

Pyrotechnically Generated Aerosols ability to extinguish cable fires

Marco de Pedis
Oskar Jonsson

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

**Brandteknik
Lunds Tekniska Högskola
Lunds Universitet**

Report 5441, Lund 2013

This report was sponsored by

NBSG & X-fire

Pyrotechnically Generated Aerosols ability to extinguish cable fires

*Marco De Pedis
Oskar Jonsson*

Lund 2013

Title

Pyrotechnically Generated Aerosols ability to extinguish cable fires

Authors

Marco De Pedis
Oskar Jonsson

marco.depedis@gmail.com
oskar.jonsson.oj@gmail.com

Report

5441

ISSN

1402-3504

ISRN

LUTVDG/TVBB-5441-SE

Number of pages: 35

Keywords

PGA, Pyrotechnically Generated Aerosols, suppression, electrical fire, cable fire, high risk facilities, decision tool.

Abstract

This study aimed to evaluate the use of Pyrotechnically Generated Aerosols in electrical fires. To represent a common starting point for these fires, a cable fire ignited by a shortcut was chosen. In order to do this in a realistic way, a new method with heating the cables from the inside was used. This study examined whether the PGA has the ability to suppress a cable fire inside an electrical cabinet and how the PGA activation affects the pressure in the compartment. It was found that PGA grenades can be used to extinguish a cable fire inside an electrical cabinet. It was also found that more grenades are not always better and that simultaneous activation is not recommended. The method regarding heating cables from the inside was shown to be both repeatable and reliable.

The authors are responsible for the content in the report.

© Copyright: Department of Fire Safety Engineering and Systems Safety, Faculty of Engineering, Lund University, Lund 2013

Brandteknik och Riskhantering
Lunds Tekniska Högskola
Lunds Universitet
Box 118
221 00 Lund

brand@brand.lth.se
www.brand.lth.se

Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Department of Fire Safety Engineering and
Systems Safety
Lund University
P.O. Box 118
SE-211 00 Lund, Sweden

brand@brand.lth.se
www.brand.lth.se

Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

Acknowledgement

There are a number of people, which have made it possible to complete this study. We want to give our most sincere thanks to the following:

Stefan Svensson - *Associate professor, Department of Fire Safety Engineering LTH, supervisor*

Tommy Magnusson - *Senior Specialist Fire protection/Nuclear safety Ringhals AB, external supervisor*

Fredrik Carlstein - *Internal rescue officer Ringhals AB*

Richard Qvarfell - *X-fire*

Sven-Ingvar Granemark - *Research engineer, Department of Fire Safety Engineering LTH*

Patrick van Hees - *Professor, Department of Fire Safety Engineering LTH*

Claudio de Pedis - *Mechanical Engineer at WesternGeco*

Peter Jonsson - *Electrical maintenance engineer at OKG*

Acronyms

IRSN – The French institute for radiological protection and nuclear safety (Institut de Radioprotection et de Sûreté Nucléaire)

LTH - Lund institute of technology (Lunds Tekniska Högskola)

NBSG - *National fire safety group* with representation of Strålsäkerhetsmyndigheten (SSM), Svenskt Kärnbränsle (SKB) and the nuclear power plants in Forsmark, Oskarshamn and Ringhals

PE - Polyethylene

PGA - Pyrotechnically Generated Aerosols

PVC - Polyvinyl chloride

SP – Technical research institute of Sweden (Sveriges Tekniska Forskningsinstitut)

Summary

It is well known that fires can cause a threat to persons in its vicinities. But sometimes the suppression of the fire is in itself dangerous. This is the case when dealing with fires in electrical components where suppression puts personnel in risk of getting electrocuted. As an alternative to commonly used methods, *pyrotechnically generated aerosols* (PGA) can be used to suppress or even extinguish the fire. The advantage of these grenades is that no person has to be present in the compartment during the suppression of the fire.

This study aimed to evaluate the use of PGA grenades in electrical fires. To represent a common starting point for these fires, a cable fire ignited by a shortcut was chosen. In order to do this in a realistic way, a new method with heating the cables from the inside was used. The aim with this study was to investigate whether the PGA has the ability to suppress a cable fire inside an electrical cabinet and how the PGA activation affects the pressure in the compartment. Furthermore, the aim was to examine if it was possible to ignite cables in a repeatable and reliable way by adding heat from the inside.

The following major conclusions were made in this study.

- **PGA grenades can be used to extinguish a cable fire inside an electrical cabinet.**
PGA can fill a room and ventilated cabinets in a fast and efficient way. As long as oxygen can enter to sustain the fire, aerosols will enter to suppress it. PGA extinguishes cable fires at an early stage, even at concentrations well below the recommended.
- **More grenades are not always better, simultaneous activation is not recommended.**
Due to the higher temperature rise and pressure build up inside a compartment after activation, it is not recommended to activate multiple grenades simultaneously. In ordinary ventilated compartments, the pressure build up will not cause a threat to the construction. Nevertheless, the user should be aware that both fumes and aerosols will be pushed into adjacent compartments through ventilation or other leakages. The extinguish efficiency will not always gain from more grenades in smaller compartments.
- **Cable fire testing by heating cables from the inside is both repeatable and reliable.**
This method is a good alternative to other methods of initiating cable fires. It replicates a real shortcut, which the standard method does not.

To attain the conclusions presented above two types of tests were conducted, cable set-up tests and full scale PGA tests. The objective with the cable set-up test was to evaluate the method and prepare a cable bundle for the full scale tests. This was done by heating the cable bundle with a kanthal wire placed in the centre of the bundle. The full scale PGA tests were conducted in a 20 ft. ISO container in which an electrical cabinet containing the cable bundle was placed. Due to both product malfunction and the human factor two grenades did not activate during the tests. Therefore two out of four tests only contained half the recommended concentration of aerosols.

In this study it is shown that PGA grenades can, in an efficient way, be used as an alternative to other extinguishing methods in electrical fires.

Swedish Summary

Det är välkänt att bränder kan utgöra fara för personer. Dessutom kan även själva släckningsarbetet av branden utgöra en risk, till exempel när det handlar om spänningssatta komponenter. Här kommer Pyrotekniskt Genererade Aerosoler (PGA) in som ett bra alternativ till vanliga släckmetoder. Dessa kräver inte att man befinner sig i det brandutsatta utrymmet eller att den exakta positionen av branden är lokaliserad.

Detta arbete avsåg att utvärdera användandet av PGA-granater i elektriska bränder. En kabelbrand, initierad av en kortslutning, valdes för att representera en vanlig antändningskälla för dessa bränder. För att kunna skapa en realistisk kabelbrand togs en ny metod fram där kablarna värmdes upp inifrån. Målet med arbetet var att utreda huruvida PGA har möjlighet att begränsa en kabelbrand inuti ett elskåp och hur PGA påverkar trycket i utrymmet. Vidare skulle testmetoden för kabelbränder utföras för att undersöka om metoden var repeterbar och pålitlig.

Nedan följer de huvudsakliga slutsatserna från arbetet.

- **PGA-granater kan användas för att släcka kabelbränder i elskåp.**
Aerosolerna fyller ett rum och ventilerade utrymmen snabbt och effektivt. Så länge syre kan tränga in till branden för att upprätthålla den, kommer PGA att tränga in för att motverka densamma. PGA släcker en brand snabbt efter aktivering, även om koncentrationen är väl under den rekommenderade.
- **Fler släckgranater är inte alltid bättre, samtidig aktivering är inte rekommenderad.**
Med tanke på temperaturökning och tryckupbyggnad inne i ett utrymme efter aktivering är samtidig aktivering av flera granater inte att rekommendera. I vanliga ventilerade utrymmen kommer tryckupbyggnaden inte att utgöra ett hot mot konstruktionen. Dock bör användare vara medveten om att både brandgaser och aerosoler kommer att tryckas ut i angränsande rum genom ventilationsöppningar och andra läckage. Släckförmågan gynnas således inte alltid av fler granater.
- **Kabeltester som initieras av en uppvärmning inifrån är både repeterbara och pålitliga**
Den framtagna metoden visade sig vara ett bra komplement till andra metoder. Den simulerar en brand startad av en kortslutning vilket andra metoder inte gör.

För att erhålla de slutsatser som presenterats ovan gjordes två typer av tester, kabeltester samt fullskaliga PGA-tester. Målet med kabeltesterna var att utvärdera metoden samt att förbereda en kabelbunt inför PGA-testerna. Detta gjordes genom att värma upp kablarna med en kanthaltråd som monterats centrerat i en kabelbunt. De fullskaliga testerna gjordes i en 20 fots ISO container där ett elskåp innehållande kabelbunten placerades. Till följd av produktfel och handhavandefel aktiverade inte två av de granater som användes i testerna. Därför innehöll två av testerna bara halva den rekommenderade koncentrationen av aerosoler.

Arbetet visade att PGA-granater kan, på ett effektivt vis, användas som ett alternativ till andra släckmetoder i elektriska bränder.

Table of Contents

1	Introduction	1
1.1	Background	1
1.2	Purpose	1
1.3	Objective	2
1.4	Delimitations	2
2	Method.....	3
3	Previous research.....	5
4	Theory	7
4.1	Pyrotechnically Generated Aerosols	7
4.2	Cable types	9
5	Test setup.....	11
5.1	Cable set-up test	11
5.2	Full scale PGA tests	13
6	Results	17
6.1	Cable set-up test	17
6.2	Full scale PGA test	20
7	Discussion	27
7.1	Cable set-up test	27
7.2	Full scale PGA test	28
8	Conclusion.....	31
9	Further research.....	33
10	References	35

1 Introduction

1.1 Background

Fires in electrical components can cause a big threat to the safety in high-risk facilities. The fact that it has potential to destroy vital equipment calls for an early suppression. Many extinguishing methods may however put personnel in danger, since a person has to be close to the fire in order to suppress it with e.g. a portable fire extinguisher (Magnusson et al. 2006). The use of water in these environments is also a problem since water conducts electricity and therefore put the user at risk of getting electrocuted (Särdqvist, 2006).

An alternative method to the conventional extinguishing systems is *pyrotechnically generated aerosols* (PGA). PGA does not require a person to be present in the fire compartment during the suppression of the fire. The risk of getting electrocuted is therefore reduced.

One study conducted with PGA contains full-scale experiments with electrical cabinets including a heptane pool fire (Ekström and Nilsson, 2009). This report showed that the PGA penetrates the electric cabinet in an efficient way to put out a pool fire inside an electrical cabinet in almost every test set. The problem regarding the ventilation conditions in electrical cabinets is mentioned in another report, by IRSN, which concludes that ventilation openings had a great impact on the heat release rate (Casselmann et al. 2004).

There has not been any research done that includes the extinguishing ability of PGA during a cable fire inside an electrical cabinet. A fire in an electrical cabinet can involve energized electrical equipment in which electrical current can supply the fire with energy (Linteris, 2009). A likely fire scenario is a shortcut inside a cable bundle, which leads to a temperature rise (Keski-Rahkonen and Mangs, 2002). This temperature rise can act as an ignition source to a full-developed cable fire (Linteris, 2009).

The standard test procedure to ignite a cable bundle is to use a propane burner as a pilot flame and thus create a cable fire using external heating (SP, 2013). When using this standard test method it is not taken into account that a shortcut leads to heating from the inside.

A more extensive description of previous researches is presented in chapter 3.

1.2 Purpose

This study aims to evaluate how PGA affects a cable fire in an electrical cabinet. The purpose is to increase the knowledge about the use of PGA during electrical fires.

This study is the examination part of the bachelor degree in fire protection engineering at Lund institute of technology (LTH), Sweden. Therefore the aim is also to apply the knowledge that has been obtained during the past three years of education.

1.3 Objective

The objective of this study is to investigate if PGA can be used to extinguish a cable fire in an electrical cabinet and if it is possible to ignite cables in a repeatable and reliable way by heating them from the inside. This study aims to be a tool in the decision process of whether to use PGA for suppression in electrical fires.

1.3.1 Research Questions

The following questions are examined in this study.

- Does PGA have the ability to suppress a cable fire inside an electrical cabinet?
- How does the PGA affect the pressure in the compartment?
- Is it possible to ignite cables in a repeatable and reliable way by adding heat from the inside?

1.4 Delimitations

The following are considered to be outside of the scope of this study.

Neither the ventilation in the electrical cabinet nor the ventilation in the compartment is varied in this study. One cable set-up and one type of PGA are examined. Furthermore, the effect of PGA to humans, animals and environmental is not taken into account in this study.

2 Method

This study has been conducted by cable set-up tests and full scale PGA tests. This choice of method is made based on the absence of previous research done in these specific areas.

Cable set-up tests were selected to gather information regarding the behaviour of a cable fire that has been heated from the inside. These cable fire tests should be seen as a preparation to the full-scale PGA test, as it was meant to prepare a premade test set-up and collect information regarding temperature rise and time to ignition. Full-scale PGA tests were made to evaluate the ability to suppress the cable fire inside an electrical cabinet and register the pressure build up caused by the PGA.

The test procedure of heating a cable bundle from the inside is carried out as an alternative way of initiating a cable fire. The aim with this test set-up is to create a realistic cable fire that is difficult to suppress due to the heating inside the cable bundle. The test set-ups are described further on in this report.

In order to obtain this report, the study was divided into different steps. The first one was to gather information regarding previous research in the specific area and this was done by literature search. After this, the tests were conducted. The cable set-up tests were carried out in the fire laboratory at Lund institute of technology and the full scale PGA tests were carried out at Ringhals nuclear power plant. After these tests, the results were interpreted and discussed which led to the conclusion of this study.

3 Previous research

Extinguishing fires with PGA

The research that has been carried out in this area involves extinguishing a heptane pool fire inside an electrical cabinet with PGA (Ekström and Nilsson, 2009). It was showed in this report that the PGA suppress a fire under these conditions in all tests except one. The location of the fire and the PGA-generator affected the outcome, and it was showed that the ventilation conditions also affected the extinguishing ability. However, these tests did not include cable fire, which is why the study presented in this report focuses on cable fire. Ekström and Nilsson (2009) also conducted tests regarding pressure build up and it was shown that it did not affect the construction in a significant way. This test was conducted in a small-scale test set-up, and that is why the study in this report examines the pressure build up inside a full-scale room.

In *An Evaluation of Aerosol Extinguishing System for Machinery Space Applications* (Back et al. 2009) the United States Coast Guard preformed full-scale fire tests. It turned out that the aerosols had the ability to suppress a Class B fire (pool fire) in an efficient way, but only one out of 14 Class A fire (wood cribs) was extinguished (Back et al. 2009). It should be noticed that this test set-up involves fire where the aerosol had direct impact, there were no obstacles present. To investigate the aerosols ability to penetrate smaller openings, the fire in this study is placed inside a cabinet.

Fire in electrical cabinet

Tests have been carried out to determine the heat release rate of electrical cabinet (Keski-Rahkonen and Mangs, 1996). The heat release rate in this report was determined to a maximum value of 200 kW. The ignition source in this test set-up was a propane burner, which led to a direct influence of the flames to the cable bundle. This is, however, the standard test procedure of cable fires which generates an external effect on the cables. The test set-up can be found on SP website (SP, 2013).

A report, written by IRSN, presents a number of parameters that affects the heat release rate. The parameter that had the most influence on the heat release rate was the configuration of the ventilation-openings, in the matter of size and position (Casselmann et al. 2004).

Extinguishing agent

A report, written by Linteris (2009), was aimed to put together a method to determine the amount of extinguish agent needed to suppress fires in energized electrical equipment (Linteris, 2009). The main issue regarding suppressing this kind of fire is when electrical energy is still being added to the combustion. This will occur e.g. when the current into an electrical cabinet is not turned off. In this report (Linteris, 2009) several previous researches are presented. Some previous work reproduced the failure mechanisms, e.g. shortcut, to simulate an authentic electrical fire. Other reports used external energy source such as external heat flux generator or high resistance wire in order to represent energy input into an electrical device.

4 Theory

4.1 Pyrotechnically Generated Aerosols

Aerosols used for fire suppression are created in two ways, the dispersion method and the condensation method. To create dispersion aerosols, small particles are created mechanically from a solid or liquid and suspended in a gas. The particles used for fire suppression are typically in the range of $10^{-9} - 10^{-3}$ meters in diameter. In the other method, the condensation method, a solid is combusted to create the aerosols. Aerosols created by the condensation method are also called *pyrotechnically generated aerosols* (PGA) (Kangedal et al. 2001). This study will only focus on PGA.

PGA are created by the combustion of a solid. This solid usually consists of salt, e.g. potassium nitrate (KNO_3), diluent and resin as binder. The salt is placed in a generator and can be used in a grenade or mounted in a fixed generator to be placed on any surface, see Figure 1 and Figure 2. During combustion, the salt reaches high temperatures, generally over 1000 Kelvin, and therefore needs to be cooled before leaving the generator. Magnesium- or aluminium oxides are commonly used to cool the aerosols due to their high melting point and heat capacity. These metals are placed as small spheres near the exit which forces the combusted salts to pass through them. The spherical shape increases the surface area and thus makes it easier to absorb heat. The high melting point of these materials prevents them from melting and therefore stops the flow of the aerosols. This could otherwise lead to a rapid rise of pressure, which in worst case could lead to an explosion. When the generator is activated the aerosols pass through the cooling unit and a barrier of filters before leaving the generator. In addition to the aerosols many gases are produced during the combustion. The gases mostly consist of nitrogen and oxygen but also smaller amounts of carbon dioxide, carbon monoxide and hydrocarbons (Kangedal et al. 2001).

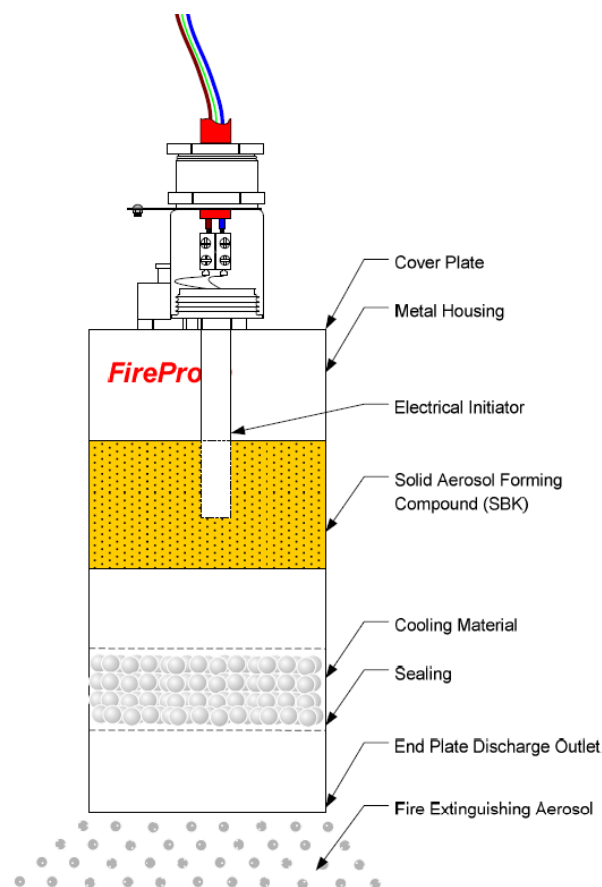


Figure 1. Cross-section of a FirePro- PGA grenade (FirePro 2011)

4.1.1 Extinguishing factors

The fire-extinguishing mechanisms of PGA are heat absorption and chemical interference (Jacobson, 2011). Both these mechanisms depend on the surface area of the aerosols particles. A smaller particle distribution gives a larger total surface area given a fixed volume. This makes it easier for the particles to absorb heat and react, which is more efficient for fire suppression (Kangedal et al. 2001). Different fuels require different amounts of extinguishing agent for suppression. As it is also dependent on the volume of the enclosure, the amount of agent needed is described as a concentration (g/m^3). *FirePro* recommends a concentration of $64,74 \text{ g/m}^3$ when suppressing electrical fires (FirePro, 2011).

4.1.2 PGA grenades

In this study PGA grenades by *FirePro* are used, but the theory is similar comparing to other brands. Figure 1 shows a cross-section of a PGA grenade made by FirePro with a single discharge outlet. The grenade can be activated in three different ways: by applying a given voltage to the live parts, removing the safety pin or by a temperature sensitive glass bulb. The grenades used in this study are activated by removing the safety pin. The combustion starts 5-10 seconds after activation (FirePro 2011).



Figure 2. PGA grenade (left) and a fixed PGA generator (right) (FirePro 2011)

4.2 Cable types

EKK

This cable has a rated voltage of 300/500 Volt and is named according to the Swedish standard SS 424 17 01 (Svensk Elstandard, 2003). The equivalent name for this cable, using the European standard *CENELEC*, is S05VV-U.

This cable consists of five solid copper-cores, each with a cross section area of 1,5 mm². The insulation and jacket are both made from PVC (Svensk Elstandard, 2003). The outer diameter of the cable measures 11,6 millimetres. Figure 3 shows a cross-section of an EKK-cable. This cable type is flame retardant and meets the IEC 60332-1 standard (Amokabel, 2013).

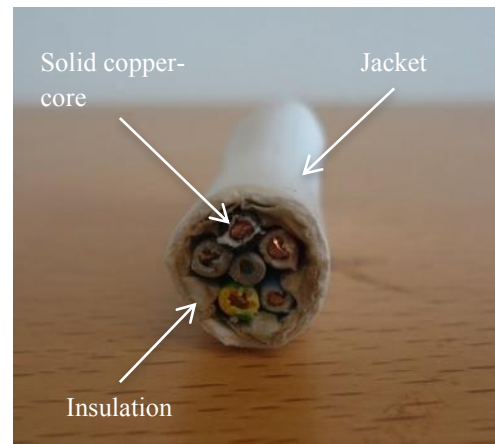


Figure 3. Cross-section of an EKK-cable

ELLY

ELLY is the name according to the Swedish standard SS 424 16 75 (Svenska Elektriska Kommissonen, 2002). ELLY cables are used underground for telecommunication.

This cable consists of four solid copper cores, each with a cross section area of 0,6 mm². The insulation and jacket are both made from polyethylene (PE). The outer diameter of the cable measures 6,5 millimetres. This cable type is not flame retardant (Ericsson AB, 2013). Figure 4 shows a cross section from an ELLY cable used in the tests.

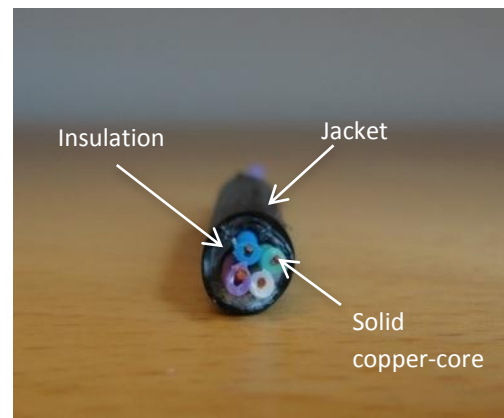


Figure 4. Cross-section of an ELLY-cable

Table 1 shows a specification of the cable types used in this study.

Table 1. Cable specifications.

	ELLY (Ericsson AB, 2013)	EKK (Amokabel, 2013)
Insulation material	Polyethylene (PE)	Polyvinylchloride (PVC)
Jacket material	Polyethylene (PE)	Polyvinylchloride (PVC)
Outer cable diameter	6,5 mm	11,6 mm
Linear density	3,9 kg/100m	21,0 kg/100m
Conductor	Solid copper	Solid copper
Number of conductors	4	5
Conductor area	0.6 mm ²	1.5 mm ²

5 Test setup

The following is a description of the test set-up for the cable fire and the full-scale PGA test regarding the extinguishing ability.

5.1 Cable set-up test

In order to create a cable fire by heating the cables from the inside, a test rig was made. The test rig was constructed of a threaded rod, size M10, which was connected to a car battery (12 V). Between the two threaded rods a 10-centimetre EKK cable was mounted with a kanthal wire twined around. This is presented in Figure 5. The kanthal wire was 50 centimetres long and one millimetre in diameter.

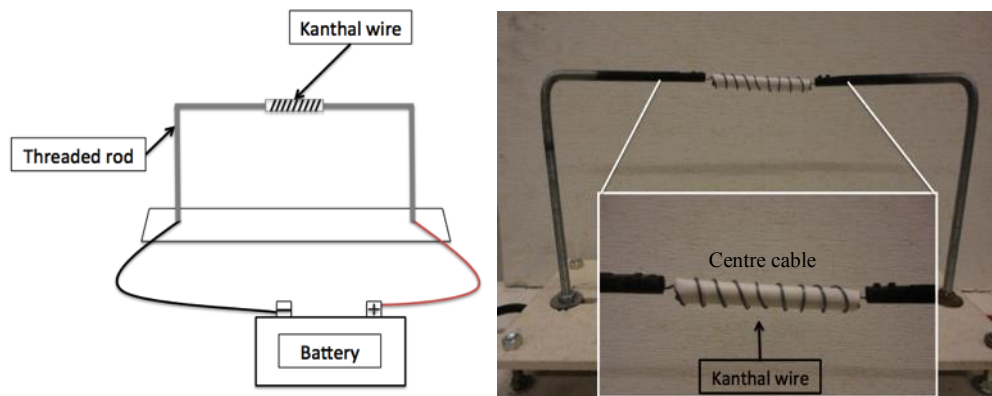


Figure 5. Test rig set-up

To be able to measure the temperature inside the cable bundle, a thermocouple was placed under the kanthal wire, as seen in Figure 6.

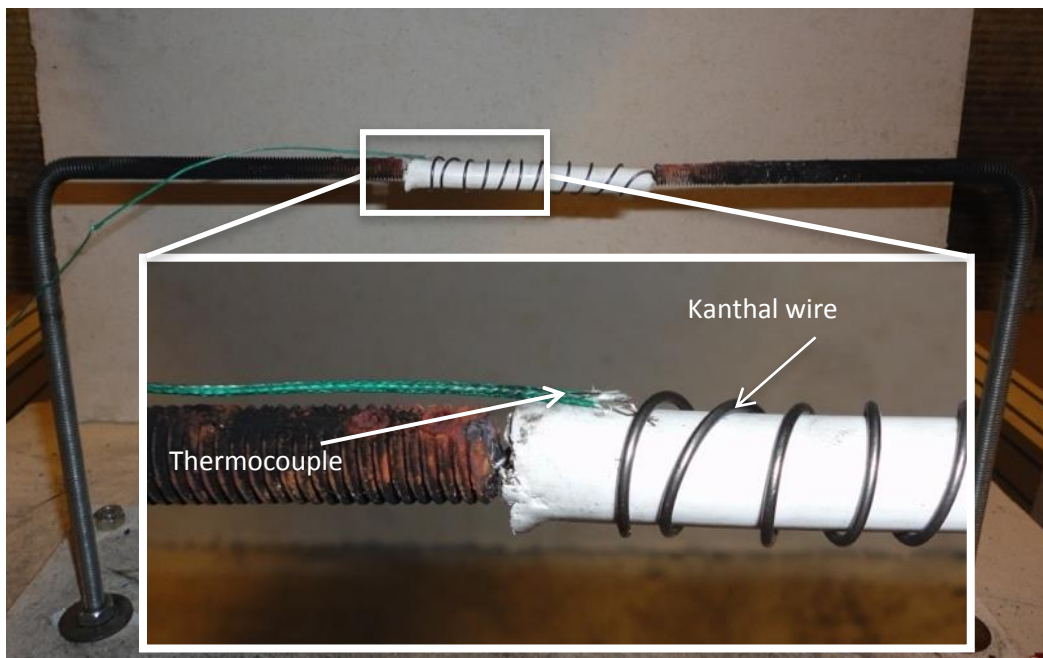


Figure 6. Picture of the thermocouple placement in the test rig.

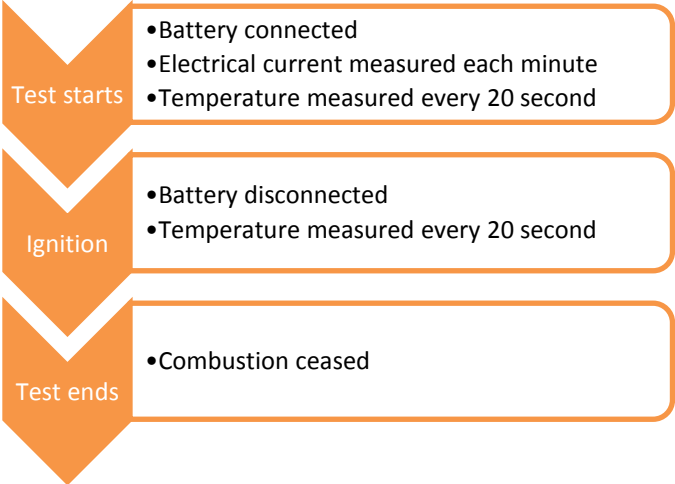
Eight ELLY cables were put together, around the rods and the EKK cable, using plastic cable ties. ELLY cables were chosen because of the lack of fire retardant in this cable type. Two aluminium containers were placed under the cable bundle to keep the melting polyethylene close to the cable bundle and therefore be able to contribute to the heating. Tests with only EKK cable were conducted, as a pre-test, but no self-sustaining fire was achieved due to the fire retardant in these cables. However, EKK cable was used as the centre cable because it made the kanthal wire stay in place during the whole test due to the fire resistance in this type of cable.



Figure 7. The test rig

5.1.1 Test procedure

The test procedure of the cable set-up test in chronological order is shown below. This procedure was repeated four times with each test named A-D.



5.2 Full scale PGA tests

The full scale tests of the PGA grenades were divided into two major steps. The first one was a reference test to examine how the enclosure behaved, in terms of temperature and pressure, when no grenades were used. The second one was carried out to investigate how the PGA affected the cable fire and the enclosure.

5.2.1 The enclosure

The full scale tests were carried out in a standardized 20 ft ISO container. On the inside of the container an inner wall had been constructed using aluminum studs, insulation and fireproof gypsum boards. This made the total volume inside of the container 27 m^3 . Figure 8 shows a sketch of the container. The door shown in the picture led out to another, open, container which will be treated as ambient air. A pre-test showed that the door had to be open during the heating phase in order to supply enough oxygen to create a cable fire inside the electrical cabinet. As the cargo opening had been shut by the inner wall, one of the cargo doors were held open to enable cables to pass through it. Both containers had a water seal which were linked through a pipe under the containers. The water seal in the test container was filled with water to stop gases and aerosols from exiting this way. There were also a small hole in the wall next to the cabinet for pressure measurement. A thermocouple, *thermocouple 4*, was placed at two meters height between the door and the cabinet.

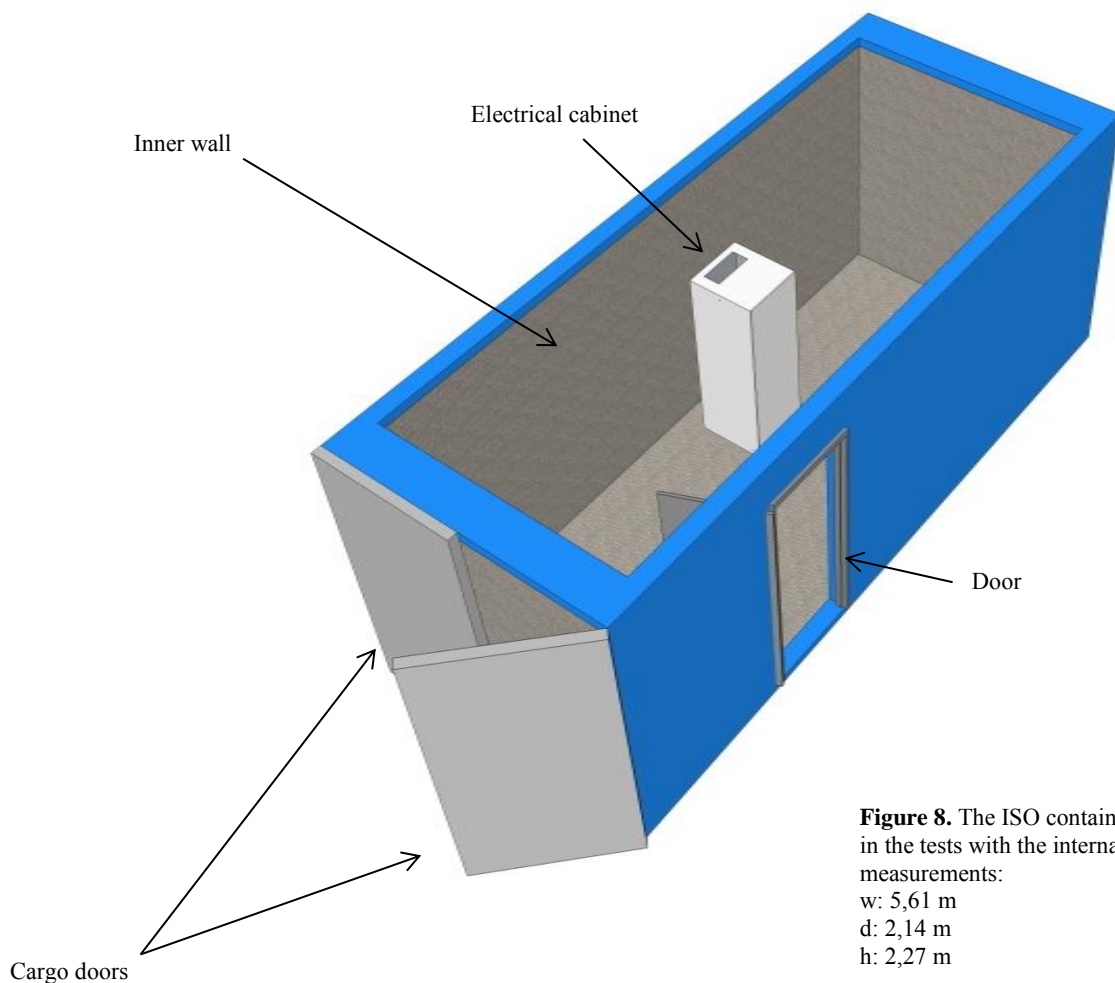


Figure 8. The ISO container used in the tests with the internal measurements:
w: 5,61 m
d: 2,14 m
h: 2,27 m

5.2.2 The electrical cabinet

The cabinet used in the tests was designed to replicate a common electrical cabinet. It was constructed using steel plates with a rebar grid in the center to hold the cable test rig described in chapter 5.1. Figure 9 shows a sketch of the cabinet. The choice of ventilation conditions in the electrical cabinet was based on the report *Electrical ignition sources in nuclear power plants* (Keski-Rahkonen and Mangs, 2002). Therefore the cabinet had two ventilation openings, one at floor level measuring 40x2 centimeters and one at the top measuring 40x15 centimeters.

Thermocouples were placed at the ventilation openings, the upper one called *Thermocouple 1* and the lower one called *Thermocouple 2*, shown in the figure. *Thermocouple 1* was used for measuring the temperature of the fumes exiting the cabinet and to monitor when the cables ignited. *Thermocouple 2* was used for measuring the temperature of the air and aerosols entering the cabinet. *Thermocouple 3* was placed in direct contact with the kanthal wire. This thermocouple was used for comparison with the cable set-up test to see how the different conditions affected the heating.

5.2.3 The grenades

The grenades used in these tests were *FP-1000M* by *FirePro* which carry 1000 grams extinguishing agent. The minimum design application density for electrical fires of these grenades were $64,74 \text{ g/m}^3$ (FirePro, 2011). Since the volume of the container was 27 m^3 , two grenades were needed to obtain the required concentration. This resulted in a total concentration of 74 g/m^3 extinguishing agent.

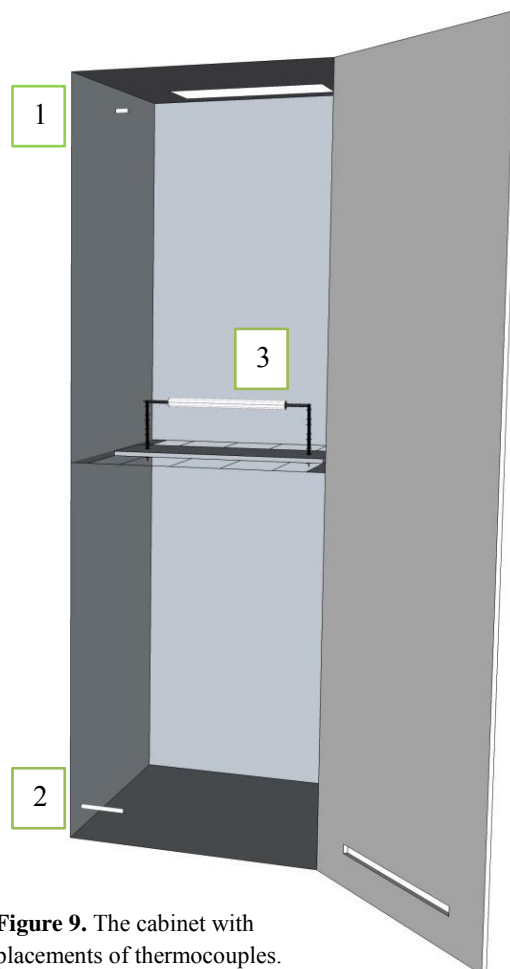
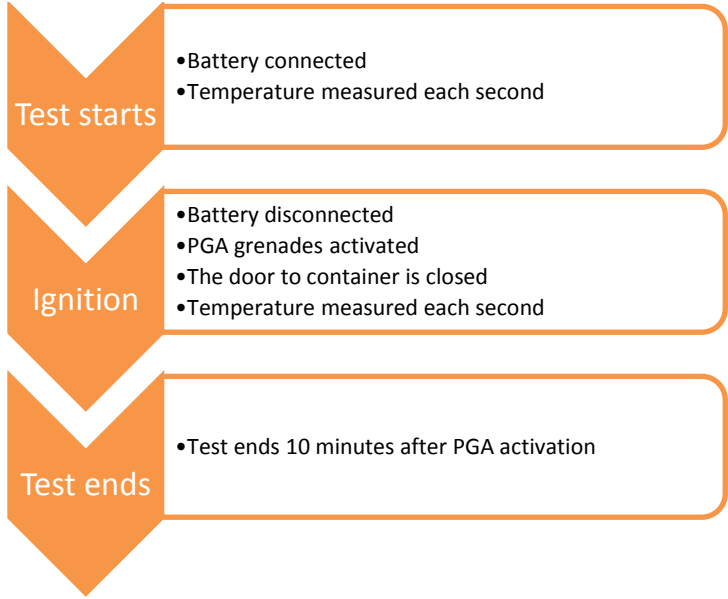


Figure 9. The cabinet with placements of thermocouples.
The cabinet had the measurements:
w: 0,55 m
d: 0,59 m
h: 1,68 m

5.2.4 Test procedure

The tests with the grenades were divided into three steps.



A reference test was conducted using the same steps as above but without PGA grenades, called *test 0*. This was made for comparison with the other tests to see how the grenades affected the temperatures and pressure in the container and electrical cabinet.

Two grenades were used in the tests. The grenades, named *Grenade 1* and *Grenade 2*, were placed in front of the cabinet as shown in Figure 10. Two cameras were placed in front of the grenades to be able to monitor their behavior after activation. A third camera was placed on the floor inside the cabinet to capture the flow of aerosols into the cabinet.

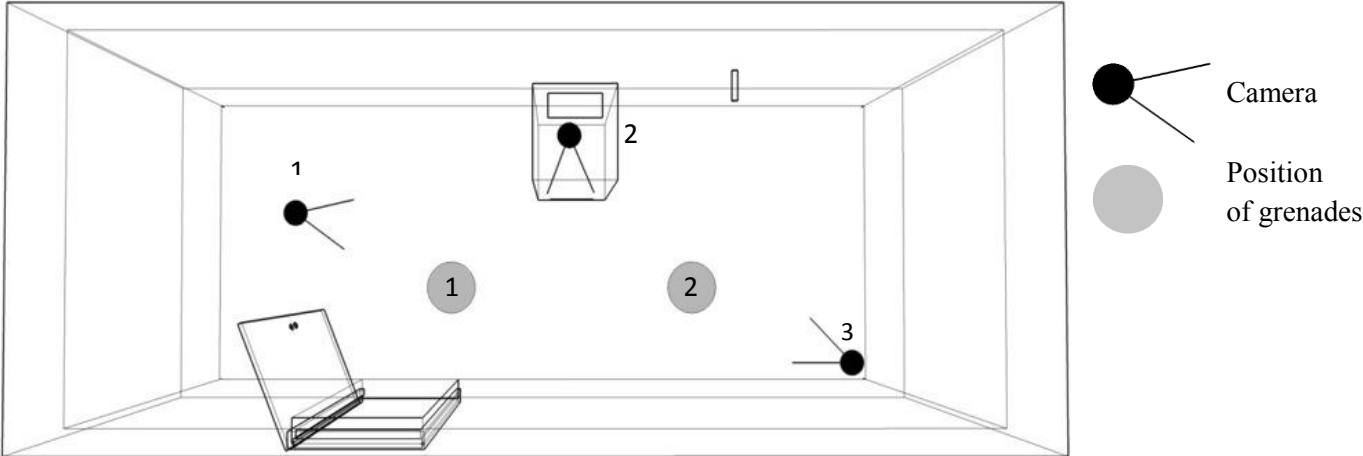


Figure 10. Grenade- and camera positioning inside the container

6 Results

The results from both the cable set-up tests and the full-scale PGA tests are presented in this chapter.

6.1 Cable set-up test

The major results from the tests are listed below.

- The fire is able to sustain itself after ignition without any heat being added
- The cables ignited when the inner temperature of the bundle reached about 730 °C
- A fragment of the PE melted and caused a pool fire
- Combustion ceased after 14 minutes
- Average power input was 220-250 Watts

6.1.1 Phases

From the measurements of temperature over time, three phases of the fire were found.

- **Heating phase.** Represents the time from when the heating of the cables starts until the time when the cable bundle is ignited.
- **Burning phase.** Represents the time from when the bundle is ignited until the time when it reaches a peak in temperature.
- **Decay phase.** Represents the time after the second peak in temperature until there are no visible flames.



Heating phase

Ignition



Burning phase

6.1.2 Temperature

The maximum temperature in all the tests was found at the point where the cables ignited. The ignition of the cables were instantaneous and could with ease be distinct from earlier, smaller, flames. The ignition temperature varied between 660 °C and 770 °C. Figure 11 shows a graph of the temperature as a function of the time from the four tests.

When the battery was connected a rapid increase in temperature occurred. This is explained by the direct contact between the thermocouple and kanthal wire.

After ignition the battery was disconnected which lead to a drop in temperature. This temperature drop is shown in the figure as the start of the burning phase. At the end of this phase the temperature reaches a new peak. This took place at the time when the plastic cable ties melted and openings between the cables occurred. This allowed more air, and thus more oxygen, to be present in the combustion, which can explain this rise in temperature. At this point the entire bundle was burning and a large amount of PE had formed a pool fire in the aluminium containers.

After the second peak in temperature, most of the combustible material in the cables had either been melted or combusted, the combustion only continued in the containers below. Since there were no more drops being added, the area of the pool fire declined.

The moments for different events during the tests are presented in Table 2.

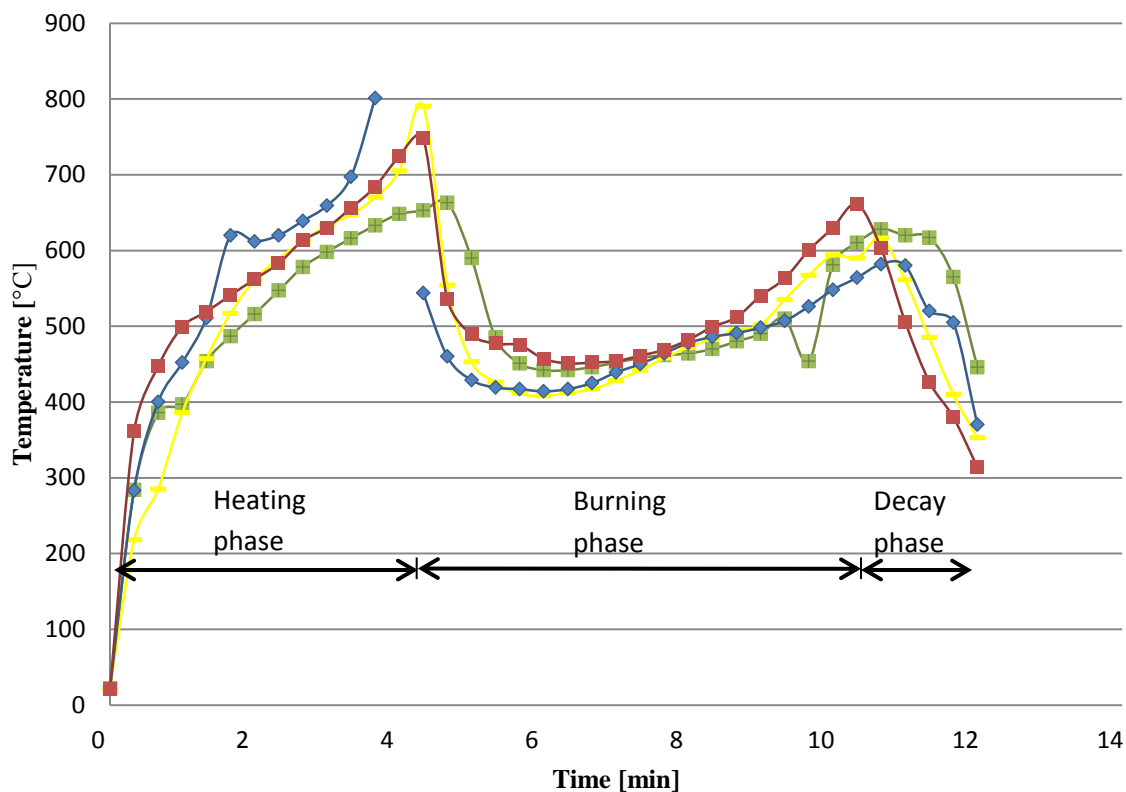


Figure 11. Shows the inner temperature of the cable bundle as a function of time.

Table 2. Results from cable set-up tests

	A	B	C	D	Average
Time to drops forming [min:s]	3:45	3:40	3:20	3:40	3:35
Time for visible flames [min:s]	4:40	4:15	6:40	4:15	4:20
Time to ceased burning [min:s]	12:50	14:15	15:10	12:00	14:00
Temperature when flames occurred [°C]	660	770	-	740	725

6.1.4 Power input

In this section the power input to the kanthal wire is presented. The voltage output from the battery was 12 V and the current in the circuit was measured with a clamp multimeter.

The power input into the kanthal wire and the temperature are presented Table 3. The decrease of power during the tests is explained by the temperature rise in the kanthal wire. This temperature rise led to an increase of the resistance in the circuit, which led to a decrease in current and therefore a decrease in power (Borgström et al. 1996).

Table 3. Power input and temperature of the kanthal wire

Time [min]	A		B		C		D	
	Temp. [°C]	Power [W]	Temp. [°C]	Power [W]	Temp. [°C]	Power [W]	Temp. [°C]	Power [W]
0	20	247	20	251	20	253	20	250
1	400	227	390	234	450	238	500	235
2	520	226	560	234	610	238	560	234
3	600	224	630	234	660	236	630	234
4	650	223	710	234	-	238	720	238

6.2 Full scale PGA test

The major results from the full-scale PGA tests are listed below.

- The cable fire was extinguished shortly after the grenades were activated, even when half the recommended concentration was used
- The overpressure could reach 4,7 kPa when the grenades activated. This was enough to push water through the water seal in the test container and into the adjacent container
- Due to the human factor and product malfunction, two grenades did not activate
- The grenades did not move after activation
- A fluid with a texture similar to oil was found on the surfaces inside the container

6.2.1 Observations

In *test 1* and *test 2*, only one of the two grenades activated. In *test 1* the safety pin did not come out when the big metal ring was pulled. Instead the smaller ring broke which left the safety pin still in place as seen in Figure 12. In *test 2* both grenades safety pins were removed correctly but due to an unknown product malfunction, one of the grenades did not activate.



Figure 12. Not activated PGA grenade. Before and after.

In *test 3* both grenades activated one second apart. This led to a high pressure build up inside the container which caused the wall towards the cargo opening to collapse as seen in Figure 13. One of these cargo doors had been left open during the tests to enable cables to be led through it. For pressure measurements this door was closed before the last test.



Figure 13. Collapsed inner wall at cargo opening

The aerosols spread in the container and electrical cabinet just a few seconds after activation. This can be seen in Figure 14. As seen in these pictures, the aerosols penetrate the electrical cabinet in an early stage.

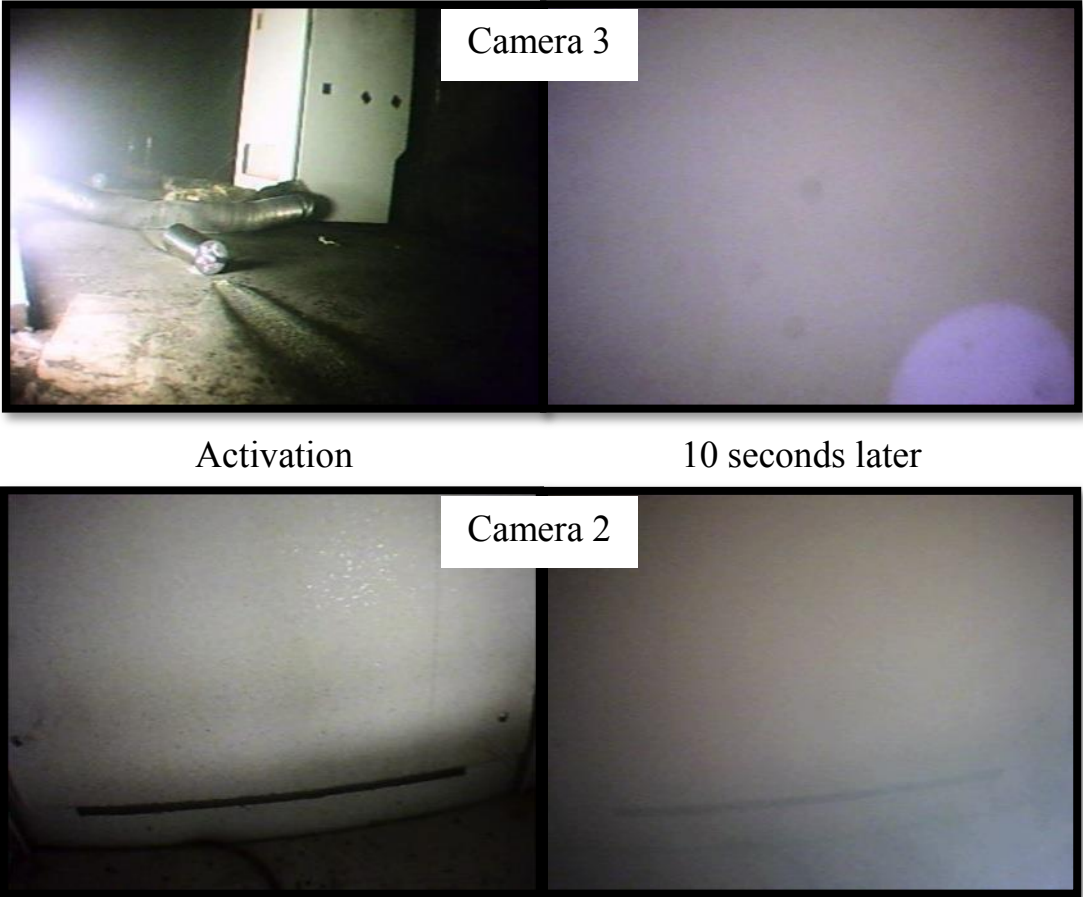


Figure 14. This figure shows how the aerosols quickly spread in the container and cabinet. After 10 seconds the visibility was close to zero.

As seen in Figure 15, the grenade was intact and did not move during or after activation.



Figure 15. Grenade after usage

Table 4 shows a summary of the observations from the different tests.

Table 4. Summary of tests

Test	Number of PGA grenades activated	Comment
0	0	Control test
1	1	Human factor causes one grenade not to activate
2	1	Product malfunction causes one grenade not to activate
3	2	Wall collapsed
4	2	Water in the water seal was pressed out

6.2.2 Temperature

In this section the results from the thermocouples are presented.

In Figure 16 the temperatures of *Thermocouple 1* are presented for each test. The time zero in this figure has been set as the time of ignition of the cables. This thermocouple was placed five centimeters below the ceiling in the electrical cabinet. As seen in Figure 16 the temperature in the electrical cabinet is reduced when the PGA grenades are activated. The peak in temperature approximately one minute after ignition occurs due to the temperature of the aerosols.

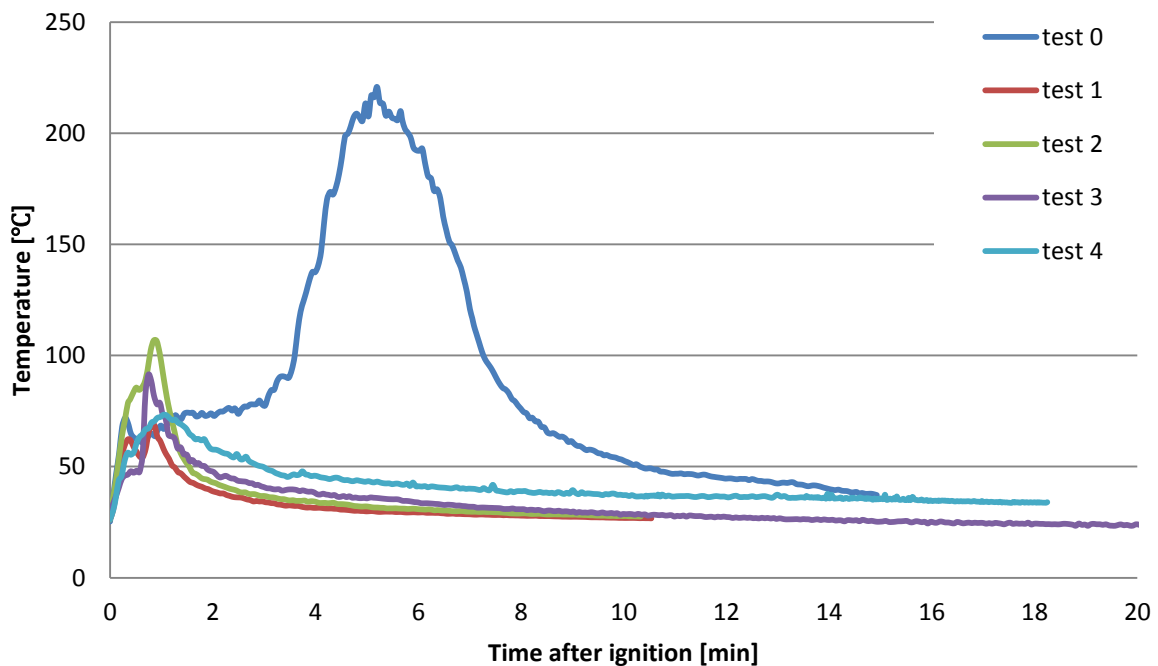


Figure 16. Temperature profile of *Thermocouple 1* after ignition of the cable bundle

In Figure 17 below, temperatures from each test are presented for *Thermocouple 2*. The time zero in this figure has been set as the time of ignition of the cables. This thermocouple was placed five centimeters above floor level inside the electrical cabinet, close to the lower ventilation opening. The figure shows that the temperature increases when the PGA grenades are activated. It also shows a difference in temperature between the tests when two grenades activated (*test 3 and test 4*) and the tests when one grenade was activated (*test 1 and test 2*). There was a small increase in temperature in the control test without PGA grenade activation, *test 0*.

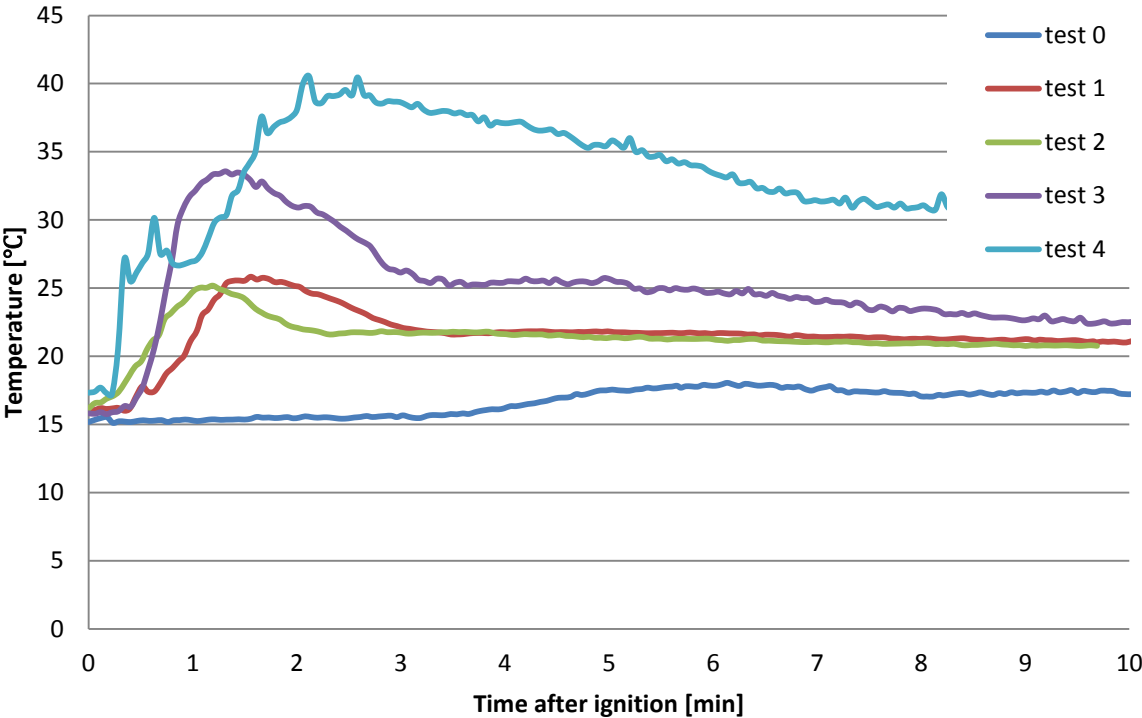


Figure 17. Temperature profile of *Thermocouple 2* after ignition of the cable bundle

In Figure 18 below, the results from *Thermocouple 3* is presented. Only *test 0* is presented because this test can be compared to the temperature profiles from the cable set-up tests. The time zero in this figure has been set as the time when the battery was connected.

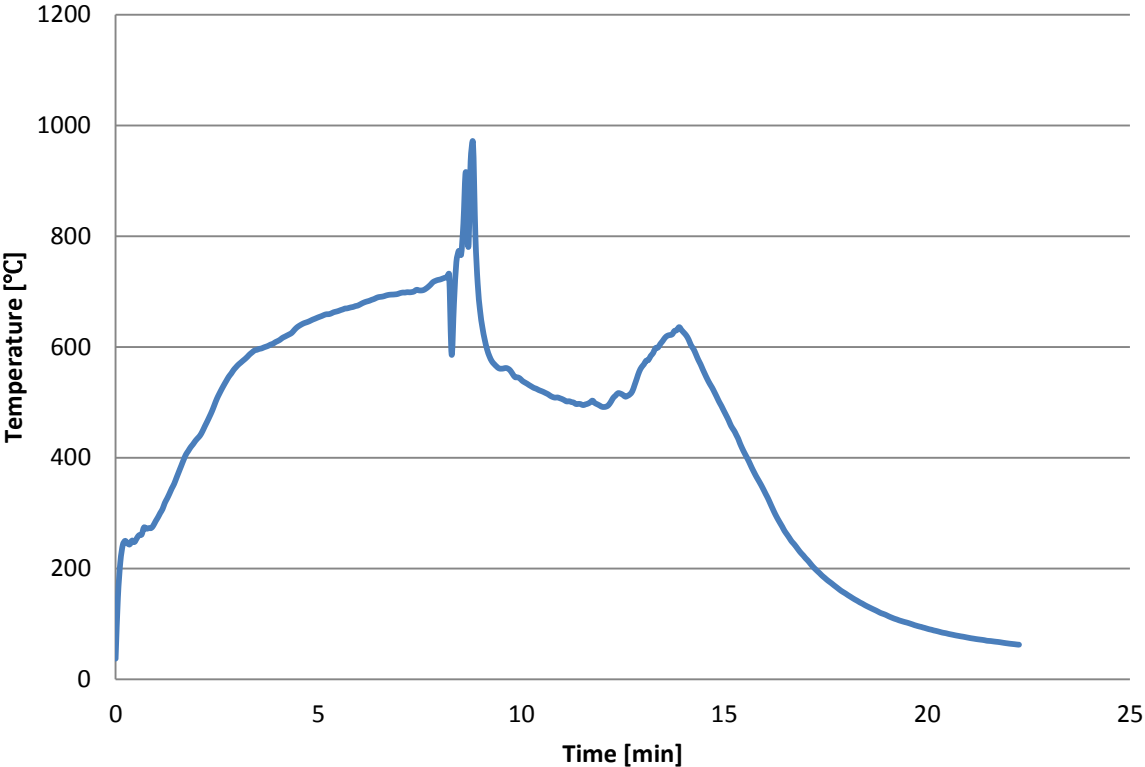


Figure 18. Temperature profile of *Thermocouple 3* during *test 0*, control test

In Figure 19 the temperatures of *thermocouple 4* are presented for each test. The time zero in this figure has been set as the time of ignition of the cables. This thermocouple was placed inside the container, two meters above floor level. The behavior of the temperature in this thermocouple is similar to *thermocouple 2*, which is presented above. There is a difference between the tests where two grenades activated (*test 3 and test 4*) and the tests where one grenade was activated (*test 1 and test 2*). *Test 3 and test 4* reach a higher temperature than *test 1 and test 2*, which is most likely explained by the number of grenades used in the different tests. During the control test, *test 0*, a small increase in temperature was noticed, which also is similar to the temperature behavior in *thermocouple 2*.

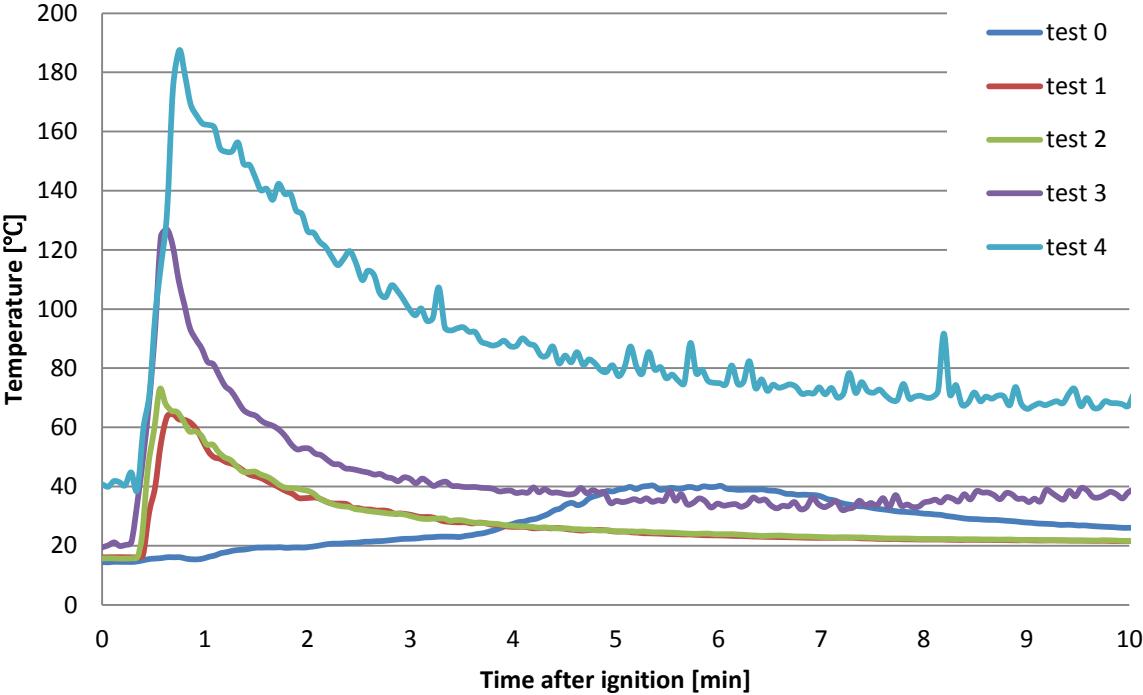


Figure 19. Temperature profile of *Thermocouple 4* after ignition of the cable bundle

6.2.3 Overpressure

In this section the overpressure inside the container during PGA activation is presented.

As seen in Figure 20 below, there is a difference between overpressure in the tests. There is a higher overpressure in *test 4* compared to *test 1*, *test 2* and *test 3*. This is explained by the fact that in *test 1* and *test 2*, one grenade was used. During *test 3*, the wall collapsed which is why the pressure rise in this test is smaller compared to *test 4* although two grenades were used in both these tests.

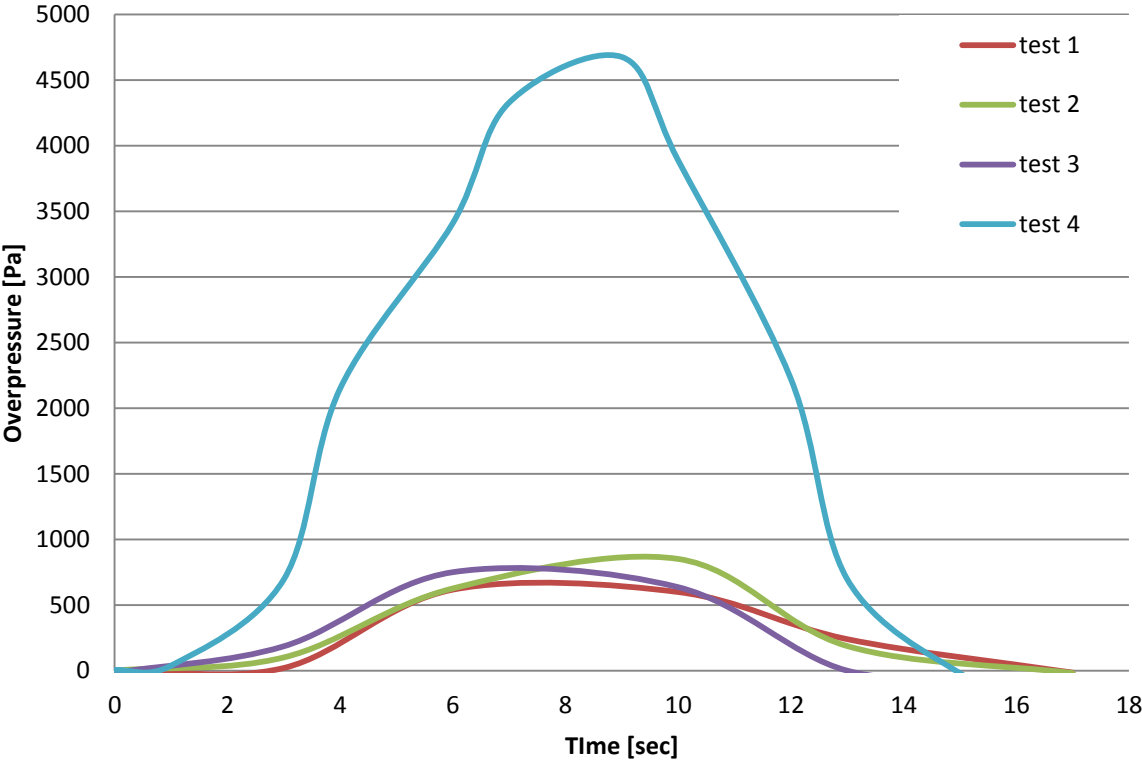


Figure 20. Overpressure in the container during activation of the PGA grenades

7 Discussion

The discussion below is divided into the cable set-up tests and the full scale tests.

7.1 Cable set-up test

One of the questions asked in this study was whether it was possible to ignite cables in a repeatable and reliable way by adding heat from the inside. The cable set-up tests showed that it was. All the graphs of the temperature showed similar results and the time for ignition did not vary significantly. Even when the conditions changed from testing inside without air restrictions to outdoors in cold and humid weather inside of a cabinet, the method worked in a repeatable way, which is seen Figure 21. The only significant difference was that the ignition got delayed in the full scale tests, probably because of the lower air temperature and oxygen restriction in the cabinet.

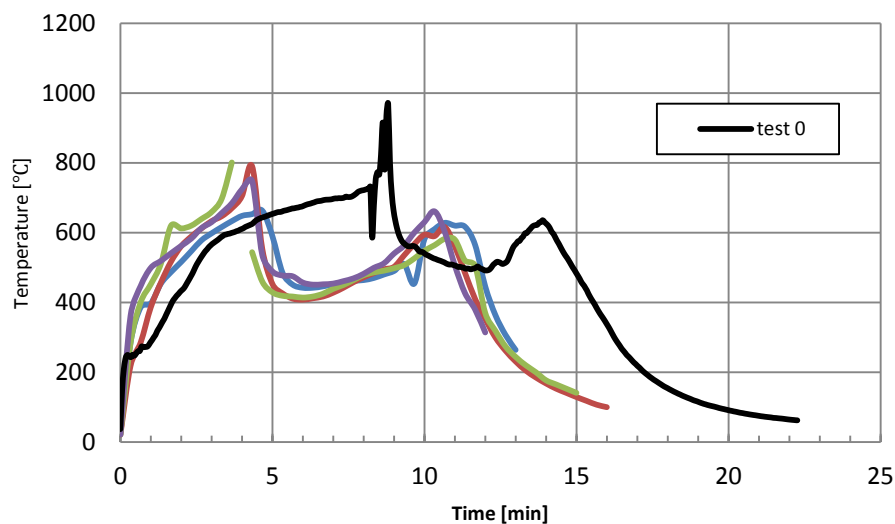


Figure 21. Comparison of outdoor cable reference test and indoor cable set-up tests

The biggest problems in the cable tests were to get the cables to burn. Many cables nowadays are fire-resistant and will not burn without external heat being added. Therefore telecommunication cables for undergrounding were used due to their absence of fire retardant additives. As the main focus was to create a cable fire, this cable type was chosen even though indoor usage is unlikely.

7.2 Full scale PGA test

7.2.1 Suppression

The results from the full scale PGA tests showed that the PGA extinguished the fire. The temperature in the upper layer of the cabinet declined after the grenades activated in relation to the reference test where the temperature continued to rise. When looking at the cable bundle after a PGA test it is clear that the burning stopped shortly after the cables had started melting, as seen in Figure 22. This and the fact that the cables melted at around 40 seconds before ignition, proves that the fire extinguished shortly after the grenades were activated. This fast and effective suppression of the cable fire indicates that PGA grenade not only can extinguish this small fire but also most likely reduce and delay a larger fire.



Figure 22. Extinguished cable bundle

A problem that occurred during this study was whether the aerosols would be able to enter the cabinet at all. This was of course required for any suppression of the fire. The penetrability into the cabinet was dependent of the ventilation conditions, which therefore needed to be determined. This study chose the ventilation openings based on a previous report, *Full scale fire experiments on electronic cabinets II* (Keski-Rahkonen and Mangs, 1996), as no other standards for fire tests in electrical cabinets were found. After examining the pictures from the camera inside the cabinet it was found that the aerosols entered the lower opening, just a few seconds after the grenades were activated. Other constellations with different ventilation positions and areas would probably not affect the PGA:s ability to suppress the fire. However, as long as oxygen can enter to sustain the fire, aerosols will enter to suppress it, at least in these volumes. Smaller openings will not worsen the fire since it was shown by IRSN that the heat release rate depends greatly on the ventilation (Casselmann et al. 2004).

7.2.2 Overpressure

There was a difference between the tests regarding overpressure. The difference between *test 4* and the other tests with PGA grenades is most likely explained due to the fact that the cargo door was closed. As described in the test set-up, the container was insulated with fireproof gypsum boards and insulation material, which made the container almost airtight. The only major available exit for the aerosols in *test 4* was the water seal. In ordinary compartments, the overpressure is not expected to be as high as 4,7 kPa due to the higher leakage area in these compartments compared to the container used in the tests. Therefore the overpressure should not be of concern when using PGA grenades in ordinary compartments with normal leakage areas and ventilation. However, the pressure build up

might result in fumes and aerosols being pushed into adjacent rooms through ventilation and leakages. This makes it inefficient to activate multiple grenades at once.

7.2.3 Activation time

In this study, the grenades were activated 15-20 seconds after ignition of the cables. This time period was chosen since the focus was to study the extinguishing ability when a cable fire has arisen. In real scenarios the time when the grenade would be activated depends on various factors e.g. the time to detection, how close personnel is to the fire and how they act after detection. Further research should be done to evaluate how the PGA grenades can affect different stages of the fire e.g. if they can prevent a cable fire to start if they activate during the heating phase.

7.2.4 Number of grenades

Due to both the human factor and product malfunction two of the tests only contained one grenade. Even though it was not optimal for the tests, it showed some interesting results. The use of recommended concentration (two grenades) did not extinguish the fire more rapidly than if only one was used. In fact, the only significant difference in temperature was that two grenades caused it to rise substantially more inside the container than when only one was used. The overpressure of the container was also a lot higher when two grenades were used. The temperature rise inside the compartment should be taken into account when using the PGA grenades, to avoid damaging vital equipment. A solution to this problem might be not to activate several grenades at once.

7.2.5 Malfunctioning grenade

One of the grenades did not activate because it had not been prepared correctly. The spring is divided into two metal strips, which are folded around the activator. These were not pushed together correctly before the metal ring was pulled out which led to the grenade not activating. A short manual on the grenade could prevent this, even though the user is supposed to have this knowledge.

In *test 2*, one PGA grenade that did not activate even though the spring was correctly removed. Despite this, the grenade did not function properly. The cause of this is not determined; it could be a manufacturing error or failure in arming the grenade.

7.2.6 Disconnection of the battery

When producing the cable fire in this study the battery was disconnected when the cables ignited. Disconnection of the battery was chosen to represent that a fuse blows or the power into the electrical cabinet is turned off. Shutdown of power input to the electrical cabinet or into the fire compartment is a common procedure in nuclear power plants (Magnusson et al. 2006). On account of that, disconnection of the battery then ignition occurred was chosen. Further research including how the extinguishing ability is affected if the power is not turned off is desirable.

7.2.7 Number of tests

The different PGA tests were conducted twice, two with one grenade activated (*test 1* and *test 2*) and two tests when two PGA grenades were activated (*test 3* and *test 4*). As seen in the result section, the temperature behaviour is similar between the tests with the same amount of PGA grenades activated. This similar behaviour in temperature indicates that the results from the tests are reliable and the margin of error is negligible.

7.2.8 Secondary effects

Secondary effects, damage to components and construction, must be taken to account. As described earlier in this chapter, the pressure rise in an ordinary compartment is not expected to be as high as 4,7 kPa due to higher leakage area in ordinary compartments compared to the container used in this study. Therefore, the secondary effects due to pressure rise are not seen as a risk. The grenade was intact and did not move during or after activation. This shows that there is no risk for damage due to moving grenades or fragmentation during or after activation, for these types of PGA grenades. It was also shown in this study that the temperature rise inside the compartment could be as high as 190 °C when two grenades activated. This temperature rise and the high temperature near the outlet of the grenades should be taken into account when using the grenades as this could damage components inside the compartment. The fluid with texture of oil that was fluid inside the compartment could cause secondary effects. This is, however, not proven and further research about this substance and how it affects components is desirable. One theory is that this fluid is created when the aerosols and water vapour in the air interact. This theory is based on the fact that the relative humidity during the test day was 80-100 % (2013-11-08, Ringhals, Sweden).

8 Conclusion

These conclusions are based on tests conducted under specific conditions. When the results from this study are taken to account, it is important to notice the specific requirements of different scenarios.

- **PGA grenades can be used to extinguish a cable fire inside an electrical cabinet.**
PGA can fill a room and ventilated cabinets in a fast and efficient way. As long as oxygen can enter to sustain the fire, aerosols will enter to suppress it. PGA extinguishes cable fires at an early stage, even at concentrations well below the recommended.
- **More grenades are not always better, simultaneous activation is not recommended.**
Due to the higher temperature rise and pressure build up inside a compartment after activation, it is not recommended to activate multiple grenades simultaneously. In ordinary ventilated compartments, the pressure build up will not cause a threat to the construction. Nevertheless, the user should be aware that both fumes and aerosols will be pushed into adjacent compartments through ventilation or other leakages. The extinguish efficiency will not always gain from more grenades in smaller compartments.
- **Cable fire testing by heating cables from the inside is both repeatable and reliable.**
This method is a good alternative to other methods of initiating cable fires. It replicates a real shortcut, which the standard method does not.

9 Further research

An evaluation of how PGA grenades can affect different stages of the fire should be made. Is it possible to prevent a fire by using PGA during the heating phase and how do they perform during a fully developed cable fire?

An investigation of how the extinguishing ability is affected if the power into the cabinet or the fire compartment is not turned off should be made. This will cause the heating to continue and therefore challenge the PGA. This can be the case when a fuse malfunctions or in scenarios where the power needs to be withheld.

A comparison of the method with heating the cables from the inside with other standard test methods should be conducted. This should evaluate the differences in heat release rate and fire behaviour between the methods. The method used in this study has potential to be an alternative to the standard methods.

Examine whether the PGA grenades create different by-products when they are used in different environmental e.g. humid weather. This includes an investigation of the fluid that was found inside the container. Under which circumstances does it appear and does it affect electrical components?

10 References

- Amokabel (2013). [Online]. *Building cables - EKK*. Last accessed 2013-10-03 at: www.amokabel.com
- Back, G. Beene, D. Boosinger, M. Forssell, E. Nash, L. Weaver, E. (2009). *An Evaluation of Aerosol Extinguishing Systems for Machinery Space Applications*. P 43-65.
- Borgström, Stig. Jönsson, G. Kullberg, R. (1996). *Elektricitetslära med tillämpningar*. Lund: Studentlitteratur.
- Casselmann, C. Mélis, S. Rigollet, L. Such, J.M. (2004) *Modeling of Electrical Cabinet fires based on the CARMELA Experimental Program*. Saint-Paul-lès-Durance: IRSN.
- Ekström, J and Nilsson, B. (2009). *Pyrotekniskt genererade aerosoler - experimentella studier med avseende på funktion och risker rörande människa och teknik*. Lund: Department of Fire Safety Engineering and Systems Safety, Faculty of Engineering, Lund University.
- Ericsson AB (2013). [online]. *Telecom Access Copper Pair Cables - Abonnentledning TEL 310 0706*. Last accessed 2013-10-03 at: www.ericsson.com/ourportfolio/telecom-operators
- Firepro (2011). *Information, instruction & user manual. Fire Extinguishing Aerosol Systems*. Cyprus, Firepro.
- Jacobson, E. *Powdered aerosols performance in various fire protection applications*. [online]. Last accessed 2013-10-11 at: http://www.nist.gov/el/fire_research/
- Kangedal, P. Hertzberg, T. Arvidson, M. (2001). *Pyrotekniskt genererade aerosoler för brandsläckning - en litteraturstudie*. Borås, SP.
- Karlsson, B and Quintiere, J. G. (1999). *Enclosure Fire Dynamics*. Boca Raton, CRC.
- Keski-Rahkonen, O and Mangs, J. (2002). *Electrical ignition sources in nuclear power plants: statistical, modeling and experimental studies*. P 209-221. Espoo, VTT Building Technology, Fire technology.
- Keski-Rahkonen, O and Mangs, J. (1996). *Full scale fire experiments on electronic cabinets II*. Espoo, VTT Building Technology, Fire technology.
- Lintieris, G.T. (2009). *Clean Agent Suppression of Energized Electrical Equipment Fires*. [online]. Last accessed 2013-11-20 at: www.nfpa.org
- Magnusson, T. Ottosson, J. Lindskog, B. Söderquist Bende, E. Eriksson, F. Haffling, S. (2006). *Bränder i driftrum*. Stockholm, Statens kärnkraftsinspektion.
- SP technical research institute of Sweden (2013). *Cable fire testing and research*. [online]. Last accessed 2013-09-04 at: www.sp.se
- Svensk Elstandard (2003). *Svensk Elstandard SS 424 17 01*. [online]. Last accessed 2013-09-19 at: <http://shop.elstandard.se>
- Svenska Elektriska Kommissionen (2002). *Svenska Elektriska Kommissionen SS 424 16 75*. [online]. Last accessed 2013-10-03 at: <http://shop.elstandard.se>
- Särdqvist, Stefan (2006). *Vatten och andra släckmedel*. Karlstad, Räddningsverket.