Fire Extinguishing in Complex Facilities

– A Study of Large Fire Extinguishing

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Abstract
This report analyzes fire extinguishing solutions that might cut time between fire alarm and fire extinguishing at the European Spallation Source. A special design fire with a very high peak heat release rate is used. The method used includes a literature study, meetings with supervisors and ESS representatives and participation in workshops and study visits. Some fire protection measures are already planned, but additional measures are investigated, namely automatic fire extinguishing systems and manual fire suppression. The conclusion of the report is that the time aspect is crucial and that combining different local automatic extinguishing systems with an on-site First Responder team might save crucial time. The team should be educated in firefighting, equipped with several fire suppression systems and have the possibility to use positive pressure ventilation. Also, some improvements for an intervention by the municipal fire brigade are presented.

Illustrations are made by the author if nothing else is specified.

The author is responsible for the content of this report.

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Preface

This project report is my last examination before becoming an actual Fire Protection Engineer. I would not have been able to do this work on my own, so I would like to thank the following people:

- **Fredrik Jörud** (European Spallation Source ERIC), for all meetings, discussions, provided information, workshops, study visits and more,
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Hampus Ragnar
Bodafors, December 2017

Summary

The European Spallation Source, ESS, will be the world's most powerful neutron source, where research in many different fields of science will be conducted. The ESS Fire & Explosion Safety Program endorses implementation of a defense in depth approach to prevent, quickly extinguish and prevent spreading of fires in the facility. Due to the facility's complex operation, there are some challenges concerning manual fire extinguishing procedures that requires research.

The objective of this report is to evaluate possible fire suppression solutions to cut time between fire alarm and successful fire extinguishing for a fire at ESS-facility. The method used to analyze the matter includes a literature study, meetings with ESS representatives and LTH supervisors and participation in workshops and study visits.

The study focuses on one representative design fire of up to 70 – 100 MW in the Instrument Hall, a 130 000 cubic meter compartment with a number of so called instrument caves, housing instruments where the neutrons from the spallation are applied to samples. Some of the instrument caves will be covered by radiation shielding of borated paraffin wax or polyethylene in large quantities, which create the potential great fire hazard. Some fire protection measures are currently planned, i.a. installing sprinkler in the Instrument Hall ceiling, which has been designed to suppress and limit the fire down to maximum 6 MW.

The large design fire can create problems concerning fire safety. A municipal fire brigade intervention might be possible, given the right conditions, but can be improved by e.g. adding points of access, enabling earlier smoke ventilation and good preparations. However, since the time aspect is crucial regarding fire extinguishing, faster firefighting alternatives have been evaluated.

To enable a faster fire suppression, one option is to install automatic fire suppression systems in some of the instrument caves to suppress fires locally. Suitable systems with pros and cons are presented in the table below.

Table showing pros and cons of different automatic fire extinguishing systems suitable for the ESS case.

System	Pros	Cons
Water mist sprinkler	• Multiple fire suppression mechanisms • Less water damage than e.g. conventional water sprinkler	• Might damage equipment • Possible flooding issues
Gas extinguishing system	• Clean • Little property damage	• Not very fast extinguishing • Problems when the instruments are being rebuilt
Foam extinguishing system	• Good against pool fires • Little water damage	• Environmental hazardous • Might damage equipment
Powder extinguishing system	• Effective against most fires • Fast extinguishing	• Might damage equipment, even outside the fire compartment • Consumed once deployed
PGA system	• Effective against most fires • Fast extinguishing • Does not damage low current circuits	• Might damage equipment, even outside the fire compartment • Consumed once deployed • Strongly reduced visibility

Another option is to enable a manual fire suppression by an onsite, ESS-employed First Responder educated in firefighting and equipped with suitable firefighting equipment, possibly accompanied by an additional First Responder as safety crew. The First Responder will not be allowed to perform smoke diving in dense smoke, but can perform a fire suppression effort from outside the fire compartment using a cutting extinguisher, or an internal fire suppression using a vehicle mounted high-pressure water suppression system, a portable fire extinguisher or an extinguishing grenade if the fire compartment conditions are safe enough. Positive pressure ventilation, PPV, could also be used to improve the conditions in the fire compartment enough to enable a safe internal intervention.

A combination of these systems and procedures would lead to a possibility to suppress a variety of fires faster than if only depending on an intervention by the municipal fire brigade, fulfilling the objective of the study, i.e. to find and evaluate faster alternatives to extinguish a fire at the ESS facility.

Swedish Summary

European Spallation Source, ESS, kommer att bli världens starkaste neutronkälla, där forskning inom många olika vetenskapsområden kommer genomföras. ESS:s Brand- & explosionssäkerhetsprogram stödjer genomförandet av ett ordentligt skydd för att förebygga, snabbt släcka och förhindra spridning av bränder i anläggningen. På grund av anläggningens komplexa verksamhet finns det vissa utmaningar när det gäller brandsläckningsrutiner som fordrar djupare studier.

Målet med denna rapport är att utvärdera möjliga brandsläckningslösningar för att förkorta tiden mellan brandlarm och lyckad brandsläckning vid en brand på ESS. Den metod som används för att analysera ämnet innefattar en litteraturstudie, möten med ESS-representanter och LTH-handledare samt deltagande i arbetsmöten och studiebesök.

Studien fokuserar på en representativ dimensionerande brand på upp till 70 – 100 MW i instrumenthallen, ett 130 000 kubikmeter stort utrymme med ett antal så kallade instrumentgrottor, inhysande instrument där neutroner från spallationen appliceras på prover. Några av instrumentgrottorna kommer att täckas av strålningsskydd av borerat paraffin eller polyeten i stora mängder, vilket skapar den potentiellt stora brandfaran. Vissa brandskyddsåtgärder är för närvarande planerade, bl.a. att installera sprinkler i instrumenthallens tak, vilket är dimensionerat för att kunna dämpa och begränsa branden ner till maximalt 6 MW.

Den stora dimensionerande branden kan skapa problem när det gäller brandsäkerhet. En insats av den kommunala räddningstjänsten kan vara möjlig med de rätta förutsättningarna, men kan förbättras genom att t.ex. lägga till fler angreppsvägar, möjliggöra tidigare brandgasventilation och goda förberedelser. Dock, eftersom tidsaspekten är kritisk gällande brandsläckning, har snabbare brandbekämpningsalternativ utvärderats.

Ett alternativ för att göra en snabbare brandsläckning möjlig är att installera automatiska brandsläckningssystem i några av instrumentgrottorna för att bekämpa bränder lokalt. Lämpliga system med för- och nackdelar presenteras i tabellen nedan.

Tabell som visar för- och nackdelar hos olika automatiska släcksystem som passar för ESS-fallet.

System	Fördelar	Nackdelar
Vattendimsprinkler	• Flera släckmekanismer • Mindre vattenskada än t.ex. vanlig vattensprinkler	• Skulle kunna skada utrustning • Möjliga översvämningsproblem
Gassläcksystem	• Renligt • Liten egendomsskada	• Inte särskilt snabb släckning • Problem när instrumenten byggs om
Skumsläcksystem	• Bra mot pölbränder • Liten vattenskada	• Miljöfarligt • Skulle kunna skada utrustning
Pulversläcksystem	• Effektivt mot de flesta bränder • Snabb släckning	• Skulle kunna skada utrustning, även utanför brandutrymmet • Förbrukat efter användning
PGA-system	• Effektivt mot de flesta bränder • Snabb släckning • Skadar inte svagströmskretsar	• Skulle kunna skada utrustning, även utanför brandutrymmet • Förbrukat efter användning • Kraftigt reducerad sikt

Ett annat alternativ är att möjliggöra manuell brandbekämpning av en ESS-anställd första insatsperson på plats som är utbildad i brandbekämpning och utrustad med lämplig släckutrustning, möjligen i sällskap av ytterligare en insatsperson som skyddsfunktion. Första insatspersonen kommer inte att få rökdyka i tät brandrök, men kan utföra en släckinsats från brandutrymmets utsida genom att använda en skärsläckare, eller en invändig släckinsats med ett fordonsmonterat högtryckssläcksystem, en handbrandsläckare eller en släckgranat om förhållandena i brandutrymmet är tillräckligt säkra. Övertrycksventilering kan också användas för att förbättra förhållandena i brandutrymmet tillräckligt för att möjliggöra en säker invändig insats.

En kombination av dessa system och procedurer skulle leda till en möjlighet att bekämpa flera olika bränder snabbare än om man endast är beroende av en insats av den kommunala räddningstjänsten, vilket uppfyller studiens mål, d.v.s. att hitta och utvärdera snabbare, alternativ att släcka en brand på ESS-anläggningen.

Abbreviations

CAFS.......................... Compressed air foam system

ERT........................... Emergency response team

ESS........................... European Spallation Source

HRR.......................... Heat release rate

LTH........................... Lunds Tekniska Högskola (The Faculty of Engineering at Lund University)

MSB.......................... Myndigheten för samhällsskydd och beredskap (Swedish Civil Contingencies Agency)

MW........................... Megawatt (unit of power)

PE............................. Polyethylene

PGA.......................... Pyrotechnically generated aerosols

POA.......................... Point of access

PPV.......................... Positive pressure ventilation

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1 Introduction

The last course of the Fire Protection Engineering program at Lund University is the Bachelor thesis. It is made up by a project, which corresponds 22,5 credits, where the student applies and develops the knowledge gained during the education. The course is also a practice in how to, in a scientifically way, attack and study a subject in the fire safety subject area.

1.1 Background

On August 31, 2015, the ESS project was established by the European Commission as a European Research Infrastructure Consortium, or ERIC, and is now known as European Spallation Source ERIC. The ERIC legal framework was created by the European Commission in 2009 to facilitate the joint establishment and operation of pan-European research infrastructures like ESS. The European Spallation Source ESS AB operated as a Swedish limited partnership, or AB, owned jointly by the Swedish and Danish governments from 2010 to September 30, 2015.[1] The research that will be conducted at ESS will be based on the world's most powerful neutron source and be 30 times brighter than the leading active facilities today. This enables research opportunities in fields like energy, cultural heritage, life sciences, fundamental physics and environmental technology.[2]

The Fire & Explosion Safety Program (ESS-0004722) endorses implementation of a defense in depth approach to prevent fire from starting, detect and quickly extinguish those fires that do start and prevent the spread of those fires that have not been extinguished. At some areas, the automatic suppression system may not per definition be able to extinguish the fire but only to suppress, then the extinguishing procedure is dependent on manual intervention. For areas where no automatic suppression system is installed, the manual intervention is crucial to get in compliance with the program, i.e. to quickly extinguish.

When it comes to fire protection in this facility, the municipal fire brigade response time is expected to be 10 minutes.[3] The response time is the time from alarm to the fire brigade until the actual work operation is initiated on site.[4] Due to the complexity of the facility's operation, there are some challenges concerning fire extinguishing procedures that emphasize research activities. The operation efficiency of the municipal fire brigade and the facility's emergency response team (ERT) are of certain interest.

1.2 Purpose and Objective

By experience, the time between fire initiation and achieving an efficient extinguishing procedure is crucial for a successful intervention. The main objective of the study is to evaluate possible alternatives to achieve a successful intervention. The possibilities to minimize time to successful intervention is evaluated, i.e. to cut time between fire alarm and successful fire extinguishing, is also an objective of the study.

The elapsed time from an initiated fire to suppression is a known factor of significant importance to achieve successful intervention. Successful intervention is in this study defined as the possibility to achieve extinguishing capacity to limit damages from a fire to a local part of the fire compartment.

1.3 Method

The method used in this report followed the structure shown in figure 1 below.

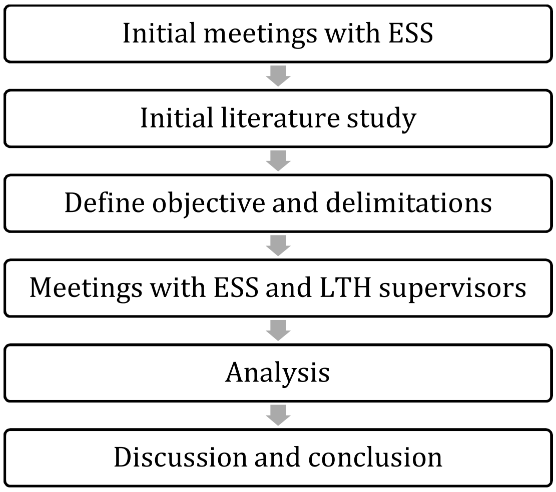

Figure 1. The method used in this project.

First, a couple of meetings with ESS were conducted, where the basis for the project was formed. With this first information, an initial literature study was done to see what information was available on the subject. The information from the meetings and the initial literature study were then used when defining the objective for the project, which was done in consultation with ESS and the LTH supervisors. With the basis for the project done, additional meetings with ESS and the LTH supervisors took place to further delimit the work and prepare for the project's analysis part.

The analysis part of the project consisted of several various methods. The main method used was a literature study, where literature on the subject were analyzed in order to evaluate possible solutions to achieve the project objective. A couple of workshops at ESS were also attended, where e.g. fire protection in the facility was discussed. At these workshops, the different parts of the concerned interests of the fire safety at ESS were represented, e.g. involved ESS staff, representatives from the municipal fire brigade and involved fire safety consultants. Also, a larger workshop about the FCC study was attended, which involved people from i.a. CERN, DESY, Fermi Lab, MAX IV and LTH. This workshop also included a study visit to the newly inaugurated MAX IV laboratory, a particle accelerator with some similarities to ESS concerning complexity of rescue intervention, which is also located just next door to ESS as a neighboring research facility. Discussions with the LTH supervisors and ESS were carried out during the analysis to give important input to the project.

Finally, the analysis was further discussed and the results were compiled into a conclusion.

1.4 Target Group, Limitations and Delimitations

The target group for this report is the European Spallation Source ERIC. Possibly, the conclusions can also partly be used when dimensioning the fire protection of similar facilities.

This project was initiated early fall 2016 and the bulk assessment was performed during winter 2016-2017. As ESS is not yet built and the plans are preliminary, the design is continuously being revised and changed, which complicates some parts of the project, since there might be some future changes that could affect the reasoning in this report.

The study has delimitations as follows:

- The project only covers fire hazards; no radiation, chemical or other hazards have been analyzed. Neither does the project investigate flooding issues due to extinguishing media used in fire suppression.
- Only one design fire scenario has been used, since it is considered to be a worst-case scenario, representable enough for the other fire hazards in the facility.
- The different automatic and manual extinguishing systems that are analyzed in the report are systems already on the market. There are always new extinguishing systems being developed, but for an extinguishing system to be considered acceptable in the safety case of the fire and explosion program, the technique should be verified in use.
- The different extinguishing systems come in a large variety of designs by various manufacturers, but this report is delimited to analysis and evaluation of the different system concepts only, to keep a neutral stance in the choice of manufacturer and product.
- The analysis aims to shorten the time from fire alarm to fire suppression and does therefore not cover the fire detection phase. The main focus is put on solutions to start a fire suppression as early as possible after fire alarm, sufficient enough to either extinguish the fire or suppress it to keep it on a satisfactory level until the arrival of the municipal fire brigade.

2 Prerequisites

In the fire safety dimensioning of the complex done by ESS with some other participants, eight large scenarios were formed to correspond to all previously formed scenarios. One of these scenarios involves a fire in the Instrument Hall, a large compartment with a volume of about 130 000 cubic meters (approximately 130×50 square meter floor area), in which there will be a number of compartments, called instrument caves, housing instruments where the neutrons from the source are applied to samples and are detected by the instruments. The Instrument Hall has a height of about 20 meters and the complexity of the floor area usage is large due to the placement of the instrument caves and all the connections to them etcetera. The surroundings of the Instrument Hall differ between the walls in different directions. One of the long sides will completely abut other parts of the complex, such as the Target Building where the spallation take place, and the other three sides will have close access to the open.[5] For a sketch of the Instrument Hall, see figure 2 below.

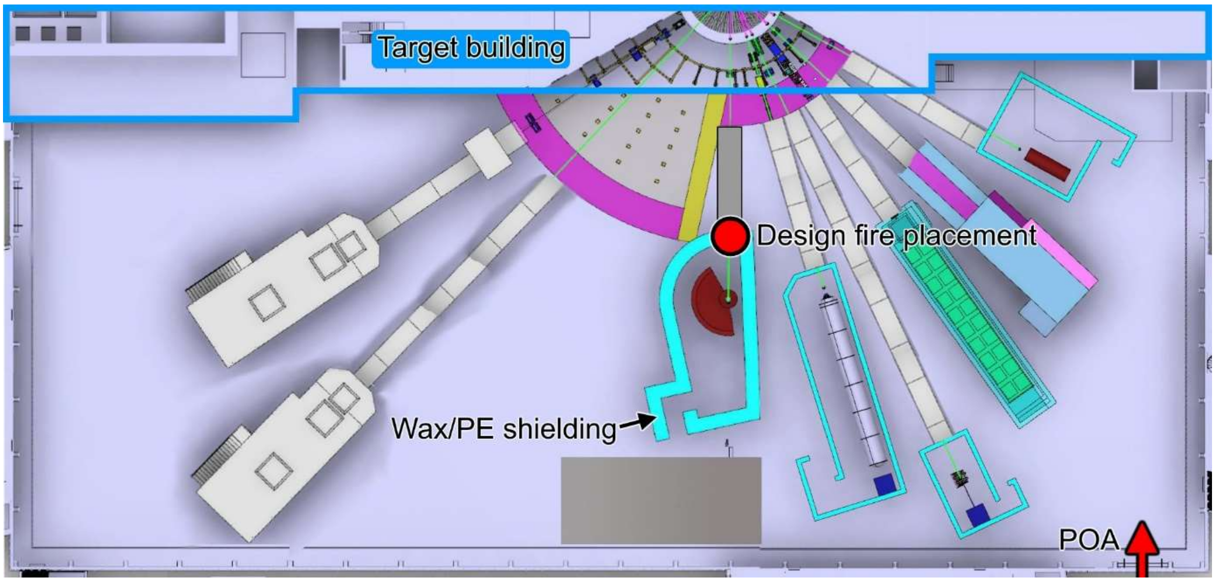

Figure 2. Preliminary construction sketch of the Instrument Hall with the instrument caves. Placement of the design fire and closest point of access, POA, are marked. (Used with permission from the European Spallation Source ERIC)

Some of the instrument caves will have a protective borated paraffin or PE radiation shield cover to prevent neutrons from travelling outside the caves.[6] This creates a considerable fire hazard because of the fire properties of the materials, resulting in possible fire peak HRRs of 70 or 100 MW, for paraffin and PE respectively, with the amount of shield material that is required for one of the instruments.[7] The fire is assumed to grow as a fast growing fire.[33] To prevent or minimize such a fire the following measures are currently planned:

- Automatic wet pipe fire suppression inside instrument cave
- Sprinkler in Instrument Hall ceiling
- Allow only redesign of one instrument simultaneously or apply 5 meter safety distance
- Paraffin is protected in steel containers
- PE is protected behind fire rated cladding[6]

With sprinkler installed in the Instrument Hall ceiling, the 70 MW fire will only rise to about 6 MW before being suppressed by the sprinkler.[6]

The Instrument Hall will also contain control hutches and offices, user laboratories close to the instrument stations, mechanical, electrical and optical workshops, support laboratories and offices and meeting rooms in adjacent areas.[3]

3 Analysis

The analysis part of this report is one large comprehensive assessment of fire protection solutions, mixed with facts and logical reasoning. First, the main problem, the special design fire case with its complications, is presented in a more specific way in chapter 3.1. Then, different solutions are processed and compared in chapters 3.2-3.5, in order to, in a scientific way, come up with possible solutions to the problem.

3.1 Large Design Fire Problems

First, we can try to imagine what happens if a fire starts and the sprinkler for some reason malfunctions. The HRR would then be able to rise to very high levels of up to 70-100 MW. A fire of that magnitude is very big if you compare it to a common apartment fire, which can develop an effect of about 2-5 MW[8] and is what a Swedish municipal firefighter team is normally equipped and prepared for.

As mentioned earlier, sprinkler will be installed in the Instrument Hall ceiling, which will be activated by heat from the fire at about 6 MW, according to calculations done by WSP.[9] The fire will then be of a size that is possible to suppress, unlike a 70-100 MW fire. Still, it is a large fire and it is not so easily extinguished. Since the sprinkler system is activated by the heat from the fire and the ceiling height is about 20 meters, the sprinkler activation time might be long because of the entrainment of colder air into the fire plume on the way up. This means that during the time from fire start to sprinkler activation there will be no automatic fire suppression. Instead of waiting for the sprinkler to activate, another suppression method can be implemented, that is able to suppress the fire earlier and hopefully keep the HRR lower than the calculated 6 MW. The wet pipe water suppression system in the ceiling, however, is designed for fire suppression and could be able to extinguish a fire. The challenge is rather to identify various means of extinguishing capacity which are credible to reach the objective of a successful intervention. Therefore, complements to the Instrument Hall ceiling sprinkler should be considered.

One way to analyze a HRR progression over time is to us the t-squared fire model.[32] Assuming a rapid fire growth rate of 0.047 kW/s^2, the fire will reach a HRR of 6 MW after 6 minutes and a peak HRR of 100 MW will be reached after 24 minutes. For a graphical illustration of the HRR, see figure 3 and 4 below.

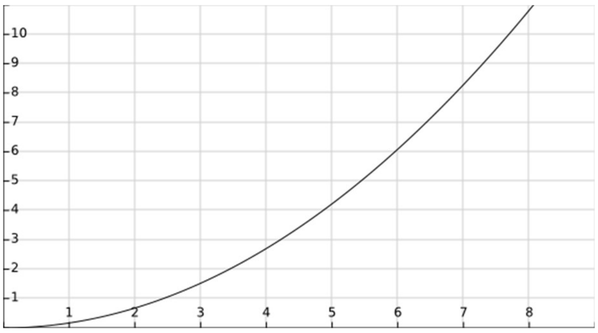

Figure 3. HRR curve for a fast-growing fire (α=0.047 kW/s2) up to 10 MW, where the Y-axis shows HRR in MW and the X-axis shows time in minutes.

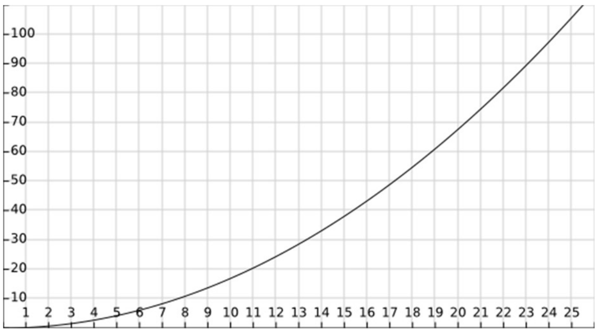

Figure 4. HRR curve for a fast-growing fire (α=0.047 kW/s2) up to 100 MW, where the Y-axis shows HRR in MW and the X-axis shows time in minutes.

To calculate the flame heat flux to a target, a method by Modak can be used, which approximates a fire as emanating from a point source. With a simple formula, as shown in Equation 1 below, the radiant heat to a remote target can then be calculated if given the HRR of the fire and the distance from the flame to the target.

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi {R_0}^2} \qquad \text{(Equation 1)}$$

$$\dot{q}'' = heat\ flux$$
$$\chi_r = fraction\ of\ total\ energy\ radiated$$
$$\dot{Q} = HRR$$
$$R_0 = distance\ from\ target\ to\ fire\ center$$

The radiation fraction depends on fuel and flame size and configuration.[32] This formula can also be used to calculate e.g. the minimum distance between a firefighter and a fire. By assuming a radiant fraction of one third (1/3) and setting a maximum tolerated heat flux and the HRR to 6 MW, Equation 1 can be used to calculate the minimum distance between a person and a fire as in Equation 2 below. Using the so-called NASA-table, the former Swedish Rescue Services Agency set a demand on their firefighting clothing to withstand a heat flux of 1.75 kW/m^2 for five minutes[34], which is used in the calculation to approximate the maximum heat flux to a firefighter, wearing protective clothing, fighting a 6 MW fire for five minutes.

$$R_0 = \sqrt{\frac{\chi_r \dot{Q}}{4\pi \dot{q}''}} = \sqrt{\frac{6{,}000}{12\pi * 1.75}} \approx 10\ m \qquad \text{(Equation 2)}$$

With a 100 MW fire, the minimum distance would be about four times longer, showing the immediate difference between fighting a 6 MW and a 100 MW fire, as the firefighter must be further away from the larger fire to not get burnt.

3.2 Manual Fire Suppression by Municipal Fire Brigade

When the fire alarm activates at ESS, the municipal fire brigade will be dispatched to the site for a rescue operation. If the fire brigade is to execute a successful suppression effort, which is desired, there are some problems concerning the crew safety as well as practical issues.

3.2.1 Municipal Fire Brigade Practical Issues

For the municipal fire brigade to perform a successful internal manual fire suppression, there are some practical issues that can be analyzed to improve the chance of success. Firstly, the route from the closest point of access, POA, to the fire is about 70 meters[9], which is long compared to a standard hose layout of the normal low-pressure water suppression system in the Swedish fire brigades, where the fire hose length is usually 50 meters from a manifold. This can of course be extended, enabling longer hose length.[10] One parameter is crucial when it comes to firefighting with water – the distance between the nozzle and the fire.[11] It is therefore important that a team of firefighters can get close enough to a fire to be able to manually extinguish it. Also, the complexity of the structure in the Instrument Hall will be high, due to placement of instrument caves and connections. These problems with the long POA to fire route and the configuration of the Instrument Hall, the instruments and their caves with radiation shielding are not easily changed to make a fire more accessible, because they must be placed in that way to connect to the neutron source. One possible solution is to install more POAs to shorten the distance from the entry point to the fire. This is not so easily done either though, because there will be other building parts adjacent to the Instrument Hall walls. However, it might be possible to slightly change the configuration to create more possible POAs.

FDS-simulations done by WSP show that the design fire will fill the Instrument Hall with smoke, making a manual fire suppression operation hard with poor visibility. Therefore, smoke hatches will be installed, which has been shown to be efficient enough to make an inside operation possible. These will be manually activated by the municipal fire brigade (after sprinkler activation to avoid non-activated sprinkler due to release of warm gases through smoke hatches).[12] One of the difficulties here is that the fire brigade has a certain time to get to the ESS site, because the fire station is situated in another part of Lund. The smoke hatches will not be activated until the fire brigade arrive on site and makes the decision to open the smoke hatches. By this time, the Instrument Hall will probably be filled with smoke and the time it takes to extract the smoke will delay the internal fire brigade operation further. Possibly, the decision to open the smoke hatches could be made earlier, either by the fire brigade remotely before arrival or by someone in the ESS ERT. That could make an internal fire brigade operation possible earlier. It could also reduce the smoke damage to equipment in the Instrument Hall, which can also make it interesting to investigate.

Another way to open smoke hatches is to install an automatic system, triggered by e.g. a thermal fuse or smoke detectors. This system is not recommended in facilities with only ceiling sprinkler together with risk for very fast fire growth, e.g. high stack storage.[13] Although the Instrument Hall has a risk for fast fire growth, there will possibly not only be ceiling sprinkler installed, but also other extinguishing systems. Therefore, automatic opening of smoke hatches might be an option in the ESS case and should be further investigated.

When considering the amount of extinguish media needed to put out a fire manually, it is important to have enough resources to provide firefighters with sufficient amounts of water. Standpipes will not be installed in the Instrument Hall[3] but there will be an outer fire hydrant system installed at the ESS site. This will be sufficient to supply at least two groups of smoke divers and also the effective area for water suppression for two hours.[3] Instead of using this system, which takes a while to set up to be able to get close enough to the fire, which is far away from the POA, a standpipe system could be installed to decrease the hose length needed for a manual fire suppression inside the Instrument Hall, either connected to the onsite basin or fed by a fire engine's pump system. However, this is maybe not one of the biggest issues. What can be considered more important is that the amount of water supplied is sufficient, which should be the case with the outer fire hydrant system.

At CERN in Geneva, a compartment with a fire of a HRR of above 20 MW means that no firefighters will enter, not only because of the crew safety, but also because smoke and other fire products already have damaged most things in the compartment. Instead, they work defensively, restraining the fire and protecting adjacent rooms. It is also usually said that smoke divers can manage fighting a fire of up to about 15-20 MW.[14] A fire at ESS, not suppressed before the arrival of the municipal fire brigade, may reach above 20 MW, which speaks against an inside intervention. Although, with a working sprinkler in the Instrument Hall ceiling, the fire should be below 20 MW.

3.2.2 Municipal Fire Brigade Crew Safety

A conclusion one can draw from the discussion of some of the subjects above is that an internal operation by the municipal fire brigade might be practically possible, given the right conditions with i.a. sprinkler activation. Also, the Swedish municipal fire brigades should only, according to the Swedish Work Environment Authority's regulations, operate in dense smoke if it is safe for the crew and primarily in a lifesaving effort.[8] With a well performed evacuation, an inside operation is therefore not totally justified because there are no lives to save. Some more factors that need to be weighed in in the risk valuation before a smoke diving operation are listed below.

- The extent and spread rate of the fire
- The risk for backdraft
- If there is information about which chemicals that are present at the incident scene
- The physical conditions at the site and the type of object and risk situation
- The size and composition of the fire and rescue team
- Available rescue equipment
- The education, experience and qualification of the staff
- If medical personnel and police is present or on route[15]

With all these factors in mind in the short onsite risk valuation, the decision to enter a building is to be made by the fire brigade, and if the conditions are considered safe enough with low estimated risk, an inside operation could still be possible. What is important to note is that one cannot count on the fire brigade to take a certain decision in a specific situation. The decision is theirs and depends completely on the situation. An intervention by the municipal fire brigade would be an intense situation with limited time with important decisions[15], which makes the situation hard, even for an experienced fire officer.

The time optimizing objective of this work should also be mentioned when it comes to an intervention by the municipal fire brigade. The municipal fire brigade is expected to begin an intervention within 10 minutes from alarm to SOS alarm, while the time it takes to start a manual suppression is presumably longer, since it takes some time to start the actual fire suppression. The estimated time from fire alarm at ESS to the actual start of fire suppression by the municipal fire brigade is assumed to be in the order of 25 minutes, according to the municipal fire brigade in Lund, Räddningstjänsten Syd.[5] This means that the fire will be able to rage for about 25 minutes until any manual fire suppression is done, and with the presumable harsh conditions in the Instrument Hall after 25 minutes of fire, an inside intervention by the municipal fire brigade is not very likely.

To sum this up, in the fire scenario described earlier, ESS cannot depend on an intervention by the municipal fire brigade to achieve a successful intervention, even if it is fully reasonable with the right conditions. However, an intervention could be facilitated with sprinkler, smoke ventilation, appropriate POAs and good preparations. Still, to even shorten the time to fire suppression, other solutions should be investigated to dampen the fire until the fire brigade arrives and minimalize potential hazards, environmental impact and property damage. This can be done in different ways, such as installing automatic fire suppression systems or preparing the ESS ERT for some sort of manual fire suppression.

3.3 Automatic Fire Suppression Systems

One of the options, which is already partly implemented, is to install automatic fire suppression systems in the facility. This would not jeopardize any people as in a manual suppression effort. On the other hand, automatic systems are often expensive and need regular testing and maintenance. In the ESS facility, it might also not be so easy to install more automatic fire suppression systems in the Instrument Hall due to the complex structure and that instruments have to be able to be exchanged or redesigned in the future.

What must also be considered when installing automatic fire suppression systems is the risk of unintentional activation.[9] The sanitation costs after activating an extinguishing system might become extensive, which is maybe not viable when compared to the benefits in a possible fire accident. The sanitation costs can also be compared to the value of the potential property damage done by a fire, to provide a basis for a risk acceptance vs risk prevention evaluation.

At the moment, sprinkler in the Instrument Hall ceiling is planned to be installed. Additionally, sprinkler will be prepared for the instrument caves.[16] The sprinkler in the hall ceiling will be almost 20 meters above the floor, which is not optimal for a sprinkler system, since the drops will have a high fall down to the fire. Although there are sprinkler systems designed for high ceilings, automatic fire suppression systems in certain instrument caves may be suitable to complement this. Preferably, the instrument caves are treated separately to design the automatic systems in the most efficient way for each case. By adding automatic systems in the instrument caves the fire load is protected locally and together with the sprinkler system this will make a better fire protection for the Instrument Hall. The following system evaluations concern protection of the inside of instrument caves individually.

3.3.1 Sprinkler

When it comes to water sprinkler, water has obvious disadvantages around electronical equipment due to its electrical conductivity. The damage to the facility and equipment done by the water can be worse than the fire damage itself. The sprinkler is often heat activated[3], which makes the activation occur first after the fire has developed enough to reach a certain temperature. At this time the fire has already grown enough to make smoke and heat radiation damage.

The water released by a sprinkler system must also be taken care of, which can be extensive and expensive. Sprinkler could for these reasons be considered to be best suited for protection of structures.[16] While this is not the main objective in this work, alternatives to conventional water sprinkler should be investigated.

3.3.2 Water Mist Sprinkler

Water mist is still a technique under fast development. The extinguishing properties of a water mist system must be verified for the specific fire hazard and the fire rooms volume and geometry. While lesser in volume than conventional sprinkler, these systems leave residual water after use, necessitating cleanup.[17] Water mist has three main fire suppression mechanisms, which are

- gas phase cooling,
- oxygen depletion and flammable vapor dilution
- and wetting/cooling of fuel surface.[18]

A water mist sprinkler system could be an option in this case, but it must then be further investigated due to the relatively new technique in such a complex facility as ESS. The damage a water mist system could do to the expensive equipment is unknown because of lack of knowledge about the instruments and equipment that will be put inside the instrument caves. However, compared to a normal sprinkler system, a water mist sprinkler system does less water damage[19] and smaller water drops have a bigger surface area, which means that they, theoretically, will evaporate faster.[20]

Considering the benefits a water mist sprinkler system has compared to a normal sprinkler system, it should be considered as an option to put inside instrument caves. However, some limitations with water mist is that the small drops have a short range, the drops have a short life span, small drops collide and unite to larger drops and large drops hit obstacles like walls and therefore have trouble filling a room volume.[21] The short range should not be a problem since the system is intended to be installed inside instrument caves, which are not very large compartments. The other problems might be minimized by installing the system in a certain way so that the nozzles cover the complete volume without causing too much collision. However, this system should be further investigated as an option.

3.3.3 Gas Extinguishing System

Gas extinguishing systems are often not the most effective agent from an extinguishing technical point of view, but the cleanliness is a large advantage in many cases and the most gases make no or small damage if accidently activated. Gas extinguishing systems can be a good option if the value of the things protected is large. The usage is most effective in confined spaces, otherwise there is a risk for reignition.[22]

Implementing a system like this in the instrument caves seems suitable, regarding the protection of the expensive equipment. One main issue though, is the confined space condition, which can be difficult to achieve in the caves, since they are designed to be opened occasionally during maintenance, repair and installation. When the caves are opened, the gas will lose much of the effectiveness in its extinguishing properties. This could possibly be made up for by identifying compensatory measures whenever an automatic suppression system is out of operation.

3.3.4 Foam Extinguishing System

For spaces where the fire cannot be accessed, filling the compartment with light foam can be the best extinguishing method. Since foam contains water, there will be water damage with a foam system. However, the damage increases with longer exposure time and heavier foam, so light foam makes limited property damage in general. It does also not easily penetrate confinements such as electronics cabinets, packaging etcetera, which makes it less hazardous to encased electronics. Using light foam might also reduce smoke damage. Foam as an extinguishing agent also has advantages such as the film forming ability, which is good when suppressing burning liquids. In these fires, it is important that the foam is not disintegrated by the fuel.[16]

It is also important to have a fast and effective fire extinguishing with a minimum amount of extinguishing water to minimize the release of environmental- and health hazardous substances through air and to extinguishing water. The Swedish Civil Contingencies Agency (MSB) advices to use other extinguishing methods if extinguishing media containing foam cannot be collected and sent to destruction.[16]

In the instruments with PE or wax shielding, a fire would probably be partly a pool fire since the materials will partly melt in a fire. The properties of a foam with film forming ability is therefore suitable, if the foam does not react with the fuel and disintegrate. The room filling technique is also quite suitable for the instrument caves since it is a confined compartment with equipment creating nooks and crannies that contribute to a complex room structure. However, several foam alternatives have potential environmental impact and the fact that ESS is situated in a Natura 2000 area makes foam not suited for the facility, unless the facility has a good sewage cleaning system to take care of all the extinguishing media used, which is also the case with the water systems, which produce large amounts of contaminated water that can be hazardous to the environment. This, however, is not further analyzed in this project because of the made delimitation concerning flooding caused by extinguishing media.

3.3.5 Powder Extinguishing System

There are many different sorts of extinguishing powders on the market with different mixtures of substances. If the right powder is chosen, it can be used against most types of fires. Powder is not electrically conductive, but on the other hand, sanitation after a powder release are usually extensive. Therefore, it is suitable to avoid powder in switchgear installations and other equipment that contain relays. The salts in the powder combined with moist cause corrosion, which is not good in compartments containing machines and instruments.[23]

Many of the instruments and equipment of unique design in the Instrument Hall will have uncoated metal surfaces. Any discharge of corrosive substance will create damages of costs of unknown magnitude today. Additionally, since the powder can spread through the smallest of openings, it could possibly reach outside of the instrument cave and damage equipment and instruments adjacent to the instrument cave on fire, which is bad regarding property damage in the facility. A powder system is consumed once deployed, which means that if the system has small effect on the fire, or if the fire builds up again after deployment, there will be no additional suppression done by the system. Additionally, accidental release of powder would lead to unnecessary damage, and the sanitary costs after a powder release must also be considered.

3.3.6 PGA System

One system that is becoming more popular is PGA. The aerosol is released by a chemical reaction in the device and no or only a small pressure rise occurs. PGA is only effective in confined compartments and the aerosol provides a good reignition protection.[16] A study has shown that PGA do not affect computers or low current circuits (high current circuits were not mentioned in the study). However, a triggered PGA-system will make visibility in the compartment non-existent for a long time and exposure is health hazardous after 30 minutes of exposure. It is not supposed to be used in areas that normally are occupied, but the risk must still be considered for areas where people are staying occasionally.[24] The instrument caves will occasionally be occupied by people, but a delay in the PGA activation combined with evacuation alarm can assure that no one is in the room during activation. Considering this, a PGA system could be a suitable automatic fire suppression system for the instrument caves.

Like powder, PGA can result in corrosion.[25] Although some tests have not shown any corrosive effect[24], the risk must be considered. Additionally, aerosol particles, being even smaller than powder particles, will spread even more than powder through small openings and possibly cause even more damage. The risk of corrosion damage to the instruments and equipment in the Instrument Hall should therefore be further investigated. If it is shown to be low, or somehow avoided, PGA systems should be considered as an alternative to install in instrument caves.

3.4 Manual Fire Suppression by ESS ERT

In case of an extensive fire in the Instrument Hall, the automatic suppression system may not be able to extinguish a fire on its own. Hence, manual intervention is needed to suppress the fire to a certain level until the municipal fire brigade start their intervention. The so called ESS Emergency Response Team, ERT, is a team of people working at ESS that will get a certain roll in case of an emergency in addition to their normal occupancies. At the moment, it is meant to consist of, amongst others, one First Responder minimum, who will be available for a manual fire suppression effort. The First Responder will be a security guard with a patrol car, which can be equipped with firefighting gear and equipment. In the security patrol, together with the First Responder, there will be another security guard, who will operate together with the First Responder as a guide for the municipal fire brigade when they arrive.

An internal intervention by the First Responder will be regulated by the Swedish Work Environment Authority. If an internal intervention is considered to be smoke diving, the regulations prohibit the First Responder to operate in the compartment, due to e.g. the lack of necessary number of staff members.[26] Therefore, it is important that the First Responder is aware of in what situations he is allowed to enter the Instrument Hall and do a manual fire suppression effort. The regulations about smoke diving apply only in cases where smoke diving is performed. The definition of smoke diving is (translated from Swedish):

"The penetration of dense smoke to save lives and fight fire or similar, wearing fire protective clothing and breathing apparatus."[15]

It is also said in the regulations that they do not apply to actions expected to result in only moderate physical exertion or stress. The general recommendation comments on the application of the regulations mentions industrial rescue organizations, or similar, as an activity where they do not apply. These activities are only intended for operations of moderate physical exertion and stress, such as a short initial rescue effort or guiding a rescue team to the scene of the accident. What equipment, training, medical status and physical work that may be needed in such cases need to be assessed, based on the conditions at the site where an operation may be necessary. Important factors in such an assessment are the type of work, the physical and mental effort, the heat load and the potential duration of the operation.[15]

To sum up, if the Instrument Hall is not filled with smoke or if smoke can be removed to allow good visibility, it is not considered to be smoke diving and the smoke diving regulations do not apply. They also do not apply if the physical exertion and stress are below a moderate level, but this level is not much further defined. An interpretation may be that this relates to the amount of training in combination with individual mental and physical abilities. Then the question is if fighting a larger fire until the arrival of the fire brigade is allowed if it is not too hard physically and mentally, and it is not easy to generally evaluate. Although, if the conditions for smoke diving above are not met, a manual intervention with a fire suppression effort by the ESS First Responder is possible, but personal safety should be subject to continuous improvements with the knowledge from experienced units where the First Responder concept is in use. Still, the risks of a manual internal intervention are many and hard to assess in advance. There are physical as well as mental risks in an intervention, such as for instance excessive heat and extreme stress impact. Hence, the conditions for a manual intervention by the First Responder must be carefully assessed to prevent personal injuries. It is also said in the regulations that they can work as a guidance even if they do not legally apply.[15]

The First Responder car, filling double purposes as perimeter patrol car and ERT First Responder car, cannot be too large (e.g. a fire truck). The vehicle would more suitably resemble a so called offensive unit of the municipal fire brigade; a lighter vehicle that is equipped with a light extinguishing system of some sort, either fixed to the vehicle or portable. There are several systems of this kind on the market, so pros and cons must be evaluated to see what system is most suitable for the ESS case.

Firstly, the extinguishing systems are analyzed overall. Secondly, the systems are analyzed in four certain aspects:

1. throwing distance,
2. potential damage to equipment,
3. practicality and
4. endurance.

This analysis is mostly based on Särdqvist's[16] comparisons of different extinguishing media. The systems are then given one of three grades: good, OK or bad, and are eventually compared in relation to each other to find the most suitable extinguishing system for the ESS ERT First Responder vehicle.

3.4.1 Low-Pressure Water System

Water is the most used extinguishing agent and has many good properties, which have contributed to its domination. No other extinguishing media exist in such abundance or low price as water.[15] Though, when equipping a smaller vehicle with a normal low-pressure water system, there are some problems. First, water is relatively heavy, and a low-pressure extinguishing system normally uses large amounts of water to maintain a steady flow[16]. This means that the vehicle will not be able to carry enough water to supply enough water for more than maybe a couple of minutes. Another problem with water is its electrical conductive property. This could be a problem if a firefighter is standing in a pool of water covering the floor, close to high voltage equipment. In an early stage of a fire event, the power is possibly not yet completely shut down, which could make this hazardous.

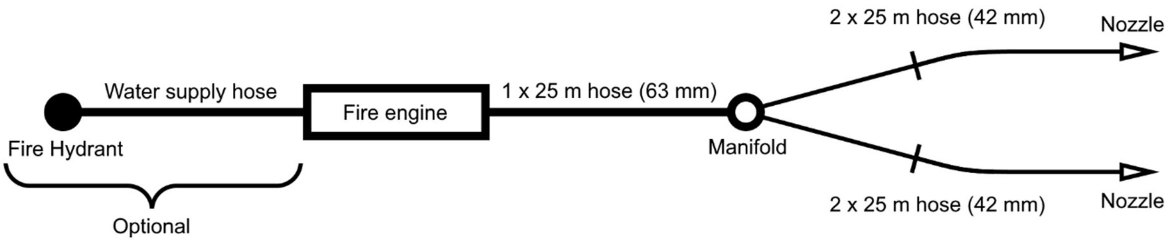

Figure 5. Principle sketch of a low-pressure water system with a so called "standard outlay" (Swedish: standardutlägg), used by Swedish fire brigades.

The low-pressure water system is the most common system used by Swedish firefighters today.[16] The setup is not easily made by one person alone, since all the connections with hoses, pump, couplings and nozzle must be made. Additionally, someone has to operate the pressure at the pump. For a principle sketch of a common system setup, see figure 5 above. To have enough people standing ready to handle such a system on short notice at the ESS facility around the clock is challenging to obtain before the municipal fire brigade arrive, due to lack of available personnel.

Water also has a disadvantage when it comes to environmental issues. The remaining extinguishing water after a fire contains pollutions from the fuel and the fire products, but also sometimes substances that has been at the fire location before and did not participate in the fire.[16] Since the ESS facility is located adjacent to a Natura 2000-area, the water must be taken care of specially carefully. An option could be to use a system that does not require the large amounts of water as a low-pressure system.

3.4.1.1 Grading of Low-Pressure Water System

The throwing distance of a low-pressure water system depends on the shape of the jet, which can be maneuvered to be open (conical) or closed (narrowed). Either way, the water jet has a *good* throwing distance.[16]

The property damage of water is by Särdqvist[16] considered to be smaller with smaller droplets. The low-pressure system, which have medium large droplets with the conical beam, is therefore considered to be *OK* when it comes to potential damage to equipment.

Concerning practicality, the low-pressure water system needs a larger amount of personnel relatively to other extinguishing systems. It also needs more equipment than some of the systems.[16] Therefore, the system is graded *OK* in terms of practicality.

The endurance of a low-pressure water system depends on if the system can be connected to e.g. standpipes or water hydrant or not. In the ESS-case water hydrants will be installed, providing a low-pressure water system with enough water for a somehow protracted period of time.

However, this analysis concerns the first intervention by a small first responder team, giving less time and personnel to do this hydrant connection. The possible amount of water carried by the first responder vehicle is limited due to weight, and without enough water the system is not very endurable. This impedes the system's endurance, lowering its available usage time and consequently its endurance. Still, the system is graded *OK* because it still can be used for some time and then be connected to a hydrant.

3.4.2 High-Pressure Water System

A high-pressure system is a system with a work pressure of 20 bar and above. The most common systems use 40 bar pressure and is effective in 9 out of 10 intervention operations and appears suitable for indoor suppression below the safety level of smoke diving. They are smaller and use less water, which make them suitable for a small vehicle. The system usually uses a rigid hose on a hose reel, which, compared to a normal low-pressure system, has a shorter time of preparation, since one does not need to connect hoses. The principle of a vehicle mounted reel can be seen in figure 6. This also creates a big disadvantage: the system cannot be expanded while in action. The usual hose length of high-pressure systems is usually between 60 and 80 meters for ¾ inch hose.[16] The extinguishing mechanism of the water mist produced by a high-pressure system is slightly different from the low-pressure system, which requires more theoretical understanding to realize the advantages and limitations of the system,[21] but this is overcome by education. Experience of high-pressure systems show a distinct reduction of water consumption, and the compiled experience from Swedish fire brigades often confirm the statements and properties attributed to the systems in theoretical publications from manufacturers and sellers.[22]

Figure 6. Principle sketch of a vehicle mounted high-pressure system reel, hose and nozzle.

A high-pressure system might be a suitable system for the ESS case due to its portability and good extinguishing properties. The minimum amount of water used is also positive, both considering salvage and water supply. Also, the short time of preparation, compared to a normal system with loose hoses, couplings and nozzles, is important in the ESS case. Since there are many different high-pressure systems on the market with different techniques, there are even more pros and cons specifically for each manufacturer's system, which are not discussed in this report.

The extinguishing properties of small water drops can also be obtained by a low-pressure system using e.g. fog nails.[24]

3.4.2.1 Grading of High-Pressure Water System

The jet from a high-pressure water system is almost like the low-pressure system jet, but with smaller droplets which reduces the throwing distance since the droplets have less kinetic energy than the larger droplets in the low-pressure system. The throwing distance of the high-pressure system is therefore considered to be *OK*.

With the same reasoning as above, this system, which have smaller droplets, the potential damage to equipment is considered to be *good*.

This system would demand the same amount of, or slightly less, personnel than the low-pressure system since they are quite similar, with the difference in form of the simplicity with the hose reel on the high-pressure system. This makes it easier to prepare, compared to connecting hoses and couplings, which requires more personnel. The hose reel also increases the practicality because it is easy to roll out fast without having to do all the coupling as with the low-pressure water system. Because of this, the practicality of the high-pressure water system is graded *good*.

As with the low-pressure system, the high-pressure water system can be connected to a fire hydrant providing it with a sufficient amount of water. Additionally, the high-pressure system uses less water, extending the usage time and making it more endurable than the low-pressure system. It is therefore graded *good* in endurance.

3.4.3 Cutting Extinguisher

The cutting extinguisher is a sort of high-pressure system, but it has certain abilities that make it unique and should therefore be treated separately. The system uses a very fine water jet under high pressure (>250 bar) which makes it possible to cut through materials, such as concrete and even steel walls. The cutting extinguisher enables a safe suppression from outside the building, which can improve the conditions for a following internal fire suppressing effort.[16] In an internal intervention, the cutting extinguisher might also be used like a high-pressure system, since it produces a water fog spray reminding of that from a high-pressure system.[24] The cutting extinguisher has a proved effect in large room volumes and fires with high HRRs.[27] For a principle sketch of a cutting extinguisher system setup, see figure 7 below.

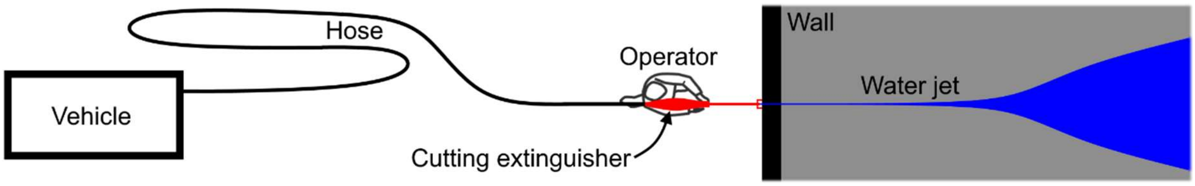

Figure 7. Principle sketch of a cutting extinguisher system. (Not to scale)

In the ESS case, a cutting extinguisher might be a good option for a First Responder. The system enables a safe suppression from safe distance outside the fire compartment. The other discussed methods require an inside suppressing effort and which, probably, in many cases involve smoke diving, which the First Responder is not allowed to do on his own, according to the Swedish Work Environment Authority's regulations.[22] With the cutting extinguisher, the First Responder can suppress a fire inside the Instrument Hall without having to evaluate if an internal suppression is allowed according to the Swedish Work Environment Authority's regulations or not. A problem that might occur is if the fire is blocked, by other instruments or equipment, from the firefighter's point of penetration. Then the water jet will not be able to reach the fire and suppress it. Possibly, the jet might still have a chance to somewhat have a suppressive effect because of the mist-like property of the small drops in the water jet. Another issue to consider is if the wall is very thick and dense. It could then lead to a longer penetration time and the jet might also be affected negatively.

It will probably be very hard for a person to aim the cutting extinguisher straight at the fire in the large compartment if the fire is far from the operator's cutting penetration point. Therefore, visual confirmation from inside the building is necessary, such as a system of surveillance cameras or IR-cameras, that can give the cutting extinguisher operator feedback on the aim and effect of the suppression. Alternatively, this could preferably be achieved by having a second person working together with the First Responder with a hand-held IR-camera. He could then see if the suppression has any effect on the fire by monitoring the temperature at openings in the Instrument Hall to see if the cutting extinguisher has any effect on the fire, and could have contact with the First Responder to help him achieve a successful fire suppression. This procedure with one cutting extinguisher operator and one IR-camera operator, who is also personal safety guard, has been used successfully in action and has proven to work well, especially combined with positive pressure ventilation, PPV.[15] The PPV method is analyzed in chapter 3.5.

The distance to the fire might also be a problem, since the small drops from the cutting extinguisher has a maximum throwing distance of about 10-15 meters[27], which is not enough in the large design fire case. Maybe, the claimed throwing distance is connected to a certain manufacture and implies the range to reach certain suppression effect. During a visit to the rescue service of Staffanstorp (Räddningstjänsten Lomma-Staffanstorp) the cutting extinguisher they use, the Cold Cut Cobra from Cold Cut Systems, seemed to have a much larger throwing distance than 10-15 meters. A substantial water fog was estimated at about 50 meters from the operator. Additionally, the manufacturer claims that the Cold Cut Cobra jet and suppression reach is up to 60 meters in compartments according to experienced incident commanders[27], so the throwing distance of cutting extinguishers should be further investigated before rejecting them as a fire suppression system option for the ESS ERT First Responder. During the study visit, the system was also said to be well proven.

If a cutting extinguisher is shown to have enough capability to have an effect on a design fire being used from outside the building, the system might very well be a suitable option for the ESS ERT First Responder.

3.4.3.1 Grading of Cutting Extinguisher

This system is not included in the comparison made by Särdqvist[16]. However, the system's water jet is quite like, if not better than, a high-pressure system in means of throwing distance. The system is therefore also considered to be *OK* in the throwing distance aspect.

Since the droplets from the cutting extinguisher is similar to the ones in the high-pressure system, it is also considered to be *good* when it comes to potential damage to equipment.

With its many similarities with a normal high-pressure water system, the cutting extinguisher has almost the same characteristics, making it about equally practical. One difference however is the nozzle, that must be changed on the cutting extinguisher to acquire either a cutting jet or a more "normal" spray jet. Still, this is done by a switch with quick couplings which makes the change done fast. Hence, the system's practicality is graded *good*.

The cutting extinguisher is considered to have the same endurance as the high-pressure water system, grading it *good*.

3.4.4 Foam

Foam has, as mentioned in the previous chapter, some advantages as a fire extinguishing agent. Traditionally, the Swedish fire brigades use foam with the firetruck's low-pressure water system by adding foam liquid to the water with a middle injector and adding air at the end of the line in the nozzle. This is not easily operated by one person alone since the foam mixture must be regulated both at the pump, the foam liquid injector and the nozzle[28], and is therefore not suitable for the First Responder.

However, there is one system that has become more popular in Sweden in recent years – CAFS. CAFS mixes compressed air into the system before the mixture reaches the nozzle. The technique creates smaller bubbles, which make the foam more stable.[16] The hot gas cooling from a CAFS is not as good as with a low-pressure water system. On the other hand, CAFS also has a hot gas cooling effect when applied on the hot surfaces in the compartment.[16] CAFS is also reported to use less water and make less water damage than low-pressure water systems and it is easier for the operator to produce a good foam mix with CAFS.

There are also lightweight CAFS-systems on the market that can be mounted on a trolley or a vehicle[29], which makes it possible for a First Responder to use. Still, the main issue with all foam systems is the environmental aspect. Since the ESS facility is located in a Natura 2000 area, possible environmental hazards should be avoided. On the other hand, there are foam liquid products on the market that are said to be environmental friendly. Some of these are said to outdo "ordinary" foam and can be added in both low- and high-pressure systems[22], so before rejecting foam as an extinguishing agent this option should be further investigated.

3.4.4.1 Grading of Foam

The throwing distance of foam depends on the mixture of air into the jet. The more air, the lighter the media and the shorter the throwing distance. In the design fire case of this report, a so called "medium" foam would probably be used, which according to Särdqvist[16] has a slightly shorter throwing distance than an open water beam. It is therefore considered to be *OK*.

The property damage of foam is by Särdqvist[16] considered to be smaller with smaller bubbles. With the medium foam the potential damage to equipment is considered to be *OK*.

To produce foam, you usually need about the same amount of personnel as with the low-pressure water system, but it needs more equipment[16], which makes it less practical. Still, there are more practical CAF-systems available on the market that requires less equipment and effort to produce foam, so, the system is graded *OK* concerning practicality.

According to Särdqvist[16], foam uses less extinguishing media than water systems, enabling a longer fire suppression. It is therefore considered *good* concerning endurance.

3.4.5 Powder

Powder is the extinguishing agent with the most extinguishing capacity per weight, and is one of the most effective extinguishing agents used by the Swedish municipal fire brigade. The time emptying a powder unit is usually relatively short. Therefore, a larger extinguishing effort with powder must be well planned and followed by usage a different extinguishing method. Usually, a small first intervention with a portable powder fire extinguisher can be made before the conditions for smoke diving has occurred.[22]

The time limitation of a powder unit is a problem in the ESS case is a problem, since the fire brigade will arrive quite a while after a supposed manual powder fire suppression by the First Responder. The powder will probably have a positive effect on the fire, but it should not be trusted completely since it will be consumed once deployed, and the First Responder will then no longer have a fire suppression unit. It is therefore maybe not suitable as a tool for the First Responder to use in extensive fires such as the design fire case. Although, a powder unit could be implemented together with other systems and, e.g. a portable fire extinguisher, that can add to the range of fire suppression units. After all, a normal powder fire extinguisher is enough to suppress a wide range of smaller fires and can be a good option as a first action. What should still be considered is the sanitary costs after a powder release, which must be compared to the possible fire damage.

3.4.5.1 Grading of Powder

According to Särdqvist[16], powder has a throwing distance like an open water jet and is therefore also considered to be *good*.

Powder is by Särdqvist[16] said to cause large property damage. It is therefore considered to be *bad* when it comes to potential damage to equipment.

According to Särdqvist[16], powder does not need a lot of neither personnel nor equipment, making it quite practical in terms of usage and handling. It is also a media that have a large effect relative to its weight, which means you do not have to bring a lot of media compared to e.g. water to extinguish a fire. With this in mind, powder is graded *good* in practicality.

The depletion time for a powder extinguishing system is relatively short, demanding some planning when fighting larger fires with only powder.[16] With such a short depletion time, powder is graded *bad* in endurance.

3.4.6 Fire Extinguishing Grenade (PGA)

A fire extinguishing grenade is a portable charge of PGA. The charge is activated by pulling a safety pin. It is then thrown, or rolled (depending on the design), into the fire compartment and the aerosol is released after a certain time delay. The name “grenade” can be confusing since it does not explode; the aerosol is released in the same way as the fixed PGA-system described earlier. The basic idea with the fire extinguishing grenade as a firefighting tool is that it should be used for a fast first intervention. The grenade is thrown or rolled into the fire room through an opening without the user having to enter. The user can then close the opening and let the grenade suppress the fire with its thermal and chemical effect.[16]

With a fire extinguishing grenade, a fast intervention is possible without risking the safety of the First Responder. That is, if the fire has only begun and the Instrument Hall is not filled with smoke and the door to the burning instrument cave can be opened safely by the First Responder. The device will work on its own and suppress the fire. But there are some concerns. Like the powder unit case described earlier, a fire extinguishing grenade will also be consumed after deployment, and like the other powder- and PGA systems described earlier, it will probably be able to spread outside the fire compartment through fine openings and damage equipment outside.

3.4.6.1 Grading of Fire Extinguishing Grenade (PGA)

When it comes to the throwing distance of the PGA-grenade, it is hard to compare to the other extinguishing systems. It is a device that is placed in the fire compartment and not held and pointed when in use like the other systems. Therefore, the throwing distance depends on the user’s ability to roll or throw the device, which differs between different operators. However, to get a good extinguishing effect, the operator must be relatively close to the fire to be able to get the device into the fire compartment. Still, the throwing distance of the grenade will probably exceed the throwing distance of a powder extinguisher, since the device is thrown, and the release of PGA adds to the distance. Therefore, the PGA-grenade is considered to have a *good* throwing distance.

From a residual value point of view, it is better to use PGA than powder, since the amount of extinguishing media is less and easier ventilated, making the secondary damage smaller.[22] Still, the system has some damage properties like powder. The potential damage to equipment of PGA is therefore considered *OK*.

PGA, sharing many properties with powder, is also light and needs few personnel and little equipment. In practicality, it is therefore also considered *good*.

As with powder, PGA is depleted after a short time of use, also giving it a grade of *bad* in endurance.

3.4.7 Extinguishing Systems Grade Comparison

To visualize the gradings of the different extinguishing systems compared in the analysis, the grades are displayed together in table 1 below. Comparing these different aspects provides better input for the discussion preceding identifying the most suitable extinguishing system for the ESS ERT First Responder.

Table 1. Grading of the analyzed extinguishing systems in the four chosen aspects. The colors clarify the grades, with green for good, yellow for OK and red for bad.

	Low-pressure water system	High-pressure water system	Cutting extinguisher	Foam	Powder	Fire extinguishing grenade (PGA)
Throwing distance	Good	OK	OK	OK	Good	Good
Potential damage to equipment	OK	Good	Good	OK	Bad	OK
Practicality	OK	Good	Good	OK	Good	Good
Endurance	OK	Good	Good	Good	Bad	Bad

3.5 PPV

A method used in many fire brigade interventions in Sweden is positive pressure ventilation, PPV. It is used either to create a better work environment for the fire fighters or to ventilate smoke for property salvage.[24] PPV is often done by placing a PPV fan in an opening, e.g. a door, to push outside air into the compartment. This will cause an overpressure in the compartment. If an opening in another part of the compartment is opened, e.g. a window or smoke vents (alternatively making a hole in the roof if there are no appropriate openings), air will be pushed out of that opening. If done right, the smoke and hot gases from the fire will then be ventilated out of the compartment leaving a better working environment for an internal intervention. PPV is often combined with an internal manual fire suppression.[30]

The First Responder will, as said earlier, not be allowed to do an internal intervention if the Instrument Hall is filled with smoke. But, if he can use PPV to ventilate the smoke out of the compartment, him then entering the compartment will not be regarded as smoke diving. He will then be allowed to do an intervention and manually suppress the fire, given that other safety conditions are fulfilled. The First Responder can perform a PPV by placing a portable PPV fan in a door opening, but he will probably not be able to open any windows or doors as exhaust air opening. The exhaust air opening could instead be the planned smoke hatches, if he is given authority to open the smoke hatches before the fire brigade arrives.

The result of a fire ventilation often relies on if the fire is fuel controlled or ventilation controlled.[31] The large Instrument Hall will probably provide enough air to a large fire, which means it will be fuel controlled and not ventilation controlled. With a fuel controlled fire, using PPV will probably not invigorate the fire, since it already has enough air. With this been said, it is still possible that the fire might be ventilation controlled. If so, PPV might invigorate the fire thus worsen the scenario and hamper an inside intervention. Hence, the person performing PPV must be aware of the effects of PPV and be qualified to do an assessment in different cases.

PPV with fans and openings is a complex procedure, but a possible option in the ESS facility is to install an automatic smoke control system, which can perform PPV by combining smoke hatches or similar with the ventilation system to pressurize compartments and evacuate smoke.[31] If the system is automated, this takes away responsibility and work from the First Responder and might reduce the risk of performing improper smoke ventilation. Still, an automatic smoke control system will not be able to judge if a fire is ventilation controlled, and might therefore invigorate it, but again, a ventilation controlled fire in the Instrument Hall is not very likely due to its large size.

When the fire brigade arrives and if they want to do an inside intervention, one method is to use PPV. This will take some time to set up – time that is crucial in the fire aspect. If the First Responder already has performed PPV when the fire brigade arrives, this will save time. That is, if the PPV is done correctly. A fast and correctly done PPV has been shown to significantly improve the work conditions for internal operations, resulting in faster results regarding internal suppression and lifesaving.[31] These good properties were also reported by firefighters at the study visit to Räddningstjänsten Lomma–Staffanstorp. However, in larger compartments, there is a risk that PPV aggravates the situation if the layered gases in the compartment mix and worsen the sight conditions and increases the temperature in the whole compartment.[30]

What must be considered that ventilation controlled fires in large compartments must be taken special care. Other measures, especially firefighting, must be coordinated on the scene, since the fire will probably increase in intensity fast after a performed smoke ventilation.[31] It is therefore very important that the First Responder does not perform a PPV on a ventilation controlled fire; this should only be done by the fire brigade, which has more resources.

4 Discussion

The following discussion is a wide selection of different general reflections on the analysis as well as on specific parts of the analysis.

4.1 Challenges and Design Fire Discussion

The fire safety problems presented in this report are, as shown in the analysis, not so easily solved. The facility is complex, but also quite unique, which makes it hard to apply a normal fire safety dimensioning procedure to it. The special approach that must be used is also not so easily defended, since the actual results from a real case cannot be replicated in advance. What can be done is a large analysis where knowledge is applied together with experience from similar cases. This requires research and a broad approach in the choice of sources, but still, the validation process must be done. There is not much to do except testing and experimenting if there are no similar previous cases. This can be expensive, but might be the best way to ensure that the chosen fire safety measures provide a qualified protection.

The interaction between the fire safety measures analyzed in this report and the already planned measures have not been investigated in this report. There might be some problems, and maybe some advantages, in these possible interactions. For instance, the steel containers and fire rated cladding (for the paraffin and PE shielding respectively) might have some interactions with some of the analyzed fire extinguishing systems. However, this is hard to investigate, since the exact configuration of the instrument caves are not known by now. Also, these aspects are time consuming and would lead to a great workload, which is not coveted in this project.

The size and HRR of the design fire in this report is arguable. The HRR of 70-100 MW is extremely high, but since a sprinkler system is planned in the Instrument Hall, the fire will be suppressed. The HRR of the fire when suppressed by the sprinkler is estimated to about 6 MW, since it is the HRR which is significantly smaller than 70-100 MW. This huge difference in HRR is not further investigated in this report. Although, it would be interesting to investigate in order to find a way to further lower the HRR to obtain an even smaller fire. If, somehow, the sprinkler system would malfunction, the fire might be able to reach the high HRR of 70-100 MW, which means that, with the analysis in chapter 3.2.2 in mind, an internal intervention would be unlikely. This contributes to the importance of implementing complementary solutions to the sprinkler system, i.e. automatic extinguishing systems in the instrument caves and manual suppression by the ESS ERT.

4.2 Miscellaneous Fire Safety Measures

Even though ceiling sprinkler is already planned to be installed in the Instrument Hall, it might be worth considering options. For instance, a water mist system is shown to have better extinguishing abilities, in some aspects, compared to conventional sprinkler. Also, the water damage is smaller and less water is required.[31] Although water mist is not as usual as conventional sprinkler, it could be further investigated as an option to the Instrument Hall ceiling sprinkler with the chance to further improve the fire protection in the facility.

A notable measure that should be better implemented in the ESS facility is multiple POAs. Multiple POAs enable an easier access to a manual fire suppression. A fire can also, in a later stage of an intervention by the municipal fire brigade, be suppressed from different angles at the same time. Multiple POAs can also shorten the maximum length from fire to POA, improving the access for both the First Responder and the municipal fire brigade. The present maximum access route length in the design fire scenario is 70 meters, which could maybe be improved to enhance a manual fire suppression effort. At CERN, there are always at least two POAs to make sure that the fire can be accessed even if one of the entries is blocked[19], which speaks for the importance of this implementation at ESS.

4.3 Time Aspect Discussion

The time aspect in this fire protection case is of great significance, both from an extinguishing and from a cost point of view. Best utilization of resources is obtained if the fire is suppressed fast.[14] The time from fire detection to suppression is crucial, since a fast extinguishing limits the fire damage. However, one cannot depend on the fire to be completely extinguished by neither an automatic system nor a quick manual effort. Still, a fire suppression is important, since it will somewhat dampen the fire. If done in an early stage, the fire will be smaller and therefore an easier target for an extinguishing system. Another important advantage with a quick fire suppression is that the damage is hopefully limited. If a flashover should occur in an instrument cave, the fire and its products would most likely be able to damage the rest of the Instrument Hall as well, which is not desired. This makes a large difference when it comes to sanitation costs.

Studying the HRR curves in figure 3 and 4, one can see the importance of attacking the fire in an early stage, since a fire probably will grow exponentially. The ceiling sprinkler in the Instrument Hall will limit the fire to about 6 MW, which is reached after 6 minutes in the t-squared fire assumption. If the fire is suppressed earlier than this, it will not reach such HRRs, also meaning less damage will be done to the surroundings. This speaks for the significance of a quick fire suppression.

Since an intervention by the municipal fire brigade is considered to take some time, compared to automatic fire extinguishing systems and manual fire suppression by the ESS ERT, and the work's objective is to shorten the time from fire alarm to fire suppression, the project focuses less on the municipal fire brigade intervention and more on other, faster fire suppression solutions. Still, the reasoning in chapter 3.2.1 contains some solutions to improve a later municipal fire brigade intervention, since it also contributes to a faster successful complete fire extinguishing. However, since the work is delimited to focus mainly on solutions to start fire suppression as soon as possible, an intervention by the municipal fire brigade is not analyzed in a very large extent.

If the aim is to suppress a fire as early as possible, an automatic extinguishing system is a fast option. Although, the systems are often triggered by a two-detector system, which means that two fire detectors have to go off before the system is activated, to avoid false alarms and releasing extinguishing media in vain. Of course, you can add a manual activation to the system, but it is a big decision for a person to push that button, since it will probably do a lot of damage to equipment, instruments and so forth. Comparing an automatic system with an all manual suppression system, the manual system is completely operated by a person, which means that the one operating it will be able to assess the situation throughout the operation. The operator can then continuously assess if the suppression has any effect, if it is needed, if there is sensitive equipment nearby etcetera. This cannot be done by an automatic extinguishing system.

The system selection depends partly on two opposing parameters: a fast fire suppression and the avoidance of false activation. With a manual system, the First Responder will be alarmed after the first detector is activated or through manual alerting, but the automatic system will wait for two detectors or a manual activation. Which of the systems leads to a faster suppression depends on the situation. The avoidance of false activation is much higher with a manual suppression system. This speaks for a manual suppression system, provided that the First Responder is quickly on the scene, ready for manual fire suppression, which could make a manual system faster than an automatic.

Maybe the choice between an automatic and a manual fire suppression system should not be a choice. Maybe a combination of the both is better. Both systems' benefits will then be implemented and complement each other. On the other hand, this means an even bigger expense, but considering the potential damage to the very expensive equipment and instruments at ESS, this could be a reasonable expense. A large fire could also, if not suppressed properly, spread to the rest of the complex and do even greater damage. A good firefighting organization is therefore an important investment, and the fire protection of the complex should maybe not be cut down in expenses.

4.4 Fire Extinguishing Systems Discussion

When choosing an extinguishing system, there are a lot of aspects that should be considered. Some of them are the extinguishing properties and effectivity, potential environmental damage, sanitation costs, purchase and maintenance costs, versatility and handling. All of these cannot be accommodated by one system, so priorities must be done. The choice should maybe also be, as discussed in the choice between manual and automatic system above, a combination of systems. For example, a combination of different automatic suppression systems for different instrument caves together with a First Responder equipped with a vehicle mounted high-pressure system and a PPV fan, supplemented by a portable fire extinguisher and a PGA grenade, is an equipage that is very versatile and able to handle a large amount of different fires.

Comparing different extinguishing systems for the First Responder vehicle, some of the systems are not very versatile and can only do a short impact on a fire. To ensure that a larger fire can be fought continuously until the arrival of the municipal fire brigade, at least one more substantial extinguishing system should be acquired. Systems of this sort that are analyzed in this report are high-pressure water and cutting extinguisher. These systems are able to suppress a fire for a longer time without running out of extinguishing media. To extend the suppression time, the system should be vehicle mounted, since a vehicle mounted system enables a larger amount of extinguishing media than a portable system, where the media has to be carried around by the operator. A foam system such as CAFS could also be a possible system, but with the possibility to add foam liquid to these two other systems, they get the same advantages as the CAFS foam. Hence, CAFS no longer has the unique foam abilities compared to the other two systems.

One of the four aspects compared in chapter 3.4 is throwing distance. The throwing distances of the systems have in this study not been measured or deeply investigated in literature due to lack of time. Instead, other, more general, input have been used to somehow qualitatively compare the system's throwing distances. What one could have done is to practically test the systems, measure the throwing distances and compare with the calculated minimum distance between fire and firefighter in chapter 3.1. Doing so would have given a much better result as it shows the actual throwing distances and if they would have been enough to fight the design fire from a safe distance.

Several of the analyzed extinguishing agents are reported to have potential property damage properties. If these properties occur in the ESS case or not is not easily investigated in this report, since the design and component composition of the instruments and equipment are unknown. Then it cannot be investigated further if e.g. PGA might have a corrosive effect to any of the components or if water mist can damage electrical equipment in the Instrument Hall. Also, the extent of the potential damage of the different extinguishing agents is unknown, which means that they are hard to compare. However, some of the damage mechanisms can be compared in magnitude, such as the amount of damage done by different water systems, as is done in the comparison grading in chapter 3.4. For instance, a water mist system does less damage than a conventional sprinkler system, since less water is used in a water mist system. Also, some of the extinguishing agents' characteristics can influence the damage extent, such as powder's and PGA's risk for spread outside a compartment, since this would worsen the potential property damage. These comparisons can make the potential property damage of different extinguishing agents somewhat comparable.

4.5 First Responder Discussion

A good and thorough education of the First Responder ensures that the equipment can be handled properly and that appropriate actions are made against different fires and in different situations. Without proper knowledge, actions against a fire could be ineffective, or in worst case invigorate the fire. The education is suitably composed similar to the Swedish firefighting education, giving the First Responder a wide range of firefighting knowledge and techniques. It is important that the First Responder knows not only how to handle the equipment, but also how a fire behaves and what effect different methods and tactics have.

There are obvious risks with the First Responder suppressing a large fire in the ESS facility singlehandedly, such as the lack of quick rescue or backup if something goes wrong. This could be avoided by adding one or more people to the First Responder post, or by enabling the other security patrol guard to assist the First Responder. As mentioned in the cutting extinguisher analysis in chapter 3.4.3, a second person is suitable as person safety guard for a suppression operator. The second person could also be of assistance in the whole intervention if they are both educated equivalently, which could improve a ESS ERT fire intervention. However, in discussions with ESS representatives, it has been shown to be hard to find workers at the facility that are suitable for the assignment in terms of around the clock availability. All of the perimeter security guards already have assignments in case of a fire alarm, and there are no other workers that have the same combination of flexibility, around the clock workhours and suitable work tasks as the security guards. Possibly the additional First Responder could be a complement for the ordinary First Responder during normal working hours when there are more people available at the facility. Since the main work at ESS will be done at normal working hours, the fire risk could be considered to be higher then. Reinforcing the ESS ERT during working hours would then mean that the ESS ERT is more forceful when the risk of fire is higher, which is good from a risk perspective. This solution should therefore be further investigated. The other solution of using the other security guard, the fire brigade guide, as a complement to the First Responder in the early fire suppression stage, since the fire brigade has a certain driving time to the site. If so, there is a risk of the First Responder being left alone when the other person goes to direct the fire brigade into the facility.

In discussions with representatives from ESS, the present primary choice of First Responder equipment is a portable powder fire extinguisher. As a result from this study and further discussions with ESS representatives, this primary choice is challenged by the cutting extinguisher with its possibility to work safely from outside the fire compartment and its good extinguishing properties. Given that the cutting extinguisher can be proven to have the ability to successfully suppress the design fire of this study from outside the fire compartment, the system could, in combination with IR-camera scanning and PPV, be expected to provide a successful fire suppression without having the First Responder performing a potentially risky indoor intervention. If a cutting fire suppression is showed not to be satisfactory in all fire cases, the system could still be used in an internal intervention like a high-pressure water system. If a cutting suppression is showed not to be satisfactory in more than a couple of fire cases, a high-pressure system could be a good alternative.

The choice of the cutting extinguisher as primary extinguishing system is also supported by the gradings of the analyzed extinguishing systems in chapter 3.4. Looking at table 1, the cutting extinguisher has the best overall grading of the systems, together with the high-pressure water system, with three “good” and one “OK” grading, showing that these two systems are the most suitable when looking at the four aspects in which the systems are analyzed: throwing distance, potential damage to equipment, practicality and endurance.

If one were to equip the ESS ERT First Responder with only one extinguishing systems, the “tool box” of the First Responder would be very small, not enabling him to use methods adapted to the current situation and fire scenario. Therefore, it would be positive to add some smaller, additional fire extinguishing systems to the “tool box”, enabling a better overall fire fighting basis. Looking at additional portable extinguishing systems among the analyzed systems, two of the most portable systems are the powder portable fire extinguisher and the PGA grenade. Both these systems will add different extinguishing properties, making the First Responder better equipped with optional methods. For example, the portable fire extinguisher is perfect for a very fast first effort, especially on small fires such as wastebasket fires. The PGA grenade has a strength in its usage, namely its unmanned depletion. The PGA grenade is just thrown or rolled into place, where it does the job by itself, without having the user occupied operating the system. The user can then do something else, such as preparing the next fire fighting effort with another extinguishing system.

5 Conclusion

The best way to cut time between fire alarm and a successful fire extinguishing is to implement a combined organization of automatic fire suppression systems and a firefighting educated and well equipped First Responder of the ESS ERT.

Automatic fire suppression systems should be installed in instrument caves with the potential of larger fires. There are a number of systems that might be suitable, each with different pros and cons. Some of them are presented in table 2 below.

Table 2. Pros and cons of different automatic fire extinguishing systems.

System	Pros	Cons
Water mist sprinkler	• Multiple fire suppression mechanisms • Less water damage than e.g. conventional water sprinkler	• Might damage equipment • Possible flooding issues
Gas extinguishing system	• Clean • Little property damage	• Not very fast extinguishing • Problems when the instruments are being rebuilt
Foam extinguishing system	• Good against pool fires • Little water damage	• Environmental hazardous • Might damage equipment
Powder extinguishing system	• Effective against most fires • Fast extinguishing	• Might damage equipment, even outside the fire compartment • Consumed once deployed
PGA system	• Effective against most fires • Fast extinguishing • Does not damage low current circuits	• Might damage equipment, even outside the fire compartment • Consumed once deployed • Strongly reduced visibility

The ESS ERT First Responder/security guard vehicle should be equipped with a number of extinguishing systems in order to enable different firefighting techniques for different types of fires. An example of an equipment arsenal that the car could be equipped with is:

- Portable fire extinguisher (powder is most effective and versatile)
- PGA grenade
- PPV fan
- Vehicle mounted fire suppression system

The vehicle mounted fire suppression system is preferably either a high-pressure water system or a cutting extinguisher. The main difference between the two systems is the cutting extinguisher's ability to penetrate e.g. walls, enabling a suppression from a safe position for the operator outside the fire compartment. Important to notice is that the cutting extinguisher must have a long enough throwing distance to be able to suppress a fire from the point of penetration if the fire is far away, and that some sort of visual feedback is needed to help the First Responder, such as for instance a second person equipped with an IR-camera or an inside surveillance system.

An alternative to the PPV fan in the First Responder equipment is to install an automatic smoke control system in the facility, which can evacuate smoke without the First Responder having to set up a PPV with fan and exhaust vent.

The First Responder of the ESS ERT should be thoroughly educated in firefighting and fire behavior, in order to perform a good and effective firefighting effort. This education is important to give the First Responder knowledge in how to use the equipment practically as well as what effect different firefighting tactics and methods have on a fire. Additionally, the possibility of adding a second person to assist the First Responder should be investigated, since this could improve the work and the personal security.

With these different systems and procedures implemented, a fire at the ESS facility will enable a faster fire suppression than would be the case if depending only on an intervention by the municipal fire brigade. Since the time from fire alarm to fire suppression probably will be shortened, the fire protection capability at the ESS facility is enhanced. This with the possibility to suppress most fires thanks to a combination of thoughtfully placed automatic fire extinguishing systems and an ESS ERT First Responder with the ability to extinguish or suppress a variety of fires in shorter time until the arrival of the municipal fire brigade. This means that the objective of this study, i.e. to find and evaluate faster, alternative ways to extinguish a fire at the ESS facility, can be considered accomplished.

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