428

The standards name is *Guide for installation methods for fiber-optic cables in electric power generating stations and in industrial facilities* and it is an American standard. It contains all information there is to know about installing and maintaining fiber optic cables. For example, there are descriptions of phenomenon's that may affect the fibers performance and how to avoid it as well as information about the most commonly used measuring devices (IEEE, 2005).

3.2 IEEE 384

The standards name is *Standard criteria for independence of class 1E equipment and circuits* and it is an American standard. Classified 1E equipment are components that are essential to emergency reactor shutdown, reactor core cooling, containment isolation or systems preventing discharge of radioactive particles to the environment. This standard gives recommendations for separation distances between classified 1E cables and regular cables as well as fiber optic cables. It states that it is not necessary to have separation between classified 1E fiber optic cables from one division and classified 1E fiber optic cables from a redundant division. The statement comes from that a fiber optic circuit has no potential to degrade another fiber optic circuit. But external hazards have to be considered, for example the specified routing in non-hazard and limited hazard areas. Depending on configuration of the installation and cables in the nearby vicinity, the distance for separation are ranging between 1.52-0.02 meters. For main control switchboards there should be separation, one way of ensuring this is by physical separation between redundant classified 1E cables (IEEE, 2005).

3.3 SS-EN 60709 (IEC 60709-2004)

The standards name is *Nuclear power plants – Instrumentation and control systems important to safety – Separation*. If separation is done correctly it is stated that it “prevents propagation of failure from system to system, propagation of failures between redundant parts within systems and common cause failures due to common internal plant hazards”. It is stated that the needs of new technologies, such as cable trays for fiber optic cables, should be evaluated when setting up limits for cable routing due to upgrading a power plant. It is also stated “fiber optic communications provide a very effective means of achieving electrical isolation, and should be applied wherever practical”. If the mechanical protection of the fiber optic cables is ensured it is allowed to install them together with power cables. In the section dealing with fire protection it is stated that flame-retardant cables should be used and they should comply with IEC 60332 (SEK Svensk Elstandard, 2012).

3.4 SS-EN 50200 (EN 50200-2006)

The standards name is *Method of test for resistance to fire of unprotected small cables for use in emergency circuits*. Some of the testing parameters required in the standard are listed as citation below:

- Diameter of cables may not exceed 20 mm.
- Test should be run for 120 minutes.
- The maximum increase in attenuation during the test should be measured for fiber optic cables.
- Test should be carried out in a suitable chamber that can dispose of any toxic gases resulting from the burning. The ambient temperature should be 25 ± 15 °C at the start of the test.
- At the end of the test each fiber should be checked for continuity.
- The source of heat should be a ribbon type propane burner; with a propane flow of 5 ± 0.2 l/min and air flow of 80 ± 4 l/min.
- The nominal temperature where the cable is placed should be at 830 ± 40 °C.
- The optical fiber cable used in the test should at least be 5 meters long and the two ends should emerge from the test chamber.
- The cable should be bent to form a 'U' shape according to the manufactures specification and then mounted on a ceramic board.
- The burner should be placed 40 ± 2 mm vertically from the cable.
- Use the nominal wavelength of operation.
- The test should be run until either a particular fire resistance classification is reached or to the point of failure (SEK Svensk Elstandard, 2006).

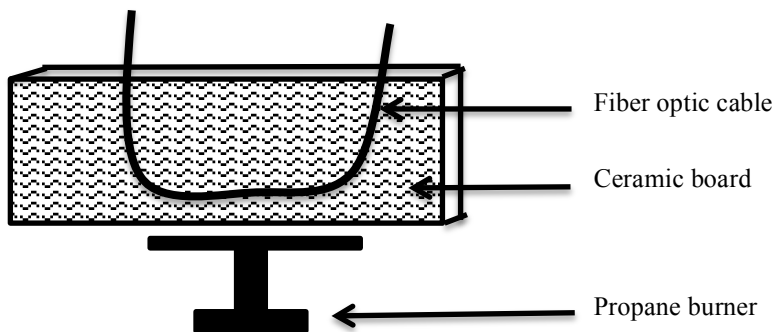


Figure 7 - Test setup reproduced from SS-EN 50200 (SEK Svensk Elstandard, 2006).

3.5 IEC 60331-25

The standards name is *Tests for electric cables under fire conditions – Circuit integrity – Part 25: Procedures and requirements – Optical fiber cables*. The test parameters is very similar SS-EN 50200 with some exceptions the most apparent one is the mounting of the cable. In this test the cable is hanging in the scaffolding instead of being mounted on a board. Specifications are found in IEC 60331-11 (CEI/IEC, 1999). Another thing that is different in IEC standard compared to the SS-EN standard is the runtime. In IEC it should be 90 or 180 minutes plus additional 15 or 30 minutes depending on experimental setup (CEI/IEC, 1999).

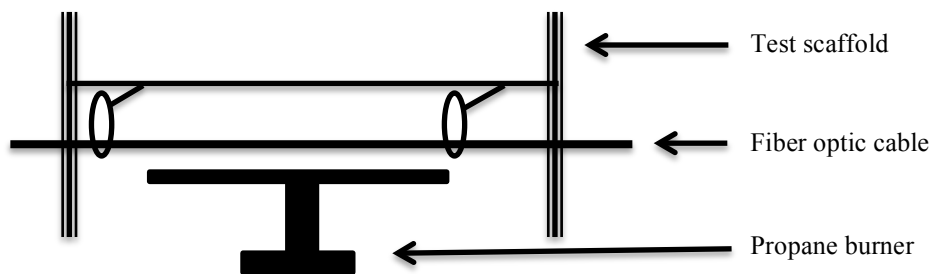


Figure 8 - Test setup reproduced from IEC 60331-11 (CEI/IEC, 1999).

3.6 Other standards

Other standards that has been read during the literary studies or reviewed before formulating the experimental setup are listed below.

- IEC 60331 series
- IEC 60332 series

4. Previous work conducted in the fiber optic field

The information that are available about fiber optic cables functionality when exposed to elevated temperatures is not particular extensive and even less research, if any, has been done to investigate communication failure modes.

4.1 SP report

SP Swedish National Testing and Research Institute have produced a report called *Performance of cables subject to thermal radiation, SP report 2000:24*. They conducted experiments on four different types of ordinary cables (F22, F24, F25 and Ekk) together with a case study of fiber optic cables. The fiber optic cables used were multimode and 850 nm laser light was used in the experiments. Three different cable configurations were tested, one 16x62.5/125 indoor/outdoor, one 4x62.5/125 indoor/outdoor and one 2x62.5/125 indoor. The experiments were conducted in a cone calorimeter and the voltage was measured, the intensity of the heat flux was increased progressively at certain times during the experiment. Both the 16x62.5/125 indoor/outdoor cable and the 4x62.5/125 indoor/outdoor cable did not fail until the heat flux was 29 kW/m² after 73 minutes. The 2x62.5/125 indoor cable did not fail before they shut down the experiment. They tested the cable with a heat flux as high as 32 kW/m², this experiment was also done progressively for 120 minutes. Despite the fact that all insulation material that surrounded the cable had burned up, the cable still functioned (Andersson & Van Hees, 2000).

4.2 IWCS reports

The International Wire and Cable Symposium, also called IWCS, is where scientist and engineers working with all types of cables gathers to present their research. Some presentations have discussed the impact of fire induced signal failure in fiber cables. Two of them are named *Fire resistant optical cable* and *Changes of transmission parameters of various types of cables during fire*.

In the report called *Fire resistant optical cable*, different types of fiber optic cables were tested according to the IEC 60331-25 and EN50200 fire test standard. The cables that were tested had special fire resistant cladding. The fire lasted for 90 or 180 minutes, plus additional 15 or 30 minutes attenuation. The increase in attenuation in any of the four cables was not greater than 0.2 dB/fiber, which is considered to be very good. The authors of the report came to the conclusion that the protective cladding was sufficient to resist the fire conditions (Caimi, et al., 2011).

In the report called *Changes of transmission parameters of various types of cables during fire* tested two types of power cables, one coaxial cable, one metallic communication cable and one fiber cable. The fiber used in the test was an OFS cable called OFS T-09-096 OPTION 1 W – ALPHA containing 24 fibers, and the conducted test followed the IEC 60331 standard. The cable has 15 fibers in the outer layer and 9 fibers in the inner layer. To pass the test the authors of the report had decided that the attenuation had to be lower than 33 dB/100 m. It was only 5 fibers in the outer layer that passed the test and the fiber that performed best had an attenuation of 10 dB/100 m. 8 out of 9 fibers in the inner layer passed the test and the fiber that performed best had an attenuation of 9 dB/100 m.

The authors observed that, during minute 5 and 20 in the test, a significant increase in attenuation occurred which according to them this is because of the mechanical tension created by the burning of the plastic cladding. They also derived the increase in attenuation as an effect of light emission in the fiber, which occurs when the fiber is subjected to high temperatures. The authors concluded that the best type of cable for signal transmission, when exposed to fire conditions is the coaxial cable. It has not as significant change in transmission as the optical or the metallic communication cable (Ritz, et al., 2012).

4.3 Other reports

There are some other reports dealing with the communication failure modes in cables when exposed to fire conditions. However, those reports are dealing with regular power cables and data cables. Two of those are summarized below.

One of these reports is the *NUREG-2128 report*, which is a compilation of three other reports. They found that, in tests conducted with cables using alternate current (AC), spurious operation due to short circuit has a high likelihood of occurring and in some cases as high as 74%. They also concluded that the cable placement relative the fire had an impact on the outcome and that the use of Thermo set (TS) or Thermo plastic (TP) cladding did not give different results (U.S.NRC, 2012).

In *SP report 2001:36, Performance of cables subjected to elevated temperatures*, there are no tests conducted on fiber optic cables. In this report, the focus is on ordinary cables (F24, F25 and Ekk) with PVC insulation material. The cables subjected to elevated temperatures showed no major damages in this experiment unlike the experiment with thermal radiation where the isolation burned up. The temperature in the cables when short circuit occurred ranged from 180-215 °C (Andersson & Persson, 2001).

5. Experiments

Two different experimental setups were engineered after discussion with researchers at a fiber manufacturing company called OFS, literary studies of work previously conducted in the field, literary studies of standardized testing methods and discussion with LTH, SP and ESS staff. In one of the experiments, a cone calorimeter according to ISO 5660 (ISO, 2010) was used and in the other one, a free burning fire was used. Some experiments were conducted with a variation in the standard setup, this will be explained later on. There were two types of cables used in all the experiments, one was a multi mode (MM) fiber cable called OM3 62.5/125. The other one was a single mode (SM) fiber cabled called OM1 10/125. In all experiments two measuring devices were used, an ODTR device and an OPM device. The devices were handled by a professional with many years of experience in the fiber optic cable field; took care of all the setup of the devices.

The ambient temperature in the room that the experiments were conducted in was 21 °C and the oxygen concentration 20.95 %.

5.1 Cone calorimeter setup

In the experiments conducted with the cone calorimeter, both the SM and the MM cables protective plastic cladding and kevlar insulation were removed to expose the individual fibers. Only two fibers were needed to do the measuring. The fibers were then mounted on top of a gypsum board and were then placed directly under the cone calorimeter as Figure 9 illustrates.

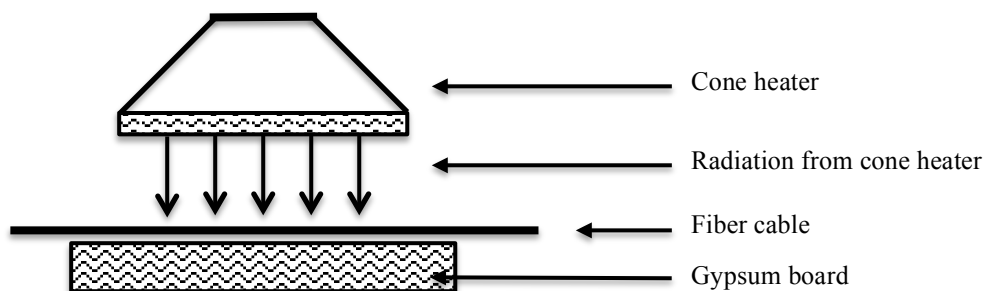


Figure 9 - Cone calorimeter experimental setup.

After discussion with LTH and ESS staff it was agreed that the heat flux, every five minutes, would increase. The starting heat flux of 15 kW/m² was chosen based on the heat fluxes used in the SP report. The table below shows the different radiation outputs against time. A chart with temperature plotted against irradiance was used to adjust the heat flux in the experiments, see appendix I for chart.

Table 1 – Heat flux at a certain time.

Time [min:sec]	Radiation [kW/m ²]	Temperature [°C]
00:00	15 (start of test)	460
05:00	25	570
10:00	35	660
15:00	45	720
20:00	50	750
25:00	50 (end of test)	750

During the 25 minutes, in both the SM and MM experiments, there was no interference detected. The signal was clean during both experiments and no attenuation could be measured, in either the OTDR or the OPM measuring devices. Used wavelength for the MM fibers was 850 nm (OPM) and 1310 nm (OTDR). Used wavelength for the SM fibers was 1550 nm (OPM) and 1310 nm (OTDR). See appendix II for additional pictures from the experiment.

5.2 Free burning setup

In the experiments conducted with a free burning fire four different setups were used. All experiments were conducted on both the SM and the MM cable except the “small bending radius experiment” which was only performed with the SM cable because the MM cable is resistant against bending. To hold the fibers in place bricks and weights were placed on top of them. Before the experiments began, a verification of the fibers was done to make sure that the weight of the bricks and weights did not affect the readings. The fibers were placed in the flames during the whole experiment and the temperature was measured with a thermocouple placed alongside the fiber.

5.2.1 Free burning experiment, standard setup

In the standard setup the protective plastic cladding and kevlar insulation were removed so that the individual fibers were exposed. Only two fibers were needed to do the measuring. The fibers were then placed directly over a round vessel, 100 mm in diameter, containing ethanol, as Figure 10 illustrates. Used wavelength for the MM fibers was 850 nm (OPM) and 1310 nm (OTDR). Used wavelength for the SM fibers was 1550 nm (OPM) and 1550 nm (OTDR). See appendix II for additional pictures from the experiment.

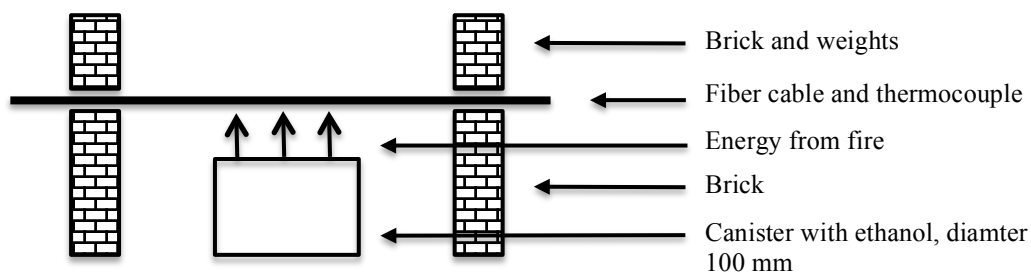


Figure 10 - Free burning experimental setup.

In both the 36-minute SM experiment and the 24-minute MM experiment no interference were detected. The signal was clean during both experiments and no attenuation could be measured in either the OTDR or the OPM measuring devices. The flame temperature fluctuated between 750-900 °C throughout the experiment.

5.2.2 Free burning experiment, small bending radius

The “small bending radius experiment” was executed with the same setup as the standard setup; only SM cable was used in this experiment. The difference between the experiments was that the fiber cable was bent with a small radius; see Figure 11 for the setup. To keep the radius intact during the experiment a steel wire was wrapped around the to fibers. The bending radius was 15 mm. Used wavelength was 1550 nm (OPM) and 1550 nm (OTDR).



Figure 11 - Free burning experiment, bending radius setup (steel wire).

After 22 minutes the signal was clean and no attenuation could be measured in either the OTDR or the OPM measuring devices. The cable was moved, approximately two cm into the middle of the fire, to see if the attenuation would increase. The attenuation started to rise directly after the cable was moved, when the fire extinguished after 28 minutes the attenuation was 2,5 dB/fiber. The temperature fluctuated between 750-900 °C throughout the experiment.

Table 2 - Results from free burning experiment, small bending radius (steel wire).

Time [min:sec]	Attenuation [dB/fiber]	Temperature [°C]
00:00	0.1 (start of test)	21
22:00	0.1	750-900
24:00	1.0	750-900
26:00	2.0	750-900
28:00	2.5 (end of test)	750-900

Another small radius experiment was conducted in which the fiber optic cables were wrapped with aluminum tape instead of steel wire. The results are presented in the table below. The bending radius was the same in the start of the experiment as in the one with the steel wire but as the time progressed the radius increased because the aluminum tape slowly melted. The temperature fluctuated between 750-900 °C throughout the experiment.

Table 3 - Results from free burning experiment, small bending radius (aluminum tape).

Time [min:sec]	Attenuation [dB/fiber]	Temperature [°C]
00:00	0.1 (start of test)	21
00:10	1.0	750-900
03:00	4.0	750-900
06:00	11.0	750-900
09:00	19.0	750-900
12:00	25.0 (end of test)	750-900

5.2.3 Free burning experiment, whole cable

In this experiment the protective plastic cladding and kevlar insulation were not removed and the whole cable was exposed to the fire. As in previous experiments two fibers were needed to do the measuring and the cable was placed directly over a round vessel, 100 mm in diameter, containing ethanol. Both SM and MM cables were tested; the results are presented in the table below. Used wavelength for the MM fibers was 850 nm (OPM) and 1310 nm (OTDR). Used wavelength for the SM fibers was 1550 nm (OPM) and 1550 nm (OTDR).

Table 4 - Results from free burning experiment, whole cable.

SM, whole cable experiment			MM, whole cable experiment		
Time [min:sec]	Attenuation [dB/fiber]	Temperature [°C]	Time [min:sec]	Attenuation [dB/fiber]	Temperature [°C]
00:00	0.0 (start of test)	21	00:00	0,0 (start of test)	21
03:00	1.5	750-900	11:00	1.0	750-900
05:00	3.0	750-900	13:00	8.0	750-900
08:00	4.0	750-900	15:00	15.0	750-900
09:00	5.0	750-900	18:00	17.0	750-900
14:00	6.0	750-900	21:00	19.0	750-900
26:00	7.2 (end of test)	750-900	25:00	21.0 (end of test)	750-900

In both experiments the temperature fluctuated between 750-900 °C. In Figure 12 the MM cable can be seen, the picture is taken after the experiment ended.



Figure 12 – The left picture is taken during the free burning, whole cable experiment (MM) and the right is taken after it ended. The broken fibers are clearly visible in the right picture.

5.2.4 Free burning experiment, cable bundle

In this experiment the protective plastic cladding and kevlar insulation were not removed and unlike “the whole cable experiment” seven cables were used and exposed to the fire. The cable that was used to measure the attenuation was placed in the middle of the bundle as Figure 13 illustrates.

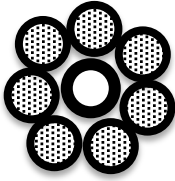


Figure 13 - Free burning experiment, cable bundle experimental setup.

In this experiment the thermocouple was placed close to the middle of the bundle to get an accurate reading of the temperature. All cables in the experiment, including the cable used for measuring the attenuation, were MM cables; the results are presented in the table below. Used wavelength for the fibers was 850 nm (OPM) and 1310 nm (OTDR). See appendix II for additional pictures from the experiment.

Table 5 - Results from free burning experiment, cable bundle.

Time [min:sec]	Attenuation [dB/fiber]	Temperature [°C]
00:00	0 (start of test)	21
03:00	0	350
06:00	0	460
15:00	0	560
20:00	0	600
32:00	0 (end of test)	600

Unlike the other experiments the temperature did not fluctuate as much and the temperature at the end of the test was not as high as in previous experiments either. The left picture in Figure 14 is taken before the experiment began and the right picture is taken after the experiment ended.

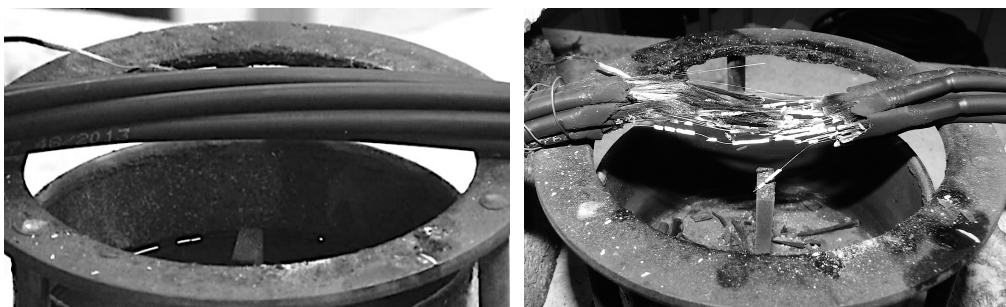


Figure 14 – The left picture is taken before the experiment began and the right picture is taken after the experiment ended.

5.3 Summary of results

To more easily compare the different experiment and the results a table with all data are presented below. For more detailed information about each experiment see chapters above.

Table 6 - Results of all experiments are presented in the table.

Experiment name	Experiment duration [min]	Attenuation, end of test [dB/fiber]	Temperature, end of test [°C]	Notes
Cone calorimeter, SM (Chap. 5.1)	25	0	750	Progressive effect increase every 5 min, radiation level at end of test 50 kW/m ²
Cone calorimeter, MM (Chap. 5.1)	25	0	750	Progressive effect increase every 5 min, radiation level at end of test 50 kW/m ²
Free burning, standard setup, SM (Chap. 5.2.1)	36	0	750-900, fluctuated during test	-
Free burning, standard setup, MM (Chap. 5.2.1)	24	0	750-900, fluctuated during test	-
Free burning, small bending radius, SM (steel wire) (Chap. 5.2.2)	28	2.5, attenuation was 0 after 22 min when cable was moved	750-900, fluctuated during test	Bend radius 15 mm
Free burning, small bending radius, SM (aluminum tape) (Chap. 5.2.2)	12	25	750-900, fluctuated during test	Bend radius 15 mm
Free burning, whole cable, SM (Chap. 5.2.3)	26	7,2	750-900, fluctuated during test	-
Free burning, whole cable, MM (Chap. 5.2.3)	25	21	750-900, fluctuated during test	-
Free burning, cable bundle, MM (Chap. 5.2.4)	32	0	600, temperature rose during whole experiment	7 cables in a bundle were used, measuring cable and thermocouple placed in the middle of the bundle

6. Discussion

The experiments generated a variety of results and this chapter focuses on discussing experimental data, error sources, interpretations of standards and previous work.

6.1 Experimental data

The first experiment conducted was the cone calorimeter experiment with progressive increase in heat flux. Both the SM and MM cable were not affected by the incident radiation from the cone heater. Even when increasing the heat flux as high as 50 kW/m^2 no attenuation could be measured neither on the OPM or the OTDR measuring devices. The only thing that happened was that the core cladding was turned into ashes and the core became visible due to the heat from the cone heater. The cables were placed on a gypsum board in both the SM and MM experiment that ensured that they were stable. Because there were no crushing or twisting forces involved in this experiment and the temperature was lower than $2000 \text{ }^\circ\text{C}$, the outcome of the results is not surprising as it is well supported by the text in chapter 2.

The free burning experiments were not as conclusive and easily explained as the cone calorimeter experiments. Four different kinds of experiments were done with the free burning setup. The first one was the standard setup i.e. the cable was stripped of its protecting cladding and kevlar insulation to expose the core. The results in both the SM and MM experiment gave the same result, no increase in attenuation were measured. At this point the fiber optic cables seemed very resistant to fire conditions.

But when the experiment with the small bending radius was performed there was some increase in attenuation measured in both experiments that were conducted. In the experiment with the steel wire no attenuation was measured during the first 22 minutes. Because there was no change in attenuation it was decided to move the cable very carefully two cm further into the fire. Within some seconds from the moment that the cable was moved the attenuation started to rise and six minutes later, when all the ethanol had burnt up the attenuation stabilized at 2.5 dB/fiber . This was found very interesting and a second experiment was performed with aluminum tape wrapped around the cable instead of the steel wire. It only took seconds for the attenuation to start increasing when the experiment had started, after twelve minutes the attenuation was as high as 25 dB/fiber . Just a few seconds after the ethanol fire was lit the aluminum tape started to unravel and the tape became very pliable due to the heat from the fire. Aluminum has a melting point at approximately $660 \text{ }^\circ\text{C}$ so this is not surprising (Södergren, 2014). This started the increase in attenuation and during the twelve minutes long experiment the aluminum tape unraveled more, resulting in further twisting of the fiber. As earlier stated in this report the fiber are fragile when exposed to crushing and twisting forces under normal conditions. It seems that the fragility increases and leads to an unstoppable chain reaction in attenuation when even the slightest twisting occurs when exposed to elevated temperatures. However, these experiments had a bending radius many times smaller than it should be according to the manufactures specifications. If the correct bending radius was used instead of the one used in the experiments it probably would not matter, this statement will be reinforced when discussing the *free burning, whole cable experiment*.

Every experiment so far had been done with the protective cladding and the insulation stripped from the cable to expose the core, which is not a very common setup in real life scenarios. The reason for doing this was because the fiber would be exposed to fire faster with this setup and thereby prolonging the exposure time. Another reason was that before the experiments were conducted it was thought that the cladding and the isolation would not impact the attenuation values. But to make sure that this was not a false assumption an experiment with the whole cable was performed. The experiment is called *free burning, whole cable experiment* and was done with both the SM and MM cable. In both the SM and MM experiments a substantial increase in attenuation were measured, at the end of the experiments the attenuation measured 7.2 dB/fiber (SM) and 21.0 dB/fiber (MM). In both experiments the attenuation started to increase after just a few minutes and did not stop until the fire went out. The MM cable attenuation increased rapidly from the eleventh minute, from 1 dB/fiber to 8 dB/fiber in only two minutes. This time is coherent with the time for when some of the ashes fell of the fiber and thereby creating a twisting force. Exactly like in the small bending radius experiments the twisting force creates an immediate increase in attenuation due to the increased fragility of the fiber when exposed to elevated temperatures. The difference in the two *free burning, whole cable experiments* final attenuation values can easily be explained by looking at a picture taken at the end of each experiment, see Figure 15.

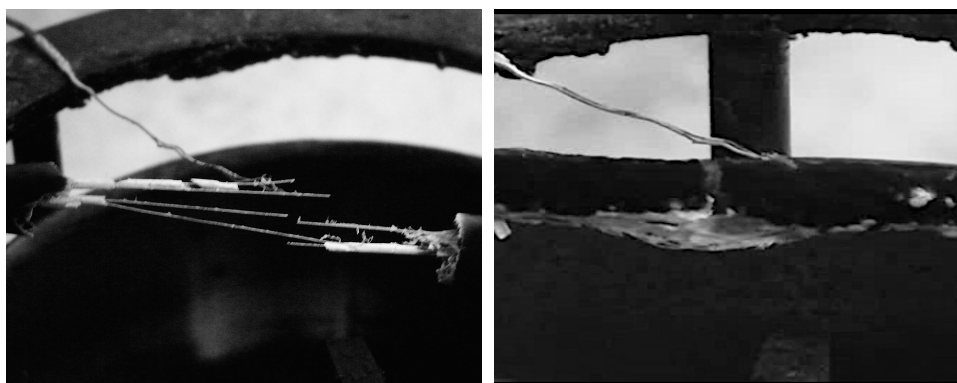


Figure 15 - The picture to the left is the MM cable and the right is the SM cable, photo is taken at the end of each experiment.

As shown in the left picture in Figure 15, representing the MM cable, the decay of the cladding and insulation is total and almost all of the ashes have fallen off the fibers. The SM cable's (see right picture) cladding and insulation has also decayed but not as much as the MM cable and there are still quite a lot of ashes laying on top of the fibers seen in the left picture. Because more ashes have fallen off the MM fibers, thereby creating more twisting forces, it is only logical that the MM fibers attenuation values would be higher than the SM values.

Another interesting observation was made towards the end of the MM experiment's runtime. When the fire extinguished, some of the fibers broke due to the mechanical and thermal stresses that were created by the swift temperature fluctuations (Samuelsson, 2014). This phenomenon can be seen quite clearly in the left picture of Figure 15, the picture is taken after the fire extinguished and there is only one fiber that is unbroken.

Physical impact when the fibers are heated up leads to severe stress, which has been discussed in previous section. However, when examining the fibers after experiments and trying to break them by pulling in each end of the cable they did not break. It seems that the fibers still can withstand a lot of pull tension even after they have been subjected to elevated temperatures.

The last experiment that was conducted was the *free burning, cable bundle experiment*. Because of the measuring cable's placement, in the middle of the bundle, no attenuation was measured during the experiment. The reason for this is that the surrounding cables worked as a shield against falling ashes of cladding and isolation as well as prolonging the heating of the measuring cable. Even though some of the fibers in the surrounding cables broke, the measuring cable's fibers did not, see Figure 14.

6.2 Error sources

The standards in chapter 3 were consolidated when constructing the experimental setup. Because of the lack of time and equipment standardized test setups like SS-EN 50200 or IEC 60331-11 could not be designed. Because of that there are some components that are not the same in the experimental setup and the setups referred to in the standards. For example, no propane burner was used and the orientation of the cables was not the same. Nevertheless, some of the parameters listed in the standards are the same as in the experimental setup that was used. For example, the nominal temperature, the length of the cable, measuring the maximum attenuation, using the nominal wavelength of operation and so on. Despite the fact that the chosen fire setups is different, methane burner used in standards and ethanol vessel used in experiments; the heat release is about the same. The fire used in the experiments produces a heat release of approximately 1-2 kW, this is a very small fire that creates almost no turbulence and quite low flame temperatures. Real fires are much larger, even in their growth phase, which creates a lot more turbulence and higher flame temperatures due to re-radiation and self-heating. Because of this reason it becomes slightly difficult to predict what will happen in a real fire scenario and how this will affect the fiber optic cables. To draw further conclusions more experiments have to be conducted in future work.

Another error source was the difference in the runtime of the experiments compared to the runtime recommended in the standards. In the standards the minimum runtime is a lot longer than the runtime that was used in these experiments. The reason for not having longer runtimes in the experiments is because of the designated receiver of this report, i.e. ESS. The experimental setup was designed as a real scale test for real applications, with fires in the developing stage instead of in the fully developed stage. The fires that could emerge in ESS have also been assumed to be local and with small ignition sources and thus shorter burning times.

An additional error source is that there was not time to repeat all the experiments several times to validate the output data. Longer cables should also have been acquired to get better use of the OTDR device; the device became slightly redundant because of this. Other than this there are very few error sources, the premises were the experiments took

place was in a controlled environment and the measuring faults from the devices are within the designated margin of error.

6.3 Interpretations of standards

One of the major issues that needed to be answered before this thesis began was whether fiber optic cables could be used in nuclear power plants or other facilities that are dealing with nuclear radiation. This concern originated from rumors going around in the nuclear community saying that fiber optic cables were not safe to use in these types of facilities. But after literary studies of American, Swedish, European and international standards it became clear that the statement, is not supported by the standards. According to both the American IEEE 384 and the SS-EN 60709 standards it is possible, and in many ways preferred, to use fiber optic cables over traditional cables. SS-EN 60709 states, "Fiber optic communications provide a very effective means of achieving electrical isolation and should be applied wherever practical" (SEK Svensk Elstandard, 2012). In this context it should mean that fiber optic cables is a safe and reliable means of communication with negligible probability of failure modes occurring. This interpretation is also supported by output data derived from the experiments that has been conducted in this report. Another conclusion that can be drawn is that as long as the cables:

- Are not directly exposed to fire,
- Simultaneously not subjected to crushing or twisting force,
- And the mechanical and thermal stresses are handled in an appropriate way,
- As well as installed according to the guidelines recommended in standards, such as IEEE 384 and IEEE 1428,

there should be no large risk for the use of fiber optic cables in nuclear power plants or other facilities that are dealing with nuclear radiation.

6.4 Previous work

As stated earlier in this report, there are not many articles, reports or experiments conducted in this particular field of work. Those that were found during the literary studies are listed in chapter 4. If the studies that has been done to ordinary cable, in the *NUREG-2128 report* and the *SP report 2001:36*, are compared to studies that has been done to fiber optic cables. It can be concluded that ordinary cables have a much higher frequency of error and damage occur at a relatively low temperatures compared to fiber optic cables. Both the *SP report 2000:24* and the *IWCS report on Fire resistant optical cable* confirms that statement as well as the conclusions that has been drawn from the experiments conducted in this report.

In the *IWCS report Changes of transmission parameters of various types of cables during fire* it is stated that fiber optic cables are not as good as coaxial cables. This conclusion was based on the attenuation levels in the fiber optic cables being over the defined damage limit for 11 out of 24 fibers (one cable contained 24 fibers) in their experiment. The damage limit for the fiber optic cables was decided to be 33 dB/100m. The authors' conclusions are based on the change in capacity, for the coaxial cable versus the fiber optic cable, over the course of their 90-minutes long experimental runtime. However, after 30 minutes, it is only four fibers that have a higher attenuation level than the defined damage limit. Which translates to a capacity change of 17% according to the damage

criteria. Compared to the coaxial cable that has a change of 14% at this time. Due to this fact it is tough to draw the conclusion that the coaxial cable is better than the fiber optic cable, even though it is true ever so slightly. It is also hard to compare different types of cables as they are constructed of different kinds of cladding and isolation materials.

Despite the IWCS report most of the other reports and experimental findings in this thesis support the statement that fiber optic cables should be reliable under fire conditions when tested according to standards.

6.5 Other observations or findings

In this report no damage limits has been defined, the reason for this is that the measuring unit that was used in the experiments was dB/fiber. Available damage limits have the unit dB/1000m or dB/100m. Because none of them are of the same unit as the unit that was used in the experiments the available damage limits could not be used.

One of the aspirations in the beginning of the work was to develop a computational model for fiber optic cables that would predict when a critical point was reached in the signal transmission that would lead to communication failure modes. After the experiments had been conducted it was obvious that it would take further testing and experimentation to be able to develop such a model. The reason being is that as long as the fiber core is stable and is not exposed to external forces it can withstand normal fire conditions. The main reason for this seems to be the high melting temperature of the fiberglass, 2000 °C, which is a much higher temperature than a normal fire could develop i.e. 900-1200 °C (Drysdale, 2008, p. 169). But there are many uncertainties in that statement and further experiments are needed to investigate these findings.

Another way of developing a computational model could be to calculate the different melting temperatures and decay properties of the materials that the fiber optic cable consists of. But this also needs more testing and experimentation to determine exactly when the fiber core becomes too fragile to withstand external forces. It would also be hard to develop a model that takes into account all possible fiber optic cable configurations.

6.6 Research questions

In chapter 1.3 a couple of research question were asked. During the course of this work some of them have been answered, some of them have not and some of the questions have changed in meaning. This chapter answers the research questions.

- *Can data transfer in fiber optic cables be ensured when they are exposed to fire conditions? If not, after how long will data transfer stop?*

This question cannot be answered with the findings from this report. The reason for this is that the devices used in the experiments only measured the attenuation of the light in the fibers and not the quality of the data that was transferred. To do this, another type of measuring device would be needed. However, from the

experiments it was observed that no attenuation in the fibers was measured as long as no external forces was applied. This is probably because of the fibers very high melting point, see chapter 6.5.

- *In SS-EN 60709 it says that fiber optic cables are an effective way off achieving electrical isolation. Does this mean that there will be no communication failure modes when the cables are exposed to fire conditions?*

This question is addressed in chapter 6.3. The conclusion is that fiber optic cables are a safe and reliable means of communication with negligible probability of failure modes occurring. This interpretation of “electrical isolation” is also supported by output data derived from the experiments that has been conducted in this report.

- *Are there any other standards that mention the use of fiber optic cables and if so, what do they recommend?*

The answer is yes, for instance IEEE 384 and IEEE 1428. As SS-EN 60709, they also recommend the usage of fiber optic cables in facilities that require a high level of safety. For more information see chapter 3 and chapter 6.3.

- *Is conventional fiber optic cable good enough when exposed to fire or are fire-classified cables needed to ensure that the data transfer is not affected?*

As long as standards and the other regulations are followed there should be no need to use fire-classified cables. For more information see chapter 6.1 and chapter 6.3.

7. Conclusions

There are some conclusions that can be drawn from this report after analyzing the experimental results and comparing them to recent standards. The key information that was obtained from the experiments was the difference in fragility of the fiber when exposed to fire conditions compared to normal conditions. The fiber becomes very susceptible to external forces, mechanical and thermal stresses when it is heated or after it has cooled down. It was found that the fiber was especially susceptible to crushing or twisting forces. However as long as the fiber is placed on a flat surface, as in the cone calorimeter experiments and no other external forces are at work, there should be no complications to continuous use of the fiber. Previously reports conducted in this field also support this statement.

Another conclusion that can be drawn is that as long as the cables:

- Are not directly exposed to fire
- Simultaneously not subjected to crushing or twisting force
- And the mechanical and thermal stresses are handled
- As well as installed according to the guidelines recommended in standards.

there should be no large risk for the use of fiber optic cables in nuclear power plants or other facilities that are dealing with nuclear radiation. However this is based on the information obtained in this thesis.

Furthermore, it is concluded that more work and experiments are needed to derive a valid computational model such as for electrical cables that can predict critical temperatures or conditions for fiber optic cables subjected to fire conditions. It could then be used in real life applications or models to investigate when fiber optic communication failure modes occur.

8. Suggestion of future work

Further studies and experiments are needed to develop a valid computational model that can predict critical temperatures or conditions for fiber optic cables subjected to fire conditions. The same study might also be able to derive critical damage limits applicable with fiber optic cables. There are several approaches to derive the critical damage limits; one way is to examine the temperature and conditions of the fiber optic cables. Another way is to examine attenuation values linked with transmission performance in the fiber optic cables. If a computational model such as for electrical cables could be developed it would be of great assistance in predicting critical time and distances for fiber optic cables when conducting fire safety evaluations.

Another aspect that would be interesting to further investigate is how much of the data transfer are corrupted or lost when the attenuation increases. This would have to be done with some other kind of measuring device not used in this report, since the OPM and OTDR are unable to do that.

In addition it would be useful to investigate the phenomenon that creates mechanical and thermal stresses during heating and cooling of the fibers. This would also have to be done with further testing and experimentation.

The experiments that were conducted in this report were only done a few times and further testing and repetition of the experiments are needed with longer runtimes to further reinforce the conclusions. It would also be useful to conduct experiments on other types of fiber optic cables as well as with other types of experimental setup scenarios. Experiments with longer distances of cables being exposed to fire would also be interesting to investigate and how the longer distance would affect phenomena such as mechanical and thermal stresses as well as attenuation.

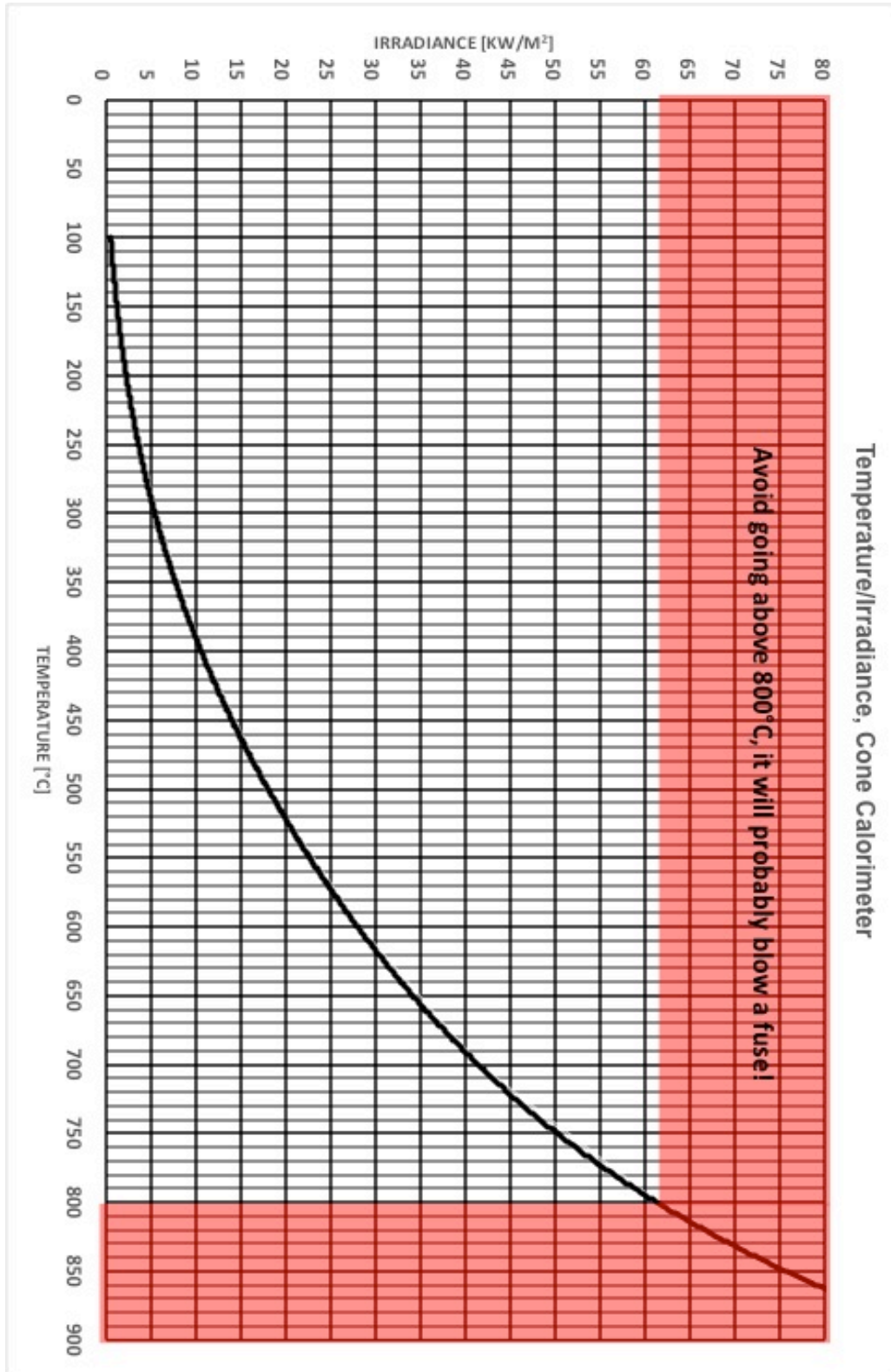
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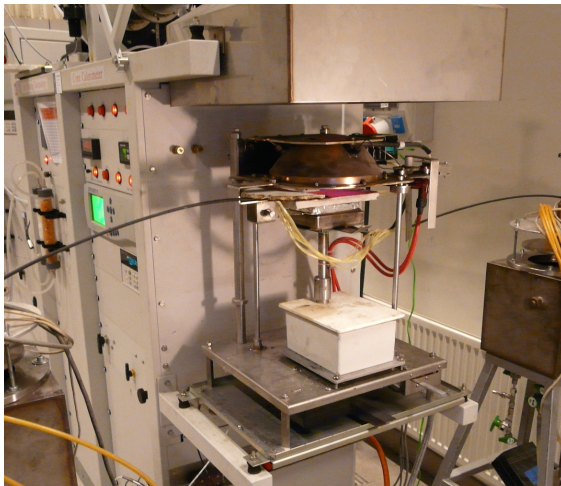
Appendix

Different appendices are presented below.

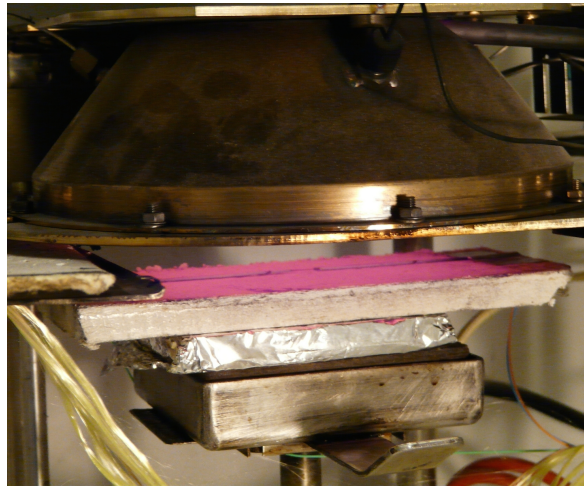
Appendix I, Cone calorimeter chart, temperature vs. irradiance



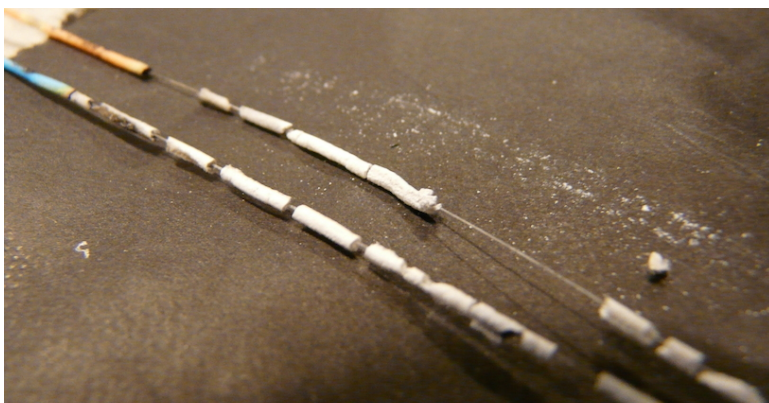
Appendix II, experiment pictures



Cone calorimeter experiment



Free burning experiment, standard setup (left picture), cable bundle setup (right picture)



Fiber after the experiment

