

Cooling experiments with water and foam

**Study into flue-gas cooling and fire extinction when deploying CAF, Firedos,
high pressure and low pressure hose lines in offensive interior fire fighting
operations**

Version: 10 september 2013 (FINAL)

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Title:	Cooling experiments with water and foam. A research into flue gas cooling and fire extinction in deploying CAF, Firedos, high pressure and low pressure hose lines in offensive interior fire fighting operations
Date:	10 september 2013
Status:	Final report
Project number:	421N1206
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Management summary

Many fire services are currently in search of the most appropriate extinguishants. Some fire services have switched to foam-forming systems like Firedos (FD) or Compressed Air Foam Systems (CAFS). There is in fire-fighting circles and in literature much discussion about the effectiveness and possibilities of applying low-pressure extinguishants in relation with these foam-forming systems. As to the CAFS, there are opinions that this extinguishing system is not suitable for flue-gas cooling, though others say that this must be possible depending on the tactics. On the other hand, some persons are convinced that the same extinguishing power and flue-gas cooling can be achieved with low-pressure or high-pressure extinguishants, or that they may even do better. In addition, there is the need for insight into how the foam-forming systems relate to each other. Two fire service regions, Noord-Holland Noord and Groningen, contacted the Fire Academy and requested that a study be done into foam systems. Other regions joined the study.

The study focused on both the flue-gas cooling capability and the extinguishing capability of Firedos, CAF, high-pressure and low-pressure water. A prepared L-shaped container was used in a test rig with the scenario of a living-room fire and was partly fitted with a brick wall, thermocouples and cameras.

In this test, a local fire load of about 2,600 MJ was chosen (about 155 kg of pinewood equivalent) and placed on a surface of about 4 m² in the living-room fire scenario. The fire load consisted of wood and polyether foam. For each system, a combined experiment of flue-gas cooling with an extinguishing medium was carried out five times during which the seat of the fire could not be touched during the flue gas cooling. The activity was carried out in accordance with a standardised method. For each system, experienced fire fighters skilled in operating the system were deployed. Temperatures, times and quantities of water and foam used, visual images and other parameters were registered. For each research question, the results of the research are given below.

1. What is known in the literature about the effectiveness of foaming agents regarding flue-gas cooling and fire extinction as compared with high-pressure and low-pressure mediums?

Various studies showed that the CAF has less capability to cool flue gases than water. The only study, as far as we could find at this moment, that differed from this, showed that not a factual flue-gas cooling but a fire extinction was performed in the test, and that this led to a decline in the flue-gas temperature.

The flue-gas cooling capacity of CAFS was not only lower when bringing the agent in the flue-gas layer but also when it was applied to walls and ceilings. However, applying and covering with CAF lead to the prevention of pyrolysis of combustible materials, and was in fact not flue-gas cooling but only preventing an increase in combustible flue gasses in the space.

It appears that CAF has a greater effectiveness than water when the creation of a knockdown and prevention of re-ignition are involved.

Based on the results of literature searches it seems that carrying out an offensive interior fire attack with CAFS does ensure a quick knockdown, but that this can be very risky due to the limited flue gas cooling capability and the ensuing presence of combustible hot flue gasses. This opinion is subscribed by the working party for alternative extinguishing systems "the WAB Werkgroep Alternatieve Blussystemen"¹ However, findings from earlier practical research, as far as we could find at this

¹ Network for repression of Security Region Noord-Holland Noord

moment, do not give sufficient insight into the effectiveness for applying CAF for flue-gas cooling in the way it is applied by some Fire Services in the Netherlands. Moreover, the effectiveness of flue-gas cooling with high pressure and low pressure and Firedos as applied by the Dutch fire service has hardly been researched in an experimental setting and described in an imitable way.

2. What is the effectiveness of foam-forming systems CAF and Firedos, and high pressure and low pressure when deployed in an offensive attack of a living-room fire?

Tests showed that the temperature trend for the entire flue-gas cooling (at TK 5) with low pressure resulted in the highest decrease. High pressure and Firedos have a comparable hose line and a less cooling effect on the temperature in the flue gases. CAF showed the least cooling of flue gases. When CAF is used, the temperature decreases 41 °C after two series of flue gas cooling whereas the temperature decreases 138 °C with low-pressure. Moreover, the cooling effect continues during the flue gas cooling, particularly with low-pressure, also when meanwhile no pulses are given and new hot flue gases are supplied. To a lesser extent, this also applies to FD and high-pressure but hardly to CAF.

When the two series of flue gas cooling are examined separately, it appears from the temperature trend line in the first series that FD cools flue gases the least. Low-pressure and high-pressure cool flue gases the best. A fall in flue gas temperature can also be seen when using CAF.

In the second series of flue gas cooling, we can see the best results again with low-pressure both regarding the other systems and regarding the first series of flue gas cooling. Noticeable is that CAF then shows the worst result with a total temperature fall of 20 °C. Another noticeable point is that FD scores worse in relation to CAF (and low-pressure and high-pressure agents) in the first series of flue-gas cooling whereas in the second series, and further away in the container, CAF hardly results in a cooling of the flue gases, and FD scores better (nearly as good as high pressure). The relatively positive effect with CAF in the first series was probably caused by a magnet effect of the CAFS by which cold environmental air is brought into the container. A possible explanation why Firedos had little effect the first time and appears to be effective in the second series is that the mix in the beginning was different from the second series.

When at the same moment the temperature trend in the entire container is examined, it strikes that with both high pressure and low pressure temperatures both in front of and behind the fire-fighting crew decline during flue-gas cooling. With FD there is only effect in the direct environment. With the CAFS we can see a short-lived decline in front of the fire-fighters, which is followed by an increase in temperature both in front of and behind the fire-fighting crew.

When the cooling capability is compared with the use of water, it appears that the flue-gas cooling capability per litre of used water is highest with low pressure. The foam-forming systems cool the least per used litre of water, and the CAFS scores worst. When comparing the cooling capability with the volume of extinguishing agent used (water, or water with air and foam) the difference between the systems using only water and the foam-forming systems is even greater.

Sudden combustions of the flue-gas layer were seen in two of the five tests with CAFS and in the extra test carried out with Firedos 0.3%. As these combustions occurred in some of the experiments with CAF and Firedos, it is not certain whether this is caused by flue-gas cooling or by extinguishing with foam, and further investigation is needed.

Though the test carried out with a valve on the CAF jet nozzle shows a better flue-gas cooling than without valve, the test was carried out only once and conclusions cannot be drawn. The same applies to the additional test with 0.3% instead of 3% extra mix for Firedos: the result appears to be better, but no reliable statements can be made about this.

In conclusion, it can be argued that water-based extinguishing systems are more capable of flue-gas cooling than the foam-forming systems, when applied in the same way as in this investigation. CAF, in the way we applied it (short shots into the smoke layer) only cools in front of the space when the attack is on the outside, presumably by the supply of cold environmental air as a result of which a form of repressive ventilation occurs. CAF applied in this way is incapable of lowering the temperature of the flue gases during an interior attack further in the container to such a degree that this would lead to safe circumstances of an interior fire attack. This applies to a lesser degree to Firedos, which does cool further in the container but only in the direct environment. Interior fire attacks with low pressure appear to be the most effective and safe for flue-gas cooling, even if compared with water use of high pressure. We emphasise that it can not be concluded from our experiments that other ways of application of DLS than we investigated, can not lead to better results, because we did only investigate one manner of application.

3. What is the effectiveness of the foam-forming systems like CAF and Firedos, high pressure and low pressure regarding the extinguishing capability in an offensive interior attack in a living-room fire?

Both high pressure and CAF realised the quickest knockdown whereby high pressure used the least water. Firedos needed the longest time to create a knockdown. However, the average duration until the first re-ignition was highest with Firedos although the tests showed much variation. This applies to a lesser degree to low pressure. Though CAF created a quicker knockdown, there is a relatively quick re-ignition within the selected research set-up, whereby almost identical results were found between the tests.

As to temperature decrease, extinguishing with Firedos is most effective (irrespective of use) in the first knockdown. Extinguishing with low pressure and high pressure gives a better average temperature decline than with CAF, but less than with FD. High pressure and low pressure score best when compared with water use and extinguishing agent. The temperature decrease with low pressure and FD in the container is steady. A declining line can also be seen with CAF and high pressure but it is noteworthy that the temperature shows peaks almost immediately after the temperature decrease and this partly undoes the cooling effect of the extinguishing. This is stronger with CAF than with high pressure.

In conclusion, it can be argued that FD may need the longest time for the knockdown, it is then very effective in reducing the temperature but uses also the most extinguishing agent. Comparing the use, high pressure and low pressure score best for extinguishing. CAF scores good in creating a quick knockdown but gives a limited temperature decline in the space (38 °C) and there is a temperature increase between the shots.

Other findings

During setting up and performing the test, it appeared that there is no unambiguous way of deploying foam-forming systems. The way of deploying CAF and the mix percentage of Firedos vary much between the various fire service regions. The way of deployment is often based on deployment techniques in other countries with other ways of constructions and materials. In meanwhile, it is known, that the way DLS was applied

in this research, is not advised by the suppliant and the manufacturer. They advise to apply pulses of 3-5 seconds, while putting foam on the walls and the ceilings.

Key question: where the flue-gas cooling effect and the extinguishing power in an offensive interior fire attack are concerned, how does the effectiveness of CAF and Firedos relate to one another and to low-pressure and high-pressure?

Literature searches and practical experiments show that flue-gas cooling with CAFS² is little effective and does not lead to a substantial decline in flue-gas temperature when applied in the way we investigated (short shots into the flue-gas layer) especially when used further in the space, in comparison with water-bearing systems. It was observed that the temperature increased and that the flue-gas layer ignited with CAF. In fire-fighting practice, this can lead to dangerous situations. For flue-gas cooling, Firedos 3% appears to be less effective than water. With less extra mix (0.3%) Firedos becomes almost as efficient as high-pressure. Therefore, adding less foam leads to better performance in flue-gas cooling. In the fire attack, CAF does create a knockdown just as quickly as high pressure, but the temperature remains high near the seat of the fire. This carries the risk of re-ignition of the environment. In the fire attack, Firedos gives the greatest temperature decline and of all tested systems has the longest effect in preventing re-ignition. However, Firedos is less effective in flue-gas cooling than water-bearing systems.

Taken everything into consideration it appears that the traditional interior attack with low pressure is the safest. This is also possible with high pressure, though to a lesser degree. Given the poor flue-gas cooling capability of CAF (applied in the way we investigated, i.e. short shots into the flue-gas layer) and the limited flue-gas cooling effect of FD, the interior attack with only one of the foam-forming systems may lead to hazardous situations. We emphasise that this conclusion can only be drawn for the way we applied DLS.

Recommendations

Based on the study results, the following recommendations can be given:

1. For a safe interior fire attack with one of the foam-forming systems applied in the way described in this report, it is necessary to combine the attack with another system that cools flue-gases effectively.
2. Ensure an unambiguous and effective way of using CAF and Firedos based on practical research, taking the usual way of construction in the Netherlands into account.
3. Given the results, consider whether low pressure should be part of the standard technique to be used for an interior attack more than currently is the case.
4. In addition to this research, study the effectiveness of the investigated systems in other types of fire, applying other methods, and under other circumstances.

² With the tested attack tactics and in situations in the Netherlands

Preface

This is the report of the comparative study into various extinguishing agents. The study was carried out by the Fire Academy in close cooperation with various fire services in the country.

The key question in this study is how foam-forming CAF and Firedos systems are related to water where the effectiveness of flue-gas cooling and extinguishing is concerned. The scenario was an interior fire in a dwelling in which the seat of the fire could only be reached by an attack route leading through a space where hot flue-gases were present.

This study was carried out at the request of the regions Noord-Holland Noord and Groningen. It is included as first phase of the research programme for the purpose of the fire service doctrine that consists of 4 phases in total.

The study could be carried out thanks to subsidies granted by the Ministry of Security and Justice and the Scientific Council of Fire Services (Wetenschappelijke Raad Brandweer), and was co-financed by:

- TRONED for supplying the test space and supporting staff
- The Fire Service regions, which also made experts and equipment available. They are:
 - Amsterdam- Amstelland
 - Utrecht
 - Zaanstreek-waterland
 - Twente
 - Limburg-Zuid
 - Brabant Noord
 - Brabant Zuidoost
 - Midden and West Brabant
 - Haaglanden
 - Noord-Holland Noord
 - Groningen
- Fire Service Academy (IFV - Institute for Physical Safety).

I am overjoyed that, after the first cautious practical experiments regarding fire, fire development and fire combat, the Dutch Fire Services (Brandweer Nederland) took another step on the path of acquiring robust and reliable knowledge for the fire service. This study is unique in the Netherlands. Carrying out practical experiments also appears to be a learning process in which we gain more and more experience. Meanwhile, the next phase starts in May and I hope that many researches will follow in which we cooperate with foreign researchers and use and involve the expertise available in the Netherlands.

I would like to thank the financiers of this study for their support for being able to carry out, I hope, permanent knowledge development of, with and for the benefit of the fire-fighting world. Knowledge development is a must for innovation. I would also like to thank the members of the team of experts. It was a very instructive but also a fun process to set up and carry out the research together, and to draw the conclusions. Skills in connection with science!

I hope you enjoy reading this report.

Ricardo Weewer
Professor of Fire Service Science

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1 Introduction

1.1 Background

Many fire services are currently searching for the most appropriate extinguishing mediums, partly because there is the social need to limit the use of water and partly because there is the need for innovation but also because the market offers and recommends an ever increasing number of fire extinguishers. When considering the costs of equipment and training, various fire services are also faced with the question whether it is possible to have the same effect with the usual foam techniques (such as Firedos) and compressed-air foam (CAF).

Based on their own research, some fire services have already made a decision. Some fire brigades have switched to compressed-air foam (or are planning to do so), and some opted for compressed-air foam instead of or in combination with high pressure.

Not only in fire-fighting circles but also in literature there is much discussion about the effectiveness and applicability of low-pressure and high-pressure fire fighting in relation to new extinguishing agents. Concerning CAF, there are opinions that this extinguishing system is not suitable for flue-gas cooling but others say that it is, depending on the extinguishing technique. On the other hand, some people are convinced that the same extinguishing power and flue-gas cooling can be reached with low pressure or high pressure, or that this is best achieved with water. Others say that low pressure can be used just as well as high pressure, or even better for flue-gas cooling. The available literature does not provide an unambiguous direction to these options.

In addition, there is the need to understand how compressed-air foam is related to another often-used foam system: Firedos.

All in all, there are conflicting statements and questions about the effectiveness of CAFS, Firedos, high pressure and low pressure concerning the capability of cooling flue gases and extinguishing them.

The Noord-Holland Noord and Groningen regions contacted the Fire Academy to request that they carry out research into foam systems together. It related to both the flue-gas cooling capability and the extinguishing capability of CAF and foam-forming agents. Gradually, this request appeared to be on the minds of several regions. It was then decided to carry out a series of experiments in which a number of these systems were to be tested under comparable circumstances.

The set-up of the study was decided in close conjunction with representatives from fire-fighting circles (in this case the participating regions). The results of the study will give independent and factual information that could contribute towards knowledge development for fire-fighting circles and help regions take decisions about investments in extinguishing agents, schooling and training.

Appendix 4 gives as background information a description of what foam is and on what principles the deployment with foam is based.

1.2 Research Questions

This study aims to give insight into the flue-gas cooling effect and extinguishing capability of compressed-air foam (CAF) and added foam (Firedos) in comparison with the standard deployment with high pressure and low pressure, and their relation to one another. The key question of this study is:

Where the flue-gas cooling effect and the extinguishing power are concerned, how does the effectiveness³ of compressed-air foam and Firedos relate to one another in an offensive interior fire attack and how do they relate to low-pressure and high-pressure?

The key question of this study is answered by replying to the following partial questions:

- a. *What is known in literature about the effectiveness of foam-forming systems regarding flue-gas cooling and extinguishing compared to high pressure and low pressure?*
- b. *What is the effectiveness of foam-forming systems CAF and Firedos, high pressure and low pressure regarding flue-gas cooling in an offensive interior attack of a living-room fire?*
- c. *What is the effectiveness of foam-forming systems CAF and Firedos, high pressure and low pressure regarding the extinguishing power in an offensive interior attack of a living-room fire?*

In order to reply to question a, a literature search was done and represented in a separate report. In order to reply to questions b and c, experiments were carried out and presented in this report. The study aims to establish the effectiveness of the various extinguishing agents and to develop knowledge about how an offensive interior attack under fuel-controlled circumstances is.

1.3 Definition

The above-mentioned tactics were studied during the experiments.

All tests were carried out five times. Three extra tests were also carried out; one with CAF with an extra valve on the jet nozzle and two extra tests with Firedos with a lower mix percentage (0.3%). The reason is given further on in the report.

These tests are considered to be bycatch. Where in this report Firedos is mentioned without stating the extra mix percentage, we used 3%.

The tests were carried out in only one test environment with one scenario. This means that the results of the study are only valid for the tested environment and scenario. The scenario had only one seat of fire, which formed the only fire load on the premises. There were no extension possibilities or other materials present than clean pinewood (pallets), foam and three sheets of chipboard. To ignite the seat of the fire, one litre of ignition fluid was used each time.

In the tests only temperatures and temperature trends during cooling of the flue gas and extinguishing the fire were measured. Also monitored were the duration of the knockdown phase and the re-ignition of the fire. "Knockdown" is taken to mean that there are no visible flames any more. The water output for both the cooling of flue gas and extinguishing the fire was also measured. Other parameters like atmospheric humidity and pressure were not measured. The quantity of wood that was factually burned was not measured and the composition of the flue-gases was not analysed.

1.4 Involvement of the fire services

For setting up, implementing and analysing the study, a team of experts was formed to make optimal use of the knowledge and experience that are present on the ground. This

³ With 'effectiveness' is meant the degree to which flue gases are cooled, how quick a knockdown is realised and re-ignition is prevented.

team of experts consisted of a professor of fire-fighting sciences and researchers and experts from the regions involved. The team defined the test protocol, took a constructive approach to the interpretation of the results, and reviewed the draft report.

2 Relevant literature

2.1 Introduction

A number of publications were found in literature related to the effectiveness of cooling and extinguishing with water and foam-forming systems.

Noteworthy in the studied reports is that the circumstances under which the experiments were carried out were always different. This, but also the scanty descriptions of the test circumstances, makes it very difficult to allow comparison and limits the possibility to compare with other experimental studies into flue-gas cooling and the extinguishing capability of foam. The employed tactics are particularly of great importance when making comparisons, as an incorrect or inefficient extinguishing system or the use of jet nozzle can lead to wrong conclusions about the effectiveness of extinguishing agents in relation to one another. In the Netherlands, a number of fire-fighting services also conducted their own studies into the effectiveness of the various fire-extinguishing agents and equipment. However, their reports are often lacking, they often do not describe under what circumstances these studies took place and an objective data registration (including measuring temperatures was often omitted).

This survey mainly discusses literature with a scientific character in which the test circumstances are described well. Appendix 1 lists all studied literature. At this time, two large studies with the same purpose are being conducted in other countries, but results of these studies have not been released yet⁴.

For various aspects of fire fighting, compressed air foam (CAF) and Firedos (FD) are compared with the use of water with high-pressure or low-pressure extinguishing systems. The issue is the flue-gas cooling and extinguishing capability.

2.2 The flue-gas cooling capability of fire-fighting foam

Flue-gas cooling by CAF is done by applying hot surfaces in the flue-gas layer. In other words, cooling occurs indirectly by evaporation of water in the foam. This takes more time than evaporation of water, because water is directly inserted into the flue-gas layer. Grimwood (2008) therefore claims that CAF can only be effective in an interior fire attack in the post-flashover stage, when the flashover has taken place and most of the present flue gases are burnt.

It appears from practical tests in Sweden (Folkesson and Millbourn, 2008; Lyckeback and Öhrn, 2012 ;) that flue-gas cooling with CAF is less effective than flue-gas cooling with water (WAB, 2013). Another study (Zhang, 2011), in which researchers claimed to have found a positive effect of CAF on flue-gas cooling, shows that the selected attack strategy was primarily focused on extinguishing the fire.

This is also confirmed in a study into the flue-gas cooling and extinguishing capability of CAF in an offensive exterior fire attack (Dikkenberg & Groenewegen, 2012).

The four above-mentioned experiments on flue-gas cooling capabilities of foam are briefly explained below.

In a practical study in 2008, the University of Lund (Folkesson & Milbourn, 2008) examined the flue-gas cooling activities of six different extinguishing systems, namely OneSeven, CCS Cobra, DSPA, Firexpress, Oertzen and a small powder extinguisher. The systems were tested during a fully developed living-room fire in a non-combustible environment (a steel container measuring 12m x 2.4m). The flue-gas cooling took place

⁴ Capabilities and limitations of compressed air foam systems (CAFS) for structural fire fighting (VS, The Fire Protection research Agency) and a PROMESIS study in France conducted by GIMAEX and CEA.

by an extinguishing agent from outside brought into the container via an opening in the window. A wall was placed about halfway in the container so the container was split into a front space and a fire space. The arrangement was such that it was not possible to reach the seat of the fire with an extinguishing agent during the flue-gas cooling. The practical study had two tests with 0.3% One Seven H300 A-foam⁵. The report did not describe the exact way the flue-gas cooling was carried out. It was found in the tests that flue-gas cooling with the OneSeven system appeared to go slower than cooling with water, but offered a better protection against re-ignition of the seat of the fire than other tested systems.

In a second study conducted by the University of Lund (Lyckeback & Öhrn, 2012), the flue-gas cooling activity of the OneSeven system and a high-pressure system were examined. Two series of experiments were performed. In the first series of experiments, the systems were tested in a non-combustible test environment. A total of 10 tests were done with 0.3% One Seven C1-100 T A foam and with 0.3% One Seven C1-200 BR A foam of which 7 tests were done with wet foam and 3 tests with dry foam. The foam was sprayed on the ceiling and a wall in two phases, both during 1-5 seconds, first in a space next to the room where the fire was, and then in the space with the fire where the foam-covered wall was opposite the seat of the fire. The study showed that the One Seven system can realise a flue-gas cooling by applying a foam layer on hot surfaces, but when measured in time, it was considerably less effective if compared with water (high pressure). Wet foam appeared to be more suitable for cooling flue gases than dry foam. It further appeared that, measured in time, compressed-air foam was more effective when sprayed on the ceiling than when applied to the walls. The second series of tests was done in a combustible environment (wooden construction) and was focussed on the extinguishing capability of the two systems. Each system was tested once. The results suggest that extinguishing is possible with compressed-air foam at a safe distance, but that flue-gas cooling is possible only to a limited extent and does less well than with water. Lyckeback and Öhrn therefore concluded that effective use of CAF is possible by attacking the fire from a compartment next to the fire compartment or by keeping the fire compartment intact, if flue gases have not spread too much in the compartment where the jet nozzle is placed. Due to its large throw length of 15 to 20 metres, CAF seems suitable for this tactic (the defensive interior attack), according to Lyckeback and Öhrn. Given that flue-gas cooling is an essential part of procedure in an offensive interior attack, CAF seems less suitable than water.

Contrary to the Swedish studies, Zhang (Zhang, 2011) claims that the CAF system is more effective than water mist. The tested compressed-air foam system is a pump with an integrated CAF system with a water supply of no more than 8 litres/min and an air supply of 1,400 litres/min at 7 bars. The test used a 0.5% class A foam (Angus Forexpan S). A comparable test was carried out in a container measuring 12m x 2.4m with fuel-controlled fire in which flue-gas cooling was started at a temperature of 350°C. The fire fighters entered the burning space and 'attacked the fire'. Though the title⁶ of the publication suggests that the study was done into flue-gas cooling, on the basis of the description of the study there are strong indications that it was a fire extinction in which flue-gas temperature was measured during the extinguishing activities. The author claims in his conclusion that there was a quick flue-gas cooling when applying the compressed-air foam system as a result of which the flashover conditions were undone and that the fire fighters could stay in the fire space until the seat of the fire was

⁵ The One Seven 300T system uses two air cylinders each with a pressure of 300 bars. With a closed nozzle, the pressure of the cylinders ensures 8 bar in the hose; with an open nozzle, a nozzle pressure of 1 bar is achieved. With an open nozzle and a water supply of 42 litres/min, 320 litre of foam is produced. The CAF system forms a very homogenous foam and this means that the foam is very stable and of good quality. The system can be used for surface cooling both in class A and class B fires. For class A foam, the mixing ratio is 0.3% and for class B foam 0.5% and for alcohol-resistant B foam 0.6%. For creating wet foam, the expansion rate is 1:7 and for creating dry foam, the expansion rate is 1:21.

⁶ Assessment of gas cooling capabilities of Compressed Air Foam Systems in fuel- and ventilation controlled compartment fires.

extinguished. When water mist was used, the fire fighters had to retreat due to decreased vision, high temperature and steam formation during the experiments. However, the decline in flue-gas temperature appears to be caused mainly by fire knockdown as a result of which the supply of new hot flue gases was avoided. The report does not give any indication that CAF has a better flue-gas cooling effect than water if only the cooling of flue gases is concerned.

In the comparative study into the flue-gas cooling and extinguishing capabilities of various tactics for the offensive exterior attacks (Dikkenberg and Groenewegen, 2012), the researchers conclude that exterior attacks with CAF is not very effective for lowering the temperature of the flue-gas layer.

2.3 Extinguishing capability

A number of studies were conducted into the extinguishing capability of foam systems.

Crampton and Kim (Crampton & Kim, 2009) compared the extinguishing effects of compressed-air foam, regular foam and water. They did extinguishing experiments in a test space of 38 m² with plasterboard walls in which a fire load consisting of wood and a sofa set (5.6MW) was ignited. After the flashover had taken place, the extinguishing activities were started. It was concluded that compressed-air foam created the quickest knockdown and that the addition of a foam-forming agent to water extinguished more quickly than with water only.

As described in section 2.1, Lyckeback and Öhrn, (Lund University, 2012) performed experiments with the flue-gas cooling capability of CAF as compared with water. They made an extensive literature search prior to the test. In various studies (including Tinsley, 2002; Folkesson and Milbourn, 2008; Taylor, 1997; Persson, 2005) the conclusion was drawn that the extinguishing capability of CAF is greater than that of water and that re-ignition takes place later, or not at all.

Richards (2003) also concluded that CAF extinguishes better than water. He indicated that a temperature of 200 °C can be created four times more quickly with 0.2% DLS⁷ (referred to as a knockdown) as compared with water⁸.

The University of Karlsruhe conducted a study into the extinguishing capabilities of One Seven, one of the various kinds of CAF. They concluded that CAF was better than other extinguishing agents in combating the seat of the fire.

In an article on Firetactics.com, Grimwood (2008) gave a literature survey. He, too, concluded from literature that CAF was a more effective extinguishing system than water, but warned that flue gases must also be taken into account in case of an indoor fire attack.

Practical experiments with offensive exterior fire attacks with various extinguishing tactics (Dikkenberg & Groenewegen, 2012) also showed that CAF was better able to create a knockdown than water. In contrast with an attack with water, the experiments showed that there was no re-ignition.

2.4 Other aspects

Water use

CAF evaporates just as quickly as water, Cnossen claimed in his study⁹ into a fire in the Dutch town of Harlingen (Cnossen, 2012, in: WAB, 2013). Less water was needed when

⁷ 0.341m³/min water and 189 litre/sec air

⁸ 0,341 m³/min water

used efficiently and this gave less steam formation. However, the same steam formation ensured more cooling when attacking a fire and this means that it is not per definition more positive (Steunpunt Tunnelveiligheid [Tunnel Safety Support Centre], 2003, in: WAB, 2013). It further appeared that the fire blazed up less quickly with CAF than with water and this makes that an extinguishing action need not be repeated often and that less water is needed (WAB, 2013).

Pyrolysis and heat-insulating capabilities of CAF

Lyckeback and Öhrn (2012, in: WAB, 2013) claimed that CAF gave better prevention than water against radiation of objects and surfaces as it forms a covering layer and penetrates the object and makes combustion stop (Colletti, 2009 and Large, 2002, in: WAB, 2013). This counters pyrolysis, and re-ignition takes place less quickly with CAF (Folkesson and Millbourn, 2008, in: WAB, 2013). This also means that radiation to another object by covering works better when the adjacent object is 'wrapped up'.

Vision

None of the studies dealt with the aspect of 'vision' (WAB, 2013). Based on several interviews with experiential experts in the Netherlands, WAB (2013) states that vision was better than when extinguished with water. It was their experience that more steam was formed using water, whereby vision was obstructed.

Ergonomics

An ergonomic advantage of CAF is the more comfortable manoeuvrability of the hose (WAB, 2013). As the hose is much lighter than, say, a high-pressure hose, it is less tiresome. On the other hand, there is the risk of 'kinking' the hose. Another disadvantage is the diminished visibility of obstacles when much CAF is used, and this increases the risk of injuries as fire fighters cannot see where they go.

Training and fire drills

According to WAB (2013), the system is significantly different from high-pressure or low-pressure systems (water). Even the tactics differ from other systems, e.g. another door procedure or handling the jet hose. Extensive investments must be made in training and drilling. After that, practising will be just as strenuous as other systems.

2.5 Conclusions from literature search

Various studies show that CAF is less capable to cool flue gases than water. The only study deviating from this showed that no factual flue-gas cooling was done during the test, but an extinguishing which lead to a decline in the flue-gas temperature. The flue-gas cooling capability of CAF is not only lower when bringing the agent into the flue-gas layer but also when applying it to ceilings and walls. Applying and covering with CAF lead to prevention of pyrolysis of combustible materials. But this is in fact no flue-gas cooling but only preventing an increase in combustible flue gases in the space. However, it appears that CAF is more effective than water when the creation of a knockdown and the prevention of re-ignition are concerned.

Based on the results of literature search, it appears that the implementation of an offensive interior attack with CAF ensures a quick knockdown, but can be very risky because of the limited flue-gas cooling capability and the presence of combustible hot flue gases. This opinion is endorsed by Werkgroep Alternatieve Blussystemen [Working Party Alternative Extinguishing Systems] (WAB¹⁰). Findings from earlier practical studies, as far we could find at this moment, do not give sufficient insight into the effectiveness of applying compressed-air foam for flue-gas cooling in the ways it is applied in the Netherlands. Moreover, the effectiveness of flue-gas cooling with high-pressure, low-

⁹ The study paid attention to the operation of One-Seven, a compressed- air foam. One-Seven is mainly used to 'wrap up' the building. One-Seven was then used cool off adjacent buildings (defensive exterior attack).

¹⁰ Netwerk Repressie van Veiligheidsregio Noord-Holland Noord [Network Repression of Security Region Noord-Holland Noord].

pressure and Firedos as applied by the Dutch Fire Services have hardly been studied in an experimental setting and described in an imitable way. That is why the Fire Academy conducted a practical study. The following chapters describe the set-up and the results of this practical study.

3 Set-up of the practical study

The study was conducted as an experiment in which two usual components of an offensive exterior attack were examined, namely flue-gas cooling and creating a knockdown. To this end, two foam-forming systems (compressed-air foam system One Seven and high-pressure extra mix system with foam-forming agent Firedos) and low-pressure and high-pressure were examined. Each system was tested five times in a standard scenario and measurements were taken on the basis of a number of parameters. The scenario was a fire in a living room. To measure factually the flue-gas cooling effect, it was important that the extinguishing agent could not reach the seat of the fire during the flue-gas cooling. On that account, the set-up was done in an L-shaped container. This section will go further into the set-up of the study and the performance of the tests.

3.1 Tested extinguishing agents

The tests were conducted with two foam-forming systems. In consultation with the team of experts, two systems were opted for which are used most often in the Netherlands, namely One Seven (compressed-air foam system and Firedos (a high-pressure extra mix system). As standard attack tactic for an interior fire, the high-pressure interior attack was taken as baseline measurement/reference, but the low-pressure interior attack was also included in the study.

The mentioned tactics were tested as an offensive interior attack¹¹. Below is a short description of the tested systems:

1. Compressed-air foam with the OneSeven system¹². Compressed-air foam (CAF) is a built-in system on the hose of the pump vehicle with a separate hose reel and a jet nozzle. With the CAF system, water and 0.4% foam-forming agent¹³ are mixed under a pump pressure of about 8 bars and a jet-nozzle pressure of 8 bars, whereby 133 litres foam per minute is brought into the space via a 25 mm (interior) hose. A foam-forming agent is added to the water via a submixer in the vehicle and air is added with a compressor before the foam mix enters the hose. The mixing process takes place in the hose. Adding air under pressure creates little air bubbles, which makes the foam more stable than foam with larger air bubbles and gives the foam adequate adhesive strength. The foam-forming agent lowers the surface tension and therefore has better penetrating capability than water. The compressor also adds power, which affects the throw length. The throw length is about 20 metres at the start of the extinguishing operation and about 10 metre after stabilisation of the pressure. In this report, the fire attacks with compressed-air foam are abbreviated as CAF.
2. High-pressure added mix system with the Firedos system. Firedos is a foam pump driven by a high-pressure pump. The foam is injected after the high-pressure pump. A regular foam-forming agent is used and a regular high-pressure jet hose that has an extra hose. The throw length is comparable with high-pressure (about 7 metres). Firedos has a covering effect and lowers surface tension. The extra mix regularly used by the regions that conducted the tests is 3%¹⁴. In this report, the deployment with the high-pressure mix system is abbreviated as FD.
3. Water via the high-pressure system. The high-pressure system brings 115 l/min water via a 19 mm (interior) jet hose into the space with a pump pressure of

¹¹ In conformity with the quadrant model.

¹² OneSeven built-in system E2400-PLC.

¹³ Setting of the test vehicle.

¹⁴ At least one region always works with another percentage (0.3%). As there is no univocal agreement about the correct percentage it was decided to adhere to the regular procedure of the regions that cooperated in the test, and that is 3%. An extra test was performed with a mixed-in percentage of 0.3%, see section 8.2.

about 25-30 bar and a jet nozzle pressure of 7 bars. Fire attacks with high-pressure are abbreviated in this report with HP.

4. Water via the low-pressure system. The low-pressure system brings 230 litre/minute water via a 52 mm (interior) jet hose into the space with a pumping pressure of about 7-8 bar and a jet nozzle pressure of 7 bars. Fire attacks with low-pressure are abbreviated in this report with LP.

The table below gives the specifications of the systems that are used.

Table 3.1 Specification of the systems

Extinguishing system	Brand /type of extinguishant	Jet hose	Use and conical angle	Pump pressure	Jet hose pressure	Mixing percentage
CAF	Class A One Seven One Seven of Germany	Regular CAF jet hose	133 l/min, bound jet ¹⁵	8 bar	7 bar	0.4%
FD	Ajax Moussel F15/FP 15	Akron Turbojet Style 1704	115 l/min 30°	27 bar	10 bar	3%
HD	Water	Akron 1711	125 l/min 30°	25 bar	7 bar	n/a
LD	Water	Akron 1720	230 l/min 30-35°	7 bar	7 bar	n/a

3.2 Parameters

During the tests, temperatures are measured, times are registered, water and foam used are recorded and visual images in the interior are assessed.

Temperature

The temperature-related parameters were:

- during the flue-gas cooling: the temperature at the start of the flue-gas cooling, the minimum temperature after the series of flue-gas cooling, the decline in temperature and the temperature trend.
- during extinguishing the fire: the temperature trend.

Twelve thermocouples were used for registering the temperatures and affixed on 2 levels and in various places in the construction. Figure 1 shows the location of the thermocouples. By placing the thermocouples in various places in the flow pattern of the flue-gas layer it was possible to establish the effect of flue-gas cooling, not only in the place where flue-gas cooling takes place but also further on in the container (both in the direction of the seat of the fire and in the direction of the exit).

To measure not only the temperature just below the ceiling but also on a slightly lower level (relevant to systems that apply insulating layers to ceilings and walls), two thermocouples were placed above one another at various locations. Where in figure 1 two thermocouples are mentioned (1-2, 3-4, 5-6, 7-8), the odd numbers are for the thermocouples that are placed highest (directly beneath the ceiling) and the even numbers are for the thermocouples on a lower level (about 40 cm beneath the ceiling). To ensure that radiation by the fire does not present a distorted picture, the thermocouples were provided with a construction to avoid this (see illustration 3.1). They were screened by a hollow square block with an insulating inner layer, and the sides of the block were open. The open sides were placed in a transverse direction of the extinguishing agent.

¹⁵ It is not possible to set the conical angle of a CAF jet nozzle, as the jet nozzle produces a bound jet.



Illustration 3.1: Thermocouples

Due to the location near the corner, thermocouples 7 and 8 were radiated by the fire. Two other thermocouples were placed in the direction of the fire (9 and 10). To return to the initial condition after the test, two thermocouples were placed on (11) and in (12) the brick wall. The thermocouples were linked to a data logger with a measuring program. This made all temperatures available on the spot and real-time.

Times

The parameters related to time were:

- during flue-gas cooling: the rate of temperature decline per shot (degrees/sec) and the duration of the effect of the cooling;
- during extinguishing: the moment at which the knockdown(s) took place and the moment of re-ignition.

The times were measured with a stopwatch. The time registration was synchronous with the temperature registration and water consumption.

Water and foam consumption

The parameters related to water consumption were:

- during flue-gas cooling: the quantity of water used per series of flue-gas cooling;
- during extinguishing: the quantity of water used per (attempt to create a) knockdown.

Water consumption was measured with a water meter.¹⁶ The water levels were measured prior to the test, after the first series of flue-gas cooling, after the second series of flue-gas cooling was calculated on the basis of the percentage that was admixed.

¹⁶ The water for HP, LP and CAF travelled from the hydrant via the water meter outside the tank. This was not possible with Firedos due to the construction of the pump system. Water consumption was indicated by markings on the gauging rod. When all was ended, the tank was filled up with the water meter until the markings.

Visual image

The parameters related to the visual image were:

- during flue-gas cooling: any particularities;
- during extinguishing: creating a knockdown and any particularities.

Visual observations were done by the safety manager and the fire-fighting team. They were asked to share their experiences in a short interview directly after the fire-fighting activities. A thermographic camera made visual observations inside. In addition, images were made with a regular, heatproof camera.

Other parameters

The following parameters were examined for the comparability of the tests:

- starting temperature in and on the wall;
- maximum temperature between ignition and the start of the test.

3.3 Test object

The tests were carried out at the Troned practice centre. The set-up of the test was selected to correspond closest with the scenario of a domestic fire.

A prepared L-shaped container was used and partly equipped with a brick inner wall, thermocouples and cameras. Both sides of the L-shaped container were 9 meter long. In the picture, the horizontal part of the container is 2.30 m wide and the vertical part is 1.70 m wide. The height is everywhere 2.25 metres. The part where the fire was is 2.00 m wide and just as long and high.

The part of the flue-gas cooling tests in the steel L-shaped container was equipped on both sides (L-shaped) with concrete building bricks to create a 20-cm brick wall. The aim was to imitate as much as possible a realistic situation. As the heat properties of a brick wall are different from a steel wall, the wall was built from the bottom to the ceiling and safely secured. See also Figure 3.1 for the set-up of the test.

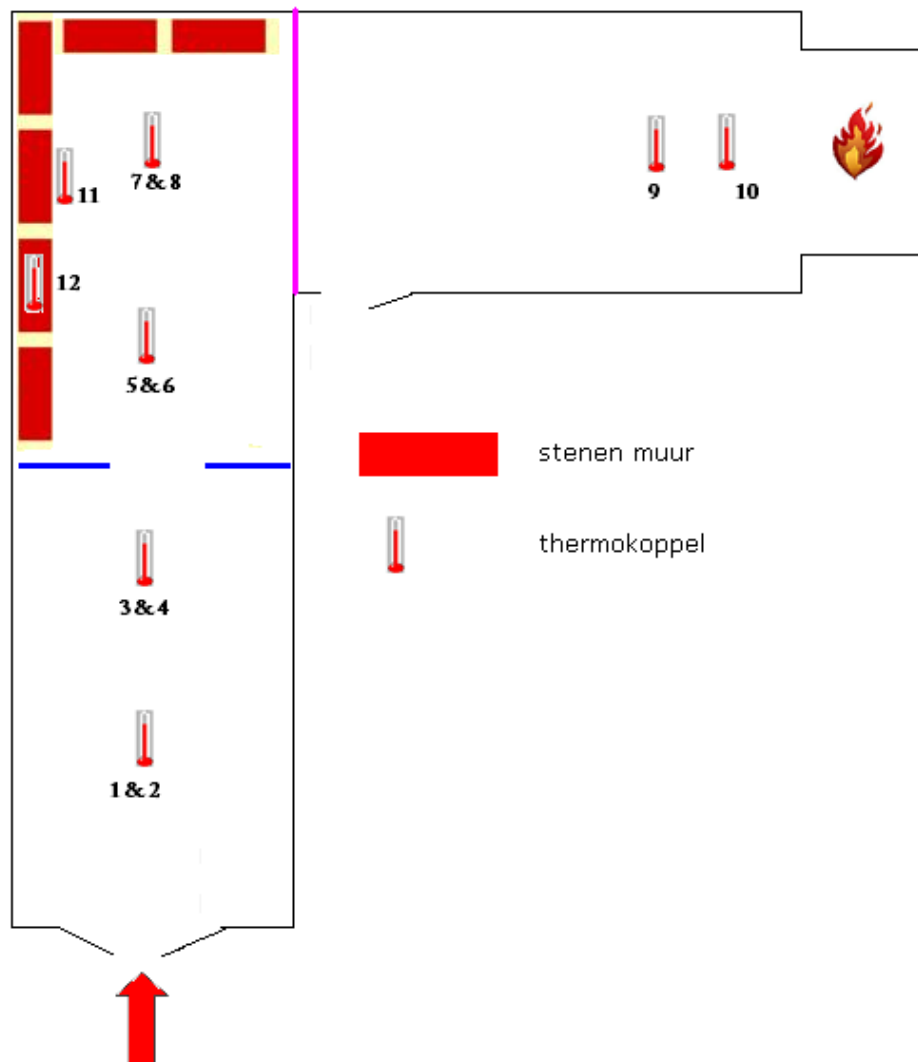


Figure 3.1. Floor plan of the container

Because the tests were performed in an L-shaped container, direct contact between extinguishing agent and the seat of the fire was not possible during the flue-gas cooling. This made it possible to cool flue gases in the front part of the container without the extinguishing agent having any effect on the seat of the fire.

3.4 Fire load

A fire was started in the container consisting of 7 pallets measuring 121cm x 102cm x 12cm (about 130 kg pinewood), 1 foam mattress¹⁷ (size 100cm x 100cm x 21cm), three sheets of chipboard (size 120cm x 100cm x 1.2cm) and a litre of ignition fluid. This local fire load was about 2,600 MJ (equivalent of about 155 kg pinewood) and placed on a surface of about 4 m² in the living-room fire scenario. The fire load consisted of wood and polyether foam. Adding the foam mattress was meant to create the most realistic situation.

¹⁷ HR polyether foam from the Recticel company, foam type R37130, density 33-36 kg/m³. The basis for polyether foam is polyurethane. Polyether is usually used as seat filler and for mattresses.

The fire load was composed as follows: four pallets at the bottom, then a sheet of chipboard, then the foam mattress and a sheet of chipboard and three pallets and another sheet of chipboard on top. See also illustration 3.2.



Illustration 3.2: Composition and ignition of the fire load

The fire load was then ignited according to a fixed pattern: half of the ignition fluid was spread on two softboard ignition strips. The remaining ignition fluid was sprinkled on the four lower pallets and then the ignition strips were ignited and slid under the pallets.

3.5 The initial situation

After igniting the fire load, the fire started to develop. In the beginning, all doors of the container were open to allow sufficient oxygen supply. Quite soon after the fire developed, the door that was closest to the fire was closed. Then the temperature started to increase. At one point of time¹⁸, the first door on the attack side was closed, which created a layer of flue gases. When the temperature on thermocouple 3 remained above 250 °C and the flue-gas layer was thick enough¹⁹, the second door on the attack side was closed. Then there was a wait of 30 seconds while monitoring whether the temperature on thermocouple 7 remained around 500 °C. When this was the case, the doors were opened after 30 seconds and the fire attack was started.

3.6 Performance of the experiments

A combined experiment of a flue-gas cooling and an extinguishing was carried out five times with each system.

The flue-gas cooling procedure consisted of two series. Each series of flue-gas cooling consisted of 3x 3 shots. In the first series, 3 shots were given from the access door at t=0, the two successive shots at t=10 and t=20. Then they advanced to the second marshalling line (the blue line in figure 1) where the second series of 3x3 shots were given at t=30, t=40 and t=50. The total duration of the flue-gas cooling was 1 minute. The layout for the flue-gas cooling was done in a way that made direct contact with the seat of the fire impossible.

After the flue-gas cooling, the fire fighters stationed themselves near the short side of the container (the pink line in figure 1) in the direction of the seat of the fire. Twenty seconds after the end of the flue-gas cooling, the team received the command of 'extinguish'. The extinguishing was carried out in conformity with the techniques described in table 3.2. As soon as the observer inside established that a knockdown was achieved (no visible flames) the extinguishing was stopped immediately²⁰. It was then monitored how long it took before the fire re-ignited. After re-ignition of the fire, they waited another 10 seconds and started extinguishing again until a knockdown was achieved again. This was repeated several times until the signal of 'end of the test' was given.

The applied tactic is very important for the effect that can be achieved with the various extinguishing agents. For instance, an inefficient extinguishing technique may lead to the wrong conclusion that the extinguishing system appears to be less effective. In preparing this study, explicit attention was therefore given to the applied tactics. For using the high-pressure and low-pressure attacks, the modern jet hose techniques were carried out by a certified CFBT instructor (compartment fire behaviour training) in accordance with the CFBT method. The attack with CAF was carried out by fire fighters with wide experience in attacking with CAF and who had recently attended a presentation given by Swedish instructors. The attacking method was decided in consultation with some of the fire service regions that use CAF. It appeared that there were great differences in the opinions about the proper use of CAF for flue-gas cooling. In essence, this means that there are two different opinions: flue-gas cooling with CAF in the regular way like high-pressure (short pulses into the flue-gas layer) or covering walls and ceilings with CAF.

¹⁸ Based on colour change of the flames from yellow to red and a mix of flames and soot above the seat of the fire.

¹⁹ With the help of a marking at 110 cm from the ground on the wall of the container.

²⁰ Contrary to the usual procedure in actual practice.

Given the set-up whereby the walls and the ceiling could not pyrolyse (steel ceiling and walls of steel and brick) it was opted for the usual method of applying the high-pressure interior attack to CAF. Because of the strong force and the throw length, it was decided to use CAF in the first series of flue-gas cooling from 7 metres from the door opening as is customary for this extinguishing system.

The Firedos system was applied by fire fighters with a recent training given by the supplier.

The detailed performance of the flue-gas cooling and extinguishing is represented in table 3.2.

Table 3.2 performing the flue-gas cooling and extinguishing per system

System	Performing flue-gas cooling	Performing the extinguishing
CAF	Flue-gas ²¹ cooling with CAF was done by giving shots in the space with a bound jet pointed into the flue-gas layer ²² . Because of the power and the throw length of CAF, it was decided to do the first set of flue-gas cooling near the outside door at 7 metres distance from the opening, so that the extinguishing agent could reach the flue-gas layer in the front of the container. The hose was flushed outside prior to the flue-gas cooling.	The extinguishing with CAF ²³ was performed by foaming in the environment of the seat of the fire and ultimately the seat of the fire with a rotary motion.
FD	To start a direct foam attack, the hose was first flushed outside prior to starting the flue-gas cooling. Then the flue-gas cooling was performed with Firedos in the way of a regular interior attack with high pressure and short shots with a jet nozzle at a conical angle of 30° and a 65° gradient in the direction of the flue-gas layer.	For Firedos, an accessory meant for extinguishing was put on the jet nozzle prior to the attack. In extinguishing, wall and ceiling are covered with foam. The jet nozzle makes a circular motion. The seat of the fire is then extinguished via a direct attack.
HD	Flue-gas cooling with high pressure was performed in accordance with the regular procedure with short shots given with a jet nozzle at a conical angle of 30° at an angle of 45° in the direction of the flue-gas layer.	In a smooth movement, the jet is pointing down at a conical angle of 35° at an angle of 45°. As soon as the seat of the fire was hit, they switched over to a bound jet.
LD	Flue-gas cooling with low pressure was performed in accordance with the regular procedure of short shots given with a jet nozzle at a conical angle of 30° and a gradient of 45° in the direction of the flue-gas layer.	In a smooth movement, the jet at a conical angle of 35° is pointing down at an angle of 45°. As soon as the seat of the fire was hit, they switched over to a bound jet.

The top-piece and the attack procedure for CAF are presented in the illustrations below.



²¹ The attack procedures as accepted in the regions of The Hague, Rotterdam-Rijnmond Port district, Zaanstad

²² In a pyrolysing environment, it is also possible to foam the walls and ceilings, but given that the walls did not pyrolyse it made no sense to choose for this tactic. That is why the regions opted for this method in consultation.

²³ The attack procedures as accepted in the regions of The Hague Haag, Rotterdam-Rijnmond Port district, Zaanstad. However, in practice they would continue with extinguishing after reaching a knockdown.

Illustration 3.3. Top-piece for Firedos

Illustration 3.4. Using CAF

3.7 Uniformity of test conditions

The described procedure of setting up, igniting and monitoring the progress of the fire is followed to ensure that each starting situation and test is carried out uniformly. The pallets came from one supplier and were stored under similar conditions prior to the test. The same applied to the foam mattresses, chipboards and ignition fluid they used. To guarantee continuity and unambiguity, the same lighter assistants were deployed.

The attack was performed in accordance with a standardised method. For each system, experienced fire fighters skilled in operating the system were deployed in all tests.

The space was reconditioned after every attack and to this end, the following actions were performed:

- removing the remains of the fire from the fire compartment,
- removing the extinguishing agent from the fire compartment,
- cooling the walls and the air until all thermocouples indicated a temperature below 100 ° C.

For reconditioning, they also used a repressive ventilator and squeegees to remove the extinguishing agent and bring the space as much as possible back in the original condition.

As the container was cold and often dry at the beginning of the day in contrast with using the container later in the day, a test fire was made to warm up the container. The fire was then extinguished to create a comparable humidity.

However, two aspects of the tests were not uniform. Firstly, the meteorological circumstances were not constant during the test week. Some days, or at some time during the day, the wind was stronger or weaker, there was rain or no rain at all, and temperatures were different. Analysis of the meteorological information of the KNMI weather station at Troned²⁴ also showed that there were differences. This is insuperable in open air. The weather conditions on the test day are given in Table 3.3. In spite of the differences, it is expected that the influence on the tests is so limited that the results are useful for the research.

²⁴ Airport Twenthe

*Table 3.3 Measurement information of the Airport Twenthe KNMI-station
(Royal Netherlands Meteorological Institute station (290))*

Date	Wind direction (degrees)	Wind speed ²⁵ (m/s)	Temperature ²⁶ (°C)	Precipitation ²⁷ (mm)	Duration of precipitation (hours)	Relative humidity ²⁸ (%)	Average air pressure (hPa)
28 Jan	SSW (200°)	5.4	3.8	3.6	3.6	91	1008.7
29 Jan	SW (222°)	5.8	10.2	5.7	9.2	93	1004.7
30 Jan	WSW (238°)	7.8	9.9	7.8	4.6	84	1004.1
31 Jan	WSW (238°)	7.0	6.7	11.7	3.2	79	1009.1
1 Feb	SW (234°)	3.8	4.9	5.7	9.9	91	1000.0

Source: <http://www.knmi.nl/klimatologie/daggegevens/index.cgi>

A second aspect that was different in the tests was the ventilation conditions. Earlier experiments showed that a time schedule for opening and closing the ventilation holes did not lead to identical fires. The development of the fire is also influenced by the temperature of the environment, humidity, wind force and wind direction. In spite of the identical fire load, it was difficult to realise every time the same development of the fire outside a laboratory environment. To reach the right temperature and based on the experts' observations, it was therefore decided to adapt the ventilation conditions in the starting phase to the developing fire until the above mentioned conditions were reached. The established protocols for reaching the starting conditions were followed from that time on. By comparing the starting temperatures, the maximum temperatures and the time needed in the heating up phase (see section 4.10) it appeared that there were no significant differences between the tests. The difference in ventilation conditions probably had hardly influenced the results of the study.

3.8 Analysis of the data

The data of the thermocouples, the registration of time and water, the experiences from interviews, the particulars from the logbook and the visual images recorded with cameras were assessed after performing the practical tests.

Before assessing the effect of the systems on flue-gas cooling and extinguishing, it was first examined to what extent the results of the five mentioned tests per extinguishing system corresponded. If it appeared that the results of the five tests with one system largely corresponded, then it says something about the reproducibility²⁹ of the study or the extinguishing system, and therefore about the possibility to make reliable statements in this study.

A significance test was done to analyse the differences. With a significance test (e.g. an F test) it can be calculated how big the chance is that a detected difference is a coincidence. If a reliability percentage of 95% is opted for, in other words, if the error margin is smaller than 0.05 (5%), we speak of a significant difference; the chance that a detected difference is a real difference and no coincidence is more than 95%.

²⁵ Average in a space of 24 hours

²⁶ Average in a space of 24 hours

²⁷ Sum in a space of 24 hours

²⁸ Average in a space of 24 hours

²⁹ The extent to which the same values are reached if the test was performed again, and that the results are reproducible.

Then it was established whether certain tests, whereby it appeared from the logbook or from the team's description that something particular happened that did not belong to the test, had to be included in the research. See also Chapter 4.

Analyses were also made to what extent the two thermocouples that were hung above one another added value to the research, and it was considered whether further analysis between the upper and the lower thermocouple was desirable.

Then the flue-gas cooling and the extinguishing were analysed. Both the two separate series of flue-gas cooling and the total temperature trend were examined. For extinguishing, analysis was done of temperature progress, the duration until knockdown and re-ignition. The results of these analyses are given in chapters 5 and 6.

As described in the Introduction, some extra tests were carried out with another mix percentage for the FD system (0.3% instead of 3%) and a test on flue-gas cooling with a valve on the CAF jet hose. Though this was seen as bycatch, the results were analysed and given in Chapter 8.

3.9 Limitations of the study

It should be noted that the results must be seen within the limitations of the research. Other than the seat of the fire, there were no fumigating materials and this made that the fire could not extend further than the direct fire location. The test was done with one kind of fire load in the mentioned test object.

The results are therefore only valid for these circumstances. However, each system that can cool flue gases efficiently will do so as well in this test environment. If a system does not cool flue gasses or not sufficiently in the tested environment, it means that this system does not perform an efficient flue-gas cooling in a number of cases. This does not mean that the system is unsuitable for other applications (such as covering liquid fires or screening off buildings, or if it is applied in other ways during an inside attack).

Another aspect to be considered in interpreting the results is that there is a continuous supply of hot flue gases from the seat of the fire in the direction of the exit when the fire is attacked. The result is that the temperature rises again after terminating a series of flue-gas cooling. Anyway, this will also be the case in a real fire due to flow.

All systems were tested for the method of flue-gas cooling and extinguishing described in section 3.6. This means that the results are valid only for this way of attacking a fire. Other tactics (including foaming walls and ceiling or longer pulses or shots) may have other effects. The systems were only tested with the above-mentioned pressures and jet hoses. Applying other pressures or materials may give other results.

4 Comparability of the tests

Before comparing the results of the study, it was examined to what extent the fires and the interventions could be compared with the various tests and systems.

4.1 Comparability of the development of the fire

The tables below give the initial temperature, the maximum temperature and the average duration of the warming-up phase.

Table 4.1 Starting temperature (°C), per extinguishing system

Extinguishing system	Average Initial temperature	Minimum initial temperature	Maximum initial temperature
Compressed-air foam	512	496	522
Firedos (3%)	508	499	525
Low pressure	504	491	518
High pressure	504	493	530
Firedos (0.3%)	507	506	508

Table 4.2 Temperature (°C) and duration (sec) of starting-up phase per extinguishing system

Extinguishing system	Average maximum temperature starting-up phase	Average duration of warming-up phase in seconds
Compressed-air foam	524	550
Firedos (3%)	522	536
Low pressure	521	533
High pressure	521	553
Firedos (0.3%)	523	499

Statistical analysis shows that the initial temperatures do not differ much ($F=0.435$; $p=0.781$), nor do the maximum temperatures ($F=0.059$; $p=0.993$) or the duration of the warming-up phase ($F=0.054$; $p=0.994$). This shows that the development of the fire prior to the attack is almost identical.

4.2 Comparability of the actions to cool flue gases

Each system was tested five times. It appeared during the performance that the first two tests with Firedos were not carried out with a correct jet nozzle technique. It was therefore decided not to include these tests and to do the tests again with another jet nozzle (these tests were indicated with FD 3 to 7). It was examined to what extent the results of these five tests with one system corresponded. See also figures 4.1 to 4.4.

Analysis of measuring thermocouple 5

For comparability, the temperature trend of the total flue-gas cooling at the location of thermocouple 5 was examined. This thermocouple was placed in the middle of the container and was not influenced by the seat of the fire. Thermocouple 5 therefore gives the best total overview of the flue-gas temperature, and the warming-up by radiation from the seat of the fire remains limited.

Analysis of variations in measured values per extinguishing system

The figures below present the temperature trend of each of the examined extinguishing systems during the tests performed. In the main, the graphs show three variations between the five tests per system: the variation on the horizontal axis, the variation on

the vertical axis, and the trend of the lines. The trend of the lines is important for the comparability of the tests. This is seen in the fluctuations in the lines of the various tests and the gradient of the decrease or increase in temperatures. The horizontal and vertical shifts are caused by the differences in the initial time and initial temperature and are not relevant to the comparability as long as the fluctuation and the gradient of the decrease and increase in temperature are comparable. This can be explained as follows:

- The variation on the horizontal axis is visible at the time of temperature increase or decrease. This variation is not relevant to the comparability; these variations occur because the interventions (series of shots) are not given for every test at exactly the same time.
- The variation on the vertical axis is visible in the level of the temperature. This variation is not relevant to the comparability; the variation in the temperature level will be within a range because the separate tests were not carried out under conditions that were 100% the same. For the four systems, the range (ΔT) is 31°C at the most.

Figure 4.1 Comparability of 5 tests with CAF (DLS): flue-gas cooling, thermocouple 5 (TK)

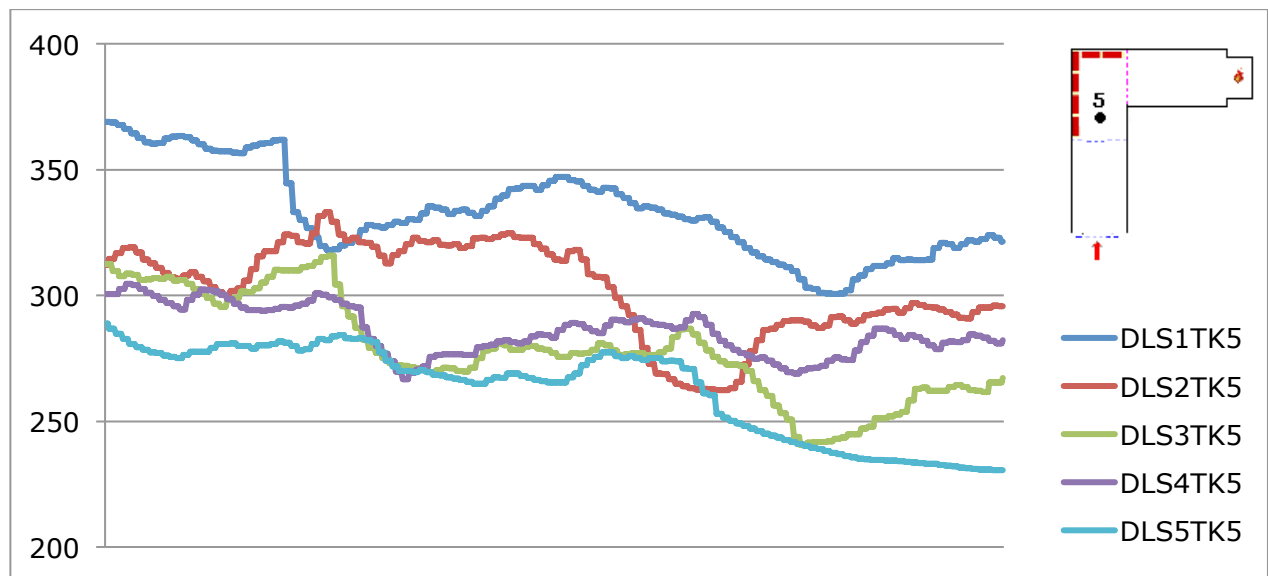
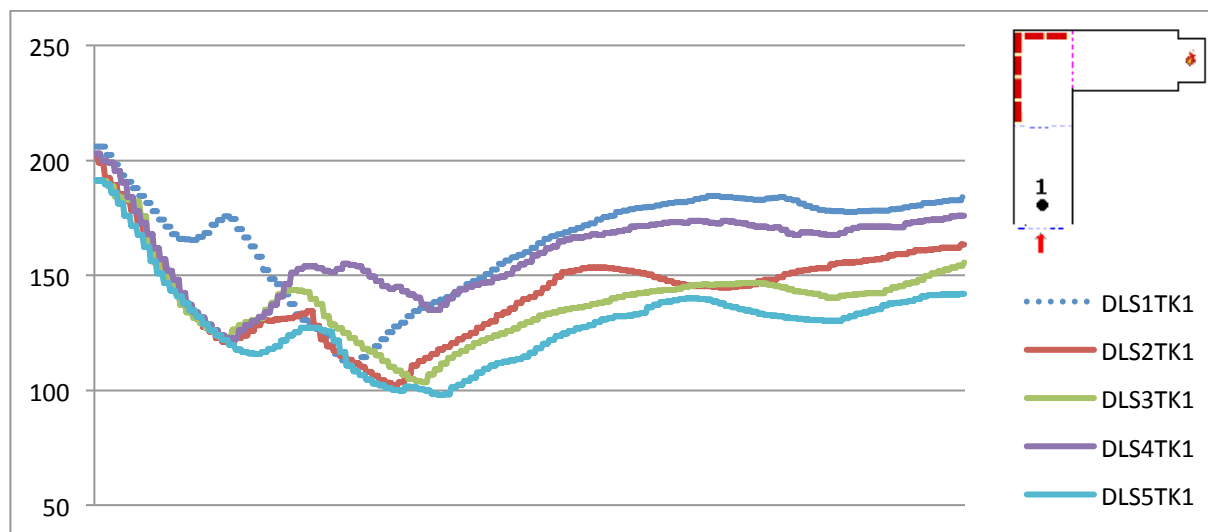


Figure 4.1 shows a strong variation in the temperature trend as compared to the five tests, and the temperature trend in all tests is rather fanciful from the beginning. The CAF1 and CAF2 tests differ most from the other three tests. Enquiries from the attack team revealed that part of the foam landed *next to* the container in the first test. Analysis of the first flue-gas cooling showed that there was indeed a deviation on thermocouple 1 of test CAF1. See Figure 4.2.

Figure 4.2 Comparability of the tests with CAF (DLS), flue-gas cooling, thermocouple 1(TK)



It was therefore decided not to include the first CAF test (DLS1) in the analysis. There is no explanation for the deviation in CAF2 (DLS2) as the attack team did not mention any particulars in performing the test.

Figure 4.3 Comparability of Firedos tests (3%), flue-gas cooling, and thermocouple 5 (TK5)

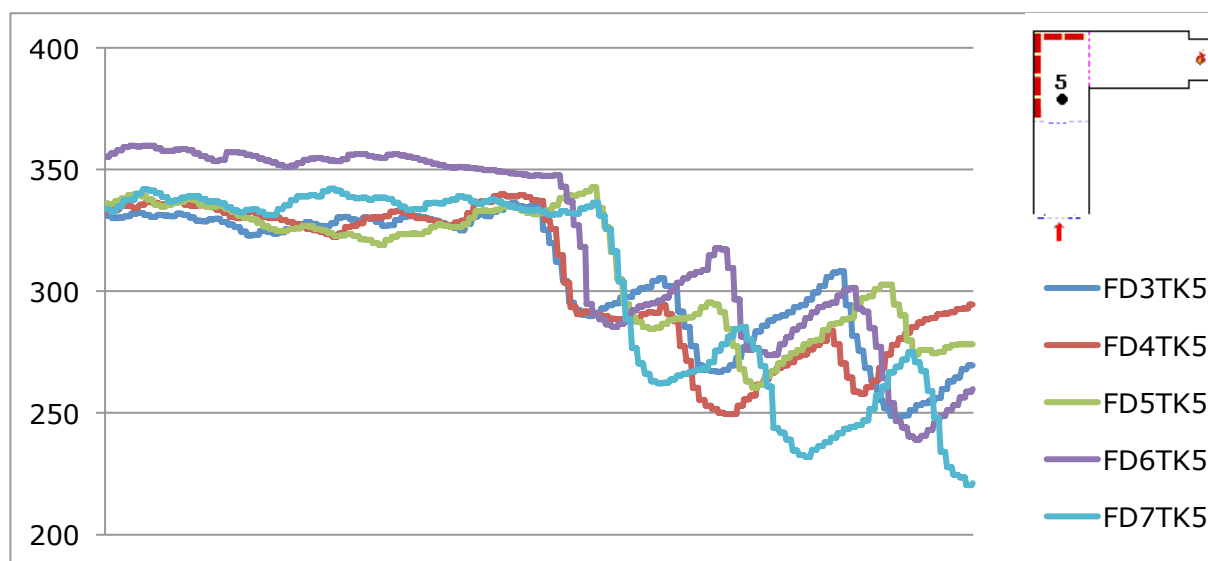


Figure 4.3 gives the tests with Firedos. Though the initial temperature in test FD6 slightly deviates from the other tests, it follows the same pattern as in the other tests. The pattern consists of a minimum temperature fluctuation in the first series of interventions (shots 1-3) and a temperature decrease after every shot in the second series of interventions. The gradient of the declines in temperature largely corresponds to the separate tests. The following increase in temperature shows a similar gradient.

The attack team notified that in the first two valid Firedos tests (tests 3 and 4), the hose was insufficiently flushed prior to the attack and that a substance left the jet nozzle that was not representative of normal Firedos foam. The effect of this substance on the flue-

gas cooling is visible in Figure 4.4. To improve comparability, the measured values are corrected at starting temperature for each test.

Figure 4.4 Comparability of the Firedos tests (3%), flue-gas cooling series 1-3, thermocouple 1(TK)

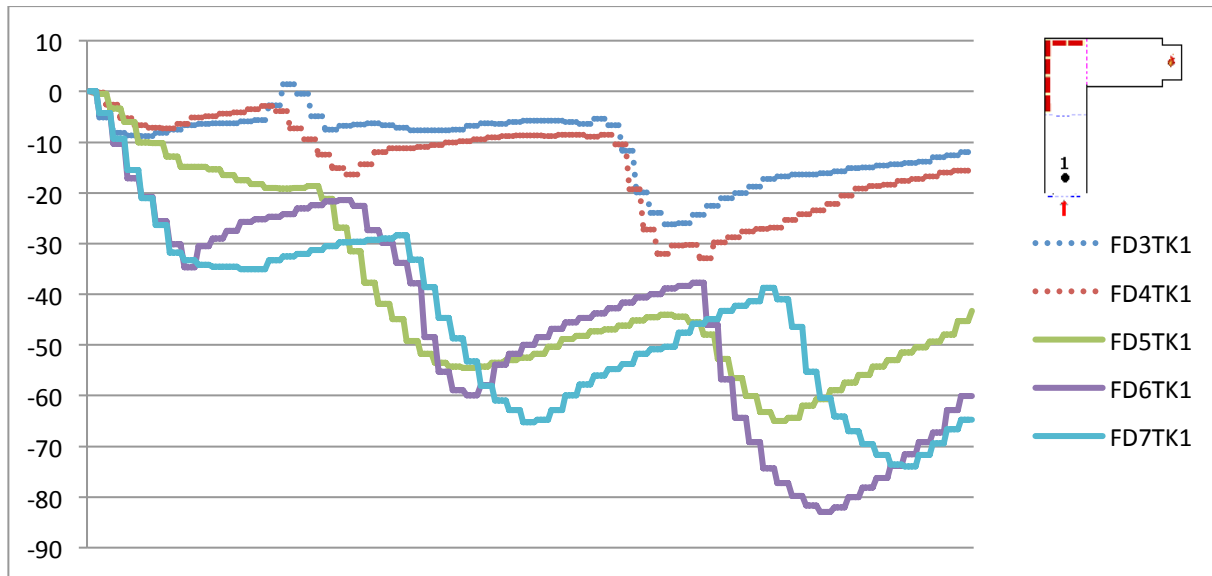


Figure 4.5 Comparability of 5 low pressure tests (LD), flue-gas cooling, thermocouple 5 (TK)

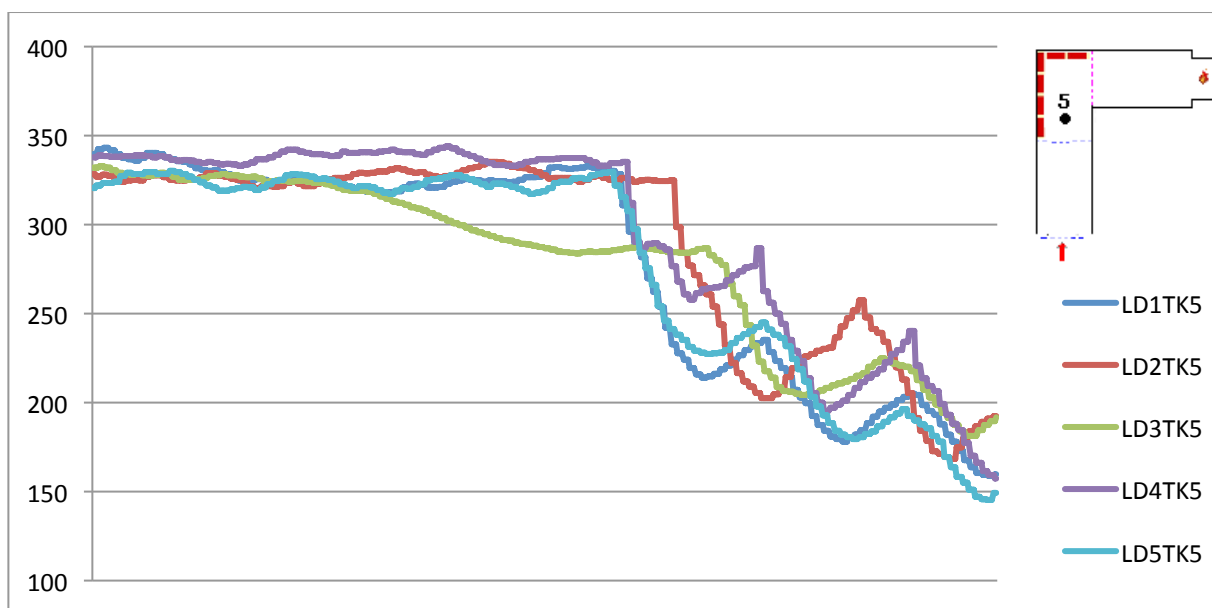


Figure 4.5 shows the tests with low pressure. Test LD3 shows a deviating decrease in temperature in the first series of interventions, but follows the pattern we saw in the other tests. For the sake of completeness, the measured values for low pressure in thermocouple 1 are compared, just as with the tests with CAF and Firedos. They are given in Figure 4.6. No particulars could be read from this.

Figure 4.6 Comparability of 5 tests with low pressure (LD), flue-gas cooling, thermocouple 1 (TK)

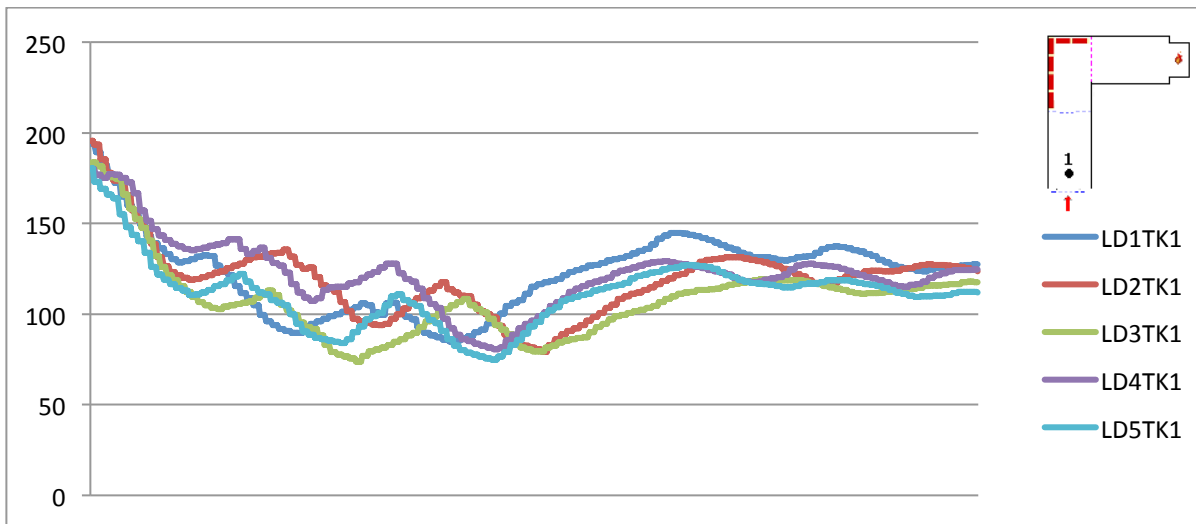


Figure 4.7 Comparability of 5 tests with high pressure (HD), flue-gas cooling, thermocouple 5 (TK)

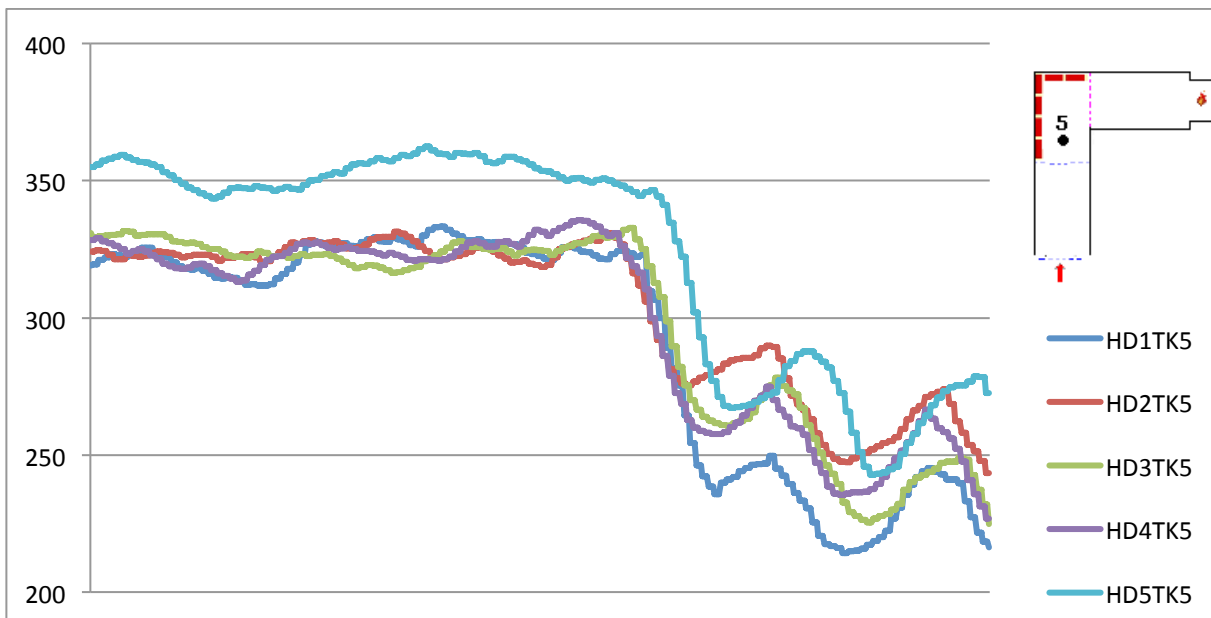


Figure 4.7 shows the tests with high pressure. High pressure test 5 has a higher initial temperature but further development is comparable with the other four tests.

Figure 4.8 Comparability of 5 tests with high pressure (HD), flue-gas cooling, thermocouple 1 (TK)

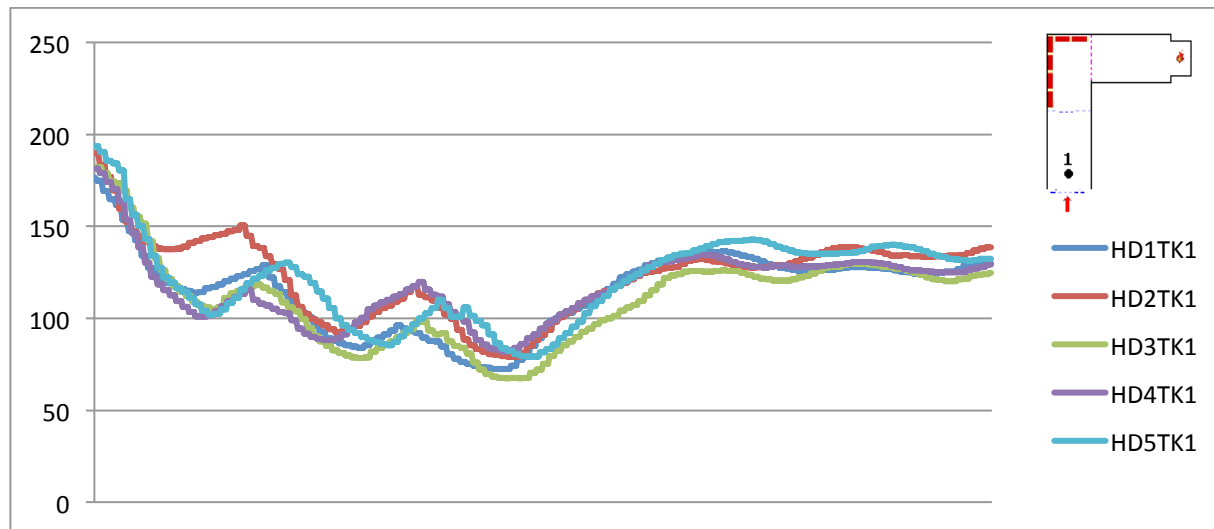


Figure 4.8 shows the measured values in thermocouple 1. No particulars could be read from this.

4.3 Conclusions of the comparability

The above figures show that CAF gives a greater variation in the temperature trend between the tests and that there is a volatile temperature trend in thermocouple 5 during the first series of interventions. This variable trend was not observed in the other tested systems. A possible explanation of this trend and the variation is that the throw length and the force of the CAF system are such that the foam splattered against the wall or against the roof when the flue gas was cooled. The location where the wall or the roof was hit determines where the foam is shifted to and this has an ever-varying effect on the results. The erratic temperature trend may also be caused by bringing cold environmental air into the container due to the force of the system. The cold air that was brought in may have caused the turbulence near thermocouple 5 given the fact that the temperature fluctuations were measured there in the first series of interventions. It was finally decided to include all CAF tests in the analysis with the exception of test CAF1. The variation is probably a direct effect on the use of this CAF system on the established conditions.

As to the Firedos tests, we see that the results in two tests deviate strongly from the other three tests. It appeared from the two valid tests (tests 3 and 4) that the hose was insufficiently flushed beforehand and that a substance left the jet nozzle that was not representative of normal Firedos foam. In consultation with Firedos experts, it was decided not to include tests 3 and 4 in the analysis of flue-gas cooling. Due to the series of *flue-gas cooling* later in the attacks, the hose was flushed and included in the analysis of *extinguishing* fires in tests 3 and 4. When compared with the other three tests with Firedos, no deviations were observed.

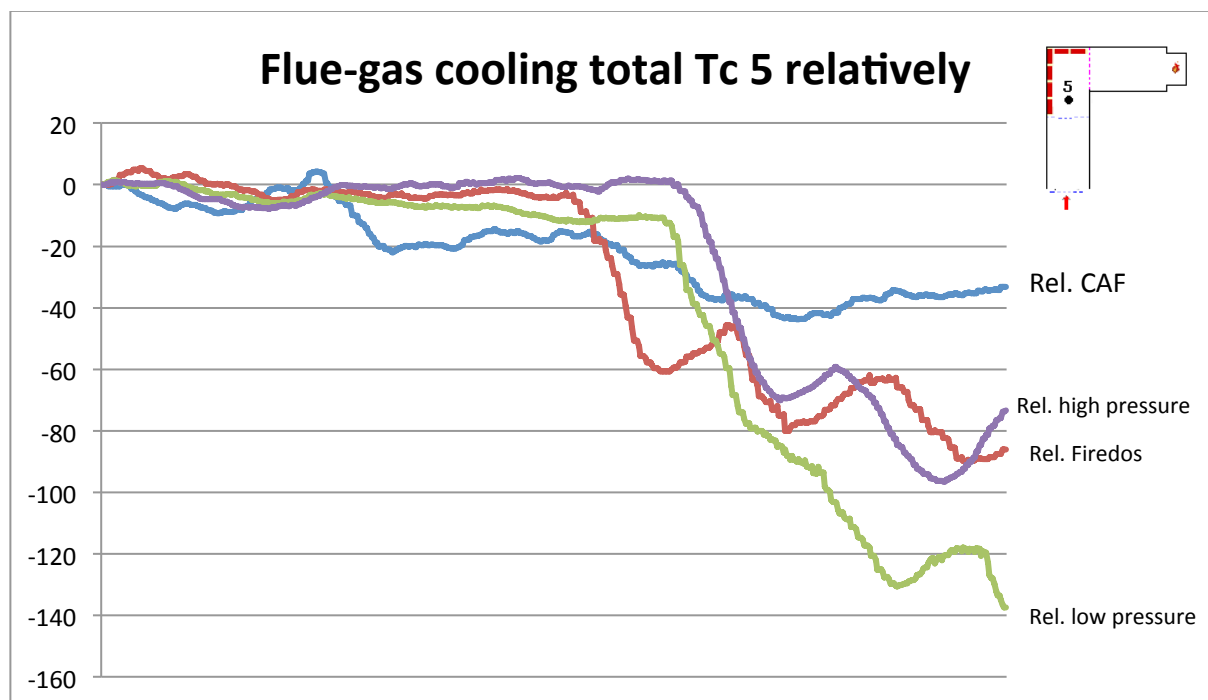
5 Results of flue-gas cooling

Each system was tested for two series of flue-gas cooling and consisted of a first series of flue-gas cooling near the outside door (3 shots at $t=0$, 3 shots at $t=10$ and 3 shots at $t=20$), and a second series of flue-gas cooling halfway in the container (3 shots at $t=30$, 3 shots at $t=40$ and 3 shots at $t=50$). Then temperatures were measured with various thermocouples. It must be noted that, considering the force and the throw length of CAF, the attack with CAF for the first series of flue-gas cooling started at a distance of 7 metres from the containers.

5.1 Temperature trend of the whole flue-gas cooling

Figure 5.1 shows the average temperature trend on thermocouple 5 for the examined systems. The figure is indexed and the initial temperature is set at 0 to compare the temperature trends. Thermocouple 5 was selected as this instrument was placed in the middle of the space and, unlike thermocouple 7, not directly radiated by the seat of the fire. It only measured the flue-gas temperature.

Figure 5.1 Temperature trend of flue-gas cooling, average relative values per system, thermocouple 5



The above figure shows that this scenario for low pressure at thermocouple 5 gives the largest decrease in the temperature of the flue-gas layer ($\Delta T_{LD}=138^{\circ}\text{C}$)³⁰. In the first part of the attack (the attack from outside) CAF gives a limited decrease of about 20 °C of the flue-gas layer further on in the container when compared with other systems. With CAF,

³⁰ Trend lines: CAF: $y = -0.0792x + 0.493$; $R^2 = 0.8441$
 High pressure: $y = -0.1749x + 23.855$; $R^2 = 0.6737$
 Firedos: $y = -0.1923x + 22.465$; $R^2 = 0.849$
 Low pressure: $y = -0.2716x + 34.76$; $R^2 = 0.7861$

The value for x in the formula of this trend line indicates the gradient of the trend line. The explained variance (R^2) is a measure that gives information about the extent to which a model approximates to the real data.

the flue-gas temperature continues in almost the same line ($\Delta T_{CAFS}=41^{\circ}\text{C}$), whereas it decreases much stronger in other systems, especially in the second set of flue-gas cooling.

The flue-gas temperature with Firedos and high pressure is comparable at the end of the set of flue-gas cooling ($\Delta T_{FD}=86^{\circ}\text{C}$; $\Delta T_{HP}=73^{\circ}\text{C}$). See also table 5.1.

Table 5.1 Total decrease in flue-gas temperature of the average values per system, thermocouple 5

System	Average initial temperature ($^{\circ}\text{C}$)	Average final temperature at t=55 ($^{\circ}\text{C}$)	Decrease in flue-gas temperature ($^{\circ}\text{C}$)
Compressed Air Foam	303	262	41
Firedos (3%)	342	256	86
Low pressure	332	194	138
High pressure	331	258	73

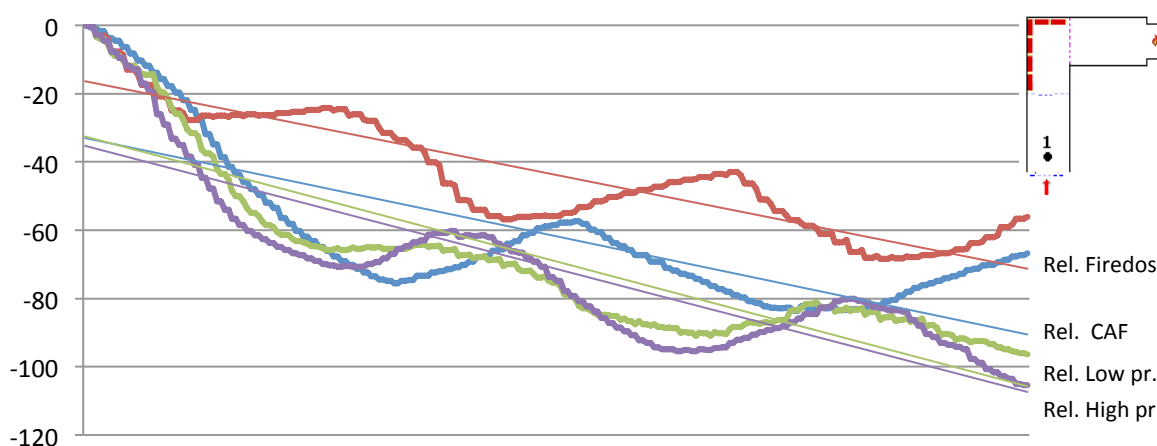
As the seat of the fire is not directly hit during the flue-gas cooling, there is a continuous stream of hot flue gases.

Especially the cooling effect of low pressure continues, even if no pulses are given in the intervening time and new hot flue gases are supplied. This applies to a lesser degree to Firedos and high pressure, and hardly to CAF.

5.2 Temperature trend of separate series of flue-gas cooling

A further analysis was carried out because it appeared that CAF caused a limited decrease in flue-gas temperature in the first series, and even less decrease in the second series. Attention was given to the decrease in temperature on thermocouple 1 during the first series of flue-gas cooling (1-3), and on thermocouple 5 for the second series of flue-gas cooling (4-6). Figure 5.2 shows the temperature trend from the start of the flue-gas cooling.

Figure 5.2 Temperature trend of flue-gas cooling series 1 (shots 1-3), average relative values per system, thermocouple 1



The above figure shows that high pressure and low pressure score best for the first series of flue-gas cooling ($-0.29t$). The trend lines for the course of temperature run almost parallel³¹ for both systems and almost coincide ($\Delta T=3^{\circ}\text{C}$). The explained variance of both

³¹ Trend lines:

High pressure: $y = -0.2884x - 34.982$; $R^2 = 0.7369$

Low pressure: $y = -0.2928x - 32.237$; $R^2 = 0.7664$

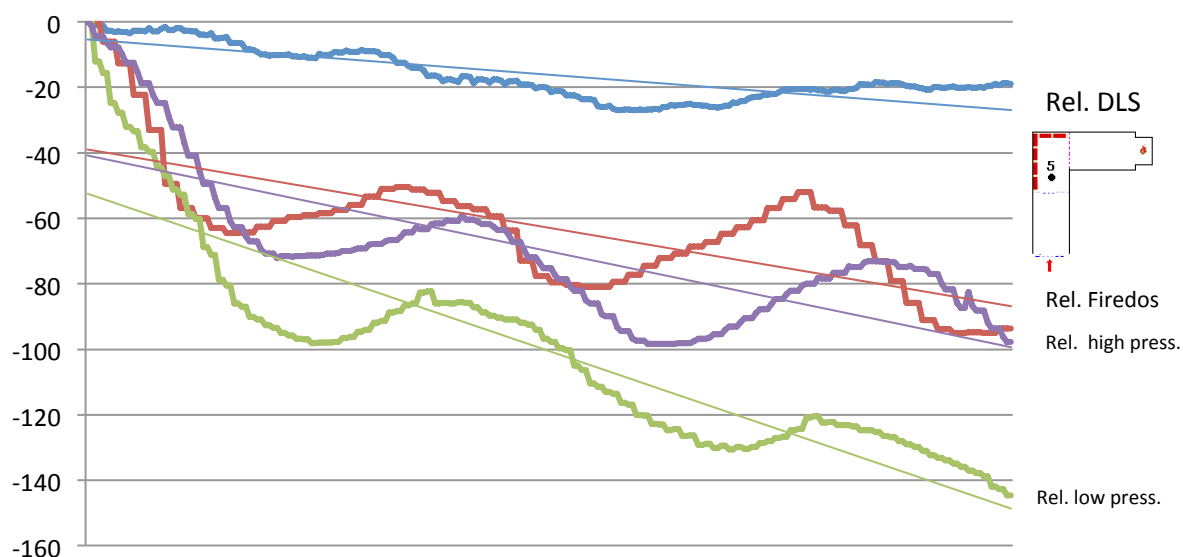
CAF: $y = -0.2303x - 32.746$; $R^2 = 0.5789$

FD: $y = -0.2197x - 16.119$; $R^2 = 0.8211$

trend lines is also good ($R^2_{HD} = 0.74$; $R^2_{LD} = 0.77$). Decrease in flue-gas temperature is also seen with CAF at certain points of time. On the other hand, the trend line is slightly less steep ($-0.23t$) which means that the temperature decreased less. The explained variance is lower ($R^2_{DLS} = 0.58$). The trend line for the development in temperature for Firedos ($-0.22t$) is almost parallel to the trend line for CAF, albeit about $17\text{ }^\circ\text{C}$ higher. This means that Firedos cools least in the first series of flue-gas cooling as seen on thermocouple 1. The measured values give a higher explained variance ($R^2_{FD} = 0.82$). The total decrease in temperature after the first series of three flue-gas coolings is about 95 degrees with low pressure, 65 degrees with CAF, 55 degrees with Firedos and about 100 degrees with high pressure.

Looking at the second series of flue-gas cooling³² the opposite result is noteworthy; CAF scores significantly less good ($-0.09t$; $R^2_{CAF} = 0.65$) in cooling flue gases than Firedos ($-0.20t$). High pressure ($-0.25t$; $R^2_{High Pr} = 0.55$) scores about as well as Firedos, and low pressure ($-0.40t$; $R^2_{LP} = 0.81$) scores best. The explained variance is highest as well. Low pressure gives a total decrease in temperature of almost 150 degrees after the second series of three times flue-gas cooling, CAF gives about 20 degrees, and Firedos and high pressure give about 100 degrees. See also figure 4.3.

Figure 5.3 Temperature trend of flue-gas cooling series 2 (shots 4-6), average relative values per system, thermocouple 5



The above figure shows the three series of flue-gas cooling with Firedos, low pressure and high pressure (each with three shots). These decreases per flue-gas cooling were further analysed. Table 5.2 presents the average temperature decrease and the average duration of cooling capability. As the three flue-gas cooling trends cannot be observed for CAF (three clear declines are lacking) the average declines and durations of the declines per flue-gas cooling cannot be calculated for CAF.

³² Trend lines:
 High pressure: $y = -0.245x - 40.557$; $R^2 = 0.5548$
 Low pressure: $y = -0.4024x - 52.049$; $R^2 = 0.8072$
 CAF: $y = -0.0902x - 5.2734$; $R^2 = 0.6535$
 Firedos: $y = -0.2003x - 38.758$; $R^2 = 0.5075$

Table 5.2 Total decline in flue-gas temperature of the average values per system, thermocouple 5

System	Average decline in flue-gas temperature per flue-gas cooling 4-6 in °C; thermocouple 5	Duration of cooling capability (per series of shots) flue-gas cooling 4-6, in seconds
CAF	-	-
Firedos (3%)	61	3.1
Low pressure	103	5.3
High pressure	77	4.4

Table 5.2 shows that low pressure gives the greatest average decline and that the decline continues longest per flue-gas cooling.

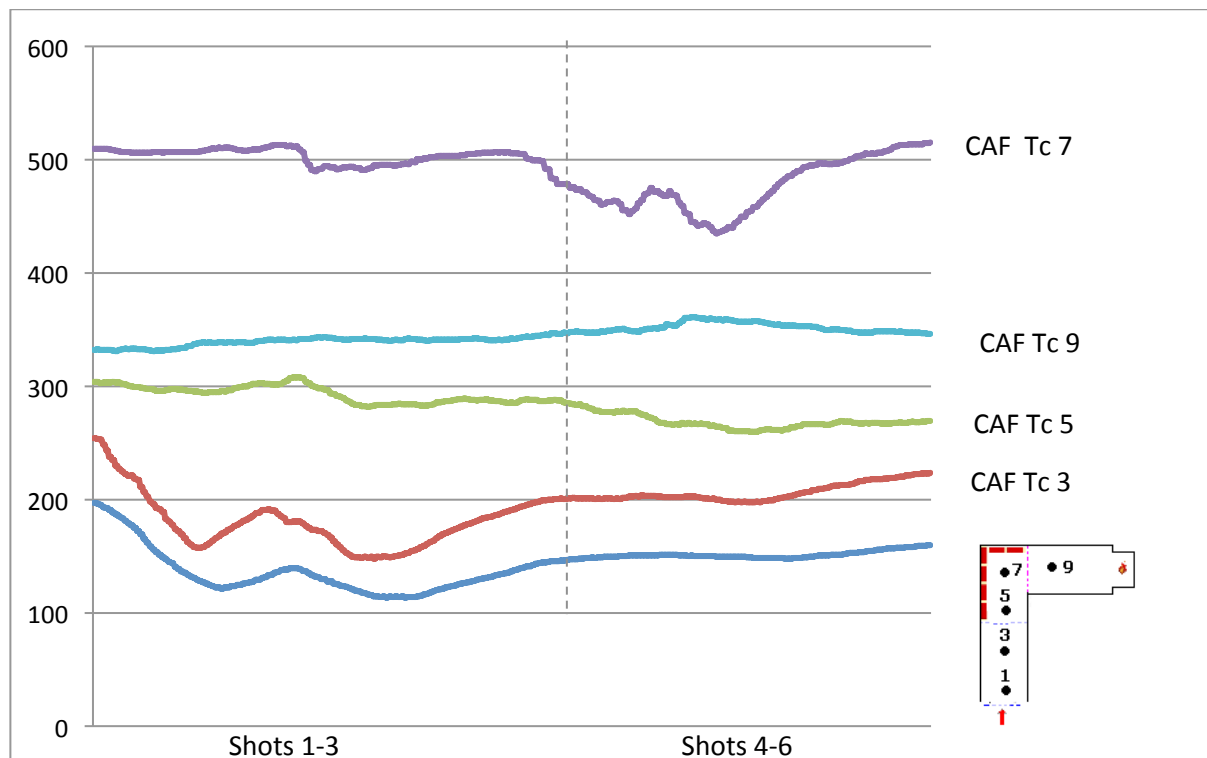
5.3 Temperature trend in the whole container during flue-gas cooling

It was then examined what the temperature trend is on the ceiling in the whole container during the series of flue-gas cooling. Figure 5.4 shows the average temperature trend per system per thermocouple.

It was expected that an effect could be seen, particularly on thermocouples 1 (in front of the container near the door) and 3 (halfway in the first part of the compartment) in the first series of flue-gas cooling. In the second series of flue-gas cooling, the values were read from thermocouples 5 (in front of the second part of the compartment) and 7 (in the corner)³³. Thermocouple 9 was placed near the seat of the fire.

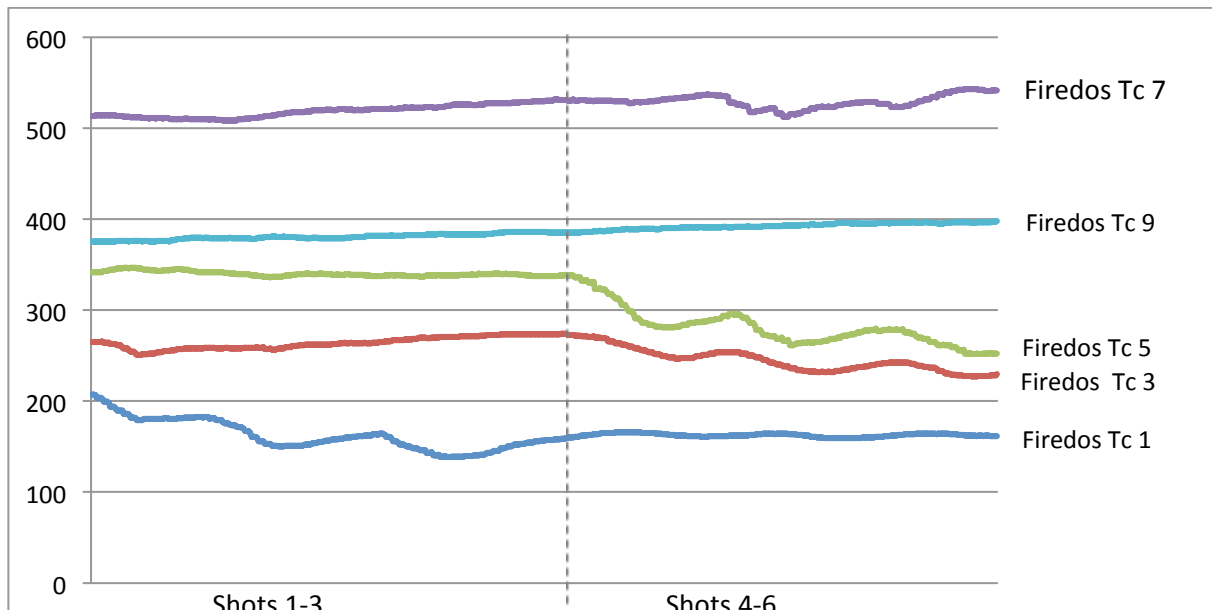
³³ Due to its location in the corner, thermocouple 7 is not only heated up by convection but also by direct radiation from the seat of the fire.

Figure 5.4 Temperature trend of flue-gas cooling with CAF, average values per thermocouple



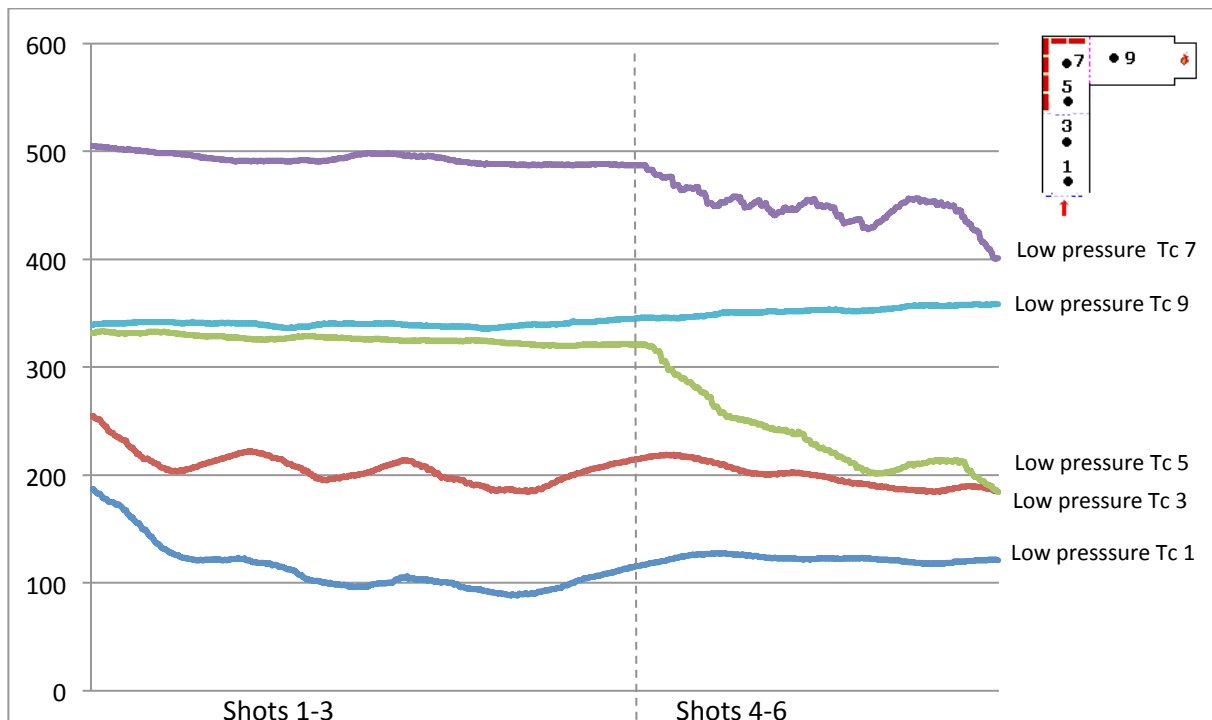
The graph of CAF shows that an effect is seen on the foremost thermocouples (1 and 3) in the first series of flue-gas cooling. In the second series (about halfway on the graph) we see a limited effect on thermocouple 7, but the temperatures read from the other thermocouples (1, 3 and 5) show no decrease and even rise slightly. This increase in temperature also takes place *behind* the fire-fighting crew. We see an increase in temperature on thermocouple 7 immediately afterwards, and this continues until the end of the series of flue-gas cooling.

Figure 5.5 Temperature trend flue-gas cooling FD, average values per thermocouple (TK)



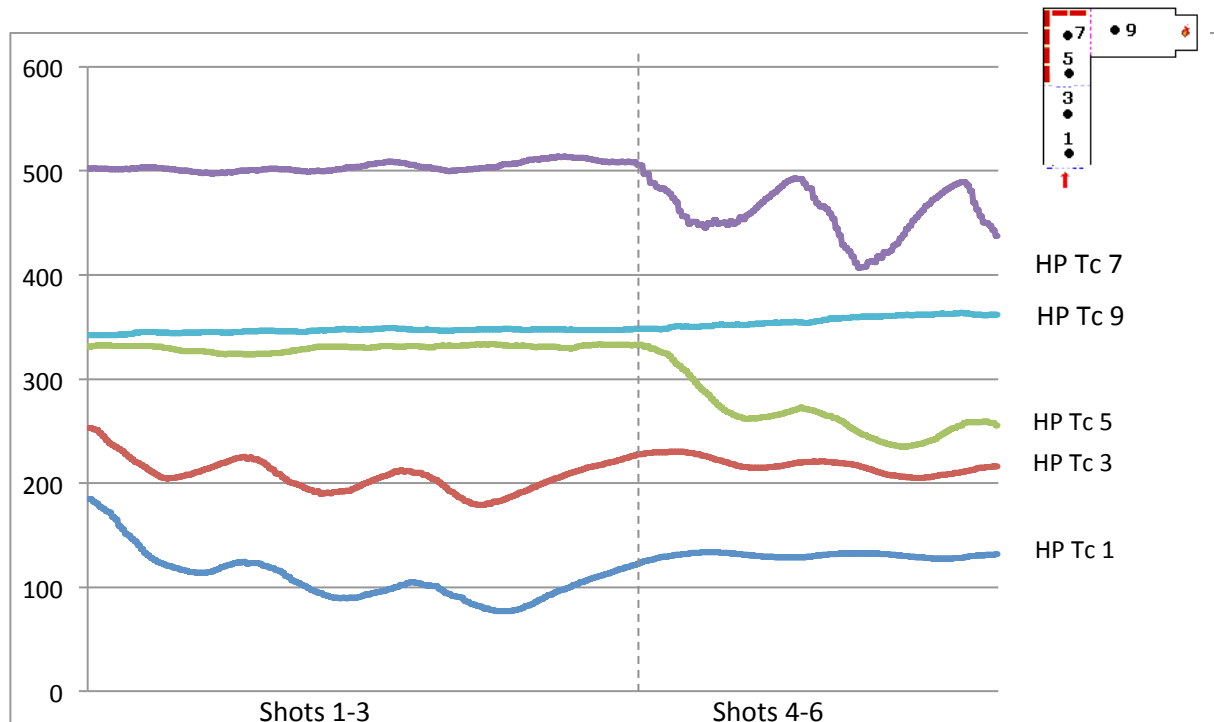
The temperature trend of the tests with Firedos shows that there is an effect on thermocouple 1 in the first series of flue-gas cooling. The effect of the second series of flue-gas cooling is seen on thermocouples 3 and 5. No decreased effect is seen on the temperatures around thermocouples 7 (further on in the container) and 9 (behind the fire-fighting team) but a small increase in temperature is observed.

Figure 5.6 Temperature trend of flue-gas cooling with low pressure, average values per thermocouple



When low pressure is used, we can see an effect of flue-gas cooling in the direct environment (thermocouples 1 and 3) in the first series. In the second series of flue-gas cooling, we see a strong effect on thermocouples 5 and 7, and a decline in temperature in thermocouple 3.

Figure 5.7 Temperature trend of flue-gas cooling with high pressure, average values per thermocouple



The graph for high pressure (figure 5.7) shows the effect of the first series of flue-gas cooling (thermocouples 1 and 3) in the direct environment; the final temperature declines. The second series of flue-gas cooling shows a strong effect on thermocouples 5 and 7 (ultimate decline in temperature), though there is a strong fluctuation in temperature. We can also see a slight decrease in temperature behind the fire-fighting crew on thermocouple 3 and to a lesser degree on thermocouple 1.

5.4 Water consumption in relation to flue-gas cooling

Water consumption was measured with a water meter during the experiments. Water consumption during the entire flue-gas cooling was compared with the total decrease in temperature on thermocouple 5. As a foam-forming agent and air is added to foam-forming systems, the total volume of used extinguishing agent is considered. This is shown in table 5.3.

Table 5.3 Average water consumption during flue-gas cooling (excluding the flushing system)

Extinguishing system	Used quantity of water in litres	Standard Deviation	Temperature decrease of total flue-gas cooling Tc 5	Temperature decrease in degrees per litre of water
Compressed air foam	29	8.8	41	1.4
Firedos (3%)	47	3.8	78	1.7
Low pressure	42	6.6	152	3.6
High pressure	32	3.5	73	2.3

Table 5.3 shows that more water is used for Firedos and low pressure than for CAF and high pressure. There is, however, a variation in the amount of litres of water in the various tests in which CAF shows the largest variation (standard deviation). The tests with high pressure and Firedos can be called quite stable as shown in the standard deviation of 3.5 and 3.8. The temperature decline of the whole flue-gas cooling (measured with thermocouple 5) is the largest in the tests with low pressure (152 °C) and the smallest in the tests with CAF (41°C). When the decline in temperature is compared with the quantity of water used, it appears that the flue-gas cooling capability of low pressure is the biggest (3.6 °C/l) and the flue-gas cooling capability of CAF the smallest (1.4 °C/l). The flue-gas cooling capability of Firedos is slightly higher than CAF but lower than high pressure.

However, not only the used volume of water but also the used volume of extinguishing agent is taken into consideration when fires are attacked and its aftercare. As it is, one litre of water is turned into many litres of foam. If a large volume of extinguishing agent is used it may lead to much collateral damage. The difference becomes stronger when looked at the volume of extinguishing agent used. See also table 5.4.

Table 5.4 Use of extinguishing agent during the flue-gas cooling

Extinguishing agent	Theoretical volume of extinguishing agent used, in litres	Standard deviation	Temperature decline in total flue-gas cooling; Tc 5 in °C	Temperature decline in °C per litre of extinguishing agent
Compressed-air foam	200	61.7	41	0.2
Firedos (3%)	142	11.4	78	0.5
Low pressure	42	6.6	152	3.6
High pressure	32	3.5	73	2.3

Per used litre of extinguishing agent, low pressure gives by far the largest decline in temperature with 3.6 °C per used extinguishing agent. This is slightly less with high pressure (2.3 °C), followed by Firedos (0.5 °C) and compressed-air foam (0.2 °C).

5.5 Possible explanations for the results found

Temperature trend of separate flue-gas cooling

When the lines for temperature trend in the four systems during the tests for flue-gas cooling are compared we see a striking result in the tests with Firedos and CAF; in the first series of flue-gas cooling (figure 5.2), Firedos scores worse as compared with CAF (and low pressure and high pressure), whereas in the second series further on in the container (figure 5.3), CAF hardly gives cooling to flue gases, and Firedos scores better (about as well as high pressure). An explanation was sought for this striking result and possible explanations are:

1. The force of the CAF jet might have sucked air inside and this causes ventilation. There was cold outside air in the first series of flue-gas cooling. In the second series of flue-gas cooling there was warm environmental air in the container and no cold air could be brought into the flue-gas layer.

CAF has a large throw length and is exits with high pressure from the jet nozzle. In the first series of flue-gas cooling, the crew stood at about 7-metre distance from the container, and this caused the jet to fan out more at the spot where the flue-gas cooling had to take place. In the second series of flue-gas cooling, the distance between the marshalling line and the hindmost wall was about 4.5 metres.

A possible explanation why Firedos had little effect the first time and seemed effective in the second series is that the mix in the beginning was different from the mix in the second series. Due to the time that the mix was in the hose, there may have been relatively more foam and less water. After a couple of shots of flue-gas cooling, the hose was flushed as a result of which the mixing ratio was better. However, it could not be established whether this was indeed the case.

Temperature trend in the whole container during flue-gas cooling

Comparing the various systems, the following is noticed about what happened in the whole space of the container:

2. Compressed-air foam had hardly any effect especially in the second series of flue-gas cooling, and the effect that it had was almost countered by the ensuing increase in temperature in the flue-gas layer. A possible explanation is that the jet caused a whirl, which worked as a form of repressive ventilation by adding and mixing cold air. Other explanations are the creation of a block by pressure differences, or that the foam-forming agent in the back of the container decomposed due to the heat. Firedos showed a limited cooling effect and this effect was stronger with high pressure and low pressure.
3. Compressed-air foam did not give a cooling effect on flue gas *behind* the fire-fighting crew. The temperature behind the crew did not decrease and even increased in spite of the flue-gas cooling efforts further on in the container. Firedos gave a temperature decrease but the decrease was smaller than with low pressure and comparable with high pressure.

Water consumption in relation to flue-gas cooling

Analysis of the flue-gas cooling effect of the quantity of water used shows that the flue-gas cooling effect of low pressure is highest despite the fact that not much more water is used. In the tests with low pressure, the effect of temperature decline per litre of used water is many times greater than in the tests with foam (Firedos and CAF).

When the total volume of extinguishing agent is taken into account, foam appears to have even a lesser effect per litre of extinguishing agent than water.

In the Netherlands, both Firedos and CAF are applied in different ways. Firedos usually has a 3% mix, but a 0.3% mix also occurs. When applying CAF, the difference can be in the chosen way of application (short pulses into the flue-gas layer or longer pulses putting foam on the walls and ceiling) or in a jet nozzle with a valve (a Swedish model that is applied there), and a jet nozzle without valve, which is most common. It is possible that these two differences have effect on the performance with Firedos and CAF. In addition to the tested systems, two Firedos tests were done with a 0.3% added mix and (requested by one fire service region) an additional test with CAF jet nozzle with valve instead of without valve as used in the regular study. These tests, which must be seen as bycatch of the study, are included in Chapter 8.

5.6 Conclusions of flue-gas cooling

The tests show that with low pressure the temperature trend of the entire flue-gas cooling (on thermocouple 5) is biggest. High pressure and Firedos have a mutually comparable and less cooling effect on the temperature in the flue gases. Compressed-air foam shows the least cooling of flue gases; the temperature decreases 41 °C after two series of flue-gas cooling, whereas the temperature decreased 138 °C with low pressure.

Furthermore, the cooling effect of especially low pressure continues during the flue-gas cooling even if new pulses are given in the intervening time and new hot flue gases are supplied. Though to a lesser extent, this also applies to Firedos and high pressure, and hardly applies to compressed-air foam.

If looking separately at the two series of flue-gas cooling, it appears from the trend line in the first series of flue-gas cooling that Firedos cools least. Low pressure and high pressure cool the flue gases best and compressed-air foam also shows a decline in flue-gas temperature.

In the second series of flue-gas cooling, low pressure shows the best results again, both compared with the other systems and compared with the first series of flue-gas cooling. It is noteworthy that compressed-air foam, in the way it is applied in this research, then shows the worst results with a total temperature decline of 20 °C. It also strikes that Firedos scores worse in the first series of flue-gas cooling as compared with compressed-air foam (and with low pressure and high pressure), where further in the container in the second series CAF has hardly any effect on the cooling of flue gases and Firedos scores better (about as good as high pressure). Probably, the relatively positive effect of compressed-air foam in the first series was caused by air being sucked in by the CAF jet and that cold environmental air was brought into the container. A possible explanation why Firedos has little effect and seems effective in the second series is that in the beginning the mix was different than in the second series.

When looking at the temperature trend in the whole container at the same time it strikes that the temperature decreased with low pressure and high pressure both in front of and behind the fire fighters during flue-gas cooling. Firedos only has effect on the direct environment. CAF shows a brief decrease in front of the fire-fighting crew to be followed by an increase in the temperature both in front of and behind the fire-fighting crew.

If the cooling capability is compared with water consumption, it appears that the flue-gas cooling capability per litre of water used is bigger with low pressure. The foam-forming systems cool least per litre of water used, in which compressed-air foam scores worst. If the cooling capability is compared with the volume of extinguishing agent used (water or water with air and foam) then the difference between the systems that use only water and the foam-forming systems is even greater.

6 Extinguishing results

This chapter describes the extinguishing results.

The speed of the first knockdown is determined from the time of the “start extinguishing” until the time that no flames were visible. At that time, the fire is still in the smouldering phase. Then it was observed how long it took before the fire re-ignited. The fire was attacked again for ten seconds after re-ignition. This process was repeated several times. As the follow-up very much depended on whether the fire re-ignited or not, only the first knockdown and re-ignition was included in the comparison between the systems.

6.1 Speed of the first knockdown and first re-ignition

Table 6.1 gives the duration until the first knockdown and the duration until the first re-ignition³⁴.

Table 6.1 Speed of first knockdown and first re-ignition

Extinguishing system	Average duration until first knockdown in seconds	Standard deviation of the knockdown duration	Average duration until first re-ignition in seconds	Standard deviation until the first re-ignition
Compressed-air foam	4.2	0.8	10.8	2.3
Firedos (3%)	6.6	1.7	26.0	10.6
Low pressure	5.8	0.8	19.6	12.1
High pressure	4.0	0.7	15.4	3.8

The table shows that high pressure and CAF realised the quickest knockdown. Moreover, the standard deviation is small which means that the various tests for each system give little variation in the duration until the first knockdown.

When looking at the average duration until the first re-ignition, Firedos takes the longest time. However, this system gives a less steady performance than high pressure and CAF in the various tests; the standard deviation for the tests with Firedos is 10.6 as compared with 2.3 for CAF and 3.8 for high pressure.

6.2 Temperature trend of the entire extinguishing (including re-ignition)

Table 6.2 compares the results of the extinguishing with the various systems for the temperature in the container. Thermocouple 10 was used for this purpose as it is located closest to the seat of the fire where the effect of the extinguishing can be best measured.

³⁴ It should be noted here that on account of the set-up of the experiments, it was not allowed to extinguish after the flames had disappeared, though this is usually done in actual practice. The results must therefore be seen within the set-up of the experiment.

Table 6.2 Comparing the effectiveness of extinguishing with various systems

Extinguishing system	Average decrease in temperature after the 1st knockdown	Standard deviation	Number of re-ignitions (per system)
Compressed-air foam	38	9.6	4 - 5
Firedos (3%)	109	13.9	2 - 4 (or more)
Low pressure	84	33.1	1-à 3
High pressure	81	32.4	4 - 5

Table 6.2 shows that extinguishing with Firedos in the first knockdown is most effective as far as decrease in temperature is concerned ($\Delta T_{FD,kd1,average} = 109 \text{ }^\circ\text{C}$) and also gives reasonably constant results ($SD_{FD} = 13.9$).

As shown in table 6.1, CAF created a quick knockdown, but is in extinguishing the least effective in decreasing the temperature ($\Delta T_{CAF,kd1,average} = 38 \text{ }^\circ\text{C}$), but is the most constant ($SD_{CAF} = 9.6$).

Extinguishing with low pressure and high pressure gives per test variable results in decreasing the temperature, but the average temperature decline is substantial ($\Delta T_{Low\ pressure,kd1, average} = 84 \text{ }^\circ\text{C}$; $\Delta T_{High\ pressure,kd1, average} = 81 \text{ }^\circ\text{C}$). Low pressure gives the least amount of re-ignitions, CAF and high pressure give the most.

Figure 6.1 gives the average temperature trend on thermocouple 10 for the examined systems. The figure below gives the results for each system.

Figure 6.1 Temperature trend for extinguishing with CAF (DLS), thermocouple 10 (TK)

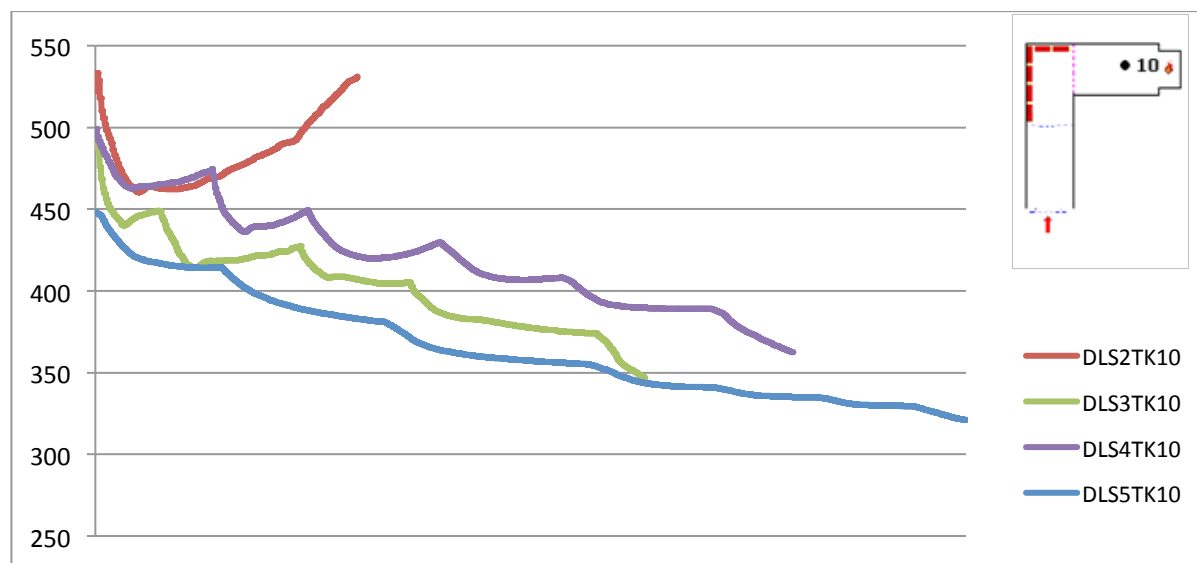
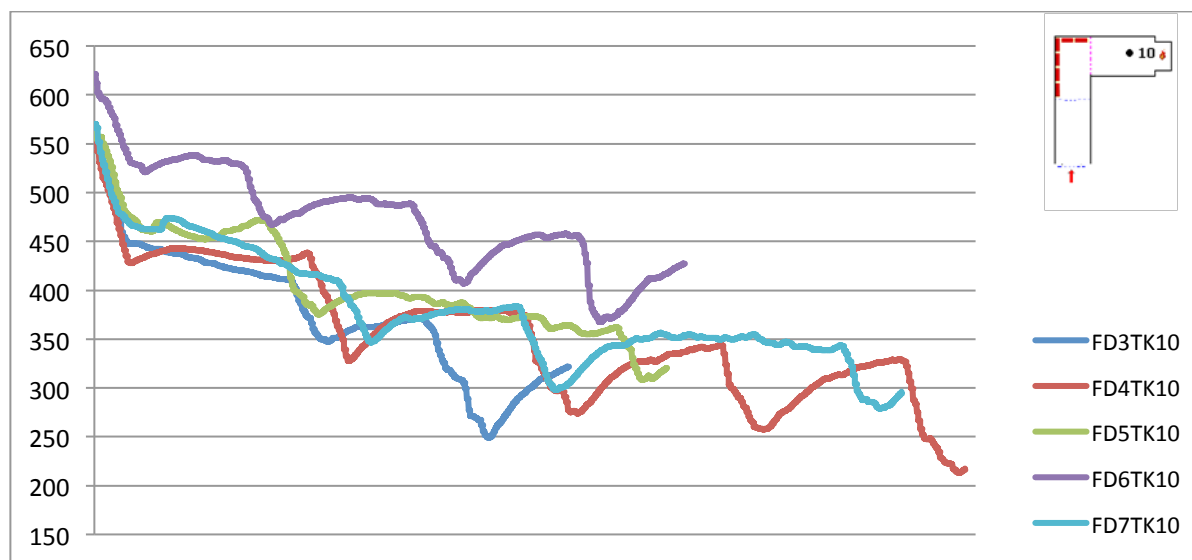


Figure 6.1 shows that the temperature in the first knockdown (kd1) with CAF is lowered with $44 \text{ }^\circ\text{C}$ ($SD=14.5$) ($\Delta T_{CAF2,kd1} = 62 \text{ }^\circ\text{C}$; $\Delta T_{CAF3,kd1} = 48 \text{ }^\circ\text{C}$; $\Delta T_{CAF4,kd1} = 36 \text{ }^\circ\text{C}$; $\Delta T_{CAF5,kd1} = 29 \text{ }^\circ\text{C}$). In the figure, the re-ignitions are visible as peaks in the graph. 4 to 5 re-ignitions have been observed in the three tests though it is difficult to read them in 'CAF5' due to the limited temperature increase.

Figure 6.2 Temperature trend of extinguishing with Firedos, thermocouple 10



The above figure shows that the separate tests with Firedos give comparable results: the initial temperature in test FD6 is about 50 °C higher than in the other tests, the temperature trend still follows the same pattern as in the other tests.

In the first knockdown (kd1) with Firedos, the temperature decreased about 109 °C (SD=13.9) ($\Delta T_{FD3,kd1} = 101$ °C; $\Delta T_{FD4,kd1} = 133$ °C; $\Delta T_{FD5,kd1} = 102$ °C; $\Delta T_{FD6,kd1} = 100$ °C; $\Delta T_{FD7,kd1} = 108$ °C). Several re-ignitions were also observed in various tests, varying from 2 in test 'FD3' to 4 or more in the other tests (the tests with Firedos were stopped after 4 re-ignitions). The tests with quick re-ignitions are visible in the table as shorter lines.

Figure 6.3 Temperature trend of extinguishing with low pressure, thermocouple 10

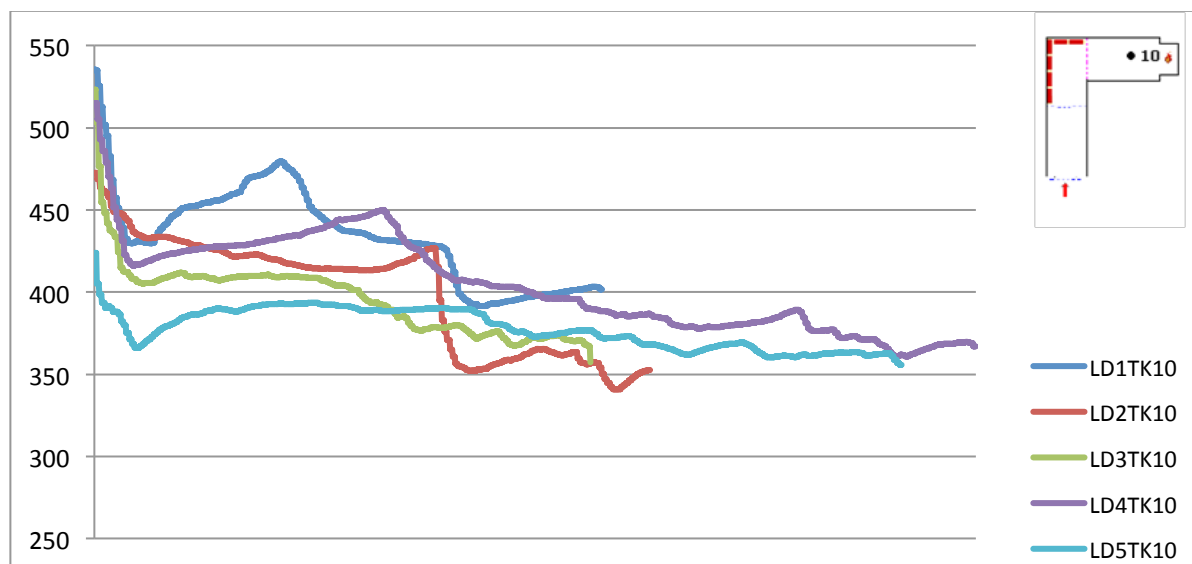
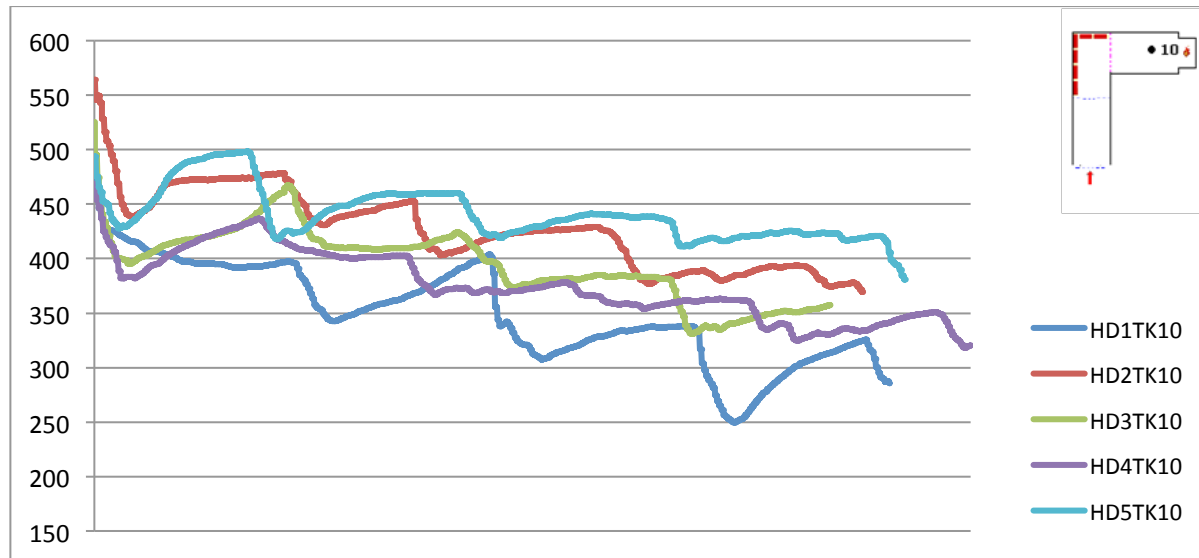


Figure 6.3 shows that in the first knockdown (kd1) with low pressure, the temperature decreases with about 84 °C ($\Delta T_{Low\ pressure\ 1,kd1} = 106$ °C; $\Delta T_{Low\ pressure\ 2,kd1} = 40$ °C; $\Delta T_{Low\ pressure\ 3,kd1} = 117$ °C; $\Delta T_{Low\ pressure\ 4,kd1} = 98$ °C; $\Delta T_{Low\ pressure,kd1} = 58$ °C). The effectiveness of the first knockdown differs very much per test (SD=33.1). After the first knockdown with the

low pressure tests, the fire flared up 1-3 times with a generally small increase in temperature.

Figure 6.4 Temperature trend of extinguishing with high pressure, thermocouple 10



In the first knockdown, the effectiveness of extinguishing with high pressure is similar to the effectiveness of extinguishing with low pressure. After the first knockdown, the average decrease in temperature is about 81 °C, which is substantial ($\Delta T_{\text{High pressure1,kd1}} = 81 \text{ °C}$; $\Delta T_{\text{High pressure2,kd1}} = 41 \text{ °C}$; $\Delta T_{\text{High pressure3,kd1}} = 129 \text{ °C}$; $\Delta T_{\text{High pressure4,kd1}} = 87 \text{ °C}$; $\Delta T_{\text{High pressure5,kd1}} = 65 \text{ °C}$), but there are great differences between the tests ($SD=32.4$). On the other hand, in the pattern of knockdown and re-ignition, the results of extinguishing with high pressure are similar to the various tests. The fire flares up 4 to 5 times per test.

6.3 Temperature trend in the whole container during extinguishing

The fire fighters were in the back of the container during extinguishing. With flue-gas cooling with CAF, it was found that the flue-gas layer behind the crew sometimes increased in temperature and even almost led to ignition of the flue-gas layer during the attack. These situations are dangerous. To get a picture of the effect of extinguishing on the temperature trend *behind* the fire fighters, the measurements of thermocouples 1, 3, 5, 7, 9 and 10 during extinguishing are analysed in this section.

Figure 6.5 Temperature trend of extinguishing with CAF (DLS), average values per thermocouple (TK)

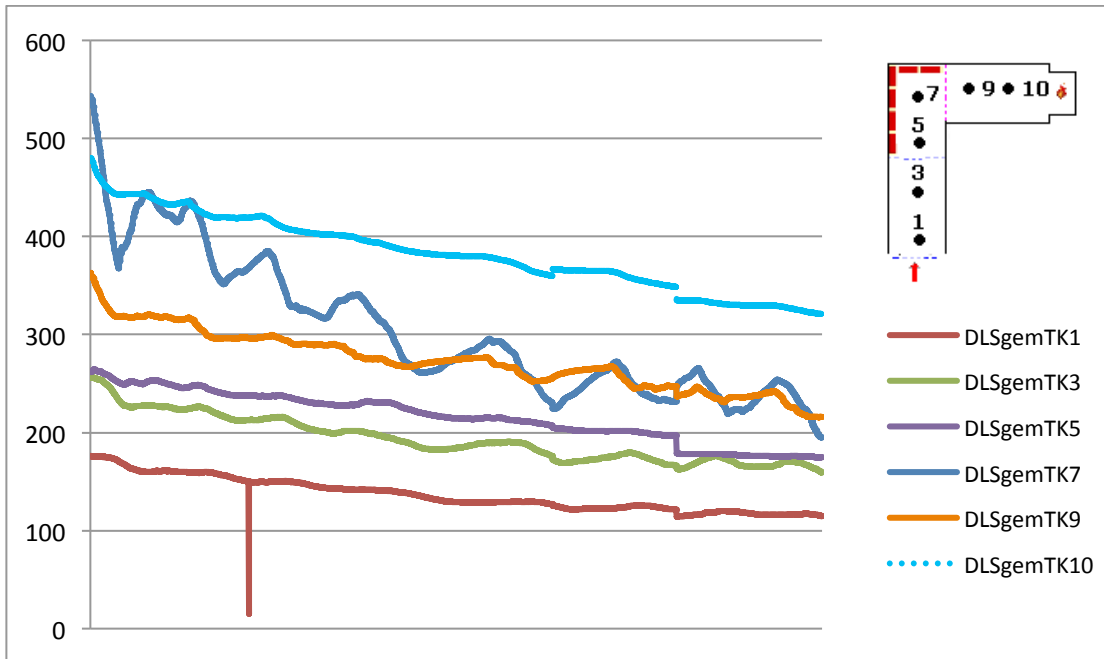


Figure 6.6 Temperature trend extinguishing with Firedos, average values (gem) per thermocouple (TK)

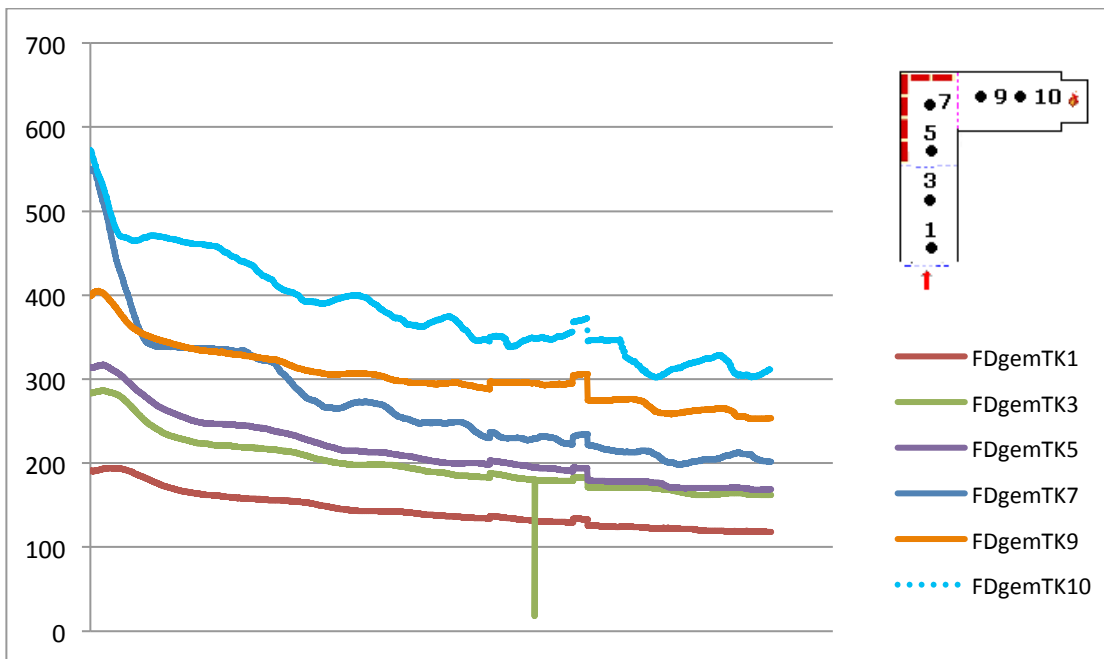


Figure 6.7 Temperature trend of extinguishing with low pressure (LD), average values per thermocouple (gem T)

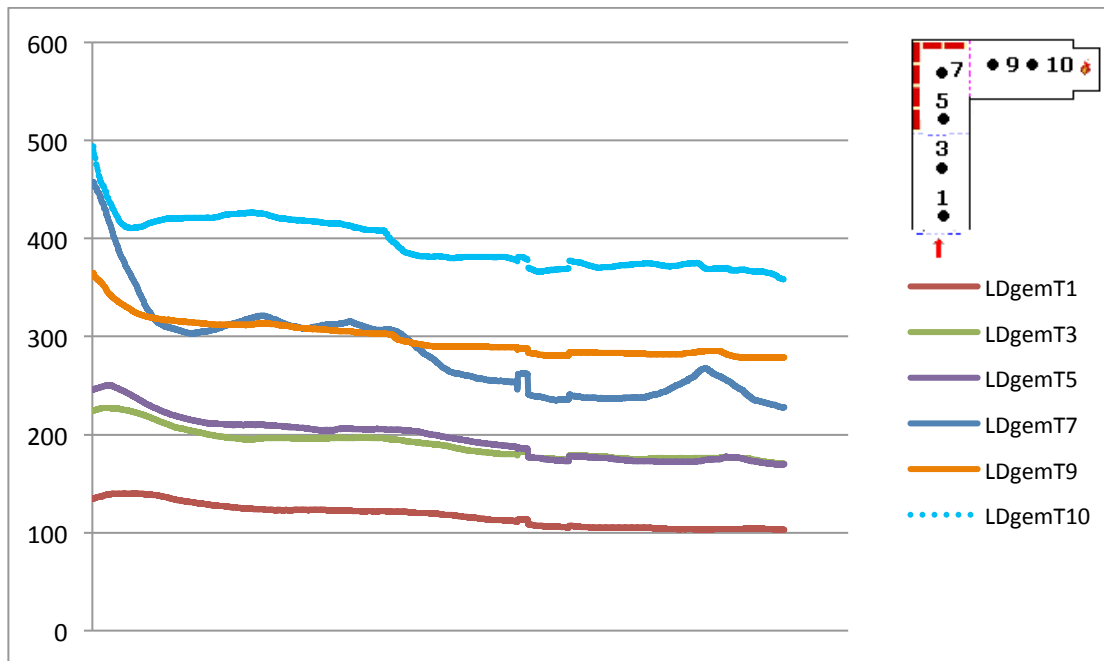
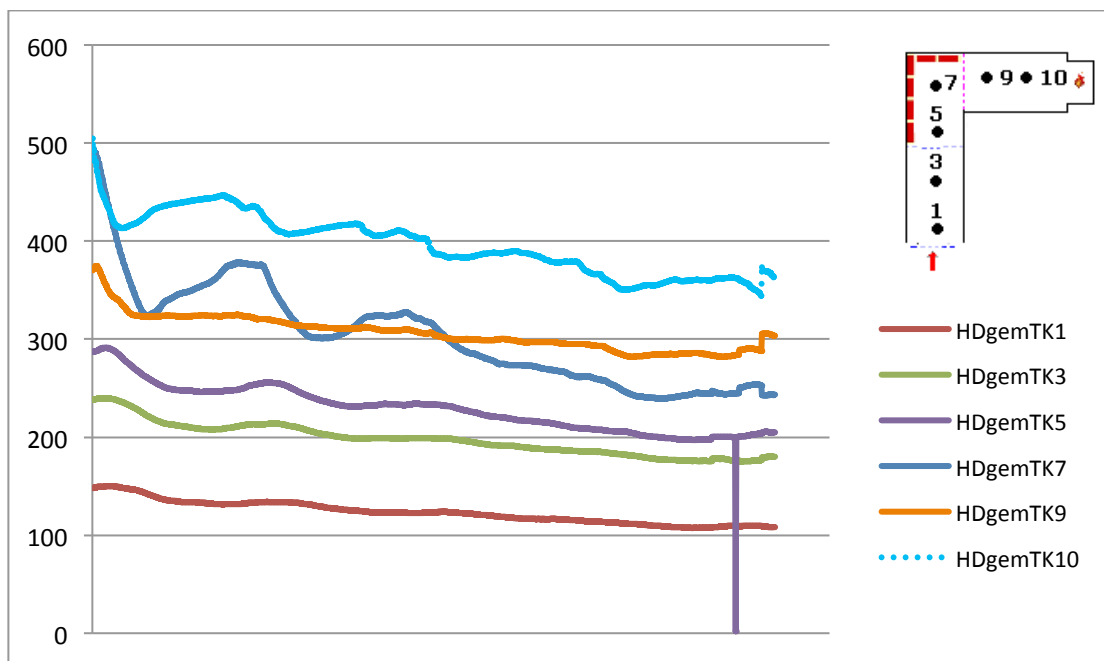


Figure 6.8 Temperature trend for extinguishing with high pressure (HD), average values per thermocouple (gemTK)



The above graph shows that low pressure and high pressure give in general a declining line in the temperature in the container. There is also a declining line for CAF and FireDOS but it is noteworthy that especially the temperature on thermocouple 7 shows peaks (especially for CAF and, to a lesser extent, for high pressure) which partly undo the cooling effect of extinguishing.

6.4 Water consumption for extinguishing and effectiveness of the systems

To compare the systems, table 6.3 gives the duration of the first knockdown, the quantity of water and the volume used and the temperature after the first knockdown.

Table 6.3 Comparing the performance of various extinguishing systems

Extinguishing system	Average duration until the first knockdown in seconds (standard deviation)	Quantity of <u>water</u> used until the first knockdown in litres (standard deviation)	Theoretical quantity of <u>extinguishing agent</u> used until the first knockdown in litres (standard deviation)	Average decrease in temperature after the first knockdown in ° Celsius
Compressed-air foam	4.2 (0.8)	9 (0.8)	63 (5.7)	38
Firedos (3%)	6.6 (1.7)	13 (6.1)	38 (18.3)	109
Low pressure	5.8 (0.8)	10 (2.7)	10 (2.7)	84
High pressure	4.0 (0.7)	7 (1.8)	7 (1.8)	81

The table shows that high pressure and CAF realise the quickest knockdown and that high pressure uses the least amount of water. The temperature decreased quickest with Firedos. High pressure and low pressure also give a substantial decrease in temperature. CAF gives a limited decrease in temperature.

When the use of water and extinguishing agent is compared with the decrease in temperature it appears that high pressure is most efficient in extinguishing per litre of water and that compressed-air foam is least effective both per litre of water and per litre of extinguishing agent used.

Table 6.4 Comparison of decrease in temperature per litre used

Extinguishing system	Temperature decrease in ° C per litre of water used for extinguishing	Temperature decrease in ° C per extinguishing agent used
Compressed-air foam	4.2	0.6
Firedos (3%)	8.4	2.9
Low pressure	8.4	8.4
High pressure	11.6	11.6

6.5 Conclusions

High pressure and CAF realise the quickest knockdown and high pressure uses the least amount of water. Firedos needs the longest time for creating a knockdown. However, the average duration until the first re-ignition is longest for Firedos, though the variation in the tests is big. This applies to a lesser degree to low pressure. Though CAF creates a fast knockdown, re-ignition is relatively quick in the selected set-up of the study, and each time almost identical results are found with CAF in between the tests.

As to the decrease in temperature in the first knockdown (regardless of the quantity used), extinguishing with Firedos is most effective. Extinguishing with low pressure and high pressure gives a higher average temperature decline than CAF but less than Firedos. If this is compared with the quantity of water and extinguishing agent used, high pressure and low pressure score best.

The temperature decline in the container with low pressure and Firedos is constant. We can see a declining line with CAF and high pressure, but it is noteworthy that the temperature shows peaks almost immediately after the decline, which partly undoes the cooling action of the extinguishing. This is stronger with CAF than with high pressure.

In conclusion, it can be claimed that Firedos needs the longest time for a knockdown, but is then very effective in bringing the temperature down. On the other hand, it consumed the highest quantity of extinguishing agent. If this is compared with the consumption, high pressure and low pressure score best in extinguishing. CAF scores well in creating a

quick knockdown but gives a limited decline in temperature in the space (38 °C) and gives an increase in temperature between the shots.

7 Other findings

The experiences in the container were reported by the observers and the crew after every attack. The experiences they shared after the tests are reported in this chapter. Though this was originally not part of the study, the examiners judged that these other findings were so important that it is justified to include them in this report.

7.1 Spontaneous re-ignition of flue-gas layer with foam systems

During the tests, it was observed that there were (sudden, spontaneous and almost full) combustions of the flue-gas layer. They took place after creating the knockdown and were not ignited by the seat of the fire, according to the observers and operators of jet nozzles. This only took place with tests with CAF and the additional test with Firedos 0.3%³⁵.

One observer of one of the tests with CAF reported:

At the time of starting extinguishing the seat of the fire, you see a knockdown, absolutely. When they closed the jet nozzle, it was getting dark and you saw the fire disappear. Suddenly the flue gases above your head ignited again spontaneously. And in these tests you don't have much flue gases (...) you have heat, flue gases and there is oxygen (...) there was only 30 cm of smoke during the testing but in a higher, broader and longer space there are much more combustible gases. In the test, the flue gas combustion took place in about 10 minutes after the fire developed, but in real life, with another mix ratio and in a later stage, you can find yourself in a completely different situation.

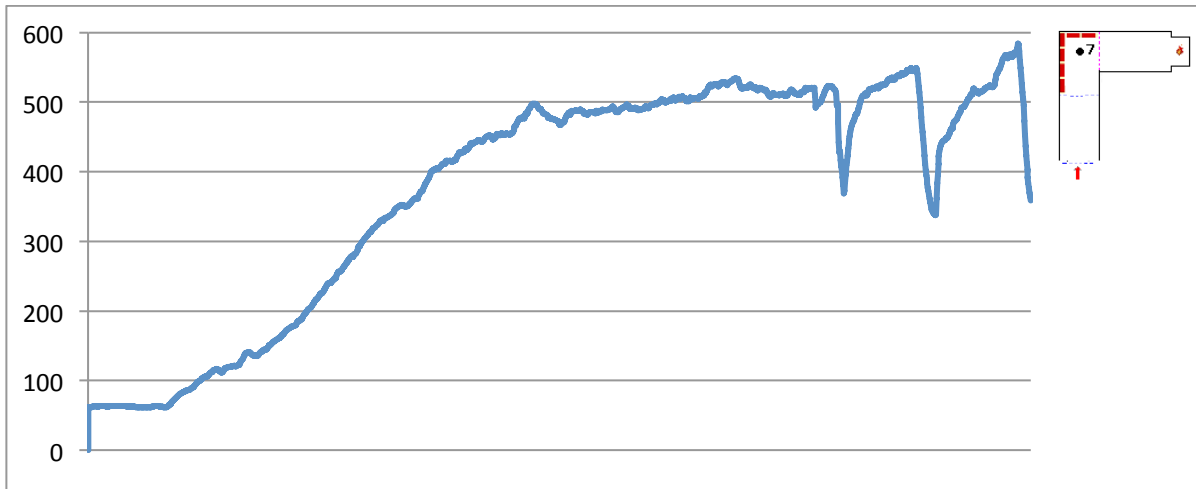
The handler of the jet nozzle in a test with Firedos 0.3% said:

In creating my knockdown, I did the same as with high pressure. But immediately after realising the knockdown and after stopping extinguishing, there was an extreme fire gas ignition. It was a complete one, and reached us. The whole ceiling of the container with the fire load was covered with fire.

In the tests in which a sudden ignition of the flue-gas layer was observed, the temperature trend in the container was examined. The temperature trend is given in figures 7.1 to 7.4. All figures show a quick temperature increase in thermocouple 7 after the temperature decrease as a result of extinguishing.

³⁵ There was a once-only ignition of the flue-gas layer with high pressure extinguishing, but this was ignited by the seat of the fire and did not reach anywhere near that far and was many times smaller and narrower.

Figure 7.1 Temperature trend from the time of ignition until the end of the test, CAFS test 2, thermocouple 7



When looking at the temperature in the whole container, the temperature of thermocouples 9 and 10 decreases (and increases later) in this test, but we see the temperature decrease and increase on thermocouple 7 to above the temperature level behind the fire fighters before starting extinguishing. The temperature behind the extinguishing crew increases from about 350 °C to about 560 ° C. See also figure 7.2.

Figure 7.2 Temperature trend throughout the whole container, with CAF (DLS) test2

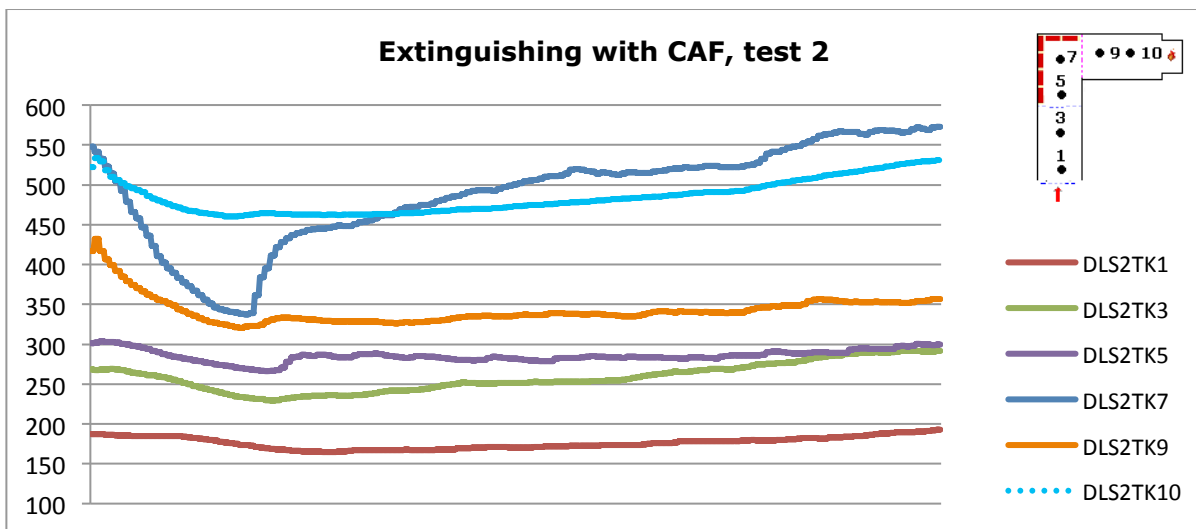


Figure 7.3 Temperature trend from ignition to the end of the test, CAF test 3, thermocouple 7

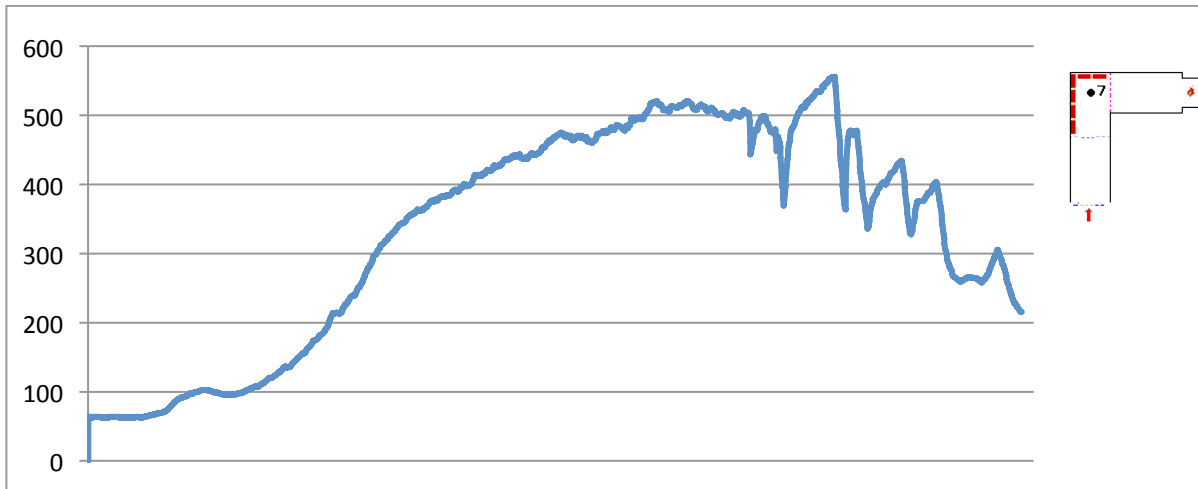
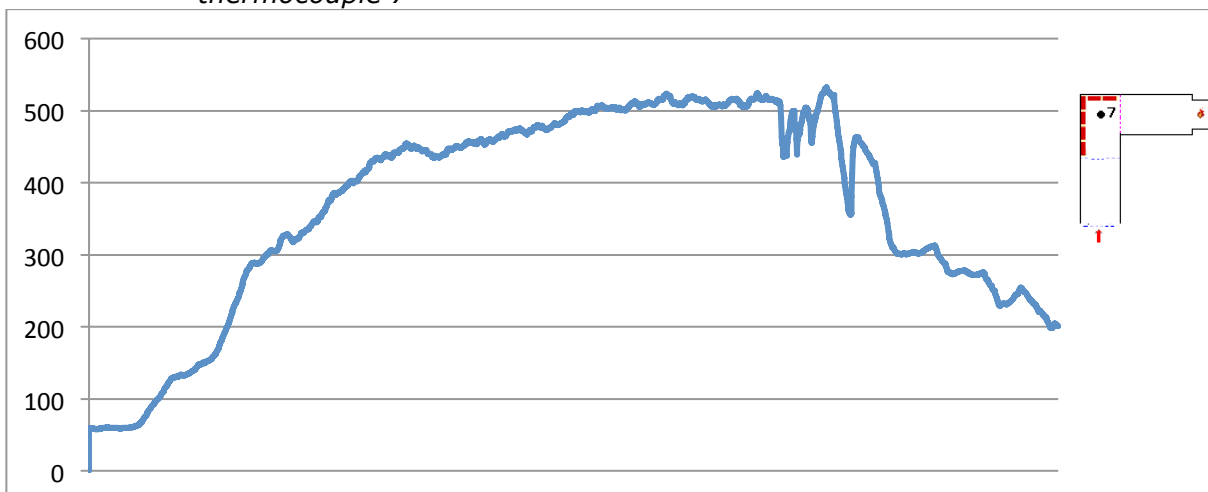


Figure 7.4 Temperature trend from ignition to end of the test, Firedos (0.3%) test 2, thermocouple 7



The sudden ignition of a flue-gas layer, especially when this is created by spontaneous combustion, can lead to very dangerous situations for the fire service. In an actual fire in a larger building, the above-mentioned situations could result in accidents. It is noteworthy that these sudden combustions of flue-gas layers took place only with foam-forming systems (two of the five tests with CAF and the test carried out with Firedos 0.3%). However, this did not happen in other tests with these systems. It can therefore not be said whether the sudden ignition of the flue-gas layer is a direct or indirect consequence of flue-gas cooling and/or extinguishing with foam. Further studies into this matter are required.

7.2 Sticking qualities of CAF

Observers made remarks about the extent to which CAF continued to stick to walls and ceilings during the test. The observer remarked that CAF no longer stuck to walls and ceilings when the container became hot and exceeded a certain temperature.

A brick wall was built in the container for the test. The observers reported having seen no difference in the sticking capability of CAF on bricks or steel in the test environment.

7.3 Experiences about heat and re-ignition

The lighter assistant remarked that the temperature of the container felt much lower with extinguishing with water than extinguishing with foam, as a result of which he could enter sooner to make the space ready for the next test. The lighter assistant also remarked that the fire was better extinguished with water than with foam.

One observer remarked that it was much less warm after low pressure than after foam and the probable cause was the throw length. It was also notified that the re-ignition after high pressure was many times severer than after low pressure.

8 Additional tests with foam systems

In spite of prior coordination about the correct tactics for deploying foam systems, there was still discussion about the mixing percentage of Firedos (3% versus 0.3%) during the tests. Moreover, the region that supplied CAF saw the Swedish valve on the CAF jet nozzle during a follow-up course. This valve was meant for fan-shaped spreading into the space. The question was whether this valve had any additional value. That is why it was decided to carry out two additional tests with Firedos with a mixing percentage of 0.3%, and an additional test with a CAF jet nozzle with valve.

The data of these tests were analysed although they were the bycatch of the original study. It should be noted that the test with CAF (with valve) was carried out only once and the test with Firedos (0.3%) was carried out twice, and the reliability of the results is therefore limited. For practical reasons, more tests with these systems were not possible in this study. Additional studies may be required to give a well-founded answer to the question what the difference is between deploying Firedos 3% and 0.3% or CAF with or without a valve.

However, to give a first indication, the results of these tests are given below and compared with the results of the CAF and Firedos systems in the original study.

8.1 CAF with valve compared with CAF without valve

In Sweden, the nozzle for compressed-air foam is fitted with a valve during the phase of flue-gas cooling. This produces a fan-like jet. The region involved had this valve on loan from Sweden and asked to do a test with this valve. That is why we did one extra test regarding flue-gas cooling with this valve. Figure 7.1 shows the temperature trend in the container. However, as a failure occurred in thermocouple 5 during the test, these data are not included in the analysis³⁶.

Figure 8.1 shows that there is a decrease in temperature in thermocouples 1 and 3 in the first series of flue-gas cooling, and in thermocouples 3, 7 and 9 in the second series of flue-gas cooling.

³⁶ Thermocouple 5 did not show any variation during the test. It is almost impossible that these are indeed the test values. It is assumed that the thermocouple ended up in the insulation material that was attached around the thermocouple holder.

Figure 8.1 Temperature trend of flue-gas cooling with CAF (DLS) with valve, per thermocouple (TK)

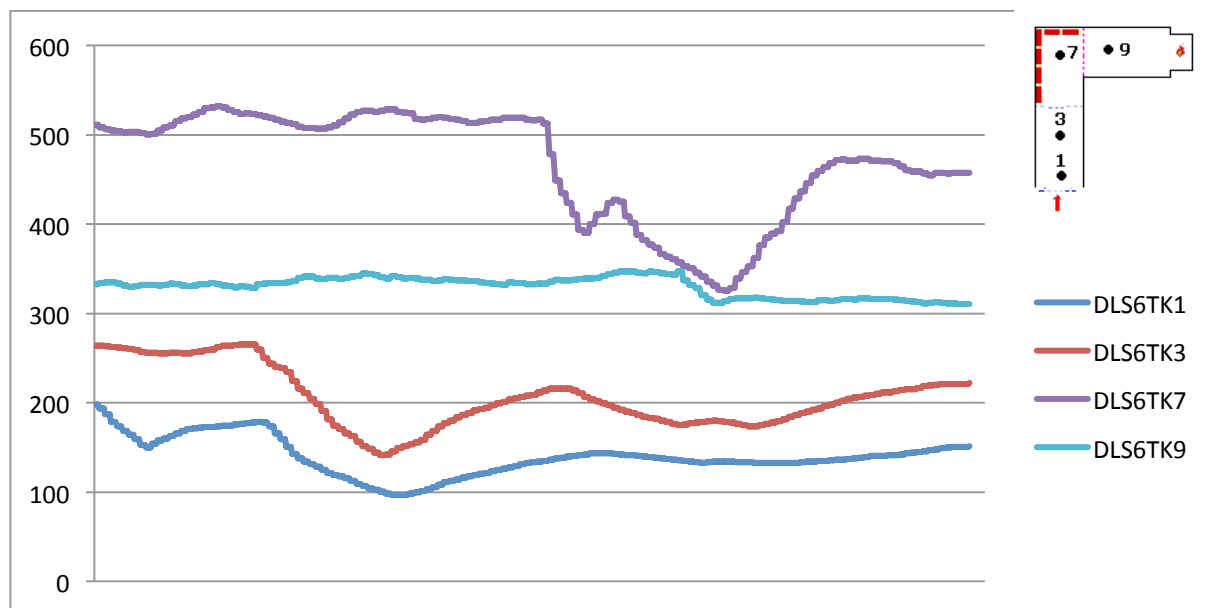
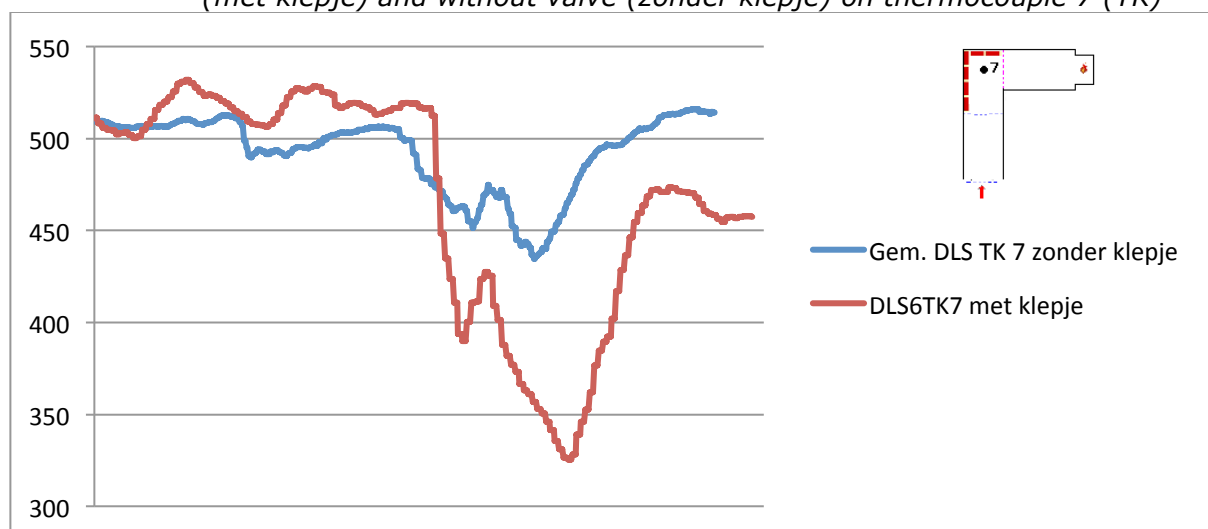


Figure 8.2 shows the lines of the test when compared with the CAF tests without valve.

Figure 8.2 Temperature trend of flue-gas cooling with CAF (Gem. DLS) with valve (met klepje) and without valve (zonder klepje) on thermocouple 7 (TK)



The figure shows that there seems to be a positive effect when the valve is used. However, it may be a coincidence as only one test was done. It should be noted that during the test, the fire-fighting crew went outside before extinguishing was realised. Due to the use of the valve and being soaked with water inside their suits because of the addition of foam, they were so wet that they suffered from the warmth that penetrated into their suits. They ended the test for the sake of their own safety.

8.2 Firedos with 0.3% as compared with Firedos 3%

As the regions handle the mixing percentage of Firedos differently, two extra tests were done with Firedos 0.3% after carrying out the standard tests with the 3% mixing. The

results of the two experiments with Firedos 0.3% were compared with each other. As the measurements of the two tests were similar, the results of both tests were averaged.

When the results of Firedos 0.3% are compared with the average of Firedos 3% and the average of high pressure is included, it appears that Firedos with a 0.3% mix cools flue gases almost as well as high pressure. The flue-gas cooling capability decreases when a higher mixing percentage is used.

Figure 8.3 Temperature trend for flue-gas cooling FD (3%) and FD (0.3%) versus high pressure, thermocouple 1

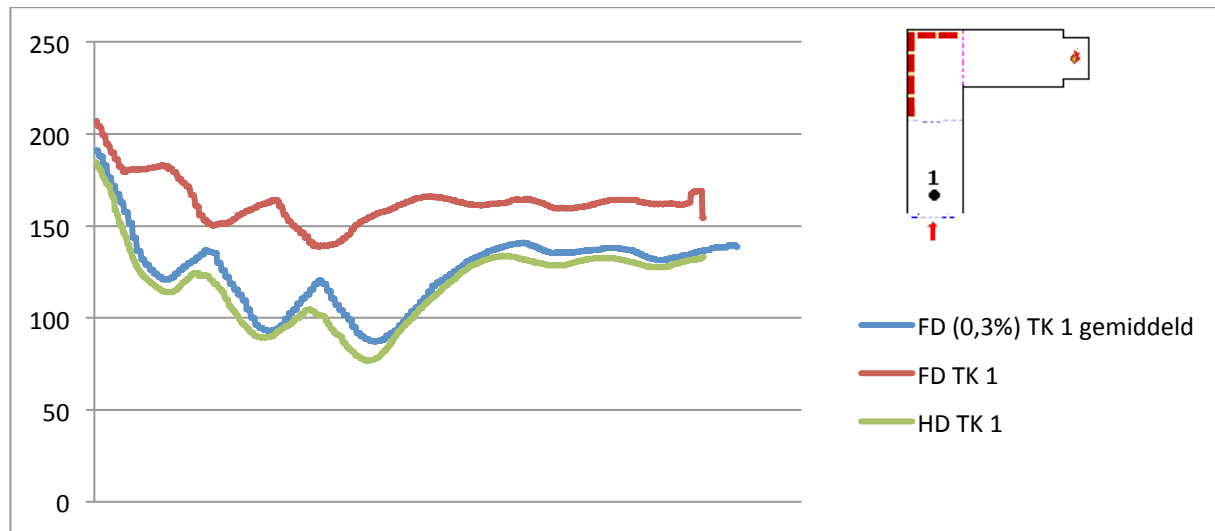


Figure 8.4 Temperature trend flue-gas cooling with FD(3%) and FD(0.3%) versus high pressure, thermocouple 7

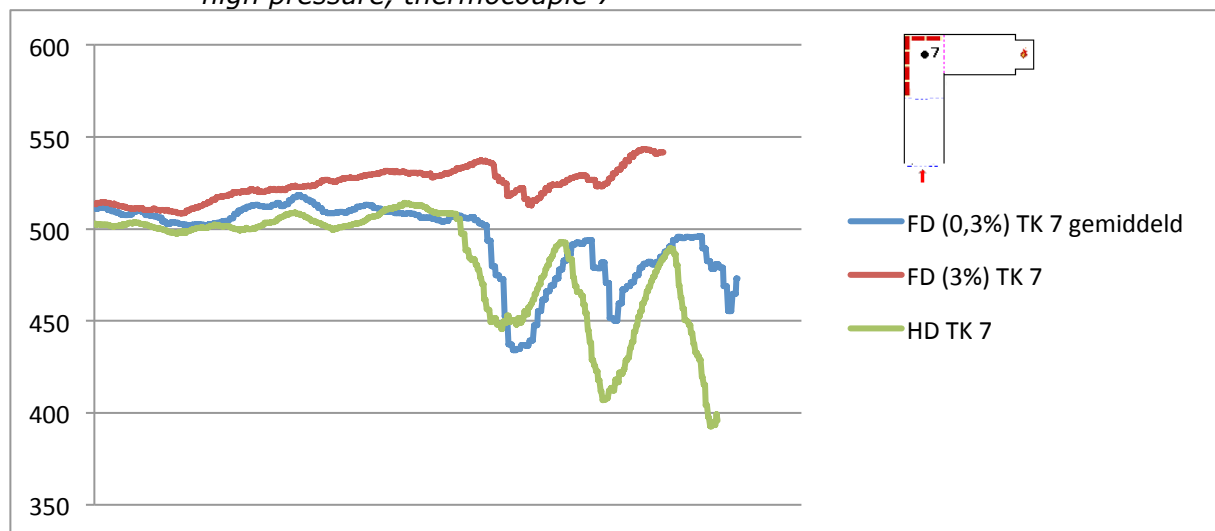
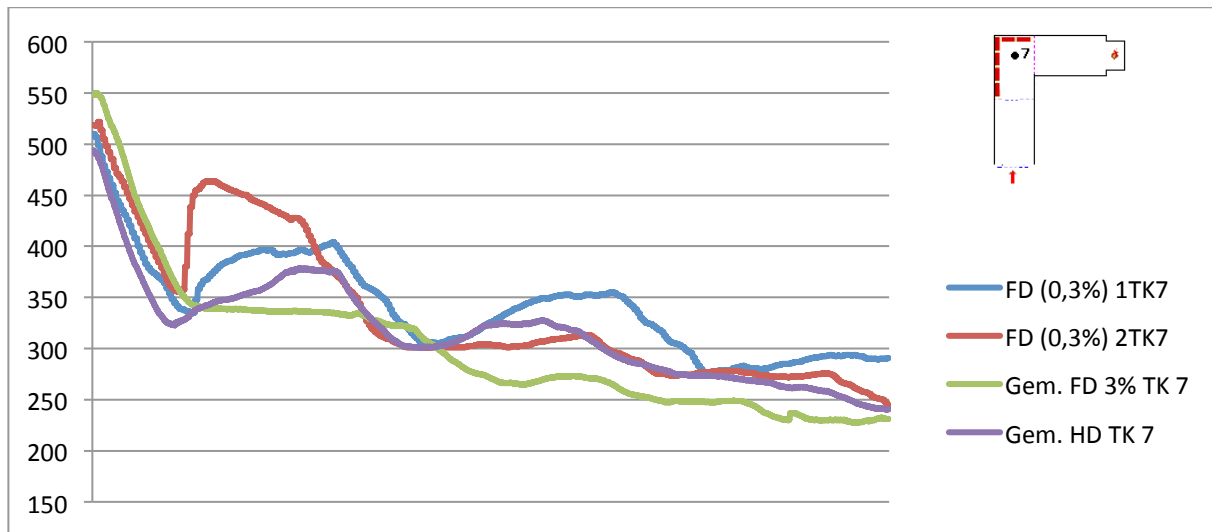


Figure 8.5 shows the results for extinguishing. As to extinguishing, it seems that Firedos 3% is the most effective. A 0.3% mix is much less effective than a 3% mix and seems to be slightly less effective than only high-pressure water.

Figure 8.5 Temperature trend of extinguishing with FD(3%) and FD(0.3%) versus high pressure, thermocouple 7



However, only a limited number of tests were conducted and it is possible that coincidence plays a role. It would be sensible to conduct a study focussed on Fireidos with various percentages to form a solid opinion about the differences in extra mix percentages.

9 Conclusions and recommendations

9.1 Conclusions

This section gives answer to the questions of the study as they were presented in the introduction.

1. What is known in the literature about the effectiveness of foaming agents regarding flue-gas cooling and fire extinction as compared with high-pressure and low-pressure hose lines?

Various studies showed that the CAF has less capability to cool flue gases than water. The only study, as far as we could find at this moment, that differed from this, showed that not a factual flue-gas cooling but a fire extinction was performed in the test, and that this led to a decline in the flue-gas temperature.

The flue-gas cooling capacity of the CAFS was not only longer when bringing the agent in the flue-gas layer but also when it was applied to walls and ceilings. However, applying and covering with CAF lead to the prevention of pyrolysis of combustible materials, and was in fact not flue-gas cooling but only preventing an increase in combustible flue gasses in the space.

It does appear, however, that CAF has a greater effectiveness than water when the creation of a knockdown and prevention of re-ignition are involved.

Based on the results of literature searches it seems that carrying out an offensive interior fire attack with CAFS does ensure a quick knockdown, but that this can be very risky due to the limited flue gas cooling capability and the ensuing presence of combustible hot flue gasses. This opinion is subscribed by the working party for alternative extinguishing systems "the WAB Werkgroep Alternatieve Blussystemen"³⁷. However, findings from earlier practical research, as far as we could find at this moment, do not give sufficient insight into the effectiveness for applying CAF for flue-gas cooling in the way it is applied by some Fire Services in the Netherlands. Moreover, the effectiveness of flue-gas cooling with high pressure and low pressure and Firedos as applied by the Dutch fire service has hardly been researched in an experimental setting and described in an imitable way.

2. What is the effectiveness of foam-forming systems CAF and Firedos, and high pressure and low pressure when deployed in an offensive attack of a living-room fire?

Tests showed that the temperature trend for the entire flue-gas cooling (at TK 5) with low pressure resulted in the highest decrease. High pressure and Firedos have a comparable and a less cooling effect on the temperature in the flue gases. CAF showed the least cooling of flue gases. When CAF is used, the temperature decreases 41 °C after two series of flue gas cooling whereas the temperature decreases 138 °C with low-pressure. Moreover, the cooling effect continues during the flue gas cooling, particularly with low-pressure, also when meanwhile no pulses are given and new hot flue gases are supplied. To a lesser extent, this also applies to FD and high-pressure but hardly to CAF.

When the two series of flue gas cooling are examined separately, it appears from the temperature trend line in the first series that FD cools flue gases the least. Low-pressure and high-pressure cool flue gases the best. A decrease in flue gas temperature can also be seen when using CAF.

In the second series of flue gas cooling, we can see the best results again with low-pressure both regarding the other systems and regarding the first series of flue gas cooling. Noticeable is that CAF then shows the worst result with a total temperature fall of 20 °C. Another noticeable point is that FD scores worse in relation to CAF (and low-

³⁷ Network for repression of Security Region Noord-Holland Noord

pressure and high-pressure agents) in the first series of flue-gas cooling whereas in the second series, and further away in the container, CAF hardly results in a cooling of the flue gases, and FD scores better (nearly as good as high pressure). The relatively positive effect with CAF in the first series was probably caused by a magnet effect of the CAFS by which cold environmental air is brought into the container. A possible explanation why Firedos had little effect the first time and appears to be effective in the second series is that the mix in the beginning was different from the second series.

When at the same moment the temperature trend in the entire container is examined, it strikes that with both high pressure and low pressure temperatures both in front of and behind the fire-fighting crew decline during flue-gas cooling. With FD there is only effect in the direct environment. With the CAFS we can see a short-lived decline in front of the fire-fighters, which is followed by an increase in temperature both in front of and behind the fire-fighting crew.

When the cooling capability is compared with the use of water, it appears that the flue-gas cooling capability per litre of used water is highest with low pressure. The foam-forming systems cool the least per used litre of water, and the CAFS scores worst. When comparing the cooling capability with the volume of extinguishing agent used (water, or water with air and foam) the difference between the systems using only water and the foam-forming systems is even greater.

Sudden combustions of the flue-gas layer were seen in two of the five tests with CAFS and in the extra test carried out with Firedos 0.3%. As these combustions occurred in some of the experiments with CAFS and Firedos, it is not certain whether this is caused by flue-gas cooling or by extinguishing with foam, and further investigation is needed. Though the test carried out with a valve on the CAF jet nozzle shows a better flue-gas cooling than without valve, the test was carried out only once and conclusions cannot be drawn. The same applies to the additional test with 0.3% instead of 3% extra mix for Firedos: the result appears to be better, but no reliable statements can be made about this.

In conclusion, it can be argued that water-based extinguishing systems are more capable of flue-gas cooling than the foam-forming systems, when applied in the same way as in this investigation. CAF, in the way we applied it (short shots into the smoke layer) only cools in front of the space when the attack is on the outside, presumably by the supply of cold environmental air as a result of which a form of repressive ventilation occurs. CAF applied in this way is incapable of lowering the temperature of the flue gases during an interior attack further in the container to such a degree that this would lead to safe circumstances of an interior fire attack. This applies to a lesser degree to Firedos, which does cool further in the container but only in the direct environment. Interior fire attacks with low pressure appear to be the most effective and safe for flue-gas cooling, even if compared with water use of high pressure. We emphasise that it can not be concluded from our experiments that other ways of application of DLS than we investigated, can not lead to better results, because we did only investigate one manner of application.

3. What is the effectiveness of the foam-forming systems like CAF and Firedos, high pressure and low pressure regarding the extinguishing capability in an offensive interior attack in a living-room fire?

Both high pressure and CAF realised the quickest knockdown whereby high pressure used the least water. Firedos needed the longest time to create a knockdown. However, the average duration until the first re-ignition was highest with Firedos although the tests showed much variation. This applies to a lesser degree to low pressure. Though CAF created a quicker knockdown, there is a relatively quick re-ignition within the selected research set-up, whereby almost identical results were found between the tests.

As to temperature decrease, extinguishing with Firedos is most effective (irrespective of use) in the first knockdown. Extinguishing with low pressure and high pressure gives a better average temperature decline than with CAF, but less than with FD. High pressure and low pressure score best when compared with water use and extinguishing agent. The temperature decrease with low pressure and FD in the container is steady. A declining line can also be seen with CAF and high pressure but it is noteworthy that the temperature shows peaks almost immediately after the temperature decrease and this partly undoes the cooling effect of the extinguishing. This is stronger with CAF than with high pressure.

In conclusion, it can be argued that FD may need the longest time for the knockdown, it is then very effective in reducing the temperature but uses also the most extinguishing agent. Comparing the use, high pressure and low pressure score best for extinguishing. CAF scores good in creating a quick knockdown but gives a limited temperature decline in the space (38 °C) and there is a temperature increase between the shots.

Other findings

During setting up and performing the test, it appeared that there is no unambiguous way of deploying foam-forming systems. The way of deploying CAF and the mix percentage of Firedos vary much between the various fire service regions. The way of deployment is often based on deployment techniques in other countries with other ways of constructions and materials. In meanwhile, it is known, that the way DLS was applied in this research, is not advised by the suppliant and the manufacturer. They advise to apply pulses of 3-5 seconds, while putting foam on the walls and the ceilings.

Key question: where the flue-gas cooling effect and the extinguishing power in an offensive interior fire attack are concerned, how does the effectiveness of CAF and Firedos relate to one another and to low-pressure and high-pressure?

Literature searches and practical experiments show that flue-gas cooling with CAFS³⁸ is little effective and does not lead to a substantial decline in flue-gas temperature when applied in the way we investigated (short shots into the flue-gas layer) especially when used further in the space, in comparison with water-bearing systems. It was observed that the temperature increased and that the flue-gas layer ignited with CAF. In fire-fighting practice, this can lead to dangerous situations.

For flue-gas cooling, Firedos 3% appears to be less effective than water. With less extra mix (0.3%) Firedos becomes almost as efficient as high-pressure. Therefore, adding less foam leads to better performance in flue-gas cooling.

In the fire attack, CAF does create a knockdown just as quickly as high pressure, but the temperature remains high near the seat of the fire. This carries the risk of re-ignition of the environment. In the fire attack, Firedos gives the greatest temperature decline and of all tested systems has the longest effect in preventing re-ignition. However, Firedos is less effective in flue-gas cooling than water-bearing systems.

Taken everything into consideration it appears that the traditional interior attack with low pressure is the safest. This is also possible with high pressure, though to a lesser degree. Given the poor flue-gas cooling capability of CAF (applied in the way we investigated, i.e. short shots into the flue-gas layer) and the limited flue-gas cooling effect of FD, the interior attack with only one of the foam-forming systems may lead to hazardous situations. We emphasise that this conclusion can only be drawn for the way we applied DLS.

³⁸ With the tested attack tactics and in situations in the Netherlands

9.2 Recommendations

Based on the study results, the following recommendations can be given:

1. For a safe interior fire attack with one of the foam-forming systems applied in the way described in this report, it is necessary to combine the attack with another system that cools flue-gases effectively.
2. Ensure an unambiguous and effective way of using CAF and Firedos based on practical research, taking the usual way of construction in the Netherlands into account.
3. Given the results, consider whether low pressure should be part of the standard technique to be used for an interior attack more than currently is the case.
4. In addition to this research, study the effectiveness of the systems in other types of fire, applying other methods, and under other circumstances.

Appendices

Appendix 1: Reference list

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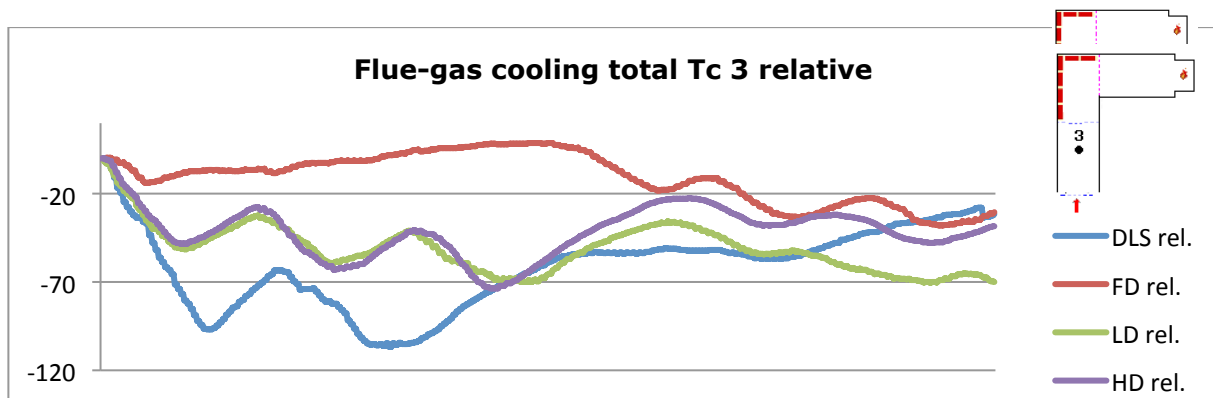
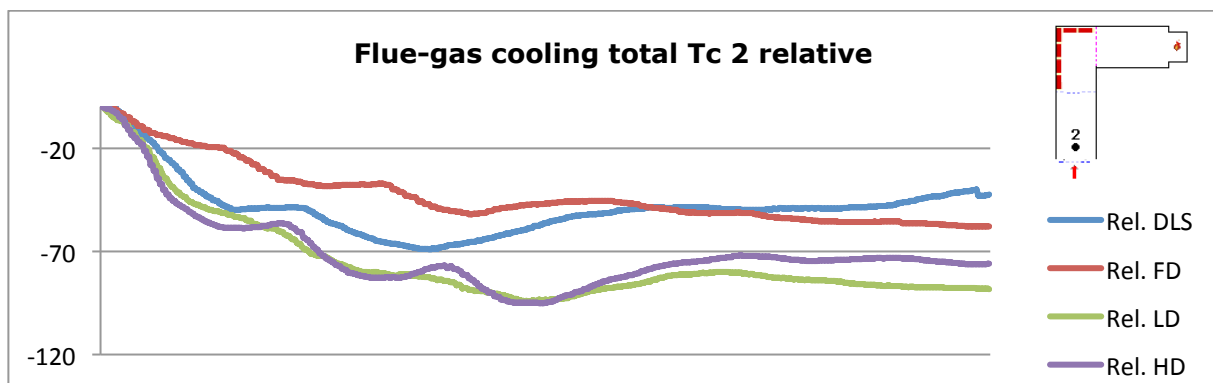
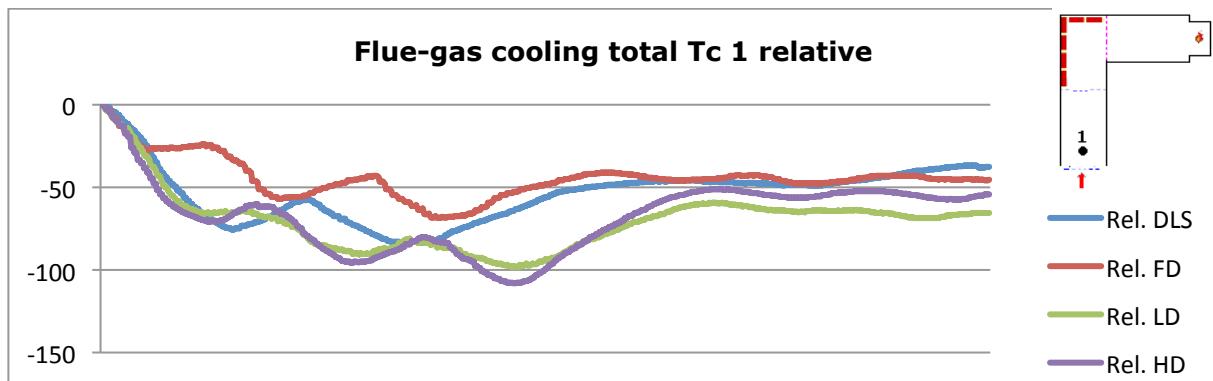
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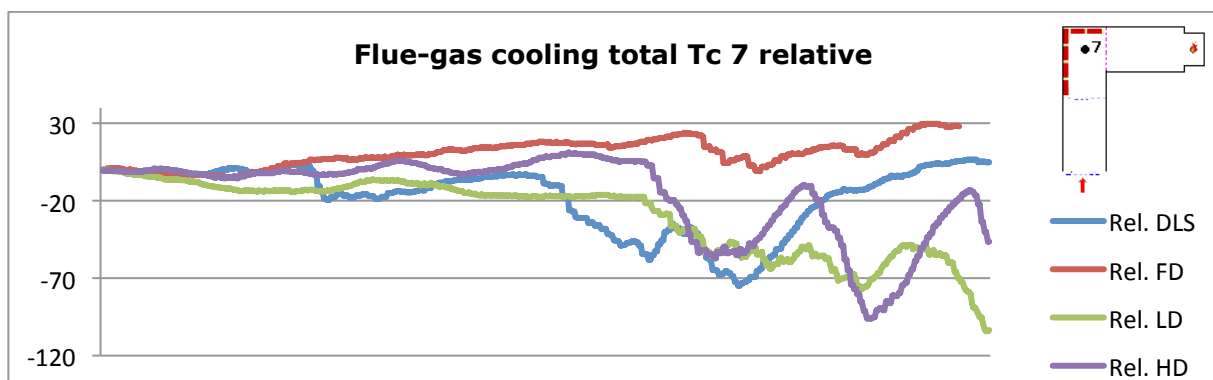
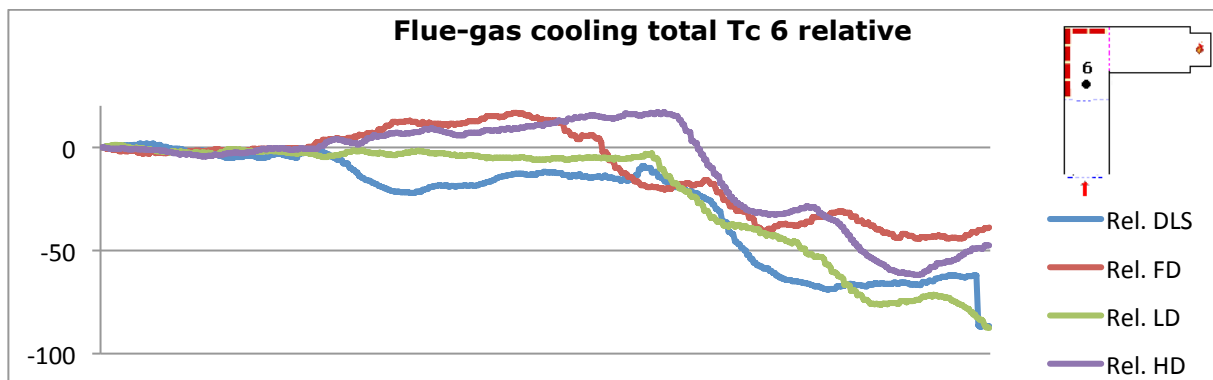
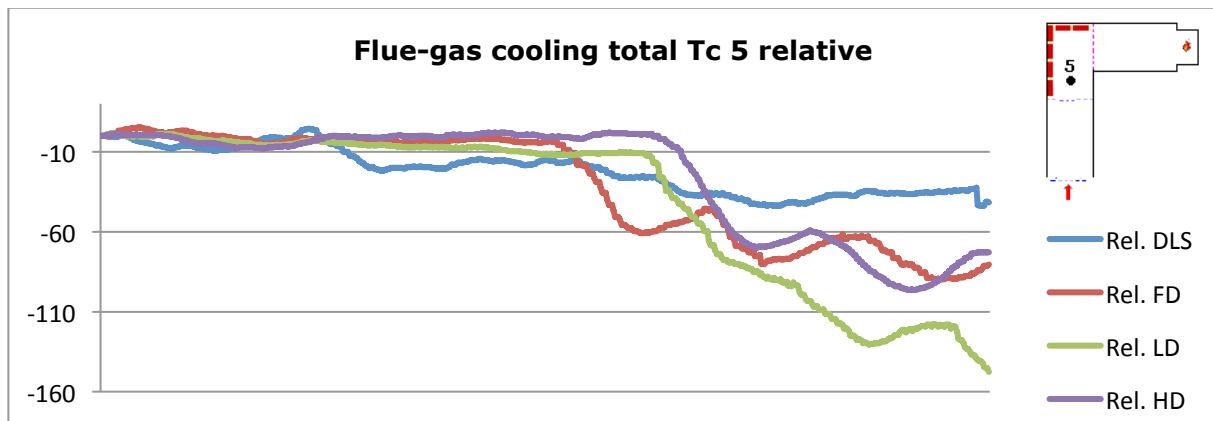
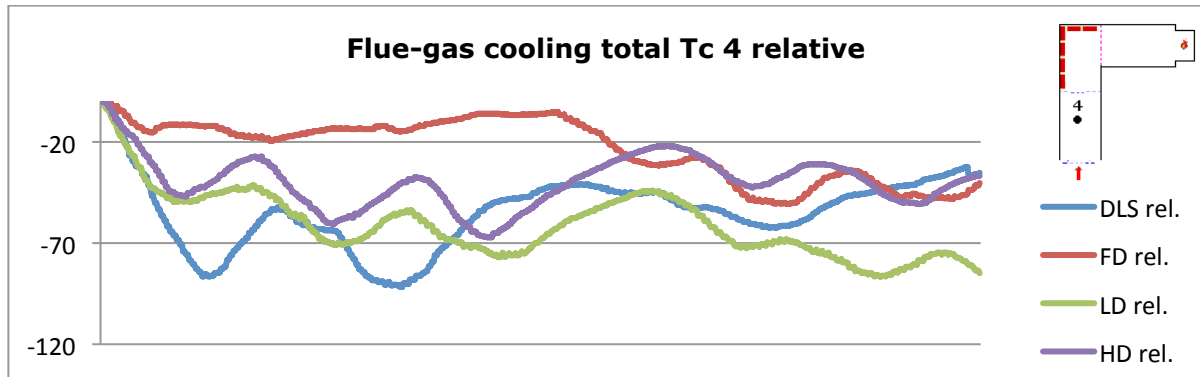
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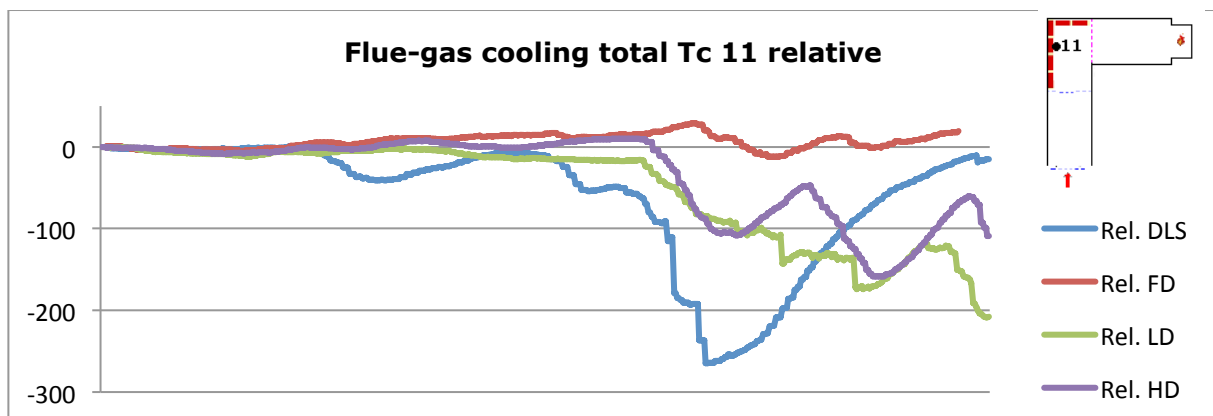
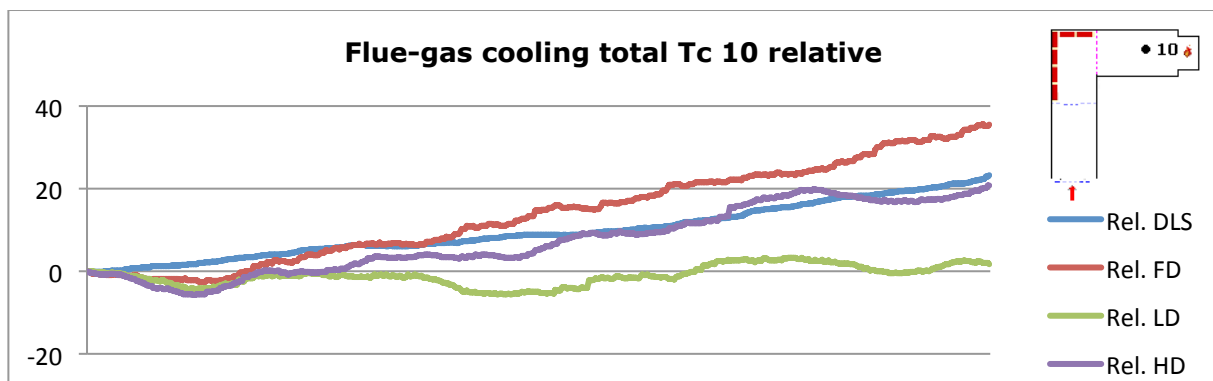
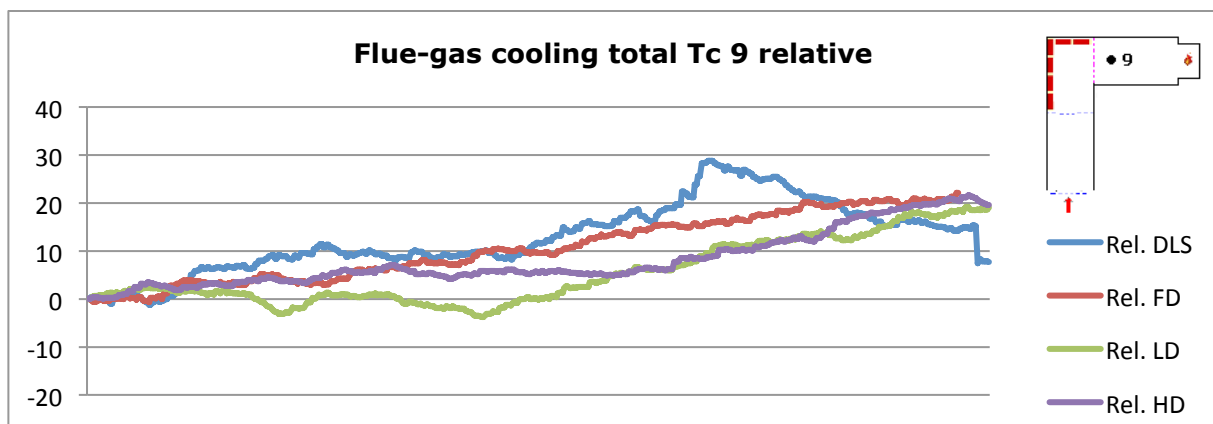
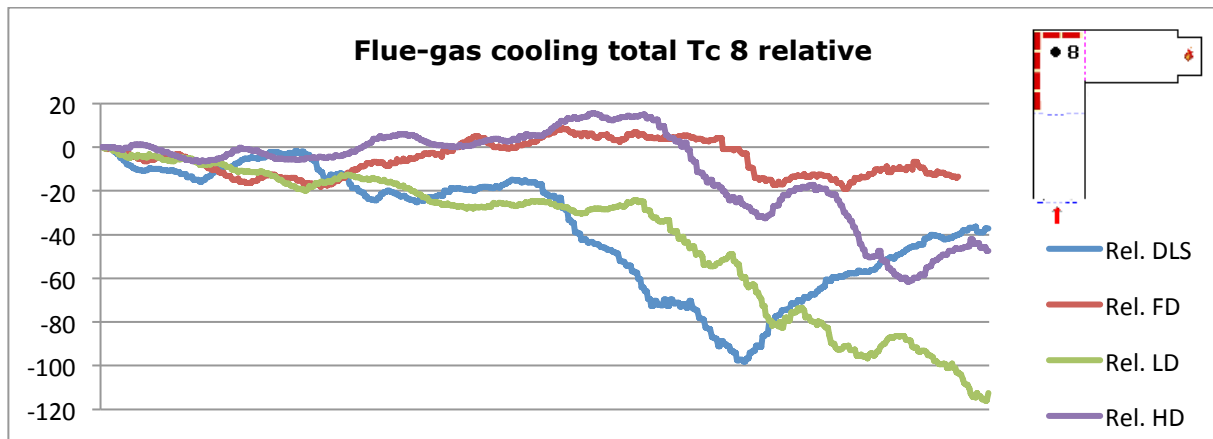
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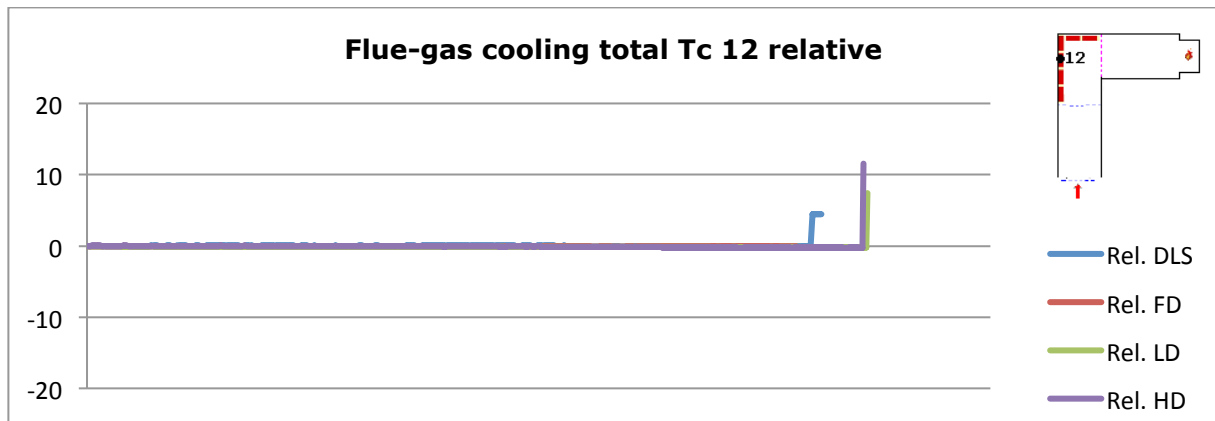
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Appendix 2: Graphs for flue-gas cooling

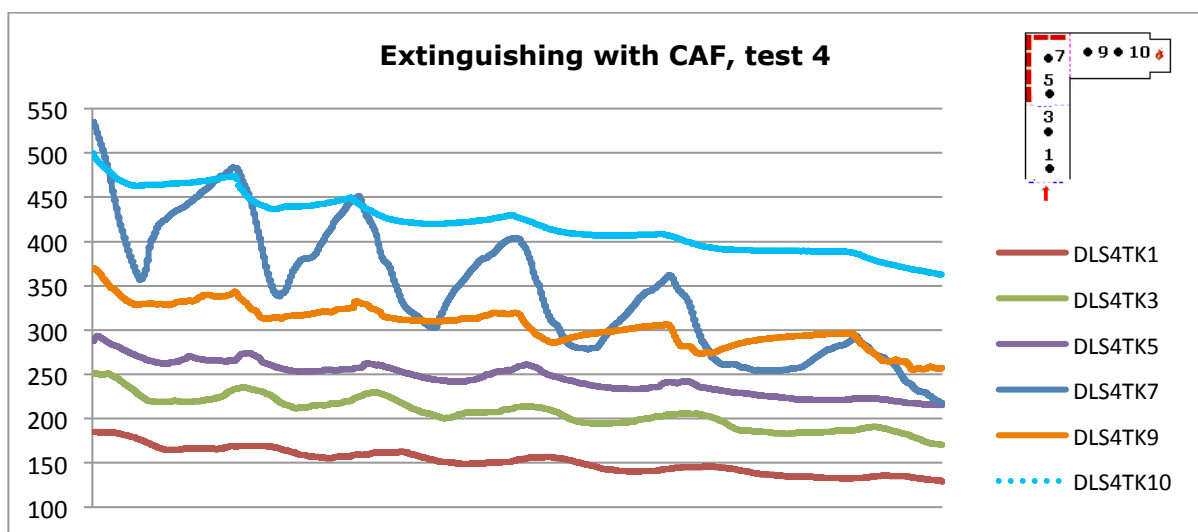
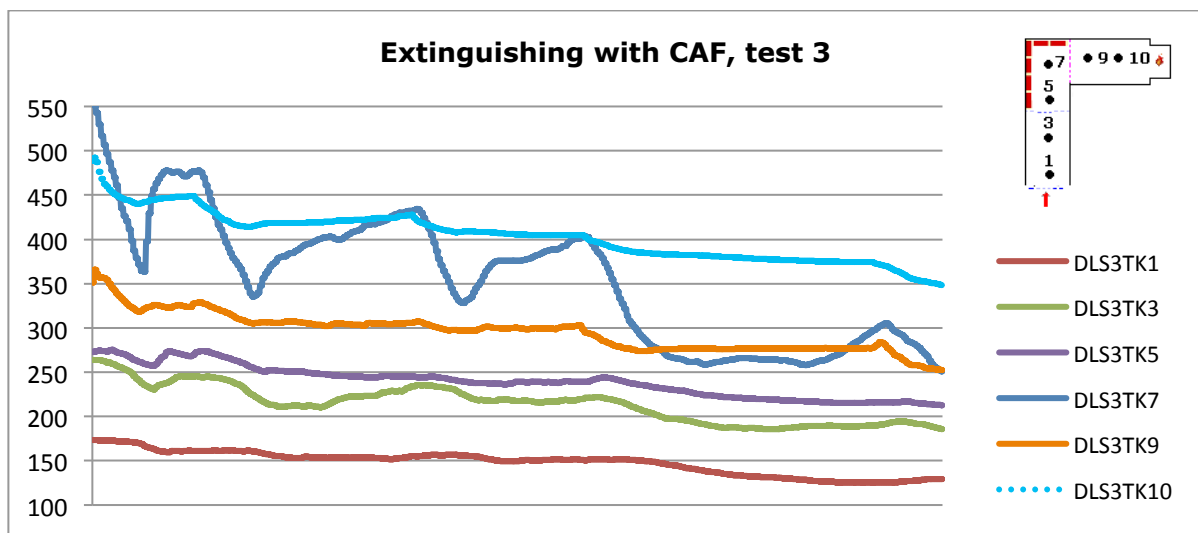
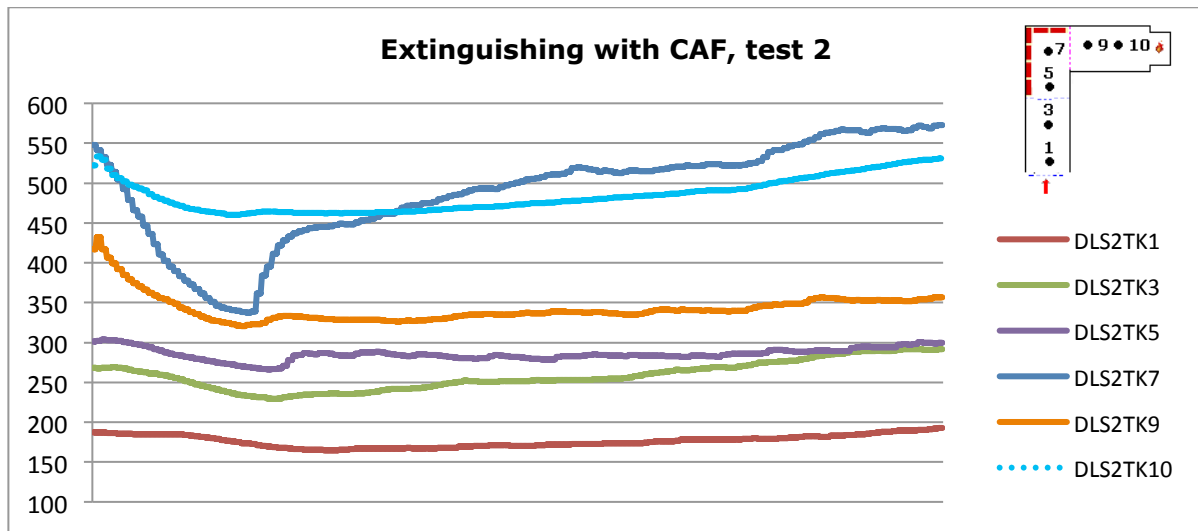


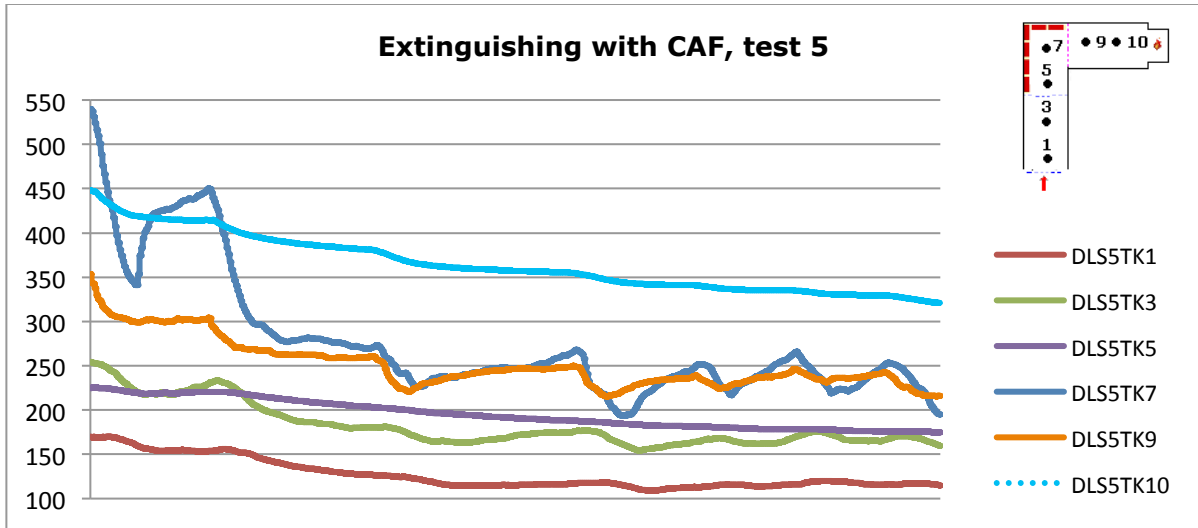


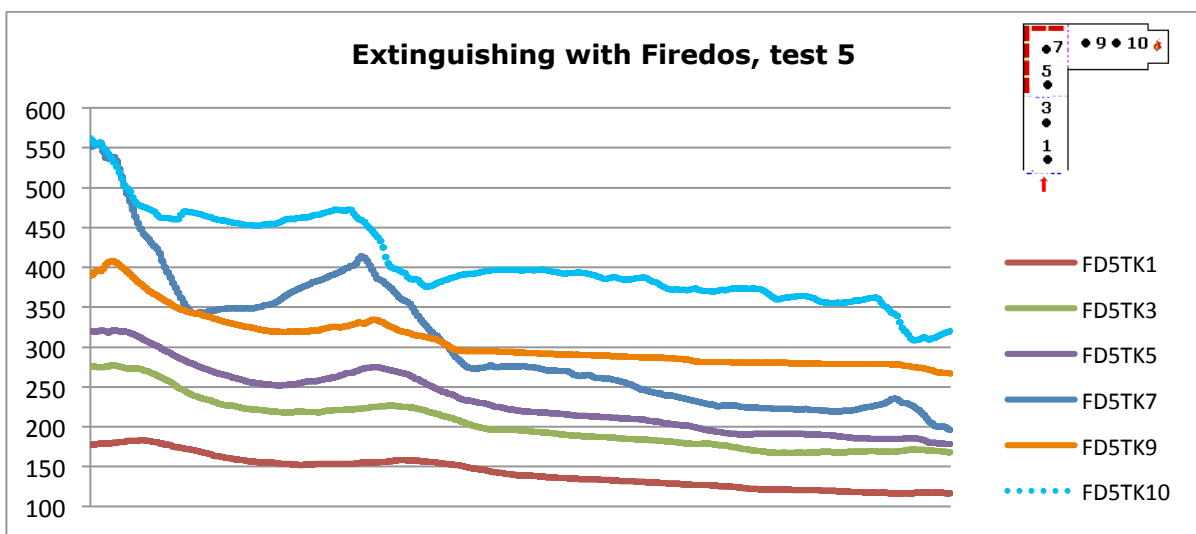
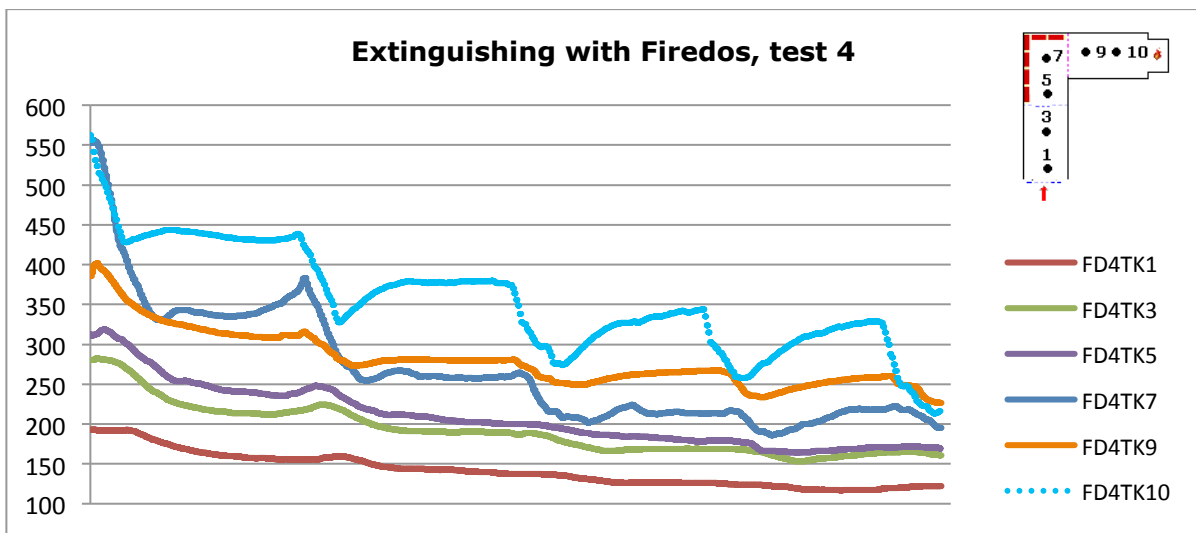
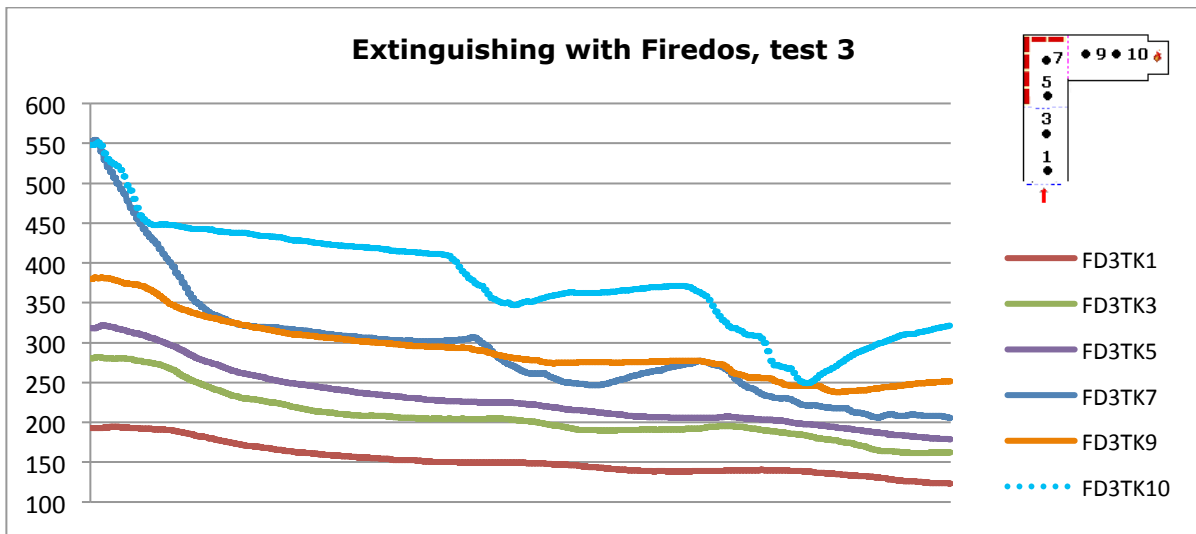


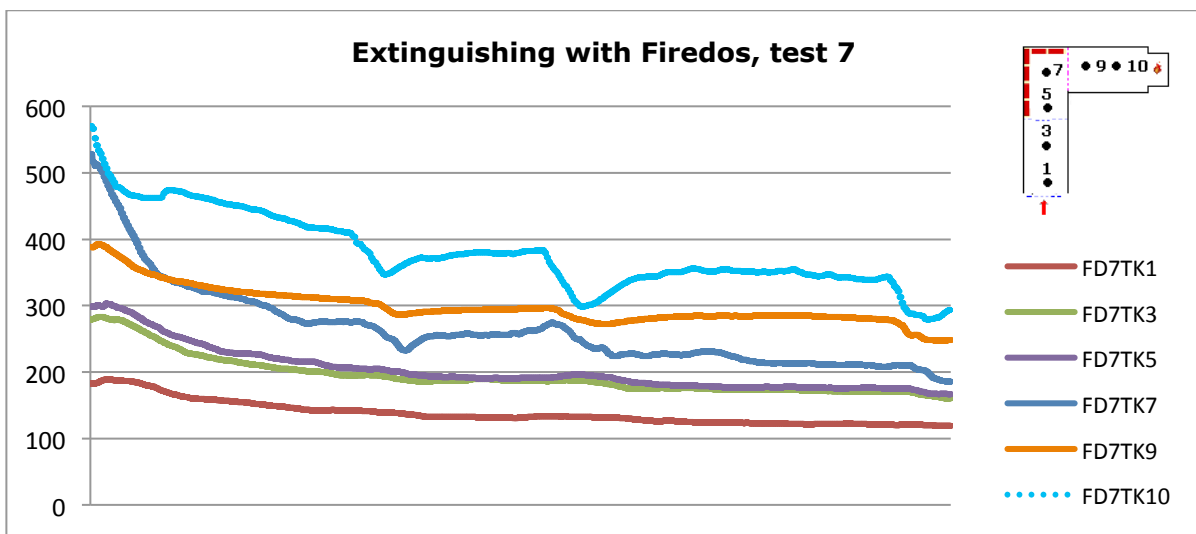
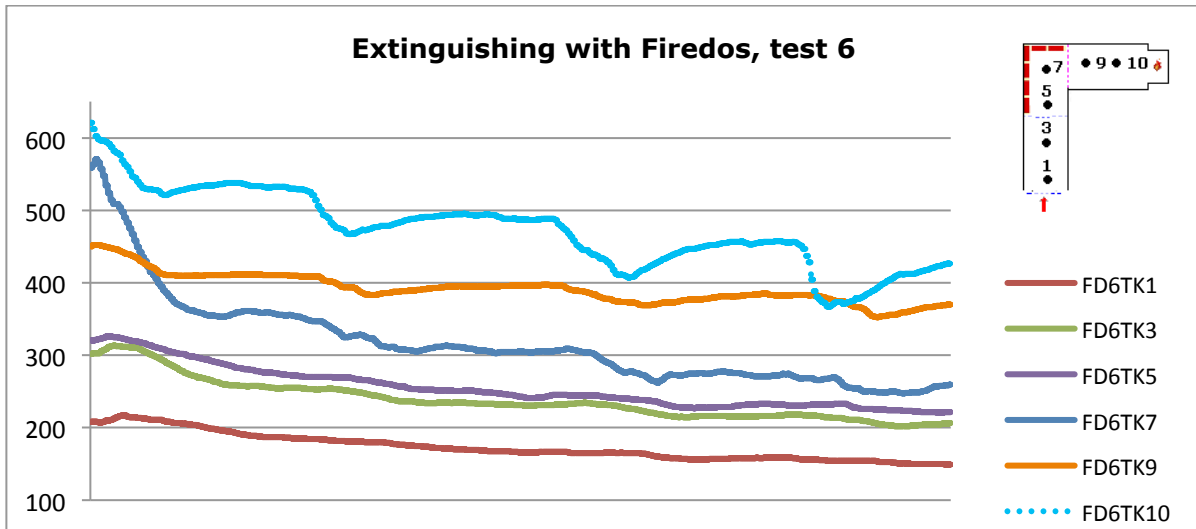


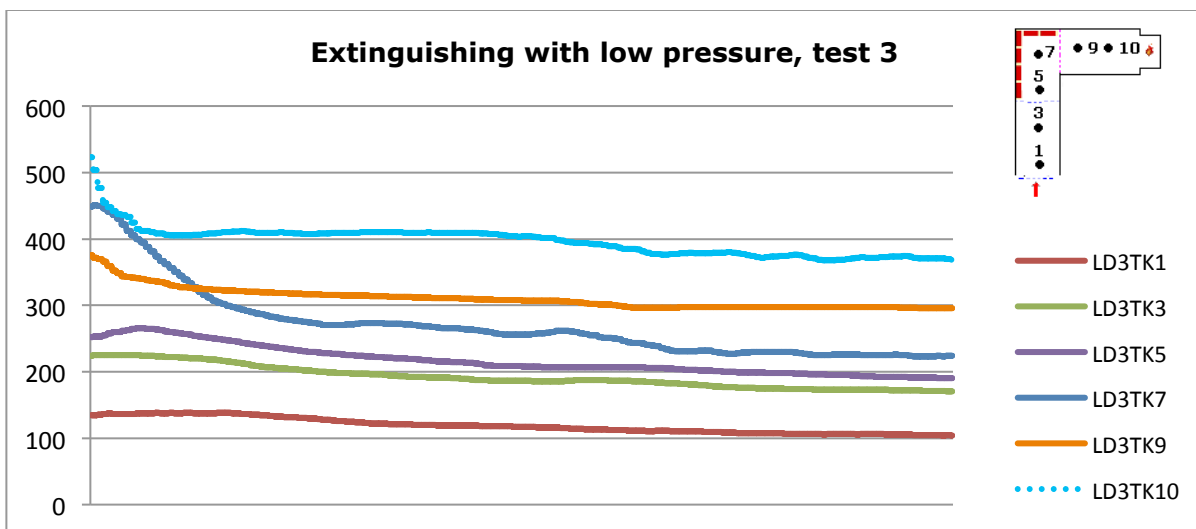
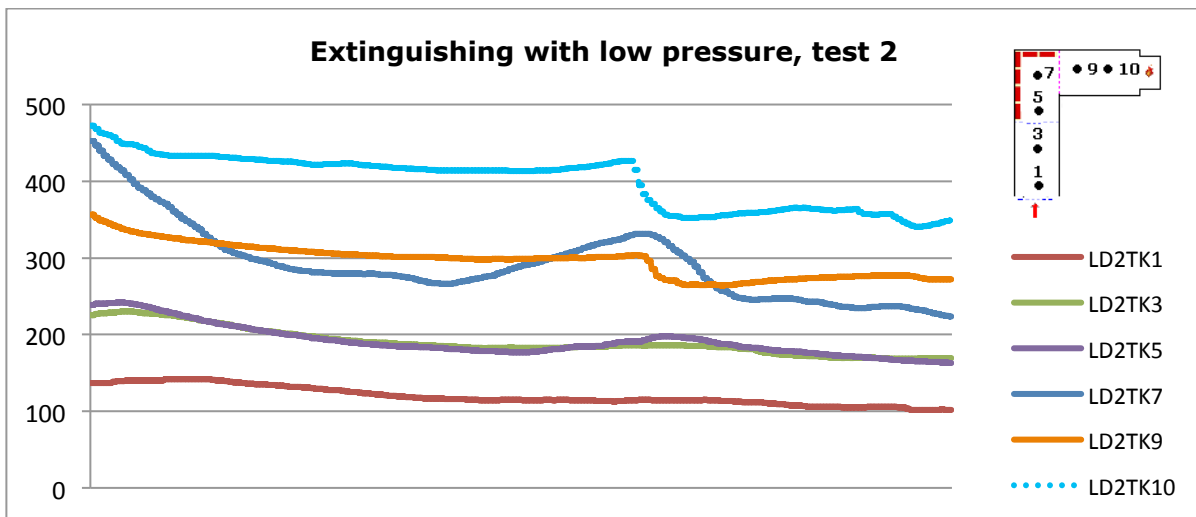
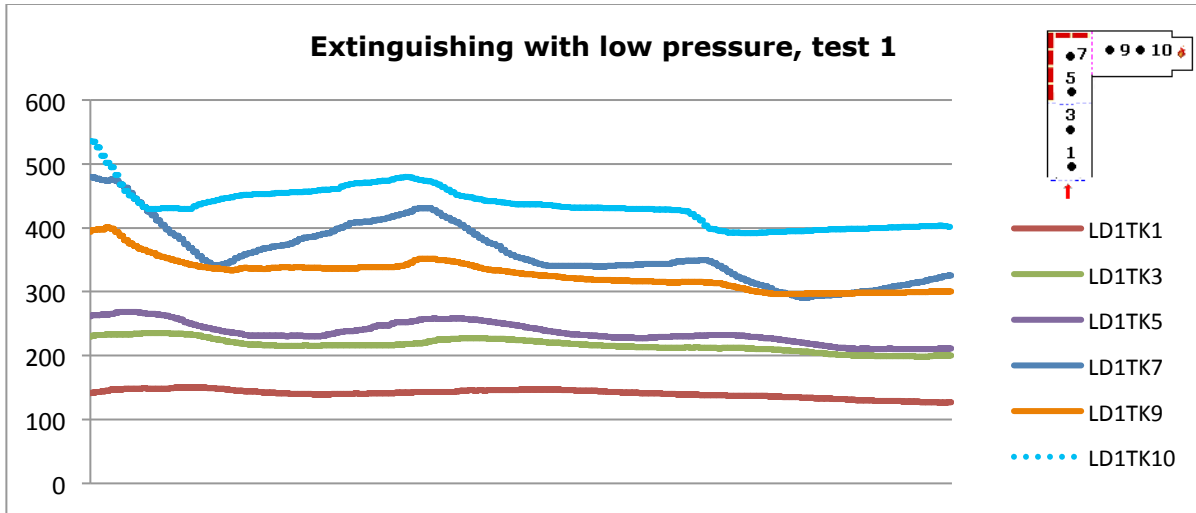
Appendix 3: Graphs for extinguishing

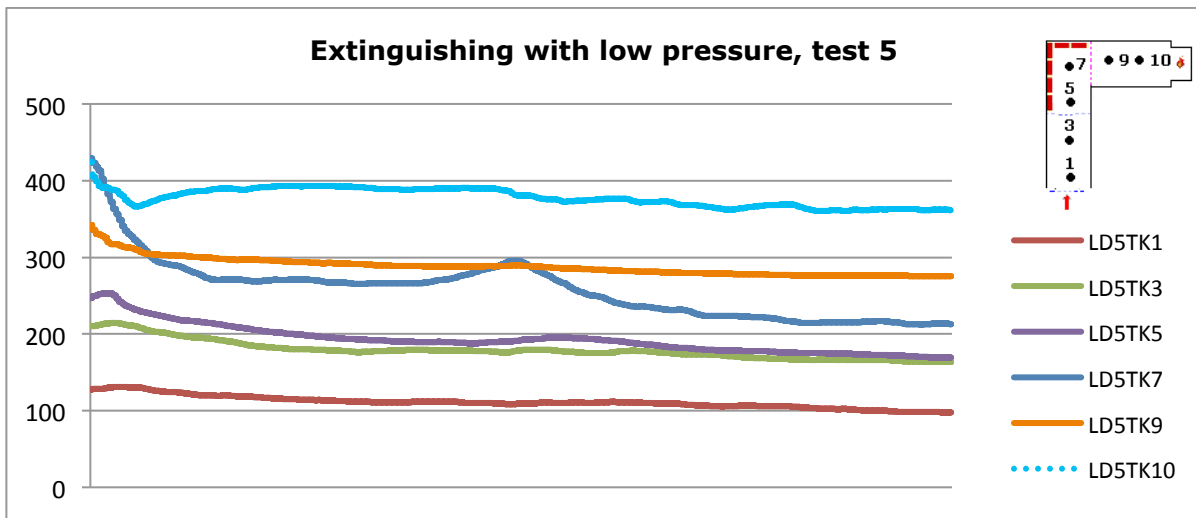
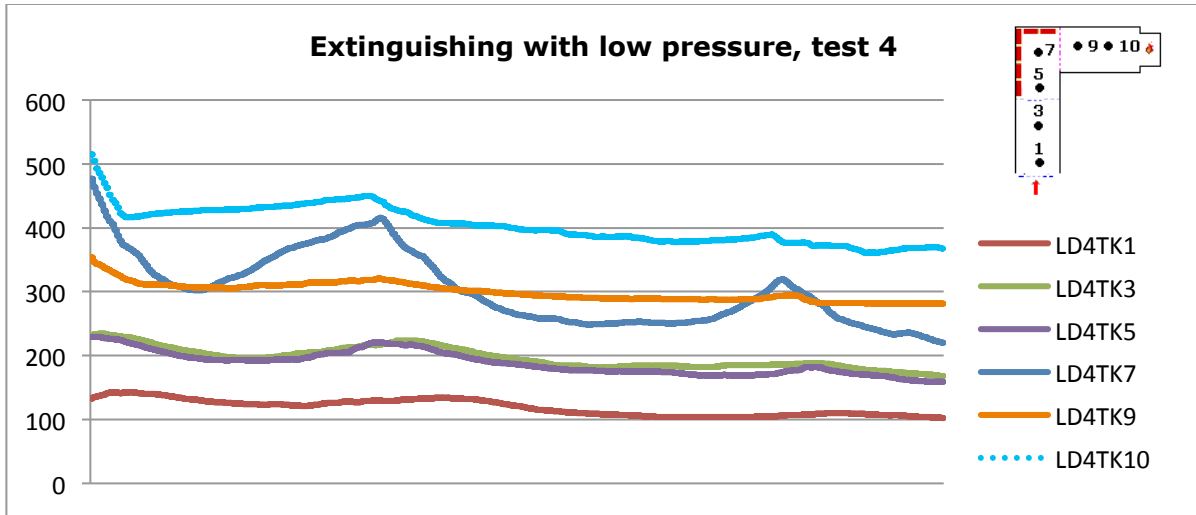


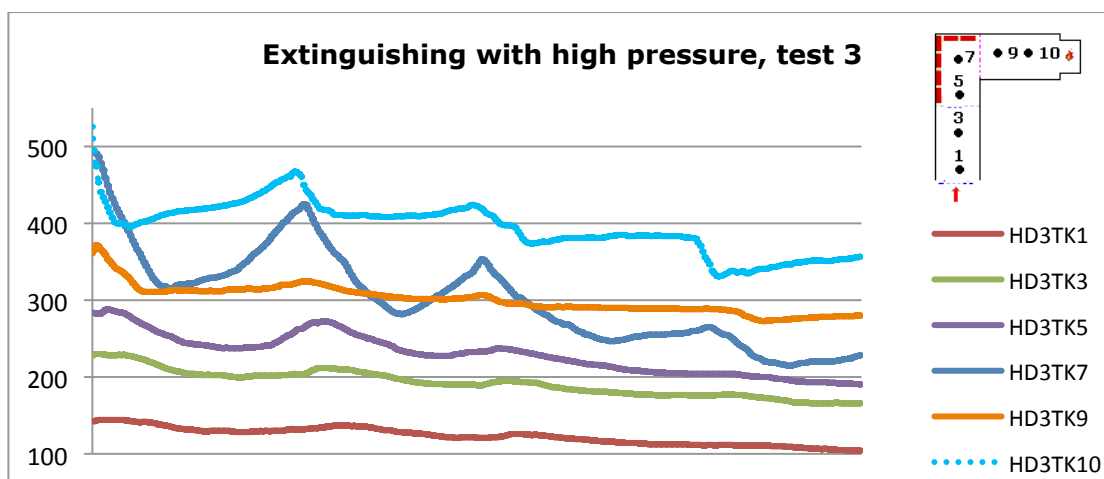
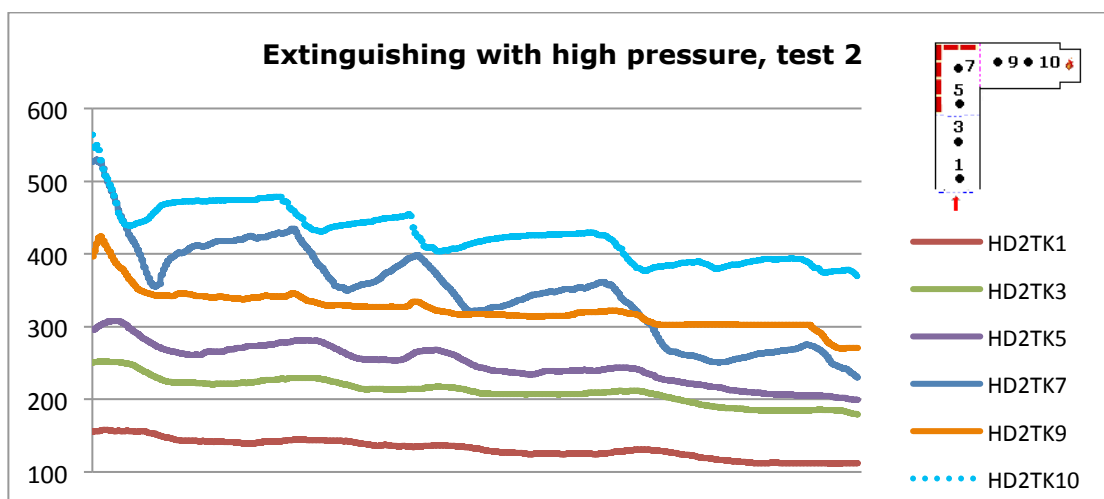
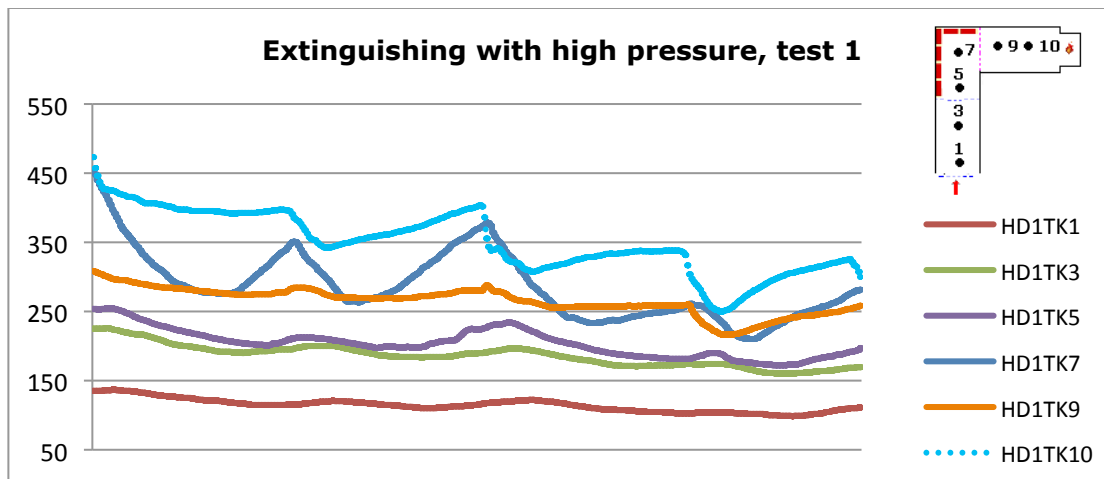


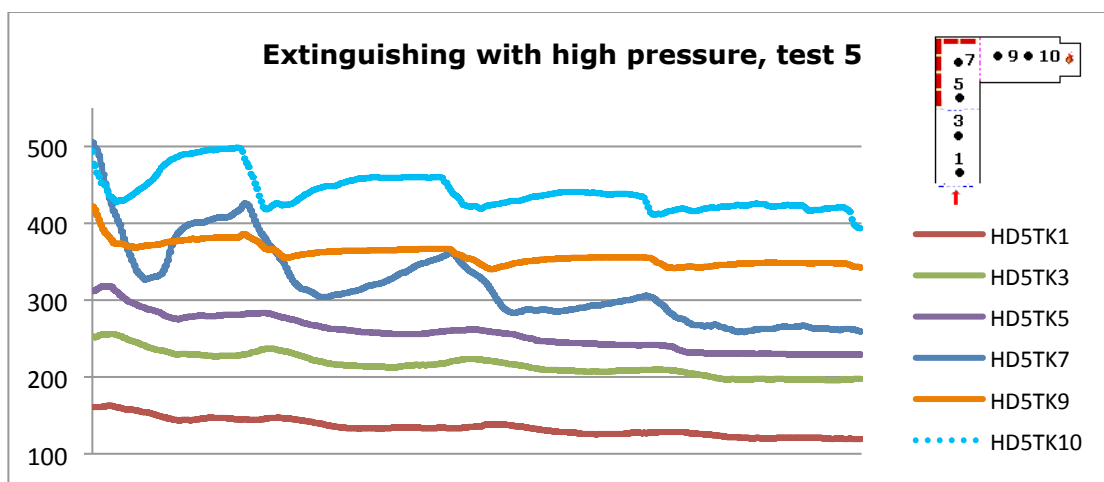
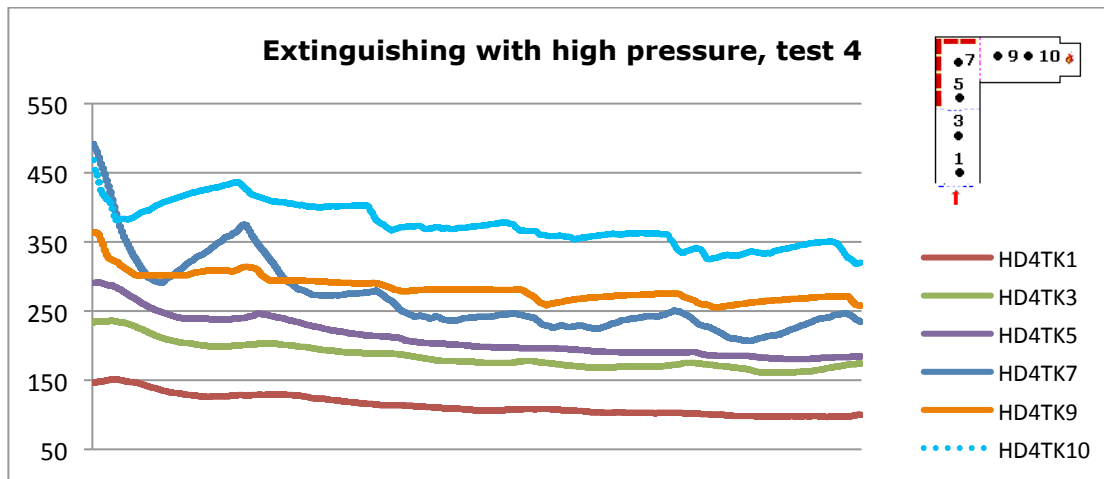












Appendix 4: Effect and application of fire-fighting foam

Introduction

This chapter gives background information about fire-fighting foam. Firstly the various foam systems available for fire attacks are dealt with, then the effect of fire-fighting foam is discussed, and finally a detailed look is given at experimental studies carried out earlier into the effectiveness of foam-forming systems on flue-gas cooling.

Fire-fighting foam

On the basis of available information it is hard to make a clear distinction between the different kinds of foam. Some foams that are meant for stationary systems are also suitable for mobile systems, and the expansion of foam is mainly relevant for application to indoor fires where a space is fully covered with foam, but is hardly relevant for cooling objects in the environment of a seat of the fire.

Below is a survey of aspects that make typification of foams possible.

Composition

The first distinction is on the basis of the composition of foam, namely organic and synthetic foams. Organic foams are based on hydrolysed proteins (albumins), and may be made of horn meal or chicken feathers. However, such protein foams are perishable, also because of corrosion or bacterial decomposition. Synthetic foams are artificial foams with petrochemical components.

(a) Polar qualities

Another distinction can be made on the basis of the polar or nonpolar qualities of foam. Nonpolar (or hydrophobic) foams are suitable for fighting fires in polar liquids (mixable with water) such as alcohol and acetone. Polar (or hydrophilic) foams mix with liquids that mix with water, and decompose the foam layer.

Figure 1 gives various kinds of foam and presents a division in the composition and polar or nonpolar quality of foam.

Figure 1 Typification of foam on the basis of composition and polar or nonpolar qualities

	Organic	Synthetic
Hydrophilic / polar	<ul style="list-style-type: none"> - Protein foam (P) - Fluor protein foam (FP) - Film-forming foam (FFFP) 	<ul style="list-style-type: none"> - Film-forming foam (AFFF)
Hydrophobic / nonpolar	<ul style="list-style-type: none"> - Alcohol-resistant foam (FFFP-AR) 	<ul style="list-style-type: none"> - Alcohol-resistant foam (AFFF-AR)

Appearance

Another categorisation of foam can be made on the basis of its appearance. This can be further divided into expansion factor, mixing ratio and air pressure.

The *expansion factor*, or foam factor, indicates the relation between the volume of the mixture (water and foam-forming agent) and the volume of foam (water, foam-forming agent and air) that develop after forming the foam. With the expansion factor, foam is further grouped into three types: heavy foam (up to 20:1), medium foam (20:1 to 200:1) and light foam (greater than 200:1). Heavy foam has a long reach with the extinguishing jet, medium foam consists of small quality bubbles and light foam is very dry with a low water content.

The *mixing ratio* is the quantity of foam-forming agent to be added to water for maximum effect. The quantity is expressed in per cents of the quantity of water and is usually between 0.1% and 6%. For application in fires of solid matter (class A fires) a mixing ratio of 0.1% to 1% is applied whereas 3% is recommended for pool fires. Fires in polar liquids may need a mixing ratio up to 6% with an alcohol-resistant foam-forming agent. Compressed-air foam with a mixing ratio of 0.3-0.6 up to 1% is applied both for class A fires and for class B fires (Lyckeback and Öhrn, 2012). This means that the mixing percentage depends on the kind of fire and the kind of foam-forming agent. There is no relation between the mixing ratio and the expansion factor.

As to *air pressure* during the foam-forming process, we can subdivide it in regular foam, in which the pressure of the added air is equal to the atmospheric air pressure, and compressed-air foam (CAF) in which the added air has a higher pressure than the atmospheric air pressure.

Extinguishing system

Fire-fighting foam can be produced and applied with the help of various extinguishing systems. Foam can be brought onto the seat of the fire with a stationary system and with a mobile system. A stationary system is an (automatic) extinguishing system that is placed in a building as a precautionary measure, especially in buildings where substances are stored that represent a fire hazard (PGS-15). A mobile system can be installed on a Rapid Intervention Vehicle (RIV) or on a mobile mixing system (submixer). OneSeven and CAF are examples of mobile extinguishing systems that produce compressed-air foam. FireDos is an admixture system in which foam is added to the water in the vehicle. The three systems of FireDos, OneSeven and CAF produce foam with a low expansion ratio, which is heavy foam. The heavy foam can be 'wet' foam with an expansion ratio of 1-5, or 'fluid' foam with an expansion ratio from 5 to 10, and 'dry' foam with an expansion ratio of 10 to 20 (Lyckeback and Öhrn, 2012).

Applications

Fire-fighting foam can be applied in various manners. The applicability and effectiveness of a type of foam for a particular application also depends on the composition and the outward appearance of the foam, but also on the fire-fighting tactics that are applied.

Possible applications of fire-fighting foam are:

- covering liquids to prevent evaporation,
- protecting objects near the seat of the fire,
- cooling of combustible gases in an enclosed space,
- attacking a fire in a pool of combustible liquid,
- attacking a fire of solid substances in an enclosed space.

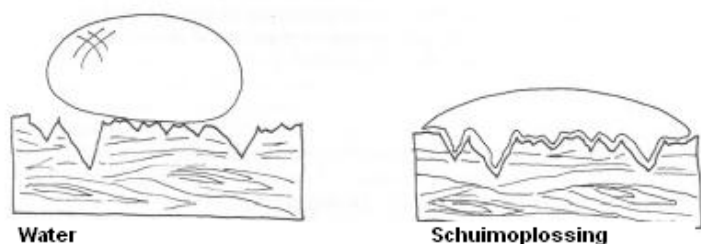
Principle of extinguishing with water and foam

Water is in itself an effective extinguishing agent as it can absorb much heat and of all liquids it needs the most energy to evaporate. The extinguishing action of water is mainly

based on cooling. However, the high surface tension³⁹ of water causes a number of unwanted effects on the absorption of heat from the environment. The surface tension of water causes the creation of relatively large drops and large drops result in a less efficient energy absorption and this influences the effectiveness of flue-gas cooling and extinguishing. Surface tension also causes that water cannot penetrate certain materials, substances and the fire well.

To increase the penetrating capability of water and to ensure that the water drops can reach the seat of the fire, certain substances can be added to water, e.g. a foam-forming agent, to lower the surface tension of water (Taylor, 1997). The effect of it is illustrated in figure 2.

Figure 2 Lowering the surface tension by a foam solution



The extinguishing action of foam is based on the following aspects (Geurts & Snuverink, 2001).

Suffocating action; displacement of oxygen

A closed layer of foam separates the seat of the fire from oxygen in the environment and prevents further supply of oxygen (air) to the burning material. Covering the seat of the fire also delays the emission of combustible vapours. The oxygen-displacing effect of light foam is even reinforced by the formation of steam, which lowers the oxygen concentration in the basis of the fire. The formation of steam takes place because too many foam bubbles (60-80%) are destroyed by the heat of the fire.

Insulating/reflecting effect

As light foam has low thermal conductivity, it prevents re-ignition of combustible materials in the environment of the seat of the fire by the insulating qualities of the air component and the reflecting qualities of the water component. That is how to avoid that the fire extends. The foam forms an insulating layer against convection and a reflecting screen against thermal radiation.

Cooling effect

Due to the water sagging down from the foam and by the formation of steam, foam also has (little) cooling effect on the seat of the fire. This effect is greater with foam with lower expansion rates than with light foam.

The extinguishing action of foam is mainly based on suffocating the fire by sealing it off from oxygen. The cooling effect of foam is limited due to the small quantity of water. The quantity of foam needed for extinguishing a fire quickly increases as the fire has more energy, and this is generally the case when a fire continues for a longer time.

³⁹ Surface tension is the physical phenomenon that the surface of a liquid bordering the liquid-gas transition behaves as a resilient layer. Surface tension depends on temperature and the tension usually lowers as the temperature increases.