# Investigation on the gas-cooling effects of CAFS

# Erik Lyckebäck Jacob Öhrn

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

Brandteknik och Riskhantering Lunds Tekniska Högskola Lunds Universitet

Report 5394, Lund 2012

# Investigation on the gas-cooling effects of CAFS

Erik Lyckebäck Jacob Öhrn

Lund 2012

Title/Titel: Investigation on the gas-cooling effects of CAFS

Language/Språk: English/Engelska

Report/Rapport: 5394 ISSN: 1402-3504 ISRN: LUTVDG/TVBB-5394-SE

The authors are responsible for the contents of this report Författarna svarar för innehållet i rapporten

#### Authors/Författare: Erik Lyckebäck, Jacob Öhrn

Fire Protection Engineering Program, Faculty of Engineering, Lund University, 2012 Brandingenjörsprogrammet, Lunds Tekniska Högskola, 2012

©Copyright Brandteknik och Riskhantering, Lunds Tekniska Högskola, Lunds Universitet, 2012

Number of pages/Antal sidor: 193 (Including appendices/Inklusive bilagor)

#### **Keywords**

CAFS, compressed air foam systems, extinguishing methods, full-scale experiments, gas-cooling, high pressure water mist, structural firefighting

#### Sökord

CAFS, tryckluftsgenererat skum, brandgaskylning, fullskaleförsök, förhöjt lågtryck, högtryckssystem, inomhusbränder, rökdykning, släckmetoder

#### Abstract

This report investigates the gas-cooling effects of compressed air foam (CAF). A literature review has been made on the subject and on related issues in order to gather information. Two experimental series were conducted, the first to evaluate the gas-cooling properties of CAF compared to water. The other one was conducted to investigate how the recommended tactic, with application from a safe distance, would affect the temperature and thereby the need for traditional gas-cooling. The results from the first experiments show that CAF has a gas-cooling effect but is less effective than water. The second series of experiments indicate that the suitable tactics may limit the need for traditional gas-cooling. However, the data is limited and further research in the area is required.

Avdelningen för	Department of Fire Safety
Brandteknik och Riskhantering	Engineering and Systems Safety
Lunds tekniska högskola	Faculty of Engineering, LTH
Lunds universitet	Lund University
Box 118	P.O. Box 118
221 00 Lund	SE-221 00 Lund, Sweden
brand@brand.lth.se	brand@brand.lth.se
http://www.brand.lth.se	http://www.brand.lth.se
Telefon: 046-222 73 60	Telephone: 046-222 73 60
Fax: 046-222 46 12	Fax: 046-222 46 12

# Preface

This thesis is the last brick in the wall before we graduate as Fire Protection Engineers from the Department of Fire Safety Engineering and Systems Safety at Lund University.

The making of this report has been very informative and interesting and we would like to give a special thanks to all those who have helped us during this process and contributed to the fine result that it became.



Our supervisor *Stefan Svensson* at the Swedish Civil Contingencies Agency for excellent support and help during the entire process.



*Fredrik Johansson* at the Swedish Civil Contingencies Agency for valuable help during the experiments at Revinge and for nice coffee breaks.



Daniel H Apeland at Nordic Fire & Rescue Service (Norway) who lent us the One Seven® CAF-systems, contributed with many good opinions and invited us to a fun and interesting CAFSweekend in Norway.

*Gunn M.H. Apeland* (Norway) and *Stefan Andreasson* (Sweden) at Nordic Fire & Rescue Service for interesting discussions and for sharing your knowledge.

Daniel Madrzykowski at National Institute of Standards and Technology (USA), Shan Raffel at Queensland Fire and Rescue Service (Australia), John Chubb at Dublin Fire Brigade (Ireland) and Marcus Worén at the Fire Department in Södertörn (Sweden) for very useful help with the literature review and guidance when choosing thesis topic.

*Erik Elvermark* at Norrtälje Fire Department (Sweden). As one of the people in Sweden with most experience from CAFS, his guidance and advice has been of great help.

*Pär Hagbohm* at the Fire Department in Östra Skaraborg (Sweden) for good hosting and for giving us the opportunity to conduct the full-scale experiments.

Johan Lindström and Glenn Appel at SP Technical Research Institute of Sweden for their reviews and good comments.

Susan Johansson (Sweden) for a linguistic review. It was as appreciated as it was necessary...

*Stefan Särdqvist* at the Swedish Civil Contingencies Agency for useful help and for making his images available for our report.

Dominic Colletti at Hale Products (USA) for letting us use his material in our report.

Lars Wahlberg at Lund University (Sweden) for counseling regarding statistical models.

*Berit Andersson* at the Department of Fire Safety Engineering and Systems Safety, Lund University (Sweden), our examiner.

Our fellow classmates Fredrik Malthe and Ivan Vukancic for their review.

Lund, November 2012

Erik Lyckebäck & Jacob Öhrn

# Summary

Compressed Air Foam Systems (CAFS) have been used in different areas of firefighting since the 1930s. However they have not gained much popularity until more recently. Over the last twenty years, these systems have grown in popularity and found a more widespread usage among fire rescue services worldwide.

The research conducted up to this point has mainly been focused on the extinguishing effects as well as the protective aspects of CAF. The results from these reports showed that CAF is more effective than water in both these aspects; however some concern is expressed as to whether CAFS can be used in structural fires and their ability to cool hot gases in compartment fires.

This report aims to evaluate the gas-cooling properties of CAFS through two series of experiments. The first set of experiments conducted in this report only looked at the gas-cooling properties of CAF and water, to enable comparison. They took place in a non-flammable environment where hot gases are subjected to both a high pressure water mist system and a One Seven® Compressed Air Foam System. A heptane pool fire produced the hot gases and temperatures were continuously measured throughout the entire compartment.

These experiments show that CAF does in fact have a gas-cooling effect when applied to the hot surfaces of the compartment. However they also showed that CAF is less effective than water when it comes to the cooling of hot gases. The comparison took into account the amount of water applied in each room, whether it was applied as CAF or as water mist. Through a statistical analysis the difference in effect was found to be significant.

The first set of experiments did not take into account that CAF is not supposed to be used in this specific manner, but rather to be applied in the room of the fire from a safe distance. Therefore, another set of experiments was carried out made to determine whether this recommended tactic would lower the gas temperature enough to limit the need for gas-cooling.

The second set of experiments was conducted in a two story building constructed of wood. Thus the materials within the fire compartment were fibrous and flammable. Two experiments were conducted in almost identical compartments, one with water and one with CAFS. The tactics used for extinguishing were appropriate for the different extinguishing agents, i.e. water was applied from inside the compartment and CAF was initially applied from the outside.

The results of these experiments suggest that with a suitable tactic CAFS might be able to control this type of fire from a safe distance and ensure that the need for gas-cooling is limited. However with only two experiments conducted there is not enough data to ensure that this statement is correct. Further research in this area is needed to evaluate whether a different tactic might be sufficient to reduce the need of traditional gas-cooling.

In the latter experiments observations were made that indicate that less water is left within the compartment after extinguishment and that re-ignition was harder to achieve when CAF was used.

# Sammanfattning

Tryckluftsgenererat skum eller Compressed Air Foam System (CAFS) har använts inom olika brandbekämpningsområden sedan 1930-talet, men det är först på senare tid som de har blivit mer populära. Under de senaste tjugo åren har dessa system blivit alltmer efterfrågade och används idag av räddningstjänster världen över.

Forskningen som bedrivits kring dessa system har framförallt inriktat sig på släckeffekten och de skyddande egenskaper som finns hos CAF, till exempel dess strålningsdämpande egenskaper. Resultaten från de här rapporterna fastställer att CAF är effektivare inom båda dessa områden. Dock så uttrycks en skepsis till hur systemet klarar av brand i byggnader och då framförallt brandgaskylning.

Den här rapporten syftar till att utvärdera de brandgaskylande egenskaperna hos CAF, genom att genomföra två experimentserier. Den första experimentserien som genomförts undersöker enbart den brandgaskylande effekten, hos både vatten och CAF, för att möjliggöra en jämförelse. Dessa försök genomfördes i ett obrännbart utrymme där heta brandgaser kyldes med dels ett högtrycksvattensläcksystem ("förhöjt lågtryck") och ett One Seven® Compressed Air Foam aggregat. Ett heptanbål utgjorde branden i utrymmet och temperaturen mättes kontinuerligt under försöken.

De här försöken visar att CAF har en brandgaskylande effekt när det appliceras på de varma ytorna i utrymmet. De visar dock att CAF inte är lika effektivt som vatten när det gäller att kyla brandgaser. Jämförelsen tog hänsyn till hur mycket vatten som tillförts i varje rum i utrymmet, oavsett om det tillfördes i form av CAF eller som vattendroppar. Genom en statistisk analys fastställdes att skillnaden i effektivitet är signifikant.

De första experimenten tar ingen hänsyn till att CAF inte är avsett att användas på detta sätt, då det snarare bör appliceras i brandrummet från ett säkert avstånd innan vidare avancemang sker in i byggnaden. Därför genomfördes en andra testserie, för att avgöra om den korrekta angreppstaktiken sänker temperaturen i brandgaserna nog för att minska behovet av invändig brandgaskylning.

Den andra försöksserien genomfördes i ett tvåvånings trähus. Där brandrummen var konstruerade av fibrösa, brännbara material. Två experiment genomfördes, i två nästan identiska utrymmen, ett med vatten och ett med CAFS. Taktiken som användes vid de båda släckningarna är den föreslagna för respektive system dvs. med vattnet användes en invändig släckinsats och med CAFS påverkades brandrummet först genom utvändig släckning och sedan genom invändig släckning.

Resultaten från de här försöken indikerar att en korrekt angreppstaktik med CAFS kan användas för att kontrollera den här typen av brand från ett säkert avstånd och sänka temperaturen till en nivå där ytterligare brandgaskylning inte är nödvändig. Dock så genomfördes enbart två försök i denna serie vilket innebär att mängden data inte är tillräcklig för att fastslå några definitiva resultat. Mer forskning krävs därför inom det här området för att säkerställa någon slutsats.

I den sista försöksserien observerades att mindre vatten låg kvar på golvet i brandrummet efter det att släckningen genomförts samt att återantändning var svårare när CAFS använts.

# **Table of Contents**

1	Intro	Introduction 1		
	1.1	Intention	1	
	1.2	Objective	1	
	1.3	Questions at issue	1	
	1.4	Method	1	
	1.5	Limitations	2	
2	Bacl	kground	3	
3	Liter	rature review	5	
	3.1	Summary	8	
4	Theo	ory	9	
	4.1	Foam	9	
	4.2	Foam generation	11	
	4.2.1	Nozzle Aspirated Foam Systems (NAFS)	11	
	4.2.2	2 Compressed Air Foam Systems (CAFS)	12	
	4.3	Extinguishing mechanisms	12	
	4.3.1	1 Extinguishing mechanisms of CAFS	13	
5	Fire	fighting systems used in the experiments	15	
	5.1	CAFS	15	
	5.1.1	1 CAFS used at Revinge	15	
	5.1.2	2 CAFS used in Skövde	21	
	5.2	High pressure water mist system	22	
	5.2.1	1 High pressure water mist system used at Revinge	22	
	5.2.2	2 High pressure water mist system used in Skövde	23	
	5.3	Firefighting tactics	24	
6	Gas-	-cooling experiments	25	
	6.1	Experimental objectives	25	
	6.2	Experimental setup	25	
	6.2.1	1 Experimental conditions	28	
	6.3	Experimental procedure	29	
7	Resu	alts from the gas-cooling experiments	31	
	7.1	Individual experiments	31	
	7.1.1	Experiment 1: Wet foam, 2 seconds application in both rooms	32	
	7.1.2	2 Experiment 2: Wet foam, 2 seconds application in both rooms.	36	
	7.1.3	Experiment 3: Wet foam, 4 seconds application in both rooms.	40	
	7.1.4	Experiment 4: Wet foam, 4 seconds application in both rooms.	45	

7.1.5	5 Experiment 5: Wet foam, 4 second application in one room.	49
7.1.6	5 Experiment 6: Wet foam, 2 seconds application in both rooms	53
7.1.7	Experiment 7: Wet foam, 4 second application in the second room.	57
7.1.8	8 Experiment 8: Dry foam, 5 seconds application in both rooms	61
7.1.9	Experiment 9: Dry foam, 5 seconds application in both rooms.	65
7.1.1	Experiment 10: Dry foam, 5 seconds application in the second room.	69
7.1.1	Experiment 11: Water, 2 second application in both rooms	73
7.1.1	Experiment 12: Water, 1 second application in both rooms	77
7.2	Summary of experimental results	81
8 Disc	ussion, gas-cooling experiments	85
8.1	Results	85
8.2	Method	87
9 Full-	-scale experiments	89
9.1	Experimental objectives	89
9.2	Experimental setup	89
9.2.1	Experimental conditions	96
9.3	Experimental procedure	96
10 Re	esults for the full-scale experiments	99
10.1	Individual experiments	99
10.1	.1 CAFS experiment: fire located in room three	99
10.1	.2 Water experiment: fire located in room two	102
10.2	Summary of experimental results	105
11 Di	iscussion, full-scale experiments	107
11.1	Results	107
11.2	Method	108
12 Co	onclusion	111
12.1	Conclusions from the literature review	111
12.2	Conclusions from the gas-cooling experiments	111
12.3	Conclusions from the full-scale experiments	111
13 Fu	urther research	113
14 Bi	ibliography	115
15 Aj	ppendix A - Results	117
16 Aj	ppendix B - Calculations	177

# 1 Introduction

Compressed Air Foam Systems (CAFS) is a fire extinguishing system which generates foam. The system combines a standard water pump with an air compressor and adds compressed air to the foam solution. The result is a more stable foam that provides new possibilities for firefighting purposes. CAFS have been around for a long time, first mainly used for wildland fire control and as fixed-pipe systems in Hangars and similar buildings. The last decades smaller, portable CAF-systems are growing more and more popular among fire rescue services worldwide. The increase in popularity is a combination of extensive research, showing good results, and stable user friendly CAF-systems becoming available on the market.

The previously conducted research focuses mainly on the extinguishing and protective features of CAF. Providing results that clearly state that CAF is much more efficient in these areas than water and several of the other extinguishing agents tested. None of the literature found by the authors of this report investigates the gas-cooling effects of CAF, even though some of the reports actually state that it is not as efficient as a water spray and should not be used to cool hot gases.

This report tries to quantify the gas-cooling effects of CAF and offer a comparison to the effectiveness of a water mist system by conducting several experiments. In addition, an experimental study comparing CAFS and water mist systems in real firefighting applications is conducted. It should be of interest to determine how effective CAF really is in order to make appropriate, well-informed decisions on whether to use CAFS or another extinguishing system depending on the situation and nature of the fire. Hopefully this report can help make these types of decisions easier.

### 1.1 Intention

The intent of this report is to investigate the gas-cooling effect, and thereby the fire inhibitory and extinguishing effects when CAF is applied to the hot surfaces of a compartment. The effects are investigated for both the compartment containing the fire and an adjoining compartment.

### 1.2 Objective

The main objective of this report is to describe and quantify the gas-cooling effects of CAF. An additional objective is to evaluate how CAFS is used in a realistic firefighting environment.

#### 1.3 Questions at issue

The main questions to be answered in this report are:

- How does CAFS work?
- What are the differences between CAFS and nozzle aspirated foam?
- What are the differences between CAFS and water?
- How can CAFS be used for structural firefighting?
- How does CAF affect the fire and the hot gases produced?

#### 1.4 Method

To investigate the gas-cooling effects of CAF several experiments are conducted. In addition to these experiments a literature review is performed to enable better understanding about CAF and its properties. Also, a short series of experiments is conducted to evaluate the existing firefighting technique for both CAFS and high pressure water mist systems.

# 1.5 Limitations

A number of limitations were made throughout the process so it could proceed. Due to the objective, no direct extinguishing attempts were made in the first series of experiments. If the fire did not extinguish during the experimental stage, it was allowed to burn out by itself.

Variations in CAF-systems constructed by different manufacturers were not taken into account since the CAF-systems were provided by the same manufacturer.

# 2 Background

The first step to the foam systems used today was taken by an Englishman named Johnson in 1877. He invented foam generated by a chemical reaction between two aqueous solutions. A Russian named Laurent then introduced the foam in 1904 (Boyd & di Marzo, 1996), (Persson, 2005). This type was commonly used until the mid-1950s when the technique to produce mechanical foam had its break-through (Boyd & di Marzo, 1996). In 1949, NFPA published a standard regarding wetting agents; NFPA 18, Standard on Wetting Agents, which exists even today (Persson, 2005).

The two Danes E. Schröder and A. van Deurs developed a foam pump system in 1929. This system produced mechanical generated foam with a foam pump similar to a compressor. The patent rights were purchased by the Swedish company Svenska Skum ("Swedish Foam") in 1933 and cooperation began in the 1940s with the American Company Walter Kidde, which purchased the patent rights for the American market.

The production continued and the products were developed further, Svenska Skum delivered ten firefighting trucks equipped with the foam system to the Swedish Air Force in 1939 (Persson, 2005). The British Navy experimented with compressed air foams in the 1930's and the U.S. Navy in late 1940s (Persson, 2005), (Taylor, 1997). In the 1950s, a larger Air-Crash Tender was developed by Svenska Skum and the unit was sold in about 50 copies, mostly to Airports around Europe. Due to the difficulties with the control technology along with the introduction of the film forming foams, CAFS suffered a regress in the 1960s (Persson, 2005).

Cummins Industries together with Texas Forest Service regained interest for CAFS in the 1970s, the purpose was to protect bulldozers used for fighting wildland fires but it was soon found that CAFS were also effective for fire suppression and fire protection in wildland fires (Persson, 2005). The Texas Forest Service developed a water expansion system called Texas Snow Job which used a foaming agent mixed with 8 to 9 percent foam concentrate (Taylor, 1997).

During the 1980s CAFS became established as a weapon for Wildland fires along with the first "real" Class A foam developed by George Cowan and Eddie Cundsawmy in Canada (Persson, 2005). The progress of CAFS for structural firefighting started in North America in the early 1990s and spread to Europe and Australia later that decade. Early pioneer countries in Europe were Germany and Great Britain (Persson, 2005).

Water is traditionally the most used extinguishing agent even for structural firefighting. Firefighters advance towards the fire while cooling the hot smoke gases at the ceiling. A cone shaped stream of water droplets enables a larger surface of contact with the hot gases which results in more efficient cooling. When the firefighters have progressed towards the fire, water is used for cooling the fire which stops the pyrolysis. Water can also be used for covering surfaces for fire protection. Due to the low adhesion properties a lot of the water simply runs off. This combined with the often large volume flows can result in water damage, sometimes larger than the damage caused by the fire itself. At normal use, only some of the water is vaporized and the excess-water simply runs of (Särdqvist, 2006) causing water damage.

During the last years, a discussion has started in Sweden regarding the excessive use of water and how resulting water damages can be reduced. The fact that CAFS uses water more efficiently make them a viable option for the Swedish rescue services; therefore it is important to investigate all aspects of the extinguishing agent.

Background

# 3 Literature review

Reviewed literature has been gathered with the purpose of providing a summary of research in the areas mostly regarding CAFS ability to work as a fire extinguishing agent for interior firefighting.

In the work of establishing a testing procedure to evaluate the relevant properties of fire exposure protection foams, Tafreshi and his colleagues (Tafreshi, et al., 1998) found that foams with high expansion ratio will have a lower thermal expansion. On the other hand foam with low expansion ratio does not stick well to vertical surfaces because it flows too much. They also found that foam generated with high-pressure air consists of smaller sized bubbles.

More recent experiments made by Tafreshi and di Marzo (Tafreshi & di Marzo, 1999) aimed to compare the thermal behavior of both compressed air foams (CAF) and gels used as fire protection agents. The experiment regarding foam resulted in that the used foam, a 3 % protein-based foam with expansion ratio 20 and foam thickness 0.1 m, gave a good protection against radiation. The underlying surface temperature sustained the ambient temperature for about half the transient period of the foam (i.e. the temperature sustained ambient temperature for half the protection time, before the temperature began to rise). The experiment lasted for about 15 minutes and the foam-covered surface was exposed to a radiant heat flux of 18 kW/m<sup>2</sup>.

Several conclusions were made in a study that aimed to develop a model to predict the behavior of fire-protection foam subjected to heat radiation. Since the tested foams had good insulating properties, the underlying surface temperature did not exceed 100 °C until most of the foam had vaporized. The reasons were the good insulating properties of foam and that the absorbed heat was dissipated through the vaporization of water. They also concluded that foam sticks well to vertical surfaces. Tested foams were generated by a custom-built compressed air foam system and had expansion ratios between 12.8 and 32.8 and were exposed to radiant heat fluxes up to 18 kW/m<sup>2</sup> (Boyd & di Marzo, 1996).

Other laboratory experiments with similar objectives have been performed and they conclude, among other things, that CAF applied to a combustible exterior siding reduced the likelihood of ignition and flame spread (Madrzykowski, et al., 1997). The experiments compared water, foam solution and CAF and the results showed that CAF exceeded water and foam solution in its ability to penetrate into materials in most cases. The time to ignition was extended for the materials due to the mass retention of water. However the foam covered materials mass retention effectiveness was greater than both foam solution and water. The increased retentivity of foam solution resulted in a longer ignition-inhibition time when CAF was used. Foam also has good adhesion to surfaces and is more effective as a fire protection agent than water (Madrzykowski & Stroup, 1998).

Crampton and Kim (Crampton & Kim, 2009) performed several full-scale compartment fire tests to evaluate and compare the capability of manually applied CAF, hose stream with water and hose stream with water-foam solution as a fire suppression tool. The test compartment had a gypsum-lined interior and was 38 m<sup>3</sup> with a small adjacent corridor. The fire load consisted of fibrous material with a total heat release rate of 5.6 MW. Suppression started 120 s after flash over and at the same time windows were opened to simulate window breakage. Temperature data along with suppression agent consumption were recorded. The results showed that the average room temperature dropped much quicker with CAF and also that the fire was controlled much quicker with CAF. Compared to the hose stream with water or foam-water solution, CAF was clearly the most effective fire suppression agent.

Another study carried out by Crampton and Kim aimed to investigate the implementation of CAF in fixed piping systems. The conclusion was that CAF works well but it was better at extinguishing the

pool fires than the crib fires due to the partly concealed fire in the cribs. However, the foam eventually drained and soaked into the cribs and extinguished the fires. The main point is that CAF works well in fixed piping systems and is recommended in areas with limited water supply (Crampton & Kim, 2000).

To evaluate the cooling effects of CAF in structural firefighting and determine advantages and disadvantages of the system, Tinsley (Tinsley, 2002) performed a literature review supplemented with live tests. Wooden frame single story houses were used and the fuel consisted of Class A-materials. Temperatures were measured with thermocouples with 15 seconds intervals. His conclusions were that CAFS increased the suppression capability and was effective in reducing the interior temperature in structural fires. The literature review includes a chapter with advantages and disadvantages of CAFS. As many others, he states that CAFS reduces the amount of needed water and foam concentrate required and due to the lighter fluid; CAF can be pumped twice as high as water under the same pressure. The main disadvantages are that compressed air enhances the hose reaction if the hose ruptures. CAFS can also add extra expense to a vehicle and require extra training for the staff.

Folkesson and Millbourn performed tests with CAFS in their bachelor thesis from Lund University. One of their conclusions was that CAF, compared to other extinguishing agents, had better surface cooling but was not as efficient in cooling the hot gaseous phase. CAF also gave a better protection against re-ignition (Folkesson & Millbourn, 2008).

In 2010, an experimental study was performed to assess the gas cooling capabilities of CAFS. Two experimental set-ups were used, one for fuel-controlled compartment fires and one for ventilation-controlled compartment fires. Two connected standard steel shipping containers were used for the fuel-controlled fire and one for the ventilation-controlled fire. Fibrous Class A-materials were used and CAFS was compared to a traditional water mist suppression agent. The study also investigated whether or not CAF, due to the extra supply of air bounded in the foam could cause a backdraft. The results showed that CAF was superior to the water mist in the fuel-controlled experiment, the flames extinguished almost completely and the firefighters could advance further into the compartment. This was because the untenable situation with drastically reduced visibility and increased temperature did not occur. On the other hand, little difference was observed between the two agents suppression efficiency. Experimental results also indicated that the extra air supplied within the CAF did not contribute to a backdraft (Zhang, et al., 2011).

Taylor has studied whether or not the efficacy, effectiveness and safety of firefighters, who operate under limited personnel conditions, could increase by equipping them with CAFS and Class A foam. He found that CAFS increased the crew's suppression capability and at the same time, reduced the stress and weariness of hose line operators. CAFS are also effective for suppression of structural fires from the outside, they conserve water and together with Class A foam may create long-term cost savings and reduced property damage. On the other hand it is concluded that CAFS requires more training, it creates a slippery surface on the floor and the foam concentrate could irritate skin, eyes and upper respiratory tract. It can also be corrosive to some metals and can corrode apparatus, paint and finish (Taylor, 1997).

Persson conducted a literature review for the Swedish National Testing and Research Institute in 2005 (Persson, 2005). It aimed to summarize knowledge and experience on the use of Class A foams, including CAFS. The main conclusions were that Class A foam gives a clear increase in efficiency compared to regular water and also improves re-ignition properties. CAF provides a good protection against heat radiation and reduces the amount of excess water. The distinctive white foam cover also

creates a good visualization of the protection durability when foam is used for preventive protection of surfaces. Different areas of application for different types of foams are concerned superficially, foams with higher expansion ratio (dry foams) are suitable for indirect application, and give good protection against heat radiation. Dry foam can also be used to cover piles of smoldering material after fire knock down to create a long lasting cover which stops air entrainment and drain into hot areas. Additional foam can then be applied to areas where the foam layer has diminished. Foams with lower expansion ratio (wet foams) on the other hand are suitable for structural firefighting.

An article in Fire Chief strengthens this theory and states that dry ("shaving cream-consistency") foams are suitable for pretreatment of exposed surfaces while wet foams are preferred for deep-seated fires and direct attacks (Carringer, 2009).

Paul Grimwood wrote an article at Firetactics.com (Grimwood, 2008) where he reports on different research projects. The conclusions in this article are more or less the same as in many of the earlier reports; CAF is a more efficient fire suppression agent than plain water, it covers surfaces better than water and the foam penetrates into the covered material more easily than plain water. The strength of CAFS is in the un-shielded post-flashover fires involving open-plan areas. However, the weakness is "shielded" pre-flashover fires. For instance if the fire is at the end of a long hallway with large amounts of unburnt smoke gases, it is not possible to "coat" the gases with a straight-stream.

Two field-test reports have been studied. The first report was written by Boston Fire Department who retrofitted one of their engines with CAFS. It was then tested in suburban environments for one year. The purpose was to evaluate the effectiveness and suitability of CAFS as a firefighting agent in an urban environment. They concluded that CAFS and Class A foams are extremely effective for interior firefighting and reduce the time until the fire is under control, at the same time reducing reducing the amount of water needed to control and extinguish the fire. They also found that the fire suppression effectiveness was at least equivalent to that of the water stream. The time to achieve knock down was about the same as for water but with CAFS, about half the flow rate was used. The problems they experienced were mostly technical issues due to the retrofitting of the engine. A few firefighters experienced problems with skin irritations due to the foam concentrate (The Boston Fire Department, 1994).

The other field-test is a similar project from Australia conducted by Queensland Fire and Rescue Service. They installed a combined CAF and high-pressure water mist system in two pumpers and evaluated them for 12 months. Except for some technical problems with the system, mainly with the combined nozzles, some advantages and disadvantages were found. For instance, CAFS use less water and extend limited water supplies; CAF has better penetration into the fuel and better ability to provide a long lasting protective barrier than water. On the other hand CAF does not directly cool accumulated smoke gases and due to the need of a different approach, additional training is required for operators. Finally, it was stressed that there is no universal firefighting tool and that advantages and disadvantages should be considered for every system (Raffel, 2010).

# 3.1 Summary

The main points from the literature review are listed below:

- CAF adheres well to vertical surfaces, however foams generated with too low expansion ratio contain too much water and therefore flow too easily to adhere.
- CAF shields the underlying surfaces from radiant heat flux very well and much better than water.
- The likelihood for re-ignition of a foam-covered surface is reduced in comparison to an unprotected surface.
- CAF exceeds water in mass-retention effectiveness and the ignition-inhibited period is also longer for CAFS than for water.
- CAF-systems are effective for suppression of interior structural fires and some results indicate that the main strengths are post-flashover fires or fuel-controlled fires.
- CAFS weakness is shielded pre-flashover fires.
- The indoor environment for firefighters is improved when a CAFS is used for suppression, this due to the improved visibility that occurs compared to when water is used.
- CAF and Class A foams are superior to plain water as a fire suppression agent and penetrate materials more easily.
- Dry foam should be used for fire protection and wet foam for fire suppression.
- CAFS reduces the total amount of water needed and thereby extends limited water supplies.
- The main disadvantages with CAFS concerns retrofitted vehicle-installations or the extra expense to vehicles.
- The handling of the foam concentrate can be a problem and cause skin, eyes and upper respiratory tract irritations as well as skin dermatitis.
- The foam can be a problem if it forms a slippery surface on the ground or when it covers the floor.
- The CAFS hose lines are easier to operate which decreases the weariness of the firefighters.
- CAFS can be pumped twice as high as water under the same pressure.

# 4 Theory

The following chapter describes what foam is and how it can be generated. It also gives an account of the extinguishing mechanisms of foam.

# 4.1 Foam

Foam is one of the most common fire suppression agents when plain water is insufficient (Särdqvist, 2006). Depending on type of foam detergent, foam can be used for various types of fires in fibrous materials (Class A fires) or liquid pool fires (Class B fires).

Foam is a combination of water, air (most commonly, also carbon dioxide or smoke gases can be used) and foam detergent. The Class A detergent contains surfactants that are both oleophilic and hydrophilic which reduces the water's surface tension. The surfactants have similarities with hydrocarbon compounds and improve the ability to wet and penetrate charred porous materials that occur in Class A fires. A Class A foam can also be used for liquid pool fires with non-polar fuels such as oils. The principle of reduced surface tension is shown in figure 1 below.



Figure 1. The principle of achieving reduced surface tension of water by adding a foam detergent (Persson, 2005). With permission from D. Colletti

The Class B detergent contains substances with oleophobic properties and has been adapted to prevent fuel pick-up from liquid petroleum pool fires (Persson, 2005).

Film forming foams can be used for non-polar liquid fuel fires, when the foam is drained, it produces a thin layer of water on top of the fuel. The water floats out and does not form drops and sink to the bottom due to the low surface tension. The foam then floats on top of the water. The film can, if it is damaged, to some extent repair itself due to the constant drainage from the foam.

Polar fuels such as alcohols can dissolve the film from a film forming foam which is thereby destroyed. Alcohol resistant film forming foams contain substances that react with the fuel and form a gel below the foam. The chemical reaction only continued in the foam front which means that if the gel under the foam is damaged, it is necessary with further application to maintain protection (Särdqvist, 2006). Figure 2 and 3 show the function of both film forming foam and alcohol resistant film forming foam.



Figure 2. Drainage of film forming foam has established an aqueous film on top of the flammable liquid. With permission from S. Särdqvist (Särdqvist, 2006)



Figure 3. Alcohol resistant foam floats on top of the gel which prevents foam degradation caused by the burning liquid. With permission from S. Särdqvist (Särdqvist, 2006)

The foam factor or expansion ratio describes the quote between the expanded foam and the liquid. Three main types of foam are defined; low expansion foams provide long operation range, medium expansion foams consist of small bubbles of good quality and high expansion foams are very dry with low water content. Generally, a high expansion foam provides a more efficient extinguishing effect and a lower rate of application is needed (Persson, 2005) (Särdqvist, 2006). The different types of foams are summarized in table 1. As shown in the table, low expansion foams are divided into wet, fluid and stiff or dry foams and these are very often generated by CAF-systems. Data for medium and high expansion foams have been deleted in the 2011 edition. The opinion is that foam types with expansion rates exceeding 50:1 have not been evaluated and that they are probably of little operational effectiveness (NFPA, 2011). Data from earlier editions are presented due to the knowledge of use for medium and high expanded foams in Sweden.

	Foam Type			be	
	Low Expansion			Medium Expansion	High Expansion
Expansion Ratio	Wet 1-5	Fluid 5-10	Stiff or Dry 10-20	20-200	200-1000
Consistency	Watery, sloppy	Watery shaving lather, sloppy	Dry or stiff lather	Dry foam, medium to large bubbles	Very dry foam, large bubbles
Generator	Non-aspirating, aspirating, CAFS	Aspirating, CAFS	CAFS	Large screened foam tubes	High-expansion generator
	$\leftarrow \text{Direct or indirect attack} \rightarrow$			Exposure protection,	
Usage	Penetration, Overhaul	$\leftrightarrow$	Exposure protection, blanketing	blanketing, fill voids, overhaul	Fill voids and spaces

Table 1. Different types of foams and their characteristics. Revised from NFPA 1145, table 4.3.2 (NFPA, 2006) (NFPA, 2011)

### 4.2 Foam generation

The amount of foam detergent required varies dependant on whether it is a Class A or Class B fire and, on which type of foam generation system is used. For Class A fires, a common percentage of foam concentrates range from 0.1 % to 1.0 % while 3.0 % is often recommended for Class B fires. For fires in polar fuels, up to 6 % mixing of alcohol resistant foam concentrate can be required (Särdqvist, 2006). Studied literature and product specifications shows that CAF-systems generally uses less amount of foam concentrate, normally 0.3-0.6 %, up to 1.0 %, for both Class A and Class B fire applications (Persson, 2005), (Zhang, et al., 2011), (Nordic Fire & Rescue Service, 2012).

Foam concentrate can be mixed with water by various types of pumps and injectors. Mechanical pumps use the water flow to control the foam solution proportion, electronic pumps are controlled by a computer and the foam concentrate proportion is independent of the water flow. The mixing can also be regulated by an injector using the venturi principle to control the mixing. Mixing with an injector is flow controlled.

Most nozzle aspirated foam systems (NAFS) use some kind of mechanical pump or injectors for mixing while compressed air foam systems (CAFS) use electronically controlled mixing. Many of the mechanical pumps construction do not allow the operator to shut off the water flow, this results in an incorrect mixing ratio of foam concentrate and water.

To produce expanded foam from foam solution, air needs to be mixed with the solution. The technique of the mixing process is the most obvious difference between NAFS and CAFS.

#### 4.2.1 Nozzle Aspirated Foam Systems (NAFS)

Due to the construction of the nozzle, air is able to entrain in the nozzle. The solution and the entrained air then pass through a fine mesh where expanded foam is produced, see figure 4. The generated foam type (medium or low expanded) depends on the construction of the nozzle. A low expansion nozzle allows less air to be entrained than a medium expansion foam nozzle.



Figure 4. The principle of a medium expansion foam nozzle. With permission from S. Särdqvist (Särdqvist, 2006)

The NAF-systems are flow dependent even though the low expansion nozzles are not as flow dependent as the medium expansion nozzles. The systems are highly sensitive to hose line kinks or if the nozzle is unintentionally covered by an object that prevents air from being entrained. This changes the foam solution and air ratio, which changes the foam expansion ratio. The operator range for nozzle aspirated medium expansion foams is 5 - 10 m (Särdqvist, 2006). The NAFS equipment is cheap and requires almost no extra training for the operators (Carringer, 2009).

#### 4.2.2 Compressed Air Foam Systems (CAFS)

CAF-systems do not use the same technique as aspirated nozzles. Instead, the air is supplied from a compressor or bottles with compressed air. The addition of the air takes places before the hose line and the hose line often serves as the mixing chamber. The foam solution is homogeneously mixed and gets a more consistent structure due to the rough interior hose lining (Carringer, 2009). Since air is already mixed into the unexpanded foam, friction loss is reduced when forced through the hose line (Brooks, 2012). The mixing process is not flow-dependent which makes a non-continuous application possible.

Recommended nozzles are smooth-bore nozzles or open ball valves (Särdqvist, 2006). If ordinary fognozzles are used, the foam structure erupts and the foam expansion ratio changes which creates a wetter foam. It is also recommended to use a nozzle with the same diameter as the hose line and that the hose line is rigid (Persson, 2005).

The foam generated by CAFS is generated at higher system pressure than NAFS and this results in a larger amount of smaller bubbles (Tafreshi, et al., 1998). Foam consisting of small bubbles is more stable than foam consisting of large bubbles (Särdqvist, 2006), therefore it adheres better to vertical surfaces (Tafreshi, et al., 1998). Stable foam degrades slower. The compressor also adds energy to the foam which extends the operator range (Taylor, 1997).

### 4.3 Extinguishing mechanisms

The theory behind extinguishing fires is well documented. Extinguishment of a fire is achieved when combustion is interrupted. Combustion can be simplified as a chemical reaction where flammable gases react with oxygen to form carbon dioxide, water and energy. Energy is released from the combustion process in the form of heat and emitted light. In order for the combustion to continue, the heat release rate must be enough to heat the combustible material while suffering from losses due to factors such as radiation from the flame and incomplete combustion (Särdqvist, 2006)

When the heat losses become greater than the heat released, the combustion stops and thus the fire is extinguished, this effect is thermal and the most common reason for fire extinguishment. A few select extinguishing agents also affect the free radicals, which are produced as an intermediate step in the combustion process; this effect is chemical and referred to as inhibition (Särdqvist, 2006).

When some form of extinguishing agent is applied to a fire, the energy losses increase as the agent is heated; if enough of the agent is applied the fire is extinguished. Two main forms of extinguishing mechanisms are used, surface cooling and gas phase interaction. Surface cooling is intended to lower the temperature of the oxidizing material, decreasing the rate of pyrolysis and thus decreasing the supply of flammable gases. When the extinguishing agent is heated within the flame, the gaseous phase of the combustion is affected and the reaction rate is decreased (Särdqvist, 2006).

#### 4.3.1 Extinguishing mechanisms of CAFS

Compressed air foam is essentially a mix of water and air, with the addition of a foaming agent. The main extinguishing agent of CAF is water, therefore it is important to understand how water performs as an extinguishing agent and how the bubble structure of the foam impacts this performance (Taylor, 1997).

Water alone is a good extinguishing agent due to its high thermal inertia and heat of vaporization, which enables it to efficiently absorb heat. The high surface tension of water however causes some unwanted effects when absorbing heat from the surroundings. The surface tension causes water to form relatively large droplets that tend to roll off surfaces. Larger droplets cause the total water surface in contact with the hot surroundings to decrease, thus limiting its efficiency. The surface tension also limits the penetration of water into different materials and substances (Taylor, 1997).

Many different approaches exist to make water a more efficient extinguishing agent, several of them focus on increasing the contact area with the hot surroundings; mainly by producing smaller droplets, by increasing water pressure and altering the nozzles which disperse the water. Adding some form of agent to increase the penetrating capabilities is also common.

To achieve an optimal efficiency the water droplets must be very small in size; different reports state that the optimal diameter is reach between  $250 - 1000 \mu m$ . The problem with droplets this small is that they tend to vaporize in the fire plume and never reach the fire itself (Taylor, 1997).

When CAF is produced using a Class A foam, the surface tension is lowered, thus negating the droplet build-up and increasing the penetrating ability. The low surface tension of the water allows air bubbles to form within the foam, separated by very thin layers of water. This bubble structure is an important part of extinguishing mechanisms of CAF (Taylor, 1997).

CAF consists of a large number of small bubbles, these normally range from  $300 - 1200 \mu m$  and the bubbles may vary in size within the same foam (Tafreshi, et al., 1998). When the foam is subjected to heat, the air within the bubbles expands, causing the bubbles to pop. When a bubble pops the water is fractioned into extremely small particles that get heated and vaporize almost instantly. This mechanism also allows the foam to transport water close to the fire source without it vaporizing on its way there, but still retains small and effective droplets. Another advantage that the foam structure holds over plain water is that it is able to adhere to vertical surfaces, staying in place and releasing moisture as the foam diminishes (Taylor, 1997), (Tafreshi, et al., 1998), (Madrzykowski & Stroup, 1998).

In addition to providing efficient cooling, due to the properties mentioned above, CAF has a number of favorable qualities. It serves as a good insulator from both radiation and convection, due to the mixture of air and water within the bubbles and its reflecting and scattering properties (Tafreshi, et al., 1998). The thermal diffusivity of air, CAF and water are displayed below in table 2. A material with large thermal diffusivity obtains temperature rises faster in the material than materials with low thermal diffusivity. The thermal diffusivity of CAF is higher than water but on the other hand it

adheres better to surfaces with a thicker layer. This is beneficial when a surface needs fire exposure protection but also when a hot surface is covered to prevent it from releasing heat to its environment. It is also documented to prevent the release of flammable vapors and even interrupting the chemical chain reaction through inhibition (Taylor, 1997).

Table 2. Thermal diffusivity of air, CAF and Water

	Thermal diffusivity [m <sup>2</sup> /s]
Air (Drysdale, 1998)	$2.2*10^{-5}$
CAF (Tafreshi, et al., 1998)	5*10-7
Water <sup>1</sup> (Kodur & Harmathy, 2002)	$1.45*10^{-7}$

<sup>&</sup>lt;sup>1</sup> See Appendix B for the complete calculation.

# 5 Firefighting systems used in the experiments

Different types of systems were used in the experiments, CAF-systems to perform the actual tests and high pressure water mist systems, for the conducted comparison. The operating techniques differ between the systems and are also briefly described.

# 5.1 CAFS

Two different CAF-systems were used, one for the experiments at Revinge and one for the experiments in Skövde.

#### 5.1.1 CAFS used at Revinge

The CAFS used in the Revinge experiments was a One Seven® system provided by Nordic Fire & Rescue Service (NFRS). The model OS C1-100 T is a mobile solution, in this case installed on a trailer as shown in figure 5.



Figure 5. One Seven® CAFS C1-100 T mounted on a trailer

A centrifugal pump generates a maximum water flow of 570 l/min at 8 bar pressure and the air compressor supplies the system with a maximum air flow of 2100 l/min at 8 bar pressure. However, the system only uses one third of the air flow. This model has the capability to provide CAF from a 1.5" outlet with a theoretical water flow of 140 l/min and at the same time provide 350 l/min of water from an additional outlet. The CAFS unit can provide foam with two mixture ratios; "wet foam" with mixture ratio 1:5.5 (water/foam-concentrate:air) respectively "dry foam" with ratio 1:12. The theoretical expansion ratio of the foam at 1 bar pressure ranges from 6.5 to 15. The mixing ratio of foam concentrate can be adjusted depending on which type of foam concentrate (Class A or Class B) is being used.

The flow provided by the system was measured prior to the experiments using calibration equipment. The results from the measurements are presented in table 3. The measured flows are lower than the theoretical partly due to the difference in water flow but mainly due to friction losses in the hose line.

### Firefighting systems used in the experiments

	Theoretical value	Measured value
Air, pressure [bar]	8	7.835
Water flow, dry foam [l/min]	60	54
Water flow, wet foam [l/min]	140	132
Air flow, dry foam [l/min]	720	570 (approximately)
Air flow, wet foam [l/min]	770	700 (approximately)
Expanded dry foam [l/min]	710	624
Expanded wet foam [l/min]	910	832

Table 3. Results from provided flow measurements of the CAFS

A 38 mm (1.5") rigid hose line in combination with a straight-bore nozzle was used, see figure 6. The hose line was completely extended to its full length of 50 m at all time. Class A foam with the concentration 0.3 % was used in the experiments. The CAF-system is operated from a panel and the change from dry to wet foam is achieved by pushing a button. The mixing of air, water and foam concentrate are default settings which ensures a correct mix. Figure 7 shows the operator panel and the reel for hose line storage.



Figure 6. The One Seven® nozzle used in the experiments. The attached lip was not used



Figure 7. Control panel for the One Seven® CAF-system mounted with the hose line reel

The system builds up pressure when the nozzle is closed. This causes an extra flow spike when the nozzle is opened again and the operator gains extra range. The enhanced flow could be used for long range application but from short distance, the foam is smashed to the surface and the foam structure erupts. The steady state flow is smooth and almost without recoil. Figure 8 - 11 show both the spike and the steady state flow for dry and wet CAF. As noticed in the figures, the differences in operational range between dry and wet CAF are small even though the wet CAF is more fluid which facilitates a quicker application rate per area.

# Firefighting systems used in the experiments



Figure 8. Flow spike with dry CAF



Figure 9. Steady flow with dry CAF



Figure 10. Flow spike with wet CAF



Figure 11. Steady flow with wet CAF

The generated foam is shown in figure 12 - 13 and as can be seen, the foam attaches easier on rough surfaces than on smooth surfaces such as metal. Dry foam also attaches better than wet foam. However, both types of foam attach better than water which just runs off. Dry CAF generates a thicker layer of foam than wet CAF. Firefighting systems used in the experiments



Figure 12. CAF during coating. Dry foam to the left and wet foam to the right



Figure 13. Wet CAF on both a rough and a smooth surface a couple of minutes after coating

#### 5.1.2 CAFS used in Skövde

For the full-scale experiments in Skövde, also a One Seven® system provided by Nordic Fire & Rescue Service was used. This system, an OS C1-200 BR, was mounted in a Ford 550 Super Duty as shown in figure 14. It can provide both wet and dry CAF from two 1.5" outlets, one in the front and one in the rear. The OS C1-200 BR is very similar to the previous described system and the only main differences are the number of CAF-outlets and that the Ford mounted system has a flow measuring device installed. The system was adjusted to provide 122 l/min of water in order to be as similar as possible to the system used at Revinge. The control panel and the flow measuring device are shown in figure 15 below. The flow is presented in table 4 below and is based on the measured water flow and the mixture ratio of water and air (1:5.5 for wet foam). Class A foam with a concentration of 0.3 % was used in this experiment as well as previous; also the same type of nozzle was used (figure 6). To be able to reach the fire from the vehicle 100 m hose of 38 mm (1.5") diameter was required, two 25 m rubber lined textile hoses were connected between the pump and the ordinary 50 m rigid hose.



Figure 14. One Seven® CAFS OS C1-200 BR mounted in a Ford 550 Super Duty



Figure 15. Control panel for the One Seven® CAF-system mounted with the hose line reel. The flow measuring device in stand-by to the right

Table 4. Flow of the CAFS OS C1-200S

	Flow [l/min]
Water flow, wet foam	122
Expanded wet foam	793

# 5.2 High pressure water mist system

Two different high pressure water mist systems were used, one for the experiments at Revinge and one for the experiments in Skövde.

#### 5.2.1 High pressure water mist system used at Revinge

For the two water experiments, a high pressure water mist system was used. This system operates with 38 bars pressure at the pump, the pressure at the nozzle is reduced to approximately 18 bars due to friction losses. The system produces water mist and the flow from the nozzle was measured to 107 l/min.

The hose line diameter is 18 mm (3/4") and the length is 40 m. It is stored at a centrum reel but was completely extended during the experiments. Figure 16 shows the system and the nozzle.



Figure 16. High pressure water mist system mounted in the truck and the nozzle. Note the design of the tip which, combined with the high water pressure, generates the water mist

Water is not a compressible fluid so when the nozzle is closed the pressure does not build up. Instead a relief valve is opened and the flow from the nozzle is almost constant. This does not cause that extra flow spike that CAFS obtain and compared to the CAF flow spike the range of operating is significantly shorter. The effective range is about the same for the water mist system and the CAFS when it has obtained a steady flow.

The spray pattern is similar to a traditional nozzle generating a fine atomized water mist; this can be seen in figure 17. The nozzle used is not a commercial product but it is installed on one of the fire trucks at Swedish Civil Contingencies Agency's (MSB) training grounds in Revinge outside Lund and is therefore used in these experiments.



Figure 17. Flow and spray pattern of the high pressure water mist system

#### 5.2.2 High pressure water mist system used in Skövde

The high pressure water mist system used in Skövde is similar to the one used at Revinge. It operates with a pump pressure of 40 bars and the pressure at the nozzle was measured to 21 bars. The hose line is 80 m long and the diameter is 18 mm (3/4"). The flow from the nozzle was measured to 103 l/min and is shown in figure 18 together with the pressure gauge.

Also, like the other system this does not create the flow spike that is obtained with CAFS and the spray patterns are similar to each other.



Figure 18. The high pressure water mist system mounted on the truck. The picture to the right shows the nozzle and the pressure gauge device. Photo: Pär Hagbohm

Firefighting systems used in the experiments

# 5.3 Firefighting tactics

When operating the two extinguishing systems, different tactic and techniques are required. The more powerful CAF-stream enables a longer range which allows application from a safer distance, further away from the fire.

The commonly used tactic when using CAFS is to start the application of CAF from a distance as far away from the fire as possible, often through a window when fighting structural fires. The ceiling is coated from the outside and if there are several windows, application through numerous of them are preferred. The firefighters then proceed indoors to extinguish the fire. On their way towards the fire compartment, the firefighters coat the ceiling and walls to prevent ignition and thereby secure their route of retreat.

Due to the shorter range of the water stream when extinguishing fires in traditional meaning by gascooling with an atomized water stream, external extinguishing is seldom an alternative. The firefighters instead enter the compartment and cool the hot gases on their way towards the fire compartment to be able to extinguish the fire.
# 6 Gas-cooling experiments

*The following chapter presents objectives, setup and details regarding the conducted experiments at Revinge.* 

# 6.1 Experimental objectives

The first set of experiments conducted in this report intends to compare the gas-cooling effects of compressed air foam to those of water. Several experiments were conducted to ensure repeatable results and to form a good base for analysis. The overall objective for the experiments is to study the temperature change in a hot gas layer when CAF is applied to the hot surfaces of the compartment. The CAF is applied both as wet foam and dry foam in an attempt to quantify the gas-cooling effects; finally these results are compared to the effects of water.

# 6.2 Experimental setup

The testing compartment used is the so called "fire exercise building" (brandövningshuset) at the Swedish Civil Contingencies Agency's (MSB) training grounds in Revinge outside Lund. The "fire exercise building" is a three story building with three compartments joined together by a stairwell. The floor structure of the building consists of prefabricated concrete plates and the walls are constructed using 15 cm thick leca blocks, covered by a fire resistant finish on the inside. The "fire exercise building" is shown in figure 19 below.



Figure 19. The "fire exercise building" at MSBs training grounds in Revinge

### Gas-cooling experiments

The testing compartment is located on the second floor and consists of three rooms joined together by door openings. The compartment is connected to the stairwell by a single door. During the experiments all doors and windows leading to the outside were closed except for the door to the stairwell. The door on the first floor of the stairwell was also open, providing the sole inflow of air.

In the experiments a heptane fire was lit in the middle room of the compartment. The pool diameter was 0.8 m and a loading cell was placed below. Water was poured into the pool to smooth out the bottom. For every experiment, 201 of heptane was used. The heat release rate was calculated to approximately 1 MW, see Appendix B for complete calculations. After extinguishment, the pool was re-ignited before the next experiment so that the earlier heptane burnt out to ensure that every experiment started with exactly 201 of heptane. The position of the heptane pool is shown in figure 22. Several type-K thermocouples were placed in all three rooms as well as in the stairwell. Four thermocouple trees (TCTs) were used, with four thermocouples in each tree. Three thermocouples were placed in the stairwell at different heights, but with the same positioning in regard to the inner walls. Therefore this is also considered a TCT in the following figures. Single thermocouples were placed in the first and middle rooms of the fire compartment; two directly below the ceiling and two on the walls.

The thermocouples placed on the walls were held in place by a heat resistant sealant (figure 20) and served as a way to determine when the extinguishing agent has been applied. When these were hit by either CAF or water a distinct drop in temperature marks the beginning of the application in the room. The exact placement of the thermocouples and measurements of the compartment are shown in figure 21 - 23 below. The height of each individual thermocouple is presented in table 5.



Figure 20. Thermocouple attached to the wall by a heat resistant sealant



Figure 21. Compartment with measurements, view from above



Figure 22. Placement of the thermocouples and the heptane pool inside the compartment, view from above



Figure 23. "Fire exercise building" with thermocouple placement, view from the side

## Gas-cooling experiments

Thermocouple(-s)	Height above 2nd floor [cm]
X 1-4 a	25
X 1-4 b	95
X 1-4 c	165
X 1-4 d	195
X 5 a	100
X 5 b	410
X 5 c	720
o 1	210
o 2	240
o 3	240
o 4	210

	Table 5.	Height	above	2nd	floor	for	each	individual	the	rmocouple
--	----------	--------	-------	-----	-------	-----	------	------------	-----	-----------

The experiments were also recorded with an infrared camera to provide thermal images of the experiments and the application.

#### 6.2.1 Experimental conditions

The experiments were conducted for three days during one week in late August. the weather these days shifted as shown in table 3 although the temperature was around 20 °C on all three days. The winds were weak, from dead calm to almost no wind at all.

Table 6. Weather during the experiments

Day	Weather
1	Sunny
2	Fog in the morning, sunny in the afternoon
3	Rainy

After every conducted experiment, doors and windows were opened and the building was ventilated by a positive pressure ventilator (PPV-fan). The wall-mounted thermocouples in the fire compartment recorded temperatures around 90  $^{\circ}$ C after an experiment. The ventilation was allowed to proceed until the temperature had dropped to about 70  $^{\circ}$ C, this took about one hour. Overnight, the temperature dropped to approximately 40  $^{\circ}$ C.

# 6.3 Experimental procedure

In each of the experiments temperatures within the compartment were recorded for at least one minute prior to ignition. When the heptane fire was lit the time of ignition was recorded. The fire was allowed to burn for seven minutes without interaction.

At seven minutes after the ignition a firefighter, positioned in the stairwell, applied the extinguishing agent of choice through the door for a pre-determined period of time, ranging from 1-5 seconds. He then proceeded to enter the first room and applied the extinguishing agent through the second doorway into the middle room. The route of attack is shown in figure 24 below.



Figure 24. Positioning and movement of the firefighter in the compartment

The application method differs between water and CAF. The CAF was applied to the hot surfaces of the compartment, in these experiments mainly to the ceiling and opposing wall. To ensure a steady flow of foam, the CAFS nozzle was opened and foam was allowed to flow freely down the stairwell for a few seconds. Once the pressure spike was negated and a steady flow was reached, the firefighter began to apply the foam. During the movement inside the compartment, the nozzle remained open but was aimed towards the floor.

The water spray nozzle on the other hand does not need to be opened in advance; therefore the application could start at once. The water was applied with a sweeping motion, intended to cover a large volume of hot gases within the compartment rather than covering the hot surfaces, since this is the traditional gas-cooling technique. None of the extinguishing agents were aimed towards the heptane fire that was not supposed to be affected directly. The firefighter was instructed to start the application by hitting the thermocouples placed on the opposing walls, to enable a distinct reading when the application was started.

When the application of the extinguishing agent was completed, the firefighter stayed inside the compartment to visually observe the effects and the temperatures were recorded for another seven minutes. Furthermore the firefighter applying the extinguishing agent was accompanied by a second firefighter who was equipped with an infra-red camera to document the experiments.

Table 7 shows in which order and on what day the experiments were performed, and also the type and amount of extinguishing agent used. The application time was chosen on estimations of how long would be reasonable, just enough to have an impact but not so short that it would be difficult to apply

the predetermined application time. The application time varies with the extinguishing agent but the application times were chosen to obtain as similar amounts of water as possible.

Experiment	Day	Extinguishing agent	Application time [s]	No. of coated rooms	Amount of water used for extinguishing [1]
1	1	Wet foam	2	2	4.4 + 4.4
2	1	Wet foam	2	2	4.4 + 4.4
3	1	Wet foam	4	2	8.8 + 8.8
4	1	Wet foam	4	2	8.8 + 8.8
5	1	Wet foam	4	1	0 + 8.8
6	2	Wet foam	2	2	4.4 + 4.4
7	2	Wet foam	4	1	0 + 8.8
8	2	Dry foam	5	2	4.5 + 4.5
9	2	Dry foam	5	2	4.5 + 4.5
10	2	Dry foam	5	1	0 + 4.5
11	3	Water	2	2	3.6 + 3.6
12	3	Water	1	2	1.8 + 1.8

 Table 7. Overview of the experiments and extinguishing agent used

# 7 Results from the gas-cooling experiments

Results and observations from each of the gas-cooling experiments are listed below, together with selected graphs and footage. A summary of all the experiments is given at the end of this chapter. All of the data obtained from the experiments is presented in its entirety in Appendix A.

# 7.1 Individual experiments

Some of the results are consistent throughout the entire series of experiments, the thermocouple trees X1 and X5 show virtually no effect from the application of extinguishing agents and are therefore not included in the detailed analysis in this chapter. All the fire scenarios eventually become under ventilated. This can be observed in the temperature-time graphs provided in the following chapter, however differences in temperature do exist between the different experiments, hence the curves are displayed for every single experiment.

To quantify the fluctuations in temperature during the experiments, graphs are included to show the rate of change in temperature as a function of time. The rate of change in temperature shows the increase or decrease rate between the different measuring points, since the measuring device records the temperature every second this gives an approximated first derivative of the temperature-time curve with  $dX\approx1$  second. The "Application starts" marker within these graphs marks the time when one of the thermocouples placed on the walls is hit by foam or water, therefore this time is not necessarily the exact starting time of application.

Since the application of extinguishing agent is performed by a person and not by a constructed rig, some difference in application time and the covered surface is to be expected. Therefore thermal images from the experiments are added to describe these differences and provide a better understanding of the variables. The dark areas in the images are cooler than the lighter areas, this therefore indicates where the extinguishing agent has hit the ceiling and walls and cooled the surfaces. Due to a failure with the loading cell, no data could be recorded.

#### 7.1.1 Experiment 1: Wet foam, 2 seconds application in both rooms.

The temperature as a function of time within the entire compartment is shown in figure 25 below.



Figure 25. Temperature as a function of time for all thermocouples in experiment 1

The maximum temperature within the compartment peaked at about 500 °C around 200 seconds after ignition. After this peak the maximum temperature stabilized around 450 - 500 °C for the remainder of the experiment, this was due to the under ventilated conditions of the compartment. The maximum temperature was measured from the X2d thermocouple of the X2 TCT, which was located closest to the fire.

Application of the wet foam started at approximately 420 seconds after ignition. This show in figure 25 above as the temperature drops in certain measuring points around this time. The measurements from X2 showed that the fire in this experiment remained largely unaffected by the application of wet foam within the compartment, since no significant fluctuations in temperature near the fire occurred.

The gas-cooling effect of the wet foam was shown in TCT X3 and X4. The temperature as a function of time for these thermocouples, as well as the rate of change in temperatures is shown in figure 26 - 29 below.



Figure 26. Temperature as a function of time for X4, experiment 1



Figure 27. Rate of change in temperature for X4, experiment 1







Figure 29. Rate of change in temperature for X3, experiment 1

As figures 26 and 27 indicate, the temperature changes in the first room of the compartment where the TCT X4 is placed were quite small. The largest decrease in temperature occurred in X4c where the temperature dropped nearly 15 °C at a rate of almost -3 °C/s, whereas the other measuring points of this TCT remained largely unaffected throughout the application of the foam. The effects of the foam were much more distinct in the room of the fire where the X3 TCT was placed. Figures 28 and 29 show that the application had good effect on the thermocouple X3d closest to the ceiling. The temperature dropped by 150 °C with a maximum drop rate of roughly -50 °C/s, while X3c showed a more modest drop in temperature of about 30 °C with a maximum rate of nearly -10 °C/s. The exact temperature differences and maximum rates of change in temperature are shown in table 8 below.

l able 8	Table 8. Temperature difference and maximum rate of change in temperature, experiment 1				
TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [ $^{\circ}C/s$ ]		
X4d	-8.3	14.8	-1.5		
X4c	-14.6	6	-2.8		
X4b	5.4	7.3	2.2		
X4a	4.9	3	2.6		
X3d	-162.2	4.5	-51.6		
X3c	-21.6	3.1	-8.2		
X3b	61.5	10.5	8.6		
X3a	11.6	4.6	2.0		

Table 8. Temperature difference and maximum rate of change in temperature, experiment 1

The foam was applied for 2 seconds in both rooms. In the second room it was applied to the ceiling and the wall in direct vicinity of the TCT. The foam applied to the wall is shown as the darker grey areas within the red ellipse in figure 30 below; the TCT is illustrated as a black dotted line.



Figure 30. Thermal image showing the foam applied to the wall of room 2, experiment 1

#### 7.1.2 Experiment 2: Wet foam, 2 seconds application in both rooms.

The temperature as a function of time within the entire compartment is shown in figure 31 below.



Figure 31. Temperature as a function of time for all thermocouples in experiment 2

The maximum temperature within the compartment peaked at almost 575 °C around 200 seconds after ignition. After this peak the maximum temperature dropped and fluctuated between 300 - 400 °C for the remainder of the experiment, this was due to the under ventilated conditions of the compartment. The maximum temperature was measured from the X2d thermocouple of the X2 TCT, which was located closest to the fire.

Application of the wet foam started at approximately 450 seconds after ignition. This shows in figure 31 above as the temperature drops quite significantly around this time. The measurements from X2 showed that the fire in this experiment was affected by the application of wet foam within the second room; at the time of application the temperature close to the fire increased steadily for 40 seconds, indicating that the fire gained strength. During this period of time the foam applied to the walls and ceiling vaporized more rapidly, causing a large decrease in temperature inside the entire compartment and the fire was almost extinguished. However the fire gained strength once again; vaporized the last remaining foam and caused another drop in temperature before the fire was allowed to grow, once again stabilizing at around 350 - 400 °C.

The gas-cooling effect of the wet foam, without the effect on the fire, is shown in TCT X3 and X4. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature, is shown in figure 32 - 35 below.



Figure 32. Temperature as a function of time for X4, experiment 2



Figure 33. Rate of change in temperature as a function of time for X4, experiment 2







Figure 35. Rate of change in temperature as a function of time, experiment 2

As figures 32 and 33 indicate, the temperature dropped noticeably in the upper part of the first room, while the temperature actually increased in the lower parts. The decrease in temperature was quite similar for both X4c and –d, where the temperature dropped roughly 20 °C. As for the increase in temperature in the lower parts, it was slightly lower closer to the floor. The exact temperature changes are shown in table 9 below.

The effects of the foam were larger in the room of the fire where the X3 TCT is placed. Figures 34 and 35 show that the application had better effect on the thermocouple X3c than X3d. The temperature in X3c dropped almost 100 °C with a maximum drop rate of roughly -60 °C/s, while X3d dropped roughly 50 °C with a maximum drop rate of nearly -15 °C/s. As in the first room the temperature increased in the lower part of the room, the exact temperature differences and maximum rates of change in temperature are shown in table 9 below.

	•		
TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-26.8	6.6	-6.6
X4c	-18.3	6.6	-4.2
X4b	16.8	5.4	5.3
X4a	6.6	2.6	2.6
X3d	-55.6	8.3	-13.8
X3c	-94.4	4.0	-59.2
X3b	38.2	6.4	9.8
X3a	6	3.7	2.0

Table 9. Temperature difference and maximum rate of change in temperature, experiment 2

By examining the thermal images from the experiment it was found that foam was applied for 3 seconds in the first room and 4 seconds in the second; both to the ceiling and the wall in direct vicinity of the TCT. The foam applied to the ceiling and walls in the second room is shown as the black areas in figure 36 below; the TCT is illustrated as a black dotted line.



Figure 36. Thermal image showing the foam covered surfaces behind the TCT X3, experiment 2



The temperature as a function of time within the entire compartment is shown in figure 37 below.



Figure 37. Temperature as a function of time for all thermocouples in experiment 3

The maximum temperature within the compartment peaked at about 550 °C almost 200 seconds after ignition. After this peak the maximum temperature dropped to fluctuate between 300 - 400 °C until the start of the application, this was due to the under ventilated conditions of the compartment. The maximum temperature was measured from the X2d thermocouple of the X2 TCT.

Application of the wet foam started approximately 430 seconds after ignition. This shows in figure 37 above as the temperature drops significantly around this time. The measurements from X2 show that the fire in this experiment was affected quite heavily by the application of wet foam within the second room; at the time of application the temperature close to the fire immediately dropped, indicating that the fire was affected and weakened. When the fire started growing again the foam applied to the walls and ceiling vaporized more rapidly, causing a large decrease in temperature inside the entire compartment and the fire was completely extinguished.

The gas-cooling effect of the wet foam was shown in TCT X3 and X4. However the immediate effect on the fire shows in X3, causing problems to distinguish between the gas-cooling effects and the effect of the decreased intensity of the fire. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 38 - 41 below.



Figure 38. Temperature as a function of time for X4, experiment 3



Figure 39. Rate of change in temperature as a function of time for X4, experiment 3





Figure 40. Temperature as a function of time for X3, experiment 3



Figure 41. Rate of change in temperature as a function of time for X3, experiment 3

As figures 38 and 39 indicate, the temperature dropped noticeably in the three thermocouples X4b, –c and –d in the first room, while the temperature remained constant in X4a. The decrease in temperature was quite similar for both X4c and –d, where the temperature dropped roughly 20 °C. As for the decrease in temperature in X4b, it was an almost instant drop of about 40 °C, which was most likely caused by a small amount of foam hitting the thermocouple. The exact temperature changes are shown in table 10 below.

The effects of the foam look different in the fire room. Figures 40 and 41 shows that the application initially decreased the temperature in the two top thermocouples X3d and –c. Roughly eight seconds later the rate of decrease in temperature significantly increased and X3b was also greatly affected. This indicates that the initial effect was the gas-cooling effect of the foam, and that the latter effect was caused by the fire decreasing in strength and eventually being extinguished. Therefore only the initial effect is taken into account in the following analysis. The exact temperature differences and maximum rates of change in temperature are shown in table 10 below.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-19.7	8.0	-4.6
X4c	-25.4	8.0	-4.4
X4b	-41.0	2.7	-20.6
X4a	-	-	-
X3d	-23.2	8.3	-8.0
X3c	-22.6	4.0	-8.8
X3b	-	-	-
X3a	4.5	5.5	1.8

Table 10. Temperature difference and maximum rate of change in temperature, experiment 3

By examining the thermal images from the experiment it was found that foam was applied for 4 seconds in the first room and 7 seconds in the second. The images also reveal that some of the foam applied in the first room actually bounced of the doorframe, which caused the foam to spread out and mostly hit the opposing wall. Figure 42 below shows the stream of foam (black) bouncing off the doorframe before entering the first room.



Figure 42. Shows the stream of foam (black) bouncing off the doorframe in experiment 3

In the second room, foam was applied both to the ceiling and the wall in direct vicinity of the TCT. The foam in the second room is shown as the dark grey/black areas in figure 43 below; the TCT is illustrated as a black dotted line.



Figure 43. Thermal image showing the foam applied to the ceiling and walls of the second room in experiment 3



The temperature as a function of time within the entire compartment is shown in figure 44 below.



Figure 44. Temperature as a function of time for all thermocouples in experiment 4

The maximum temperature within the compartment peaked at almost 600 °C nearly 200 seconds after ignition. After this peak the maximum temperature dropped down to between 350 - 400 °C by the start of the application, this was due to the under ventilated conditions of the compartment. The maximum temperature was measured from the X2d thermocouple of the X2 TCT.

Application of the wet foam started at approximately 450 seconds after ignition. This can be seen in figure 44 above as the temperature drops significantly around this time. The measurements from X2 show that the fire in this experiment was only slightly affected by the application in the second room; at the time of application the temperature close to the fire only dropped 10 °C, indicating that the fire was not significantly weakened. However a more distinct peak in temperature followed, causing the foam to vaporize at an increased rate. The rapid vaporization of foam caused the temperature in the entire fire room to drop, weakening the fire. This process was repeated once more, but this time the fire was extinguished.

The gas-cooling effect of the foam is shown in TCT X3 and X4. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 45 - 48 below.





Figure 45. Temperature as a function of time for X4, experiment 4



Figure 46. Rate of change in temperature as a function of time for X4, experiment 4



Figure 47. Temperature as a function of time for X3, experiment 4



Figure 48. Rate of change in temperature as a function of time for X3, experiment 4

As figures 45 and 46 indicate, there was a slow and steady decrease in temperature in the two top thermocouples, both dropped roughly 20 °C at similar rates. In the two lower thermocouples there was no significant change in temperature. The exact temperature changes are shown in table 11 below.

The effects of the foam were bigger in the fire room. Figures 47 and 48 show that the application decreased the temperature significantly in the two top thermocouples X3d and -c.

### Results from the gas-cooling experiments

The X3d thermocouple showed a greater drop in temperature than X3c; hence the cooling effect was larger in the upper part of the room. The two lower thermocouples initially showed an increase in temperature. However the X3b thermocouple dropped significantly in temperature after a few seconds. Since this drop in temperature coincided with the drop in X3c and –d, and no decrease in temperature was shown close to the fire, this is interpreted as part of the gas-cooling effect. Therefore only the drop in temperature is displayed together with the exact temperature differences and maximum rates of change in temperature in table 11 below.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-17.2	13.7	-2.6
X4c	-21.7	13.7	-3.7
X4b	-	-	-
X4a	-	-	-
X3d	-78.5	6.8	-20.3
X3c	-35.2	6.8	-7.0
X3b	-27.3	5.3	-8.5
X3a	11.1	7.0	3.0

Table 11. Temperature difference and maximum rate of change in temperature, experiment 4

By examining the thermal images from the experiment it was found that foam was applied for 4 seconds in the first room and 5 seconds in the second. In the second room, foam was applied both to the ceiling and the wall in direct vicinity of the TCT. The foam in the second room is shown as the dark grey areas in figure 49 below; the TCT is illustrated as a black dotted line.



Figure 49. Thermal image showing the foam applied to the walls of the second room in experiment 4



The temperature as a function of time within the entire compartment is shown in figure 50 below.



Figure 50. Temperature as a function of time for all the thermocouples in experiment 5

The maximum temperature within the compartment peaked at almost 600 °C about 190 seconds after ignition. After this peak the maximum temperature dropped to fluctuate between 350 - 400 °C until the application started, this was due to the under ventilated conditions of the compartment. The maximum temperature was measured from the X2d thermocouple of the X2 TCT.

Application of the wet foam started at approximately 450 seconds after ignition. This shows in figure 50 above as the temperature dropped significantly around this time. The measurements from X2 show that the fire in this experiment was affected by the application in the second room; at the time of application the temperature close to the fire dropped 35 °C, indicating that the fire was slightly weakened. However a more distinct peak in temperature followed about 10 seconds after the application, which caused the foam to vaporize at an increased rate. The rapid vaporization of foam caused the temperature in the entire fire room to drop, and the fire to be extinguished.

The gas-cooling effect of the foam was mainly shown in TCT X3 but a slight drop in temperature was also shown in X4. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 53 - 54 below.



Figure 51. Temperature as a function of time for X4, experiment 5



Figure 52. Rate of change in temperature as a function of time for X4, experiment 5



0 – 

Temperature [°C]

Figure 53. Temperature as a function of time for X3, experiment 5

Time [s]



Figure 54. Rate of change in temperature as a function of time for X3, experiment 5

Figure 51 and 52 show a slight gas-cooling effect in the first room of the compartment. The temperature drop was slow but clear. The fire was not significantly weakened by the application in the second room, this is thought to be due to the application of foam within the hot gas layer. X4b showed a larger drop roughly 20 seconds before the application was started; this is most likely due to the CAF-nozzle being opened before the firefighter proceeded through the first room. The exact temperature differences and maximum rates of change are shown in temperature in table 12 below.

### Results from the gas-cooling experiments

As figures 53 and 54 show, the application caused a significant decrease in temperature in the three top thermocouples X3d, –c and –b. The X3c and –d thermocouples dropped to approximately the same temperature. The X3b thermocouple initially recorded an increase in temperature that was followed by a significant drop a few seconds later. Since this drop in temperature coincided with the drops in X3c and –d, and only a small drop in temperature was recorded close to the fire, this is interpreted as part of the gas-cooling effect. Therefore only the drop in temperature is displayed together with the exact temperature differences and maximum rates of change in temperature in table 12 below.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-8.9	26.3	-0.8
X4c	-10.4	19.5	-1.8
X4b	8.5	16.9	1.4
X4a	-	-	-
X3d	-44.1	6.5	-10.3
X3c	-37.4	6.5	-8.1
X3b	-22.0	5.2	-7.0
X3a	5.0	5.6	2.7

Table 12. Temperature difference and maximum rate of change in temperature, experiment 5

By examining the thermal images from the experiment it was found that foam was applied for 5 seconds in the second room. The foam was applied both to the ceiling and the wall in direct vicinity of the TCT. The foam in the second room is shown as the dark grey/black areas in figure 55 below; the TCT is illustrated as a black dotted line.



Figure 55. Thermal image showing the foam applied to the walls of the second room in experiment 5



7.1.6 Experiment 6: Wet foam, 2 seconds application in both rooms.

The temperature as a function of time within the entire compartment is shown in figure 56 below.

Figure 56. Temperature as a function of time for all thermocouples in experiment 6

The maximum temperature within the compartment peaked just above 500 °C about 190 seconds after ignition. After this peak the maximum temperature dropped down to fluctuate between 300 - 350 °C until the application started, this was due to the under ventilated conditions of the compartment. The maximum temperature was measured from the X2d thermocouple of the X2 TCT.

Application of the wet foam started at approximately 420 seconds after ignition. This can be seen in figure 56 above as the temperature drops significantly around this time. The measurements from X2 show that the fire in this experiment was affected somewhat by the application in the second room; at the time of application the temperature close to the fire dropped 20 °C, indicating that the fire was slightly weakened. However a more distinct peak in temperature followed only 5 seconds after the application, causing the foam to vaporize at an increased rate. The rapid vaporization of foam caused the temperature in the entire fire room to drop, and the fire to drop in intensity. This process was repeated another two times before the fire was extinguished, thus causing the three temperature spikes seen in figure 56 after the application starts.

The gas-cooling effect of the foam is mainly shown in the X3 and X4 TCT. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 57 - 60 below.







Figure 58. Rate of change in temperature as a function of time for X4, experiment 6





Figure 59. Temperature as a function of time for X3, experiment 6



Figure 60. Rate of change in temperature as a function of time for X3, experiment 6

Figure 57 and 58 show a distinct drop in temperature in the upper parts of the first room. The temperature in the thermocouple X4d, closest to the ceiling, decreased at a faster rate than X4c. Furthermore the temperature drop in the X4c thermocouple was slightly delayed compared to X4d. The two lower thermocouples both recorded an increase in temperature, right after the application started. The exact temperature differences and maximum rates of change in temperature are shown in table 13 below.

## Results from the gas-cooling experiments

As figures 59 and 60 show, the application caused a significant decrease in temperature in the two top thermocouples X3d and –c. The temperature recorded by the X3c thermocouple dropped more than the temperature in X3d and at a significantly higher rate. The X3a and –b thermocouples recorded an increase in temperature. The exact temperature differences and maximum rates of change in temperature are shown in table 13 below.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-29,9	3,9	-11,7
X4c	-13,7	10,6	-2,6
X4b	7,4	5,3	2
X4a	5,9	1,3	4,4
X3d	-26,6	5,3	-8,4
X3c	-61,8	1,2	-51,5
X3b	26,5	6,48	3,3
X3a	15,7	2,64	3,4

Table 13. Temperature difference and maximum rate of change in temperature, experiment 6

By examining the thermal images from the experiment it was found that foam was applied for 2 seconds in the first room and almost 3 seconds in the second room. Nearly half of the applied foam in the first room bounced off the doorframe before hitting the opposing wall. This is shown in figure 42 from experiment 3. The foam was applied both to the ceiling and the wall in direct vicinity of the TCT. The foam in the second room is shown as the upper dark grey areas in figure 61 below, the lower dark areas are non-heated areas of the wall; the TCT is illustrated as a black dotted line.



Figure 61. Thermal image showing the foam applied to the walls of the second room in experiment 6



7.1.7 Experiment 7: Wet foam, 4 second application in the second room.

The temperature as a function of time within the entire compartment is shown in figure 62 below.

Figure 62. Temperature as a function of time for all thermocouples in experiment 7

The maximum temperature within the compartment peaked around 550 °C about 180 seconds after ignition. After this peak the maximum temperature dropped to fluctuate at around 300 °C until the application started, this was due to the under ventilated conditions of the compartment. The maximum temperature was measured from the X2d thermocouple of the X2 TCT.

Application of the wet foam started at approximately 430 seconds after ignition. This is shown in figure 62 above as the temperature drops significantly in some thermocouples around this time. The measurements from X2 show that the fire in this experiment was affected somewhat by the application in the second room; at the time of application the temperature close to the fire stayed almost constant for nearly 7 seconds and then dropped some 30 °C, indicating that the fire was slightly weakened. However a peak in temperature followed about 30 seconds after the application which caused the foam to vaporize at an increased rate. The rapid vaporization of foam caused the temperature in the entire fire room to drop, and the fire to drop in intensity. This process was repeated another three times before the fire was extinguished, thus causing the four temperature spikes seen in figure 62 following the application.

The gas-cooling effect of the foam is mainly shown in the X3 TCT, however X4 is also of interest in this experiment. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 63 - 66 below.





Figure 63. Temperature as a function of time for X4, experiment 7



Figure 64. Rate of change in temperature as a function of time for X4, experiment 7



Figure 65. Temperature as a function of time for X3, experiment 7



Figure 66. Rate of change in temperature for X3, experiment 7

Figures 63 and 64 show no significant gas-cooling effect in the first room of the compartment. X4b shows a larger drop roughly 10 seconds before the application was started; this is most likely due to the CAF-nozzle being opened before the firefighter proceeded through the first room. Since there is no significant effect, these values are not presented in table 14 below.

## Results from the gas-cooling experiments

As figures 65 and 66 show, the application caused significant decrease in temperature in the three top thermocouples X3d, –c and –b. The X3c thermocouple dropped far more in temperature compared to X3d. The X3b thermocouple initially recorded an increase in temperature that was followed by a significant drop a few seconds later. Since this drop was almost linear and reduces the temperature by nearly 60 °C in a matter of seconds, it might be the result of a direct hit to the thermocouple. The exact temperature differences and maximum rates of change in temperature are presented in table 14 below.

	4. Temperature amerence a		in rate of change in temperature, experiment r
TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X3d	-104.3	9.2	-25.6
X3c	-40.1	10.5	-6.4
X3b	-60.2	1.4	-43.7
X3a	20.7	5.3	9.1

Table 14. Temperature difference and maximum rate of change in temperature, experiment 7

By examining the thermal images from the experiment it was found that foam was applied for 5 seconds in the fire room. The foam was applied both to the ceiling and the wall in direct vicinity of the TCT. The foam in the second room is shown as the dark grey/black areas in figure 67 below; the TCT is illustrated as a black dotted line.



Figure 67. Thermal image showing the foam applied to the walls of the second room in experiment 7




The temperature as a function of time within the entire compartment is shown in figure 80 below.

Figure 68. Temperature as a function of time for all thermocouples in experiment 8

The temperature within the compartment reached its maximum around 550 °C about 150 seconds after ignition. After this peak the maximum temperature dropped gradually to around 300 °C until the application started, this was due to the under ventilated conditions of the compartment. The maximum temperatures were measured from the X2d point of the X2 TCT, which was located closest to the fire.

Application of the dry foam started approximately 430 seconds after ignition. This is shown in figure 68 above, indicated mostly by the X2d and –c thermocouples from X2 TCT and TC o1 and o2 around this time. The measurements from X2 show that the fire entered a new period of growth after application and peaked at nearly 375 °C. This period was bigger than earlier periods. No obvious correlations between the application and the gas-cooling effects were noticed. The foam applied to the walls and ceiling vaporized and caused a large decrease in temperature inside the entire compartment. The temperature dropped about 160 °C in 70 seconds. A last increase of the fire after about 550 seconds vaporized the remaining foam and the fire was completely extinguished. The vaporization of foam was indicated by TC o3 and o4 which showed a clear temperature increase at the same time as the second to last period respectively the last period of fire growth lasted.

The gas-cooling effect of the dry foam was shown in TCT X3 and X4. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 69 - 72 below.



Figure 69. Temperature as a function of time for X4, experiment 8



Figure 70. Rate of change in temperature as a function of time for X4, experiment 8



Figure 71. Temperature as a function of time for X3, experiment 8



Figure 72. Rate of change in temperature as a function of time for X3, experiment 8

As TC X4d and -c in figure 69 and 70 show, the temperature decreased about 15 - 25 °C in the upper layer in the first room. X4b was probably hit with foam, which caused the fast decrease in temperature. Figures 71 and 72 show the temperature changes in the fire room. Some foam possibly hit the thermocouple X3d. The temperature rise for X3c was interrupted by a short decrease in temperature. X3b showed that the temperature closer to the floor started to decrease but an increasing temperature soon replaced it. At about the same time as the application started, the fire began to grow in strength again. A gas-cooling effect from the application of dry foam could be reduced or eliminated due to the growing fire. The exact temperature changes are shown in table 15 below, any equalizing effects caused by the increased fire intensity are not taken into consideration.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-13.49	12.12	-1.11
X4c	-23.74	7.98	-2.97
X4b	-26.65	5.22	-5.11
X4a	-	-	-
X3d	-53.13	6.84	-7.77
X3c	-11.51	4.14	-2.78
X3b	-10.95	4.14	-2.64
X3a	-	-	-

Table 15. Temperature difference and maximum rate of change in temperature, experiment 8

By examining the thermal images from the experiment it was found that dry foam was applied for about 6 seconds in both rooms; both to the ceiling and the wall in direct vicinity of the TCT. The foam applied to the wall and the ceiling in the second room is shown as the black areas in figure 73 below, the TCT is illustrated as a black dotted line.



Figure 73. Thermal image showing the dry foam covered surfaces behind the TCT X3, experiment 8



The temperature as a function of time within the entire compartment is shown in figure 80 below.



Figure 74. Temperature as a function of time for all thermocouples in experiment 9

The temperature within the compartment reached its maximum around 550 °C about 150 - 200 seconds after ignition. After this peak the maximum temperature dropped gradually to fluctuate between 250 - 350 °C until the application started, this was due to the under ventilated conditions of the compartment. The maximum temperatures were measured from the X2d point of the X2 TCT, which was located closest to the fire.

Application of the dry foam started approximately 440 seconds after ignition. This is shown in figure 74 above, indicated mostly by the TC o2 and o3 around this time. The measurements from X2 showed that the fire entered a new period of growth when application started and this period was bigger than earlier periods. This peak reached almost 400 °C and the raise was about 150 °C in 25 seconds. No obvious correlations between the application and the gas-cooling effects were noticed. The foam applied to the walls and ceiling vaporized and caused a large decrease in temperature inside the entire compartment and the fire was completely extinguished. The vaporization of foam during the last fire growth period can be identified by TC o3 and o4. The temperature exceeded 100 °C during the last period indicating that the foam was vaporized.

The gas-cooling effect of the dry foam was shown in X3 TCT and X4. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 75 - 78 below.



Figure 75. Temperature as a function of time for X4, experiment 9



Figure 76. Rate of change in temperature as a function of time for X4, experiment 9



Figure 77. Temperature as a function of time for X3, experiment 9



Figure 78. Rate of change in temperature as a function of time for X3, experiment 9

As figures 75 and 76 show there was a clear drop in temperature, 10 - 15 °C in the upper layer in the first room. However, the fire decreased in intensity at the same time, shown in figure 75. There was also a temperature increase of about 30 °C closer to the floor in X3b. The temperature then decreased when the fire was extinguished. Figures 76 and 77 show the temperature changes in the fire room. The temperature variations of X3d were possibly stronger to some extent after the application. The first temperature rise after application was interrupted by a short decrease in temperature. Also the rise of temperature in X3c was interrupted and stagnated for a short while. Considering to the increased fire

intensity, this rise was probably caused by the gas-cooling effect from the foam and is presented in table 16. The temperature drop of X3b was probably caused by a direct hit of foam. The exact temperature changes are shown in table 16 below.

	•		
TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-11.30	7.92	-1.43
X4c	-15.11	10.56	-1.43
X4b	28.55	10.56	2.70
X4a	-	-	-
X3d	-5.25	1.38	-3.80
X3c	0.52	5.34	0.10
X3b	18.83	3.96	4.76
X3a	6.34	5.34	1.19

Table 16. Temperature difference and maximum rate of change in temperature, experiment 9

By examining the thermal images from the experiment it was found that dry foam was applied for about 5 seconds in the first room and for about 7 seconds in the second room; both the ceiling and the wall in direct vicinity of the TCT were hit. The foam applied to the wall and the ceiling in the second room is shown as the black areas in figure 79 below, the TCT is illustrated as a black dotted line.



Figure 79. Thermal image showing the dry foam covered surfaces behind the TCT X3, experiment 9





The temperature as a function of time within the entire compartment is shown in figure 80 below.

Figure 80. Temperature as a function of time for all thermocouples in experiment 10

The temperature within the compartment reached its maximum around 550 °C about 170 seconds after ignition. After this peak the maximum temperature dropped gradually to approximately 300 °C until the application started, this was due to the under ventilated conditions of the compartment. The maximum temperatures were measured from the X2d point of the X2 TCT, which was located closest to the fire.

Application of the dry foam started approximately 440 seconds after ignition. This is shown in figure 80 above, indicated mostly by the TC o2 and o3 around this time. The measurements from X2 show that the fire continued to fluctuate around 300 °C within the second room after application. No obvious correlations between the application and the gas-cooling effects were noticed since the fire had already begun to diminish before the application, causing a temperature lowering by itself. The application rather stopped the diminishing fire intensity and flattened the temperature rate of change. The foam applied to the walls and ceiling vaporized and caused a large decrease in temperature inside the entire compartment and the fire was completely extinguished.

The gas-cooling effect of the dry foam was shown in X3 TCT and X4. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figure 81 - 84 below.



Figure 81. Temperature as a function of time for X4, experiment 10



Figure 82. Rate of change in temperature as a function of time for X4, experiment 10



Figure 83. Temperature as a function of time for X3, experiment 10



Figure 84. Rate of change in temperature as a function of time for X3, experiment 10

As shown in figures 81 and 82, the changes in temperature were small in the first room when the application started in the fire room. Figures 83 and 84 show the effects of the dry foam application in the fire room. The temperature in the two top thermocouples X3d and –c decreased after a short delay. The massive temperature drop for X3d, 150 °C in 6 seconds could be due to a direct hit of foam on the thermocouple. However, the temperature exceeds 100 °C at all times which indicates that just a small amount of foam hit the thermocouple and evaporated quickly. A direct hit of foam could also be the cause for the distinct drop of X3a. Notable is the delayed temperature increase of X3b that lasted until

the fire was extinguished. The exact temperature differences and maximum rates of change in temperature are shown in table 17 below.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-7.51	16.44	-0.46
X4c	-9.40	16.50	-0.57
X4b	-	-	-
X4a	-	-	-
X3d	-154.76	6.24	-24.80
X3c	-35.75	12.54	-2.85
X3b	7.84	2.46	3.19
X3a	-25.54	6.24	-4.09

Table 17. Temperature difference and maximum rate of change in temperature, experiment 10

By examining the thermal images from the experiment it was found that dry foam was applied for about 7 seconds in the fire room; both the ceiling and the wall in direct vicinity of the TCT were hit. The foam applied to the wall and the ceiling is shown as the black areas in figure 85 below, the TCT is illustrated as a black dotted line.



Figure 85. Thermal image showing the dry foam covered surfaces behind the TCT X3, experiment 10



The temperature as a function of time within the entire compartment is shown in figure 86 below.



Figure 86. Temperature as a function of time for all thermocouples in experiment 11

The temperature within the compartment peaked at about 530 °C around 200 seconds after ignition. After this peak the maximum temperature dropped gradually to 350 °C until the application started, this due to the under ventilated conditions of the compartment. The maximum temperatures were measured from the X2d point of the X2 TCT, which was located closest to the fire.

The application started approximately 400 seconds after ignition. This is shown in figure 86 above as the temperature dropped significantly around this time. The measurements from X2 show that the fire was extinguished immediately.

The gas-cooling effect of water was shown in TCT X3 and X4. The extinguishing impact on the fire was also reflected in X3 causing problems to evaluate only the gas-cooling effect separate from the decreased fire intensity. The temperatures close to the floor in TCT X2 and X4 increased when application started. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 87 – 90 below.



Figure 87. Temperature as a function of time for X4, experiment 11



Figure 88. Rate of change in temperature as a function of time for X4, experiment 11



Figure 89. Temperature as a function of time for X3, experiment 11



Figure 90. Rate of change in temperature as a function of time for X3, experiment 11

As shown in figures 87 and 88, the temperature dropped in the two thermocouples X4d and –c in the first room. A short temperature rise followed but thereafter the temperature dropped steadily until the fire was extinguished. The temperature closest to the floor in X4a increased initially and –b remained quite constant before the general knock down, only showing a short decrease in temperature. The decreased temperature was quite similar for both X4c and –d, where the temperature dropped roughly 50 °C. The temperature closest to the floor in X4a increased about 25 °C in 10 seconds. It is possible that the fast temperature decrease in the fire room presented in figure 89 was over estimated due to a

direct hit of water on the TCT. The temperatures in the fire room dropped directly after application. The exact temperature changes are shown in table 18 below.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-49.90	6.24	-8.00
X4c	-39.60	6.30	-6.29
X4b	-3.70	1.00	-3.70
X4a	17.20	8.88	1.94
X3d	-140.50	4.00	-35.13
X3c	-140.60	2.70	-52.07
X3b	-76.50	2.70	-28.33
X3a	-7.80	2.70	-2.89

Table 18. Temperature difference and maximum rate of change in temperature, experiment 11

By examining the thermal images from the experiment it was found that water was applied for about 2 seconds in both rooms; both to the ceiling and the wall in direct vicinity of the TCT. The water applied to the wall and the ceiling in the second room is shown as the black areas in figure 36 below, the TCT is illustrated as a black dotted line.



Figure 91. Thermal image showing the water covered surfaces behind the TCT X3, experiment 11



The temperature as a function of time within the entire compartment is shown in figure 92 below.



Figure 92. Temperature as a function of time for all thermocouples in experiment 12

The maximum temperature within the compartment peaked at about 500 °C around 180 seconds after ignition. After this peak the maximum temperature dropped to fluctuate at around 350 °C until the application started, this was due to the under ventilated conditions of the compartment. The maximum temperatures were measured from the X2d point of the X2 TCT, which was located closest to the fire.

Application of water started at approximately 450 seconds after ignition. This is shown in figure 92 above as the temperature started to drop significantly around this time. The measurement from X2 showed that the fire was heavily affected right after an increase of about 25 °C, then the fire extinguished almost immediately.

The gas-cooling effect of water was shown by TCT X3 and X4. The extinguishing impact on the fire was also reflected in X3 causing problems to evaluate only the gas-cooling effect separate from the decreased fire intensity. The temperature as a function of time for these thermocouples, as well as the rate of change in temperature is shown in figures 93 - 96 below.



Figure 93. Temperature as a function of time for X4, experiment 12



Figure 94. Rate of change in temperature as a function of time for X4, experiment 12



Figure 95. Temperature as a function of time for X3, experiment 12



Figure 96. Rate of change in temperature as a function of time for X3, experiment 12

As figures 93 and 94 indicate, the temperature dropped noticeably in the two thermocouples X4d and -c in the first room, while the temperatures closest to the floor in X4a and -b either increased or remained constant. The decrease in temperature was quite similar for both X4c and -d, where the temperature dropped roughly 40 °C. As for the increased temperature in X4a, a temperature rise of about 25 °C in 10 seconds occured. The exact temperature changes are shown in table 19 below.

## Results from the gas-cooling experiments

The effects of water looked different in the fire room. Figures 95 and 96 show that the application initially decreased the temperature in the two top thermocouples X3d and –c. The temperature started to decrease even before the indication that application in the fire room had started. Just a few seconds after application the temperature significantly increased in the lower parts of the compartment and both X3b and –a were also greatly affected. As shown in figure 96 the temperature increase was about 10 °C per second. The exact temperature differences and maximum rates of change in temperature are shown in table 19 below.

TC	Temp. Difference [°C]	Time [s]	Max. rate of change in temperature [°C/s]
X4d	-42.50	5.16	-8.24
X4c	-37.80	5.16	-7.33
X4b	0.00	1.00	0.00
X4a	24.20	6.54	3.70
X3d	-49.50	3.90	-12.69
X3c	-44.40	3.90	-11.38
X3b	35.70	6.54	5.46
X3a	37.78	7.86	4.81

Table 19. Temperature difference and maximum rate of change in temperature, experiment 12

By examining the thermal images from the experiment it was found that water was applied for 1 second in both rooms; both the ceiling and the wall in direct vicinity of the TCT were hit. The water applied to the wall in the second room is shown as the black areas in figure 36 below, also some of the covered area in the roof is seen in the upper edge of the figure; the TCT is illustrated as a black dotted line.



Figure 97. Thermal image showing the water covered surfaces behind the TCT X3, experiment 12

## 7.2 Summary of experimental results

The temperature within the entire compartment was similar in most of the conducted experiments. In general the maximum temperature peaked around 500 - 600 °C about 180 - 200 seconds after ignition. The fire then became under ventilated and the maximum temperature dropped to somewhere between 250 - 350 °C, where it stabilized until the application started in the second room. The maximum temperature was recorded by the X2d thermocouple, located 45 cm from the ceiling, closest to the fire source. The temperature was consistently lower in the first room of the compartment, generally stabilizing between 150 - 200 °C in the upper parts of the room.

The exception in these results being the first experiment conducted. In experiment 1 the temperature in the second room peaked just above 500  $^{\circ}$ C, a lower temperature than most other experiments, and stabilized at a higher temperature in both rooms. The effect of insufficient ventilation was not as evident in this experiment.

The fire was extinguished in all but two of the experiments, experiments 1 and 2. These results show that wet and dry CAF as well as water managed to extinguish the fire, regardless of which application time was used and without any direct application to the fire or fuel.

Several observations were made by the firefighters responsible for applying the extinguishing agent inside the compartment. First of all the foam applied to the ceiling of the compartment vaporized within a few seconds of the application. Foam that was applied to the walls vaporized at a significantly slower rate. When comparing wet and dry foam, the observation was made that wet foam formed a thinner more uniform layer on the hot surface, whereas the dry foam would form a thicker non-uniform layer with peaks of thick foam and areas with only a thin layer. The wet foam also seemed to stick to the surfaces to a higher extent than the dry foam. Other observations made concluded that the visibility inside the compartment improved the most after the second application of wet foam compared to dry foam and water.

In all the experiments where the fire was not extinguished directly following the application in the second room, the same tendencies appear; the foam applied to the ceiling vaporized quickly causing the fire to drop in intensity, when the fire later recovered the temperatures closest to the fire peaked at a higher level than before the application. This peak in temperature caused the remaining foam on the walls to vaporize at an increasing rate and once again affect the fire. This caused a number of temperature spikes following the application, eventually extinguishing the fire. The only exceptions were experiment 1 and 2, where the fire was not extinguished.

The data recorded from the experiments show that the thermocouples placed on the walls, o1 and o4, drop in temperature in the same way in all the experiments using foam. The temperature drops linearly to around 30  $^{\circ}$ C in a matter of seconds, upon the thermocouple being hit by the foam, the temperature then rose to almost 100  $^{\circ}$ C for as long as the thermocouple was covered by foam. Once the foam no longer covered the thermocouple it reached the surrounding temperature within a few seconds.

All experiments with dry foam were quite similar to each other. The maximum temperatures were given by the X2d thermocouple in TCT X2 but also from the TCs o1 - o4 varying for the different experiments.

When application of dry foam started in the first room in experiments 8 and 9, the temperature was to some extent lowered. However, the temperature began to increase again shortly thereafter and there were no obvious correlations between the application and the gas-cooling effects. In experiment 10

there was no application of foam in the first room, no gas-cooling effects were recorded in this room due to the application in the fire room.

The temperatures in X3d and -c in the fire room were either reduced or stagnated for a period of about 5 - 10 seconds before the temperature increased again. The largest temperature drop for X3d was about 53 °C in 7 seconds, in experiment 8. For X3c it was about 35 °C in 13 seconds, in experiment 10. Drops in temperature due to suspected direct hits of foam are excluded.

As figures 68 and 74 show, the application of dry foam in experiment 8 and 9 did not weaken the fire. On the contrary, the fire grew significantly in strength directly following the application. This was not seen in experiment 10 or any of the experiments using wet foam or water.

The two experiments with water show strong similarities to each other. The application clearly decreased the temperatures in both the first and the second room. The temperature drop followed immediately after the application started in the 2-second experiment and was just slightly delayed by 1 second of application.

The gas-phase interaction is clear which is shown especially in experiment 12 where the 1 second application causes complete extinguishment of the fire. The temperatures recorded by o2 - o4 at the compartment boundaries recovered much faster than in the foam experiments with complete extinguishing. As shown in figure 92 the recovery in temperatures was fast and occurred concurrently with the degradation of the fire intensity, which indicates that just a small amount of water hit the thermocouples and evaporated in the early decay-phase.

An increase in temperature closer to the floor in both rooms at the same time as application proceeded could also be seen in both experiments 11 and 12. The temperature rise in the first room was 15 - 25 °C in 5 – 10 seconds and in the fire room about 35 °C in 7 seconds, suspected direct hits of the thermocouples are excluded.

The infra-red camera, carried by the second firefighter, used to document the experiments gave the exact time of application in all of the experiments. The exact application times together with the intended application times and the total amount of water applied in each room are shown in table 20 below.

Experiment	Day	Extinguishing agent	Intended Application time [s]	Real application time, room 1 [s]	Real application time, room 2 [s]	Amount of water applied in room 1 [1]	Amount of water applied in room 2 [1]
1	1	Wet foam	2	2	2	4.4	4.4
2	1	Wet foam	2	3	4	6.6	8.8
3	1	Wet foam	4	4*	7	8.8*	15.4
4	1	Wet foam	4	4	5	8.8	11
5	1	Wet foam	4	0	5	0	11
6	2	Wet foam	2	2*	3	4.4*	6.6
7	2	Wet foam	4	0	5	0	11
8	2	Dry foam	5	6	7	5.4	6.3
9	2	Dry foam	5	5	7	4.5	6.3
10	2	Dry foam	5	0	5	0	4.5
11	3	Water	2	2	2	3.6	3.6
12	3	Water	1	1	1	1.8	1.8

Table 20. The exact application times and amount of water applied in each experiment

\*Some of the applied foam bounced of the doorpost before entering the first room, see figure 42.

When comparing the gas-cooling effect of wet and dry CAF to that of water, all the differences in temperature recorded in the experiments, displayed in table 8 - 19 in the previous chapter were divided by the volume of water that was applied inside the room. This gives an estimation of the change in temperature caused by each liter of water applied inside each room.

To enable comparison based on all the collected data, the arithmetic mean value for the X3 and X4 TCTs was calculated. Since the experiments only provide a handful of values the difference in effectiveness was tested using a non-parametric statistical model. The values used and the results from the statistical test are shown in tables 21 - 23 below, the complete calculations are presented in Appendix B.

	Temperature difference per liter of water applied [°C/l]											
TC	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9	Exp. 10	Exp. 11	Exp. 12
X4d	-1.9	-4.1	-2.2	-2.0	N/A	-6.8	N/A	-2.5	-2.5	N/A	-13.9	-23.6
X4c	-3.3	-2.8	-2.9	-2.5	N/A	-3.1	N/A	-4.4	-3.4	N/A	-11.0	-21.0
X4b	1.2	2.5	-4.7	N/A	N/A	1.7	N/A	-4.9	6.3	N/A	-1.0	N/A
X4a	1.1	1.0	N/A	N/A	N/A	1.3	N/A	N/A	N/A	N/A	4.8	13.4
X3d	-36.9	-6.3	-1.5	-7.1	-4.0	-4.0	-9.5	-8.4	-0.8	-34.4	-39.0	-27.5
X3c	-4.9	-10.7	-1.5	-3.2	-3.4	-9.4	-3.6	-1.8	0.6	-7.9	-39.1	-24.7
X3b	14.0	4.3	N/A	-2.5	-2.0	4.0	-5.5	-1.7	3.0	1.7	-21.3	19.8
X3a	2.6	0.7	0.3	1.0	0.5	2.4	1.9	N/A	1.0	-5.7	-2.2	21.0

Table 21. The temperature difference in the X3 and X4 TCTs per liter of water applied in each experiment

## Results from the gas-cooling experiments

Mean change in temperature per liter of water applied [°C/l]									
Thermocouple	Wet foam	Dry foam	Water						
X4d	-3,39	-2,50	-18,74						
X4c	-2,91	-3,88	-16,00						
X4b	1,36	0,70	-0,51						
X4a	0,69	0,00	9,11						
X3d	-5,41	-4,63	-33,26						
X3c	-4,33	-3,04	-31,86						
X3b	1,77	1,00	-0,71						
X3a	1,33	0,50	9,41						

Table 22. The mean change in temperature per liter of water applied, disregarding some measurements

Table 23. Results of statistical analysis

Null hypothesis	one tailed	two tailed	one tailed	
Null hypothesis	p-value	p-value	p-value < 0.05	
X3c (CAF) = X3c (water)	0.028	0.056	Yes	
$X3c (CAF) = X3c (water)^*$	0.036	0.071	Yes	
X3d (CAF) = X3d (water)	0.056	0.111	No	
$X3d (CAF) = X3d (water)^*$	0.036	0.071	Yes	
X3c+d (CAF) = $X3c+d$ (water)	0.001	0.003	Yes	
X3c+d (CAF) = X3c+d (water)*	0.001	0.001	Yes	
X4c (CAF) = X4c (water)	0.048	0.095	Yes	
X4d (CAF) = X4d (water)	0.048	0.095	Yes	
X4c+d (CAF) = $X4c+d$ (water)	0.001	0.002	Yes	

\* Tests disregarding the measurements caused by direct hits of CAF, see table B 5

In the cases where the one tailed p-value is less than 0.05, the effectiveness of water is significantly higher. Since this is the case in eight out of nine of these tests, the conclusion is that wet CAF is less effective in cooling the hot gases than high-pressure water mist.

# 8 Discussion, gas-cooling experiments

The following chapter contains a discussion regarding the result, conclusions and potential sources of error for the gas-cooling experiments.

## 8.1 Results

The first set of experiments conducted in this report show that CAF in fact has a gas-cooling effect when applied to hot surfaces within a smoke gas layer, though the results indicate that this effect is lower than that of water. The reviewed literature states that CAF is a durable extinguishing agent and very efficient in both fire suppression and protection, but should not be used with the purpose of cooling hot smoke gases (Grimwood, 2008).

The gas-cooling effect of CAF differs from that of water, as these experiments show, in effectiveness but also in regard to where the cooling actually takes place. When water is used to cool hot gases, a cone-shaped stream with smaller size droplets is used to cover a large volume of gases. The small droplet size allows the water to efficiently vaporize within the hot gases and the droplets that are not vaporized in the gases hit surrounding surfaces where they either vaporize on impact or roll off the surface.

This causes two effects that can be seen in these experiments, first of all the gas-cooling effect is instant. The temperature in the upper parts of the compartment is significantly reduced immediately following the start of the application; see figures 89 and 95. The other observation made in the experiments is that some of the water did not vaporize within the gases and therefore hit the hot surfaces. The fast vaporization both in the gases and from the hot surfaces led to a vapor expansion within the compartment, which also reduced the visibility. The expansion of vapor in the upper parts of the compartment pushed hot gases towards the floor which led to an increase in temperature in the lower parts of the room. The temperature increase in the lower parts was delayed from the application and can also be seen in figure 89 and 95. Several reports from the studied literature describe the same effects (Persson, 2005), (Zhang, et al., 2011).

With CAF on the other hand the main gas-cooling effect does not take place while the foam is traveling through the hot gases, but rather when the foam has been applied to the hot surfaces of the compartment i.e. through indirect cooling. This depends on the fact that CAF is applied through a straight-bore nozzle and therefore in a closed stream; this preserves the important bubble-structure of the foam but also limits the contact area with the surrounding gases. This negates some of the early vaporization that is seen in the water experiments and therefore no vapor expansion was observed in any of the CAF experiments.

Once the foam is applied to a hot surface the vaporization becomes more effective, both due to the heating effect from the contact with a hot surface and from the much larger contact area with the hot gases. However the vaporization is likely not the only gas-cooling effect of CAF. Since it covers a hot surface for an extended period of time it blocks the radiant heat from the surface to the gases and also effectively cools the surface. The radiation blocking effects of CAF are well documented and have been studied in several reports (Boyd & di Marzo, 1996), (Tafreshi, et al., 1998), (Tafreshi & di Marzo, 1999).

These mentioned effects were seen in the experiments using CAF since the gas-cooling was delayed by a few seconds after the application but also because of its slower, longer lasting rate of temperature change compared to water. The surface cooling was also seen in the thermal footage from the experiments, where a wall would have a lower surface temperature for several minutes after the foam

### Discussion, gas-cooling experiments

had vaporized. However in these experiments the intensity of the fire often decreased significantly which might have affected the time until the surface temperature rose.

Surface cooling also took place in the experiments where water was used. However the effects were smaller and lasted for shorter periods of time. Since water is the main cooling component of CAF the differences lie in the foam structure. Since CAF adheres better to the hot surfaces of the compartment and forms a thicker layer than water, the effects are greatly increased. This can be seen in the temperature readings of the thermocouples placed on the compartment walls, mainly o1 and o4.

When water covered these thermocouples a significant linear drop in temperature occurred. This was followed by a rapid increase back to the surrounding temperature; see figures 89 and 95. When the thermocouples were covered by CAF the initial drop in temperature was the same but the effects lasted longer. In most CAF experiments the temperature dropped linearly to around 30 °C, followed by an increase in temperature to just below 100 °C. The temperature then stabilized for as long as the foam covered the thermocouple before increasing to reach the surrounding temperature once the foam layer had deteriorated, see figure 48. This effect is also described by Boyd and di Marzo who state that since water evaporates at 100 °C, the underlying surface temperature will not exceed this value until the foam is gone (Boyd & di Marzo, 1996).

Another beneficial effect of CAF, though not recorded in these experiments due the structural materials within the compartment, is that it also prevents pyrolysis gases from leaving the covered material, thus preventing it from involvement in the fire, if it is flammable (Persson, 2005), (Raffel, 2010), (Taylor, 1997), (The Boston Fire Department, 1994).

The effects of CAF described above were largely seen for both wet- and dry CAF, however some differences were identified. The biggest difference occurred when dry CAF was applied to the room of the fire, in experiments 8 and 9. The application within the fire room caused the intensity of the fire to increase significantly in both of these experiments, thus causing the gas temperature in the upper parts of the compartment to just slightly decrease or even increase. This might be caused by of a number of reasons.

First of all the application causes a stirring effect within the compartment that provides the under ventilated fire with more oxygen. This combined with the fact that dry CAF contains more air and less water than wet CAF could be the reason. The extra supply of oxygen seems to have a greater effect on the fire than the vaporizing water, thus mostly negating the gas-cooling effects of the dry foam in these experiments. The addition of oxygen to the compartment might be a combination of both the stirring effect and the oxygen introduced within the CAF. Some research on the topic of oxygen provided within the CAF has been conducted by Zhang et.al. Where the effects of wet CAF on an under ventilated fire were investigated (Zhang, et al., 2011). Zhang tested if wet CAF applied to an under ventilated fire could cause back draft but found that it did not have any effect.

In addition to these effects, observations made during the experiments show that dry CAF did not adhere as well as wet CAF to the hot surfaces of the compartment. This is probably due to the lower water content of the dry CAF restricting its ability to cool the hot surface enough to efficiently stick to it. Though further research needs to be conducted in order to make a definitive statement, the results stated above indicate that dry CAF is not suitable for this kind of application in structural fires.

## 8.2 Method

The fire was extinguished in all experiments except for two, experiments 1 and 2, without any extinguishing agent being applied directly to the fire. This was probably due to the under ventilated conditions in the compartment weakening the fire and causing it to be very vulnerable to the cooling effects. This effect was neither expected before the experiments nor desired.

The reason for closing all the ventilation openings was to create repeatable conditions inside the compartment by limiting the effects of external factors such as wind and outdoor temperature. This caused problems in some of the experiments where the fire was significantly weakened or extinguished following the application. The problem in these experiments lies in determining whether the drop in temperature was a result of gas-cooling, by the extinguishing agent, or by a decrease in fire intensity. How the data was interpreted in each experiment is explained in the results chapter, but if more experiments were to be made a more robust well ventilated fire would be desirable.

The experiments were conducted in a rather large compartment and with human interaction through the manual application of the extinguishing agents. This causes some problems in repeatability and consistency. Even though the temperature within the compartment varied between the different experiments, they all more or less show the same peak in temperature and reached a stable temperature level before the application was started. Considering the relatively large size of the compartment and variation in external factors the repeatability for these experiments is considered to be adequate.

Some variations were caused by the manual application of extinguishing agent. This is to expected however since it is impossible for any human to perform the exact same application of extinguishing agent throughout all the experiments. These variations within the experiments were minimized by letting a highly competent instructor from MSB perform the application in all experiments. Furthermore the differences in application times and surfaces covered within the compartment are displayed and accounted for in the results chapter.

Discussion, gas-cooling experiments

# 9 Full-scale experiments

The following chapter presents objectives, setup and details regarding the conducted full-scale experiments in Skövde.

## 9.1 Experimental objectives

The experiments in Skövde aimed to compare CAF and water in a more realistic environment. Due to the type of the house, only one experiment with each fire extinguishing agent could be performed. The overall objective for the experiments was to study the temperature change in a hot gas layer when CAF is used as it would be used in a real situation. The CAF was applied as wet foam in an attempt to investigate the gas-cooling effects; finally these results are compared with the effects of water.

## 9.2 Experimental setup

The full-scale experiments were conducted in an older two story wooden house, shown in figure 98 below. The framework was constructed of timber and isolated with sawdust. The experiments were conducted on the second floor of the building in two almost identical compartments. They were joined together by a room with a staircase leading to the ground floor. The house plan is shown in figures 99 -101.



Figure 98. View of the house for the full-scale experiments. Photo: Pär Hagbohm



Figure 99. Ground floor of the house, view from above



Figure 100. Second floor of the house, view from above indicating the relevant rooms

## Investigation on the gas-cooling effects of CAFS



Figure 101. Part of the second floor of the house, view from above showing the fire compartments and the connecting room

The walls in all rooms were lined with painted wooden planks and in rooms two and three also with multiple layers of wallpapers. The ceiling in room three was lined with 12 mm thick beaver boards (a porous wooden fiber board), the floor was covered with a linoleum carpet, see figure 102 - 103.



Figure 102. Connecting room with part of the staircase



Figure 103. Room three before installation of thermocouples

To prevent smoke spread to adjacent rooms, the door from the test compartment was closed until the firefighters opened it but the window was open to provide a sufficient air supply. In the experiments a fire consisting of two wooden pallets (Euro-pallets) was lit with one liter of charcoal lighter fluid, see figure 108. The wooden board behind was mounted on a door to prevent smoke and fire spreading to other parts of the house. The position of the fires in room two and three are shown in figures 106 and 107.

Type-K thermocouples were installed in both the fire rooms and in the connecting room with the staircase; one thermocouple tree consisting of four thermocouples in each room and one thermocouple directly below the ceiling in each fire room. The thermocouples below the ceiling served as a marker for the start of the application, just as in the earlier experiments at Revinge. The shield in figure 109 was built next to the tree towards the door in the fire compartments to prevent direct hits of water or CAF when the firefighters extinguished the fire. The exact placement of the thermocouples and measurements of the compartment are shown in figures 104 - 107 below. The height of each individual thermocouple is presented in table 24.

		(cm)
o2.5		o 3.5
<b>X</b> 2.4	<b>X</b> 1.4	<b>X</b> 3.4
<b>X</b> 2.3	<b>X</b> 1.3	<b>X</b> 3.3
<b>X</b> 2.2	<b>X</b> 1.2	<b>X</b> 3.2
<b>X</b> 2.1	<b>X</b> 1.1	<b>X</b> 3.1
X - Initial fire placement X - Thermocouple tree o - Single thermocouple		

Figure 104. Thermocouple placement on the second floor, view from the side



Figure 105. Placement of the thermocouples inside room one, view from above



Figure 106. Placement of the thermocouples and the fire inside room two, view from above



Figure 107. Placement of the thermocouples and the fire inside room three, view from above



Figure 108. Fire load in room three. An identical fire load was placed in room two in the corresponding place



Figure 109. Thermocouple tree and protective shield in room three

### Full-scale experiments

Thermocouple(-s)	Height above 2nd floor [cm]
X 1-3 .1	45
X 1-3 .2	90
X 1-3 .3	135
X 1-3 .4	180
o 2.5	210
o 3.5	210

Table	24.	Height	above	2nd	floor	for	each	individual	therm	ocouple

### 9.2.1 Experimental conditions

The experiments were conducted during one day in mid-October. The temperature was around 10 °C, it rained and the winds were weak. The CAF-experiment was conducted in room three and the comparative water experiment was conducted in room two.

## 9.3 Experimental procedure

The experiments were conducted in one room at a time. The temperature recording was started whereon the fire was lit. The fire was allowed to grow without interaction until flashover occurred. When flashover had occurred, the firefighters had instructions to start their extinguishing attempt. The firefighters were also instructed to use the same method for extinguishing as they would have used in a real situation and make it as realistic as possible, this included direct extinguishing of the fire and not only gas-cooling.

Since the CAFS and the high pressure water system require different extinguishing techniques, the two approaches differ from each other. When CAFS was used, the application started from the outside through the window. First the ceiling was coated and then the firefighters proceeded indoors to finish the extinguishing.

When water was used the application took place from inside the compartment due to the shorter range. The firefighters were positioned outside the house, prepared to enter the house when flashover occurred. They then moved forward into the house and extinguished the fire. The reason for their positioning outside the house and not outside the fire compartment was an attempt to simulate the difference in time to initial attack that occurs due to the possibility of external attack with CAFS. The routes of attack are shown in figures 110 and 111 below. The letters indicate the firefighter starting position and their positioning during application. During the CAFS experiment, the firefighter started the application at point A, then moved to B for further application from the outside. The firefighter then proceeded indoors to point C and extinguished the fire. Point D was the starting position for the firefighters during the water experiment. When flashover occurred, they entered the house and moved to point E where they extinguished the fire.


Figure 110. The route of attack, ground floor



Figure 111. Route of attack, second floor

Full-scale experiments

# 10 Results for the full-scale experiments

*Results and observations from each of the experiments are listed below, together with graphs and footage. A summary of all the experiments is given at the end of this chapter.* 

### **10.1 Individual experiments**

Both fire scenarios are allowed to reach flashover, they also affect the adjacent compartment, room one. This can be observed in the temperature-time graphs provided in the following chapter. The difference in the systems and their extinguishing mechanisms affect the result, hence the curves are displayed for both experiments.

Since the application of extinguishing agent is performed by two different persons some differences in application are to be expected. However the firefighters who used the respective systems are familiar with them and it is therefore assumed that they are handled correctly.



10.1.1 CAFS experiment: fire located in room three

The temperature as a function of time in room three is shown in figure 112 below.

Figure 112. Temperature as a function of time for room three, CAFS

The thermocouples within the compartment show that the temperature immediately increases to just above 100 °C. The temperature then decreases before it begins to increase once again. The latter increase in temperature happens as the fire propagates through the wooden pallets. The temperature stabilizes at around 200 °C for a short period of time before slowly increasing to 250 °C and eventually causing a flashover.

The maximum temperature in room three peaked just above 700 °C about 200 seconds after ignition. This peak in temperature was recorded in the 3.5 thermocouple as the flashover occurred within the compartment.

#### Results for the full-scale experiments

At the time of the flashover the firefighter was given a signal to start the application, which occurred just a few seconds later. The first application of CAF was made from the outside through the window, and lasted for 10 seconds.

The first application started around 205 seconds into the experiment, immediately hitting the 3.5 thermocouple which plummets below 100 °C. The effect of the application is shown in better resolution in figure 113 below.



Figure 113. Temperature as a function of time for room three, CAFS, high resolution

The gauges in the fire compartment show a slight drop in temperature following the start of the application, but the large drop in temperature occurs a few seconds later. Within 30 seconds of the start of the application the temperature drops below 200 °C, where the rate of change in temperature decreases. At 255 seconds in to the experiment, the door to the compartment is opened, and a short application of CAF completely extinguishes the fire. This causes the temperature within the compartment to drop below 100 °C. In total, CAF was applied for 11 seconds.

The temperature in the adjacent compartment, room one, is shown in figure 114 below.



Figure 114. Temperature as a function of time for room one, CAFS

The temperature in room one shows an initial peak right above 60 °C recorded by the top thermocouple. This occurs with just a few seconds delay from the first peak in temperature within the fire compartment, see figure 112. The temperature drops back down below 40 °C before significantly increasing to peak just above 130 °C at the 125 second mark. This peak coincides with the short stabilization of temperature recorded within the fire compartment, but the temperature in room one starts to decrease as the fire compartment reaches flashover.

The steady decrease in temperature shows a small peak at around 150 seconds but then continues to drop until the door to the fire compartment is opened at 250 seconds into the experiment. When the door is opened the temperature rises by approximately 10°C. Figure 115 shows the room after extinguishment.



Figure 115. Room three after extinguishing with CAF

#### 10.1.2 Water experiment: fire located in room two

The temperature as a function of time in room two is shown in figure 116 below.



Figure 116. Temperature as a function of time for room two, water

The thermocouples within the compartment show that the temperature increases steadily to around 250 °C. The temperature then decreases by almost 100 °C before it peaks once again, this time between

250 - 300 °C. The temperature then drops steadily down to 100 °C before a significant increase occurs and flashover is reached.

The maximum temperature in room two peaked just below 700  $^{\circ}$ C about 210 seconds after ignition. This peak in temperature was recorded in the 2.5 thermocouple as the flashover occurred within the compartment.

At the time of the flashover the firefighter was given a signal to start the application, since the water is applied from inside the compartment, the application started with a 20 second delay. The application of water started at 225 seconds into the experiment, immediately hitting the 3.5 thermocouple and affecting the temperature within the entire compartment. In total the water was applied for 11 seconds. The effect of the application is shown in better resolution in figure 117 below.



Figure 117. Temperature as a function of time for room two, water, high resolution

The thermocouples in the fire compartment show a significant drop in temperature immediately following the start of the application, where the temperature in 4 out of 5 thermocouples drops below 300 °C in 10 seconds. A second burst of water is applied within the compartment, at the 240 second mark, which extinguishes the fire and causes the temperature within the compartment to stabilize just above 100 °C.

The temperature in the adjacent compartment, room one, is shown in figure 118 below.



Figure 118. Temperature as a function of time for room one, water

The temperature in room one shows an initial peak right above 140 °C recorded by the top thermocouple. This occurs with a 10 second delay from the first peak in temperature within the fire compartment, see figure 116. The temperature drops back down below 50 °C before significantly increasing to peak just above 150 °C at the 185 second mark. This peak coincides with the compartment reaching flashover. The temperatures drop steadily from this point until the door in to the compartment is opened at 230 s, causing a peak in temperature just above 100 °C.

As the application starts the temperature plummets below 60  $^{\circ}$ C for a short period of time, before increasing by almost 20  $^{\circ}$ C. From this point the temperature more or less decreases for the remainder of the experiment. Figure 119 shows the room after extinguishment.



Figure 119. Room two after extinguishing with water

### **10.2 Summary of experimental results**

The temperature within the fire compartments peaks around 700 °C, when flashover occurs, for both experiments. However the temperature varies before the flashover, where the initial peak in temperature was 100-200 °C higher in the water experiment compared to the CAFS experiment. This affects the temperature in the adjacent compartment, room one.

The temperature-time curve for room one show two peaks in temperature for both experiments. In the water experiment both peaks show a higher temperature than in the CAFS experiment. Since the first application of CAF is done through the window, the fire is significantly weakened before the door to the compartment is opened. This causes the peak in temperature in room one, when the door is opened, to be significantly lower in the CAFS experiments.

The effects of the application of both water and CAF look quite similar. However some differences are observed. The drop in temperature is immediate following the start of the application with water whereas, with CAF, there is a slight delay. The time until the temperature within the entire compartment drops below 200 °C is slightly longer for water and the temperature after the fire is extinguished remains higher in the water experiment. The total amount of water applied in each of the experiments is shown in table 25 below.

	Application time from the outside [s]	Application time from inside [s]	Total application time [s]	Flow [l/min]	Total volume of water applied [l]
Water	-	11	11	103	18.9
CAFS	10	1	11	122	22.4

Table 25. Total amount of water applied in each of the experiments

The total amount of water added in the form of CAF is 3.5 liters more than the regular water. The application also differs; the majority of the CAF was applied to the ceiling of the fire compartment through the window, only a short application was needed inside the compartment to completely extinguish the fire. Thus the fire was almost extinguished from the external application, even though the CAF was not aimed directly at the source of the fire. The same indirect extinguishing effect was shown in the previous experiments as well. The water however was applied directly into the compartment, covering the gases and being aimed towards the seat of the fire.

After the experiments were conducted some observations were made; more water was observed on the floor of room two. Also the walls and ceiling in room two were significantly affected by the fire and the charring was more extensive, compared to room three. Figures 115 and 119 show both rooms after the fire had been extinguished and the smoke gases had cleared out. Another observation made was that re-ignition of the compartment where CAF had been applied was harder than in the other room. This effect was also described by Millbourn and Folkesson in their bachelor thesis (Folkesson & Millbourn, 2008).

Results for the full-scale experiments

## 11 Discussion, full-scale experiments

The following chapter contains a discussion regarding the result, conclusions and potential sources of error for the full-scale experiments.

### 11.1 Results

In the final experiments, two almost identical compartments were used. This provided a good platform for comparison of the results. In both rooms two wooden pallets were ignited using one liter of charcoal lighter fluid. The fact that the lighter fluid is ignited first and burns rapidly shows in the temperature-time graphs for the experiments, see figures 112 and 116. This creates the first peak in temperature quite soon after the ignition; the temperature peaks at a higher level in room two.

The fact that the early peaks in temperature differ presents some problems in determining how the extinguishing agent affects the gas temperature in the adjacent room one. This combined with the fact that the doors to the fire compartments were closed during the experiments, due to the risk of flame spread to room one, complicates the analysis. What can be seen however is the peak in temperature created when the door to the compartment is opened. This peak is significantly lower in the CAF experiment compared to the water experiment; see figures 114 and 118. This is due to the application of CAF from the outside, before the door is opened.

The fires in each experiment were allowed to reach flashover before any application started. Both experiments reach roughly the same temperature regardless of the differences recorded before flashover occurred. Since two different extinguishing methods were used, the time between flashover and the start of the application varies for the two extinguishing agents. This was meant to illustrate the possibility of a faster application with CAF, since it can be applied from a safe distance through the window. The effects of this can be seen in the degree of charring when comparing the two compartments, see figures 115 and 119.

When comparing the extinguishing properties of the two extinguishing agents it is still clear that different mechanisms are used. The delay that occurs between the application of the CAF and the decrease in temperature is caused by the fact that it indirectly affects the fire. The CAF applied through the window in these experiments was only aimed at the ceiling of the compartment. Even though some of the CAF probably hit the seat of the fire, the largest portion of the foam vaporized from the ceiling.

The vaporization within the compartment combined with other beneficial effects of the CAF causes the temperature to drop more rapidly within the entire compartment. Apart from the vaporization the foam prevents flammable gases from being emitted from the covered material and insulates it from both radiation and convection, thus preventing the surface from being involved in the fire (Taylor, 1997), (Tafreshi & di Marzo, 1999). Even when the CAF has deteriorated the fibrous surface is more difficult to re-ignite (Folkesson & Millbourn, 2008).

The literature reviewed in this report states that CAF is more efficient and uses less water in extinguishing a fire. However in these experiments 3.5 more liters of water was applied in the form of CAF than high pressure water mist, see table 25. This might be caused by the fact that the earlier reports compared the effect to water extinguishing systems with a higher flow and larger water droplets. It may also be a result of the relatively small fires used in the experiments, fires which are comparatively easy to extinguish with both systems.

#### Discussion, full-scale experiments

The difference in applied water might be a part of the reason why the temperature drops more rapidly inside the compartment where CAF is added. Also the fire in the water experiment was allowed more time to grow compared to the fire in the CAF experiment. However, these points considered, the fact that it took nearly as much water to extinguish the fire from inside the fire compartment as it did with CAF from the outside is worth mentioning. The CAF application could be done from a safe distance, giving slightly better results and by the time the firefighter opened the door to the compartment, temperatures were already low.

These experiments indicate that CAF, when applied inside a fire compartment from a safe distance, affects the fire even without directly hitting the source of the fire. The experiments also show that the earlier suppression minimizes the damage done to the compartment, judging both by the degree of charring and the amount of excess water. Furthermore the temperatures within the compartment are significantly lowered by the first application and therefore create a better environment for firefighters advancing through the building and into the fire compartment.

There are many benefits to being able to knock down or extinguish a fire from a safe distance. The most significant benefit being the increased safety of the firefighters. Today a traditional firefighting tactic, with different extinguishing systems using water, is most commonly used. This requires firefighters to reach the seat of the fire within a burning structure before being able to extinguish it, which often involves entering a hazardous environment.

The current trend in Swedish Fire and Rescue Services is to limit the number of operations where personnel are forced to enter a hazardous environment. This is done in accordance with the law regarding safety for firefighters issued by the Swedish Work Environment Authority, which states that entering a hazardous environment should be done when lives can be saved but should otherwise be avoided. The law also states that fire extinguishment from a safe distance should be the technique of choice, when possible (AFS 2007:7, 5§).

In addition to this, a debate regarding long term health problems for firefighters is currently taking place in Sweden. Recent studies have shown that firefighters have a higher risk of developing cancer later in life than the average person. Probably due to exposure of different toxins contained within the smoke (LeMasters, et al., 2006), (Youakim, 2006). This shows that the temperature within the hot gases is not the only variable concerning firefighter safety and therefore makes another strong argument for extinguishing fires from a safe distance.

All the factors mentioned in this chapter suggest that there is a possibility that CAFS, when properly used in this type of fire, can be a good alternative to the traditional extinguishing methods using water. Providing more safety for the firefighters as well as lowering the gas temperature before even entering the fire compartment. Therefore CAFS may be used to reduce the risks involved with firefighting and minimize the number of operations where firefighters are forced to enter a hazardous environment.

The positive effects of using CAFS might be increased by incorporating a PPV-fan (Positive Pressure Ventilation). This may further limit the need for traditional gas-cooling and improve the environment for the firefighters. Therefore this would be an interesting area for further research.

### 11.2 Method

In order to determine how much water that was applied inside of the two fire compartments, the flow of water for each extinguishing system was multiplied with the time of application. During the experiments the application time was measured using a stopwatch; however these readings might not be exactly accurate. Unfortunately the experiments were not recorded using any form of video equipment and therefore the time cannot be verified. This is a potential source of error and the amount of water applied should be considered as an approximation rather than an exact amount.

Apart from the accuracy of the time it shall also be said that no limit or recommended time of application was presented to the firefighters beforehand, this naturally gives some variation between the two systems as well.

Furthermore the experiments were conducted before the rescue services in Skövde used the building for training purposes. Therefore the fire was not allowed to spread outside of the initial fire compartment. This caused some limitations, first of all the door leading to the adjacent compartment had to be closed throughout the experiment, which resulted in the temperature readings in this compartment being less useful. Also the fire was not allowed to continue beyond the point of flashover, this resulted in the fire not being as tough to extinguish as it could have been.

These points considered the experiments gave some useful information and shows the difference in application techniques, which allows some conclusions to be made. It is important to note however that only two experiments were conducted and it is not enough to determine whether the lowering of gas temperature is sufficient to limit the need for further gas-cooling. More research within this area is needed to determine the exact effects and make comparisons to traditional methods using water.

Discussion, full-scale experiments

# **12 Conclusion**

This chapter lists the conclusions made in this report.

#### 12.1 Conclusions from the literature review

- CAF and Class A foams are superior to plain water as a fire suppression agent and penetrate materials more easily.
- CAF shields the underlying surfaces from radiant heat flux very well and much better than water.
- CAF exceeds water in mass-retention effectiveness and the ignition-inhibited period is also longer for CAF than for water.
- CAF-systems are effective for suppression of interior structural fires and some results indicate that the main strengths are post-flashover fires or fuel-controlled fires.
- The indoor environment for firefighters is improved when CAFS is used for suppression, this is due to the improved visibility that occurs compared to when water is used.
- CAFS reduces the total amount of water needed and thereby extends limited water supplies.

### 12.2 Conclusions from the gas-cooling experiments

- CAF has a gas-cooling effect when applied to hot surfaces within a smoke gas layer.
- Wet CAF is more suitable for gas-cooling than dry CAF.
- Wet CAF is significantly less effective in gas-cooling when compared to a high pressure water mist.
- The gas-cooling effect of CAF is indirect through the vaporization resulting from contact with hot surfaces; therefore the effects are slightly delayed compared to water.
- Both CAF and high pressure water mist managed to indirectly extinguish the heptane pool fire in the compartment without hitting the source of the fire.
- CAF applied to the ceiling of the compartment vaporized very quickly whereas the CAF applied to the walls lasted longer.

### 12.3 Conclusions from the full-scale experiments

- CAF applied, to the ceiling of the fire compartment from the outside, is slightly more effective in lowering the temperature within the compartment compared to high pressure water mist applied from the inside.
- The results suggest that CAF applied from the outside may lower the temperature enough to limit the need for traditional gas-cooling, in this type of fire.
- More research is needed to confirm the conclusions due to the small number of experiments conducted.

Conclusion

## **13 Further research**

This report aimed to investigate the gas-cooling effects of CAFS. During the research, it has been noticed that there is already a lot of knowledge regarding CAFS even though much of it has not been quantified in research projects but rather through observations during backyard experiments. Throughout the process some interesting areas for further research have been identified.

- Quantify the gas-cooling effect of CAFS. The number of experiments conducted in this report managed to prove that CAF is less efficient in cooling hot gases than water. However, the results were too few to quantify the actual difference in efficiency. Therefore a larger study with experiments containing fewer variables would be of interest.
- Comparison between CAFS and water in real applications. The two conducted full-scale experiments indicate that the different firefighting techniques used with CAF and water give similar results. More experiments of this kind are required to determine the difference in effect between the two systems and when it is suitable to use CAFS or water.
- The use of CAFS in situations where application from a safe distance is impossible. Since the gas-cooling with CAF is less efficient than water, it would be of interest to determine if and how CAFS could be used in these situations. This question is also raised by Grimwood in an article for firetactics.com (Grimwood, 2008)
- How CAFS can be used together with other tools to improve the performance. Investigate how different tools such as PPV-fans together with application of CAF from outside a building can improve the environment inside the structure. How different attachments such as piercing nozzles can be used in structural fires.

Further research

### 14 Bibliography

Boyd, C. & di Marzo, M., 1996. *Fire protection foam behavior in a radiative environment,* Gaithersburg: National Institute of Standards and Technology.

Brooks, N., 2012. *Understanding CAFS, Class A foam, & nozzle technology*. [Online] Available at: <u>http://www.darley.com/pumps/cafs/articles.html</u> [Accessed 18 06 2012].

Carringer, R., 2009. Foam Factors. Fire Chief, 2009(03).

Crampton, G. & Kim, A., 2000. *A new compressed-air-foam-technology*. s.l., National Research Council of Canada, pp. 343-348.

Crampton, G. & Kim, A., 2009. *Evaluation of fire suppression effectiveness of manually applied compressed air-foam (CAF) system*, s.l.: National Research Council Canada.

DiNenno, P. J. et al., 2002. *SFPE Handbook of Fire Protection Engineering*. 3rd ed. Quincy, Massachusetts: National Fire Protection Association.

Drysdale, D., 1998. An Introduction to Fire Dynamics. 2nd ed. West Sussex: John Wilery & Sons Ltd.

Folkesson, O. & Millbourn, M., 2008. Släcksystem för lätta räddningsfordon, Lund: Lund University.

Grimwood, P., 2008. *Firetactics.com*. [Online] Available at: <u>http://www.firetactics.com/CAFS.htm</u> [Accessed 04 09 2012].

Karlsson, B. & Quintiere, J. G., 2000. *Enclosure Fire Dynamics*. 1st ed. Boca Raton, Florida: CRC Press.

Kodur, V. K. R. & Harmathy, T. Z., 2002. Properties of Building Materials. In: P. J. DiNenno, ed. *SFPE Handbook of Fire Protection Engineering*. 3rd ed. Quincy, Massachusetts: National Fire Protection Association.

Körner, S. & Wahlgren, L., 2006. Statistisk dataanalys. Lund: Studentlitteratur.

LeMasters, G. K. et al., 2006. *Cancer Risk Among Firefighters: A Review and Meta-analysis of 32 studies*, Cincinnati: American College of Occupational and Environmental Medicine.

Madrzykowski, D., Roadarmel, G. & Delauter, L., 1997. *Durable agents for exposure protection in wildland/urban interface conflagrations*. Gaithersburg, National Institute of Standards and Technology, pp. 345-350.

Madrzykowski, D. & Stroup, D., 1998. *Demonstration of Biodegradable, Environmentally Safe, Non-Toxic Fire Suppression Liquids,* Gaithersburg: National Institute of Standards and Technology.

NFPA, 2006. *NFPA 1145, Guide for the Use of Class A Foams in Manual Structural Fire Fighting,* Quincy: National Fire Protection Agency.

NFPA, 2011. *NFPA 1145, Guide for the Use of Class A Foams in Manual Structural Fire Fighting,* Quincy: National Fire Protection Agency.

#### Bibliography

Nordic Fire & Rescue Service, 2012. *NFRS - products*. [Online] Available at: <u>http://nfrs.no/?cid=17</u> [Accessed 25 09 2012].

Persson, H., 2005. En sammanställning av kunskaper och erfarenheter kring Klass A-skum och CAFS. Brandforsk projekt 516-021, Borås: SP Brandteknik, Sveriges Provnings- och Forskningsinstitut.

Raffel, S., 2010. *CAFS Evaluation Project, Final Report and Recommendations*, Brisbane: Queensland Fire and Rescue Service.

Särdqvist, S., 2006. Vatten och andra släckmedel. 2nd ed. Kalmar: Räddningsverket.

Tafreshi, A. & di Marzo, M., 1999. Foams and gels as fire protection agents. *Fire Safety Journal,* Issue 33, pp. 295-305.

Tafreshi, A., di Marzo, M., Floyd, R. & Wang, S., 1998. *Fire protection foam thermal physical properties*, Gaithersburg: National Institute of Standards and Technology.

Taylor, R., 1997. *Compressed air foam systems in limited staffing conditions*, Morristown: Morristown Fire Bureau.

The Boston Fire Department, 1994. *Compressed Air Foam for Structural Fire Fighting: A Field Test Boston, Massachussetts*, Emmitsburg: United States Fire Administration, Federal Emergency Management Agency.

Tinsley, M., 2002. *Compressed air foam systems: Live fire application and corresponding temperature degradation*, s.l.: United States Fire Administration, Federal Emergency Management Agency.

Youakim, S., 2006. *Risk of cancer among firefighters: a quantitave review of selected malignancies,* Vancouver: University of British Columbia.

Zhang, J., Delichatsios, M. & O'Neill, A., 2011. Assessment of gas cooling capabilities of compressed air foam systems in fuel- and ventilation-controlled compartment fires. *Journal of Fire Sciences*, 29(6), pp. 544-554.

## 15 Appendix A - Results

This appendix contains all the data provided from the experiments, in its entirety.

### 15.1 Experiment 1: Wet foam, 2 seconds application in both rooms

All data obtained from experiment 1 are presented in figure A 1 - A 8 below.



Figure A 1. Temperature as a function of time for X1, experiment 1



Figure A 2. Temperature as a function of time for X2, experiment 1



Figure A 3. Temperature as a function of time for X3, experiment 1



Figure A 4. Rate of change in temperature as a function of time for X3, experiment 1





Figure A 5. Temperature as a function of time for X4, experiment 1



Figure A 6. Rate of change in temperature as a function of time for X4, experiment 1



Figure A 7. Temperature as a function of time for X5, experiment 1



Figure A 8. Temperature as a function of time for o1-4, experiment 1



Figure A 9. Temperature as a function of time for all thermocouples in experiment 1



15.2 Experiment 2: Wet foam, 2 seconds application in both rooms

All data obtained from experiment 2 are presented in figure A 9 – A 18 below.

Figure A 10. Temperature as a function of time for X1, experiment 2



Figure A 11. Temperature as a function of time for X2, experiment 2



Figure A 12. Temperature as a function of time for X3, experiment 2



Figure A 13. Rate of change in temperature as a function of time for X3, experiment 2



Figure A 14. Temperature as a function of time for X4, experiment 2



Figure A 15. Rate of change in temperature as a function of time for X4, experiment 2



Figure A 16. Temperature as a function of time for X5, experiment 2



Figure A 17. Temperature as a function of time for o1-4, experiment 2



Figure A 18. Temperature as a function of time for all thermocouples in experiment 2

# 15.3 Experiment 3: Wet foam, 4 seconds application in both rooms

All data obtained from experiment 3 are presented in figure A 19 - A 27 below.



Figure A 19. Temperature as a function of time for X1, experiment 3



Figure A 20. Temperature as a function of time for X2, experiment 3



Figure A 21. Temperature as a function of time for X3, experiment 3



Figure A 22. Rate of change in temperature as a function of time for X3, experiment 3



Figure A 23. Temperature as a function of time for X4, experiment 3



Figure A 24. Rate of change in temperature as a function of time for X4, experiment 3



Figure A 25. Temperature as a function of time for X5, experiment 3



Figure A 26. Temperature as a function of time for o1-4, experiment 3



Figure A 27. Temperature as a function of time for all thermocouples in experiment 3

## 15.4 Experiment 4: Wet foam, 4 seconds application in both rooms

All data obtained from experiment 4 are presented in figure A 28 – A 36 below.



Figure A 28. Temperature as a function of time for X1, experiment 4



Figure A 29. Temperature as a function of time for X2, experiment 4


Figure A 30. Temperature as a function of time for X3, experiment 4



Figure A 31. Rate of change in temperature as a function of time for X3, experiment 4



Figure A 32. Temperature as a function of time for X4, experiment 4



Figure A 33. Rate of change in temperature as a function of time for X4, experiment 4





Figure A 34. Temperature as a function of time for X5, experiment 4



Figure A 35. Temperature as a function of time for o1-4, experiment 4



Figure A 36. Temperature as a function of time for all thermocouples in experiment 4

**15.5 Experiment 5: Wet foam, 4 seconds application in the second room** All data obtained from experiment 5 are presented in figure A 37 – A 45 below.



Figure A 37. Temperature as a function of time for X1, experiment 5



Figure A 38. Temperature as a function of time for X2, experiment 5



Figure A 39. Temperature as a function of time for X3, experiment 5



Figure A 40. Rate of change in temperature as a function of time for X3, experiment 5



Figure A 41. Temperature as a function of time for X4, experiment 5



Figure A 42. Rate of change in temperature as a function of time for X4, experiment 5



Figure A 43. Temperature as a function of time for X5, experiment 5



Figure A 44. Temperature as a function of time for o1-4, experiment 5



Figure A 45. Temperature as a function of time for all thermocouples in experiment 5

## 15.6 Experiment 6: Wet foam, 2 seconds application in both rooms

All data obtained from experiment 6 are presented in figure A 46 – A 54 below.



Figure A 46. Temperature as a function of time for X1, experiment 6



Figure A 47. Temperature as a function of time for X2, experiment 6



Figure A 48. Temperature as a function of time for X3, experiment 6



Figure A 49. Rate of change in temperature as a function of time for X3, experiment 6



Figure A 50. Temperature as a function of time for X4, experiment 6



Figure A 51. Rate of change in temperature as a function of time for X4, experiment 6



Figure A 52. Temperature as a function of time for X5, experiment 6



Figure A 53. Temperature as a function of time for o1-4, experiment 6



Figure A 54. Temperature as a function of time for all thermocouples in experiment 6

15.7 Experiment 7: Wet foam, 4 seconds application in the second room

All data obtained from experiment 7 are presented in figure A 55 – A 63 below.



Figure A 55. Temperature as a function of time for X1, experiment 7



Figure A 56. Temperature as a function of time for X2, experiment 7



Figure A 57. Temperature as a function of time for X3, experiment 7



Figure A 58. Rate of change in temperature as a function of time for X3, experiment 7



Figure A 59. Temperature as a function of time for X4, experiment 7



Figure A 60. Rate of change in temperature as a function of time for X4, experiment 7



Figure A 61. Temperature as a function of time for X5, experiment 7



Figure A 62. Temperature as a function of time for o1-4, experiment 7



Figure A 63. Temperature as a function of time for all thermocouples in experiment 7

## 15.8 Experiment 8: Dry foam, 5 seconds application in both rooms

All data obtained from experiment 8 are presented in figure A 64 – A 72 below.



Figure A 64. Temperature as a function of time for X1, experiment 8



Figure A 65. Temperature as a function of time for X2, experiment 8



Figure A 66. Temperature as a function of time for X3, experiment 8



Figure A 67. Rate of change in temperature as a function of time for X3, experiment 8



Figure A 68. Temperature as a function of time for X4, experiment 8



Figure A 69. Rate of change in temperature as a function of time for X4, experiment 8



Figure A 70. Temperature as a function of time for X5, experiment 8



Figure A 71. Temperature as a function of time for o1-4, experiment 8



Figure A 72. Temperature as a function of time for all thermocouples experiment 8

## 15.9 Experiment 9: Dry foam, 5 seconds application in both rooms

All data obtained from experiment 9 are presented in figure A 73 – A 81 below.



Figure A 73. Temperature as a function of time for X1, experiment 9



Figure A 74. Temperature as a function of time for X2, experiment 9



Figure A 75. Temperature as a function of time for X3, experiment 9



Figure A 76. Rate of change in temperature as a function of time for X3, experiment 9



Figure A 77. Temperature as a function of time for X4, experiment 9



Figure A 78. Rate of change in temperature as a function of time for X4, experiment 9



Figure A 79. Temperature as a function of time for X5, experiment 9



Figure A 80. Temperature as a function of time for o1-4, experiment 9



Figure A 81. Temperature as a function of time for all thermocouples in experiment 9

**15.10 Experiment 10: Dry foam, 5 seconds application in both rooms** All data obtained from experiment 10 are presented in figure A 82 – A 90 below.



Figure A 82. Temperature as a function of time for X1, experiment 10



Figure A 83. Temperature as a function of time for X2, experiment 10



Figure A 84. Temperature as a function of time for X3, experiment 10



Figure A 85. Rate of change in temperature as a function of time for X3, experiment 10



Figure A 86. Temperature as a function of time for X4, experiment 10



Figure A 87. Rate of change in temperature as a function of time for X4, experiment 10



Figure A 88. Temperature as a function of time for X5, experiment 10



Figure A 89. Temperature as a function of time for o1-4, experiment 10



Figure A 90. Temperature as a function of time for all thermocouples in experiment 10



**15.11 Experiment 11: Water, 2 seconds application in both rooms** All data obtained from experiment 11 are presented in figure A 91 – A 99 below.

Figure A 91. Temperature as a function of time for X1, experiment 11



Figure A 92. Temperature as a function of time for X2, experiment 11



Figure A 93. Temperature as a function of time for X3, experiment 11



Figure A 94. Rate of change in temperature as a function of time for X3, experiment 11


Figure A 95. Temperature as a function of time for X4, experiment 11



Figure A 96. Rate of change in temperature as a function of time for X4, experiment 11



Figure A 97. Temperature as a function of time for X5, experiment 11



Figure A 98. Temperature as a function of time for o1-4, experiment 11



Figure A 99. Temperature as a function of time for all thermocouples in experiment 11





X2a X2b X2c X2d Temperature [°C] Time [s]

Figure A 100. Temperature as a function of time for X1, experiment 12

Figure A 101. Temperature as a function of time for X2, experiment 12



Figure A 102. Temperature as a function of time for X3, experiment 12



Figure A 103. Rate of change in temperature as a function of time for X3, experiment 12



Figure A 104. Temperature as a function of time for X4, experiment 12



Figure A 105. Rate of change in temperature as a function of time for X4, experiment 12



Figure A 106. Temperature as a function of time for X5, experiment 12



Figure A 107. Temperature as a function of time for o1-4, experiment 12



Figure A 108. Temperature as a function of time for all thermocouples in experiment 12

# 16 Appendix B - Calculations

This appendix contains all the executed calculations.

### **16.1 Thermal Diffusivity**

The thermal diffusivity for water is derived from equation 17 in chapter 1-10 with values from table B.4 in appendix B from the SFPE handbook (DiNenno, et al., 2002). Used values are given in Table 26 below.

$$\alpha = \frac{k}{\rho * c_p} = \frac{0.604}{997.4 * 4.179 * 10^3} \approx 1.45 * 10^{-7} \ m^2/s$$

Equation 1

Table 26. Values needed for calculation of thermal diffusivity

		Value @ T=21.11 °C
k	thermal conductivity	0.604 [W/(m°C)]
ρ	density	997.4 [kg/m <sup>3</sup> ]
$c_p$	specific heat	4.179*10 <sup>3</sup> [J/(kg°C)]

#### 16.2 Heat release rate

The heat release rate of the heptane pool fire in the gas-cooling experiments is calculated using equations 2-4 below. The data presented in table 27 is taken from Enclosure Fire Dynamics (Karlsson & Quintiere, 2000) except the assumption that the combustion efficiency is 0.7, a common assumption for fuels that produce sooty flames, and the pool diameter.

Table 27. Values needed for calculation of the heat release rate

		Value
ṁ″	Free burn mass loss rate	$[kg/(m^2s)]$
$\dot{m}_{\infty}^{\prime\prime}$	Material specific data	0.101 [kg/(m <sup>2</sup> s)]
kβ	Material specific data	$1.1 \ [m^{-1}]$
$\Delta H_c$	Heat release rate	44.6 [MJ/kg]
χ	Combustion efficiency	0.7 [-]
$\mathcal{D}$	Pool diameter	0.8 [m]

First, the horizontal burning area is calculated with equation 2:

$$A_f = \pi * r^2 = \pi * \left(\frac{0.8}{2}\right)^2 \approx 0.503 \ m^2$$
 Equation 2

The free burn mass loss rate is calculated with equation 3:

$$\dot{m}^{\prime\prime} = \dot{m}^{\prime\prime}_{\infty} * \left(1 - e^{- \hbar \beta * \mathcal{D}}\right) = 0.101 * (1 - e^{-1.1 * 0.8}) \approx 0.059 \, kg/(m^2 s) \text{ Equation 3}$$

The heat release rate is given by equation 4:

$$\dot{Q} = A_f * \dot{m}'' * \chi * \Delta H_c = 0.503 * 0.059 * 0.7 * 44.6 \approx 0.927 MW$$
 Equation 4

## 16.3 Statistical analysis

The data gathered from the experiments were investigated using statistical methods, to determine whether the difference in gas-cooling effects were statistically significant or not. The first step was to quantify the collected data and decide how large the change in temperature was in each measuring point. This was achieved by examining the graphs and the results are presented in table B 1 below.

	Tomporatura difforence [°C]											
					Temper			<u> </u>				
TC	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9	Exp. 10	Exp. 11	Exp. 12
X4d	-8.3	-26.8	-19.7	-17.2	-8.9	-29.9	N/A	-13.5	-11.3	-7.5	-49.9	-42.5
X4c	-14.6	-18.3	-25.4	-21.7	-10.4	-13.7	N/A	-23.7	-15.1	-9.4	-39.6	-37.8
X4b	5.4	16.8	-41.0	N/A	8.5	7.4	N/A	-26.7	28.6	N/A	-3.7	N/A
X4a	4.9	6.6	N/A	N/A	N/A	5.9	N/A	N/A	N/A	N/A	17.2	24.2
X3d	-162.2	-55.6	-23.2	-78.5	-44.1	-26.6	-104.3	-53.1	-5.3	-154.8	-140.5	-49.5
X3c	-21.6	-94.4	-22.6	-35.2	-37.4	-61.8	-40.1	-11.5	4.1	-35.8	-140.6	-44.4
X3b	61.5	38.2	N/A	-27.3	-22.0	26.5	-60.2	-11.0	18.8	7.8	-76.5	35.7
X3a	11.6	6.0	4.5	11.1	5.0	15.7	20.7	N/A	6.3	-25.5	-7.8	37.8

Table B 1. Temperature difference in the X3 and X4 TCTs from all experiments

These differences in temperature where then divided by the total amount of water applied inside each room, to enable a fair comparison between the two CAFs and water. The amount of water added to each room is shown in table B 2 below and the results of the calculations are shown in table B 3.

Experiment	Day	Extinguishing agent	Intended Application time [s]	Real application time, room 1 [s]	Real application time, room 2 [s]	Amount of water applied in room 1 [1]	Amount of water applied in room 2 [1]
1	1	Wet foam	2	2	2	4,4	4,4
2	1	Wet foam	2	3	4	6,6	8,8
3	1	Wet foam	4	4*	7	8,8*	15,4
4	1	Wet foam	4	4	5	8,8	11
5	1	Wet foam	4	0	5	0	11
6	2	Wet foam	2	2*	3	4,4*	6,6
7	2	Wet foam	4	0	5	0	11
8	2	Dry foam	5	6	7	5,4	6,3
9	2	Dry foam	5	5	7	4,5	6,3
10	2	Dry foam	5	0	5	0	4,5
11	3	Water	2	2	2	3,6	3,6
12	3	Water	1	1	1	1,8	1,8

Table B 2. Table showing the amount of water applied inside of each room in all experiments

\*Some of the applied foam bounced of the doorpost before entering the first room, see figure 42.

Table B 3. The temperature difference in the X3 and X4	4 TCTs per liter of water applied in each experiment
--	--

	Temperature difference per liter of water applied [°C/l]											
TC	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9	Exp. 10	Exp. 11	Exp. 12
X4d	-1.9	-4.1	-2.2	-2.0	N/A	-6.8	N/A	-2.5	-2.5	N/A	-13.9	-23.6
X4c	-3.3	-2.8	-2.9	-2.5	N/A	-3.1	N/A	-4.4	-3.4	N/A	-11.0	-21.0
X4b	1.2	2.5	-4.7	N/A	N/A	1.7	N/A	-4.9	6.3	N/A	-1.0	N/A
X4a	1.1	1.0	N/A	N/A	N/A	1.3	N/A	N/A	N/A	N/A	4.8	13.4
X3d	-36.9	-6.3	-1.5	-7.1	-4.0	-4.0	-9.5	-8.4	-0.8	-34.4	-39.0	-27.5
X3c	-4.9	-10.7	-1.5	-3.2	-3.4	-9.4	-3.6	-1.8	0.6	-7.9	-39.1	-24.7
X3b	14.0	4.3	N/A	-2.5	-2.0	4.0	-5.5	-1.7	3.0	1.7	-21.3	19.8
X3a	2.6	0.7	0.3	1.0	0.5	2.4	1.9	N/A	1.0	-5.7	-2.2	21.0

These comparable values are used to find the arithmetic mean value for each of the extinguishing agents. The mean values are presented in table B 4 below.

Table B 4. The mean change in temperature per liter of water applied for the X3 and X4 TCTs

	Mean change in temperature per liter of water applied [°C/l]					
Thermocouple	Wet foam	Dry foam	Water			
X4d	-3,39	-2,50	-18,74			
X4c	-2,91	-3,88	-16,00			
X4b	0,16	0,70	-0,51			
X4a	0,69	0,00	9,11			
X3d	-9,91	-14,55	-33,26			
X3c	-5,24	-3,04	-31,86			
X3b	1,77	1,00	-0,71			
X3a	1,33	-1,56	9,41			

To account for the extreme values recorded when a thermocouple was hit by foam, another set of arithmetic mean values are calculated, where these extreme values are left out. The measurements that were disregarded are presented in table B 5, and the new arithmetic mean values are presented in table B 6.

#### Appendix B - Calculations

Table B 5. Table showing the measurements disregarded as direct hits

Disregarded measurements				
Experiment	Thermocouple(-s)			
1	X3d			
2	X3c			
3	X4b			
10	X3a, X3d			

Table B 6. The mean change in temperature per liter of water applied, disregarding some measurements

Mean change in temperature per liter of water applied [°C/l						
Thermocouple	Wet foam	Dry foam	Water			
X4d	-3,39	-2,50	-18,74			
X4c	-2,91	-3,88	-16,00			
X4b	1,36	0,70	-0,51			
X4a	0,69	0,00	9,11			
X3d	-5,41	-4,63	-33,26			
X3c	-4,33	-3,04	-31,86			
X3b	1,77	1,00	-0,71			
X3a	1,33	0,50	9,41			

The mean values calculated for the different thermocouples and extinguishing agents indicate that there is in fact a difference in efficiency between water and CAF. To determine whether the difference is statistically significant, a Mann-Whitney test is performed using the statistical program SPSS, developed by IBM. This test is used to compare two independent samples with too few observations to assume a normal distribution. The test will only be conducted for wet CAF and water since a comparison between dry CAF and water would be based on too few observations.

The test is based on a null hypothesis stating that there is no difference between the two samples. The results are given as p-values which state the probability of the null hypothesis being dismissed even though it is true. The one tailed p-value shows the probability of water not being more efficient than CAF, while the two tailed p-value gives the probability of there being no difference between the samples. Since water seems to be more efficient in these experiments the one sided p-value is of the biggest importance. The null hypothesis can only be dismissed if p<0.05, i.e. there is a 95% probability that the null hypothesis is not true (Körner & Wahlgren, 2006).

Several tests are conducted to see if there is a statistically significant difference between different set of samples. The conducted tests are displayed together with the results in table B 7 below.

Table B 7. Results of statistical analysis

Null hypothesis	one tailed p-value	two tailed p-value	one tailed p-value < 0.05
X3c (CAF) = X3c (water)	0.028	0.056	Yes
$X3c (CAF) = X3c (water)^*$	0.036	0.071	Yes
X3d (CAF) = X3d (water)	0.056	0.111	No
$X3d (CAF) = X3d (water)^*$	0.036	0.071	Yes
X3c+d (CAF) = $X3c+d$ (water)	0.001	0.003	Yes
X3c+d (CAF) = $X3c+d$ (water)*	0.001	0.001	Yes
X4c (CAF) = X4c (water)	0.048	0.095	Yes
X4d (CAF) = X4d (water)	0.048	0.095	Yes
X4c+d (CAF) = $X4c+d$ (water)	0.001	0.002	Yes

\* Tests disregarding the measurements caused by direct hits of CAF, see table B 5