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Field Experiments with Techniques for the Offensive Exterior Approach

Research into the effectiveness of four techniques for the offensive exterior approach compared to the interior approach with a high pressure jet

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Netherlands Institute for Safety
PO Box 7010
6801 HA Arnhem

T + 31 (0)26 355 24 00
T + 31 (0)26 351 50 51

info@nifv.nl

NEDERLANDS INSTITUUT FYSIEKE VEILIGHEID NIFV

Colophon

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Review:	Dr J.G. Post MSc
Final responsibility:	Dr J.G. Post MSc (Head Research NIFV)

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Preface

The report before you presents the results of the tests with firefighting techniques, conducted by the Fire Service Academy en the NIFV Research Department in corroboration with fire departments in the Netherlands.
The project group "Development of an Offensive Exterior Approach" decided to compare a number of firefighting techniques that are readily available, so-called "easy pickings". A number of these techniques, such as fog nails and high pressure foam, have been used by Dutch fire departments in the execution of their firefighting tasks for years. Even the cold cut system is available and operational in one of the fire departments. The working group Techniques decided to compare the following techniques:

- Cold cut system
- Fog nail
- Distributor nozzle
- High pressure foam
- Interior approach with high pressure jet.

Some additional tests were conducted, using an exterior approach with a high pressure jet.
The tests were conducted between 21 and 24 November 2011 at the TRONED practice facility in Twente; fire tests were conducted in a former test hangar for fighter jets.

The test week was made possible through the support of:

- Rockwool, who provided and attached the necessary protection to the steel construction, free of charge
- Firma Nater, who provided the cold cut system
- TRONED, who provided the testing facilities and support staff
- The fire departments who provided staff and equipment:
    - Safety District Amsterdam-Amstelland
    - Safety District Utrecht
    - Safety District Haaglanden
    - Safety District Brabant Noord

These tests are the first steps towards acquiring robust and reliable knowledge.

I hope you enjoy reading this report.

Jaap Molenaar

Department Chairman Incident Management
Fire Service Academy

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1 Introduction

1.1 Background

This project was started in reaction to fire at the boat hangar at De Punt, where three fire fighters lost their lives. From the various investigations that were conducted in the aftermath of this fire, the industry learned that an offensive interior approach was not necessarily the best method to fight fires in buildings. Dutch firefighting departments reacted by declaring that there would be no more interior approaches performed, unless there were people to be saved. This position was adopted by many fire departments, but it also raised questions. A question that was often posed was: "Is there something we **can** do?" The Fire Service Academy and NVBR's Firefighting Network set up a project under the name of "Offensive Exterior Approach" in order to offer fire fighters in the field a usable perspective for action. Two working groups were created: the working group Tactics and the working group Techniques. The working group Tactics was responsible for developing the framework and related doctrines. The working group Techniques proposed suitable techniques and conducted relevant experiments and field tests.

The project's participants decided to test the practicability and effectiveness of a number of firefighting techniques in a controlled environment that was as realistic as possible. This report contains the results of the testing period.

1.2 Reason

The working group Techniques suggested a number of techniques to experiment with. Dutch fire fighters are more or less familiar with these techniques. Concretely, the working group suggested the following techniques:

- Extinguishing fire with a high pressure jet
- Extinguishing fire with a low pressure jet
- Ventilation
- High pressure foam
- Cold cut system
- Use of thermal imaging camera's
- Fog nail
- Distributor nozzle
- DSPA (Dry Sprinkler Powder Aerosol)

In the working group the question was raised how effective these techniques were compared to each other and how they could contribute to fire fighters' safety during an operation.
The working group decided to conduct a number of experiments, where a number of techniques would be tested under similar circumstances.

1.3 Tested techniques

The working group selected four techniques to be tested in an offensive exterior approach scenario. This selection was based upon the following grounds:
- The technique is used and/or available in the Netherlands.
- It is possible to use the technique outside the building/test room.
- For each technique, experienced operators are available.

The thermal imaging camera is not an extinguishing device, but an important supporting tool. Ventilation was not tested, because when ventilation is applied, no extinguishing agents are brought into the room, as opposed to the other techniques mentioned. The DSPA was developed mainly for the purpose of creating initial knockdown in small rooms.
Therefore, only a limited number of techniques remained to be considered for testing.

The techniques that were tested are:
- Cold cut system (CC)
- Fog nail (FN)
- Distributor nozzle (DN)
- High pressure foam (HPF).

They were tested in the setting of an offensive exterior approach, and compared with an offensive interior approach with a high pressure jet (HPJ). Since the test program allowed for more tests, two offensive exterior approaches with a high pressure jet were conducted. A short description of the six techniques that were tested follows below.

1. Cold cut system: a separate device with a lance; the fire room is accessed from outside by creating a hole of approximately 5 millimetre by applying an abrasive under high pressure (300 bar). Once the abrasive has cut through the wall material, a very fine water mist is released into the room. The water mist acts more or less like a gas, due to the very fine atomization. Therefore, and because of the high pressure, long distances can be bridged. A cold cut system has to be operated continuously by firefighting personnel.

2. Fog nail: fog nails are lances that are connected to the regular or low pressure systems of the pump vehicle. The lances end in a point, with behind the point a ring with small openings. A fine water mist comes out of these openings. To be able to use a fog nail, a small opening has to be created manually, in the wall or roof from the outside (with for instance a drill or a hooligan tool). Subsequently the fog nail can be inserted. Once placed, they can function independently. There is a defensive and offensive variation of the fog nail; they differ in the cone's spraying angle, which also results in a difference in throw distance.

3. Distributor nozzle: a distributor nozzle consists of a long lance, with a rotating head at the end (with a diameter of approximately 10 cm). It is connected to the low pressure system of the pump vehicle. The water pressure makes the head rotate and the water is distributed into the fire room. The distributor nozzle can be used by inserting it from the outside through an opening - for instance through an opening in one of the walls - into the fire room. The lance is approximately 4 metres long. When in operation, the distributor nozzle has to be fixated; it has to be placed at a minimum height of 1.5 metre in the fire room.

4. High pressure foam: high pressure foam is a self-contained system, installed onto the pump vehicle, with a separate reel and nozzle. A special foaming agent for high pressure foam is added to the water through an eductor on the vehicle. Subsequently, foam with considerable adhesive strength is created by the foaming

agent, the nozzle and other factors.
Its throw distance is approximately 10 metres. High pressure foam covers better than regular foam because it is adhesive and sticks even to vertical surfaces. The high pressure foam system has to be operated continuously by firefighting personnel. High pressure foam can be used both in interior and exterior approaches.

5. Interior approach with high pressure jet: the conventional way to use a high pressure jet is in an interior approach. Fire fighters enter through a regular opening with a high pressure jet and start cooling smoke gases and extinguishing the fire.

6. Exterior approach with high pressure jet: the same materials are used as in the interior approach. However, the operation is conducted from the outside, through an existing opening and is aimed at cooling smoke gases and possibly extinguishing the fire.

1.4 Research questions

The central research question is:

How does the effectiveness of some techniques for the offensive exterior approach compare to an interior approach with a high pressure jet when fighting fire in industrial buildings?

The underlying research questions are:
1. What is the effectiveness of the tested techniques
   a. with respect to cooling smoke gases?
   b. with respect to extinguishing fire?
2. To what extent do the tested techniques contribute to the safety of fire fighters regarding the variations in temperature from the moment they enter?
3. Are there any other issues with regard to effectiveness that become apparent when testing the techniques?

1.5 Definition

During the experiments, the above-mentioned techniques were examined. The other offensive exterior techniques were not considered in this research. The defensive approach with a low pressure jet was also not tested.
All tests were conducted five times, except for the high pressure foam technique and the exterior approach with a high pressure jet. The reasons for this will be explained later on in this report.
All tests were conducted in one building and with one scenario. Therefore, the results of the tests are only valid for the tested building and scenario. The scenario contained two seats of fire; these contained all the fuel available in the building. It was not possible for the fires to spread, and the only materials present at the scene were clean pine wood and liquid fire accelerant.
During the tests only the (variation in) temperature, the duration of the approach and the duration of the knockdown phase[1] were monitored. Other parameters, such as atmospheric humidity, pressure and water flow rate were not measured. The water usage of the various techniques was estimated, based on the theoretical water usage per minute and the duration of the operation.
The amount of wood that actually burned was not measured. The composition of the

[1] Knockdown refers to the situation when there are no visible flames.

smoke gases was not analysed. The research also did not include: the time needed to ensure the techniques were operational, the skill of the operating staff, the costs and other organisational advantages and disadvantages of the techniques. The operational techniques were tested exclusively for the scenario at hand.

Because of the construction of the test facility (steel structure, partially protected) it was decided that the temperature should not reach a level that would approach the critical temperature of steel. This was accomplished by limiting the amount of combustible material and by establishing a temperature to start extinguishing the fire. At previously conducted tests with fire, a temperature of 430°C was determined to be appropriate.

The chosen research set-up and the size and shape of the test location limited the extent to which the operational possibilities of the techniques could be shown. Furthermore, subsequent questions arose when conducting the tests which could not be answered because the measuring instruments necessary to answer these questions, were not available at the time. An example hereof is: "What is the effect of a specific technique on creating a survivable environment, other than with regard to temperature?" This issue is further discussed in Chapter 5 Recommendations.

2 Research justification

2.1 Set-up of the experiments

The tests were conducted at the TRONED training facility in Enschede, in a hangar that had been prepared for the tests. A seat of fire was created at two locations in the hangar.
The fires were lit according to an established pattern and time and temperature were monitored.
A single offensive technique for the exterior approach was tested in each test, from the moment the starting temperature had been reached. Initially, the set-up was such that all techniques would be tested five times in order to obtain reliable measurement results. However, high pressure foam affected the test environment in such a way that recreating the circumstances of the starting point proved not possible. Therefore, high pressure foam was tested only three times, using different tactics. Since there was room for two more tests, it was decided to conduct an exterior approach with a high pressure jet twice.

This resulted in 25 tests of offensive techniques:
- 5 tests of an exterior approach with a cold cut system
- 5 tests of an exterior approach with fog nails
- 5 tests of an exterior approach with a distributor nozzle
- 5 tests of an interior approach with a high pressure jet
- 1 test of an exterior approach with high pressure foam, aimed at cooling down smoke gases
- 1 test of an exterior approach with high pressure foam, aimed at attacking the flame front
- 1 test of an interior approach with high pressure foam
- 2 tests of an exterior approach with a high pressure jet

A more detailed description of the way these techniques were used in the tests can be found in Section 2.5.

2.2 Test criteria

The following indicators were measured during the tests:

1. Temperature. During the tests the variation in temperature was measured by thermocouples, which were connected to a data logger and a laptop. The temperature was measured at 7 locations, both high up in the smoke layer (approximately 1 metre below the ceiling) and on breathing level (1.80 metres above floor level). The thermocouples were positioned at various locations in the hangar (see Section 2.4).
2. Time. The following times were recorded from the moment of lighting the fires: moment of reaching the starting temperature of 430°C (thermocouple 5), length of time between the start of the operation and smoke layer temperature below 150°C (thermocouple 6) and the length of time from the beginning of the operation until knockdown (no more flames visible).
3. Visual observation of fire development. During the operation, the fire development was registered with the aid of a thermal imaging camera combined with visual observation. The observations were focussed on whether or not knockdown occurred, whether or not the fire flared up again after the offensive exterior approach had ended and other possible effects.

2.3 Test location

The tests were conducted at TRONED in a hangar that was especially prepared for this purpose. The inside dimensions of the hangar were: depth 15.35 metres x width 11.60 metres x height 4.50 metres.
The structure consisted of steel beams with steel wind braces. The wall and ceiling panels were also made of steel and consisted of perforated sheet steel insulated with rock wool. The roof was covered with bitumen on the outside. The floor was made of concrete. The front of the building contained two large sliding doors; combined they were 7.30 metres wide and 4.50 metres high. On the right hand side a wicket-door was situated. In the back of the hangar on the right there was another wicket-door leading to a small room. This room contained a door to the outside. A ventilation hatch was located high up in this room. The (two) windows of the building were welded shut. Figure 1 provides a picture of the test location. Section 2.8 contains a schematic drawing of the building.

Figure 1: Test location

2.4 Scenario

Fire load

Pine wood pallets were used for fuel. A fire load was placed on two locations inside the building. Each fire load consisted of a rack containing two piles of 8 pallets. The total number of pallets amounted to 32. The fire load consisted of approximately 512 kilos of pine wood. In the test set-up it was not possible for the fires to spread.
The use of racks made it possible to move the fire loads quickly in and out of the test location. It also allowed the pallets to be placed in the same way and in the exact same place for each fire. At the bottom of the rack a sheet of softboard (1.22 x 2.44 metres) was placed under the pallets. The purpose of the softboard was to collect any liquid fire

accelerant leaking down and add it to the fire load, thus allowing the fires to develop in a similar way throughout the tests.
All pallets came from the same batch and were more or less identical. Prior to testing, all pallets were stored in the same hangar under identical conditions. This lead to the assumption that all pallets were more or less identical during the experiments.

The fire loads were placed on specific locations inside the building; the locations were marked on the floor of the hangar. Figure 2 shows the fire load locations.

Figure 2: Fire load location

Igniting the fire load
The pallets were ignited according to an established pattern:
Per pallet box two litres of liquid fire accelerant were distributed, every time in the same way.
After preparing the test set-up, the pallet boxes were ignited in an established order. It was not possible for the fires to spread during the tests.

Start, switch and conclusion of the experiment
After the fire's ignition, time and temperature were monitored from a distance.
The prearranged starting point was based on two conditions:

1. Both fire loads had to be burning completely
2. The temperature of the smoke layer had to be approximately 430°C. Thermocouple 5 was leading in determining whether the conditions were met. (To perform the tests at higher temperatures would have impacted the steel structure of the test facility, and that impact would have been too severe. Therefore, it was decided to start the operation at 430°C.)

Among other things, fire development is affected by room temperature, atmospheric humidity, wind-force and the direction of the wind. This makes is difficult to recreate the

exact same fire development outside a laboratory setting, even when working with identical fire loads.
This also proved to be the case during the experiments. In order to reach the designated temperature, the room was ventilated by opening and closing the wicket-door. The ventilation procedure was performed by an experienced stoker from the Fire Service Academy.

After both above-mentioned conditions were met, the experiment began and the offensive technique was applied from the front of the building, focussed on cooling down the smoke gases.
During the procedure, the temperature was monitored by an observer. At T = 150°C on thermocouple 6, the interior attack with a high pressure jet was started. A temperature of 150°C was decided upon because a smoke gas layer with this temperature is considered to be relatively safe from sudden spreading of the fire through flammable gases in the smoke.
When the sign to switch was given, two fire fighters would enter the building with a high pressure jet to extinguish the fire.

In principle, the measuring ended when the switch to the high pressure water system was made. The purpose of extinguishing the fire was to prepare the test room for the next experiment.
However, if the fire would flare up again after the offensive exterior technique was stopped, the test would continue until knockdown was realised again through an interior approach with a high pressure jet.

During the extinguishing of the fire, the sliding doors at the front of the building were opened and a positive pressure ventilator was activated in the room at the back of the hangar. The purpose was to remove the smoke gases and heat from the hangar as soon as possible.

2.5 Applying offensive techniques

All offensive techniques were applied from the outside, from the front of the hangar.
The techniques were used as follows:

- Cold cut system: For the cold cut technique, a self-contained unit was used with a lance and a flow rate of 60 litres per minute. The place where the small hole had to be made, using the cold cut system with regular abrasive, was marked on the hangar door. The hole was created at the start of the experiment, immediately followed by cooling down the smoke gases.
- Fog nail: Two fog nails were used in the fog nail tests. They were short high pressure lances (offensive type) with a flow rate of 70 litres per fog nail per minute. Before the start of the tests, two holes were drilled into the hangar doors, through which the fog nails could be inserted. The fog nails were inserted into the doors prior to the start of the test.
- Distributor nozzle: A standard distributor nozzle was used; it had a fixed set-up and had the possibility to swerve. The distributor nozzle was inserted through a hatch in the hangar door, which had been especially constructed for that purpose. Before the experiment started, the hatch was open, but the distributor nozzle was not yet in place. This was done at the start of the experiment. A mark was made on the distributor nozzle, to indicate how far the distributor nozzle had to be inserted through the hatch, into the hangar. The position of the operator was marked on the ground, to ensure that the distributor nozzle was used in the same manner and from the same position in each of the tests.
- High pressure foam: For the tests with high pressure foam, a pump vehicle was used with a built-in high pressure foam system. It was supplied with class A foam. For the

high pressure foam tests the same hatch set-up was used as in the tests with the distributor nozzle.

- Interior approach with a high pressure jet: The approaches with a high pressure jet were conducted with a conventional high pressure offensive hose, with a flow rate of 125 litres per minute and with a jet nozzle suitable for cooling smoke gases. The interior approaches with a high pressure jet were performed from the wicket-door at the side of the building, and in accordance with the latest Dutch teaching materials. These focus on smoke gas cooling with a special jet nozzle. Initial smoke gas cooling occurred close to the door, and then an approach further into the room was conducted, in the direction of the seat of the fire. At first the focus remained on cooling the smoke gases, with the purpose of lowering the temperature below 150°C. There would be a switch to attacking the flame front if after some time the temperature would lower insufficiently, or if the circumstances for the operators would become too uncomfortable regarding the buildup of heat.
  The interior approach with a high pressure jet was executed by experienced instructors from the Fire Service Academy, who possess comprehensive knowledge and experience in the field of smoke gas cooling. The aim was to guarantee minimum variation between approaches and maximum quality.
- Exterior approach with a high pressure jet: In addition, two exterior approaches with a high pressure jet were performed, under the same conditions as the tests with the distributor nozzle and the high pressure foam. The reason for these additional tests was that in other tests the high pressure jet was used only for interior approaches, but it can be used for exterior approaches as well. The same hatch in the hangar doors was used again for these tests. The smoke gases were cooled down with a continuous jet.

The offensive techniques that were tested were prepared to be ready for use, right in front of the hangar prior to each experiment.

2.6 Conducting the tests (method)

The tests were conducted according to a predetermined order:
After preparing the hangar, the time and temperature measuring was started. Then the fires were lit. After reaching the starting temperature (T = 430°C on thermocouple 5) the offensive exterior approach began. When the smoke gas layer had sufficiently cooled down (T = 150°C on thermocouple 6) the switch was made to extinguishing the fire with a high pressure jet. The cold cut system, fog nail, distributor nozzle and high pressure foam were used exclusively for an offensive exterior approach, and were not used to subsequently extinguish the fire. In all instances a high pressure jet was used to accomplish that. After the flames were extinguished with a high pressure jet, the hangar's sliding doors were opened and the positive pressure fan was started in the room.
Subsequently the smouldering pallets were moved out of the hangar by a fork-lift truck and the test room was restored to its original state.
In order to accomplish this, a recuperation time of 45 minutes was observed between experiments. Apart from that, the temperature of the steel construction had to be below 100°C, and the air temperature in the hanger around thermocouple 5 had to be around 20°C to start the next test. After operations where water or foam remained in the room (specifically after testing with the distributor nozzle and high pressure foam), the water and/or foam was removed manually from the hangar.
From the above, it cannot be concluded that the tested techniques are not suitable for completely extinguishing a fire. This was not researched in this test set-up.

All systems were tested five times to limit the effects of coincidence and of the environment. Two exceptions were made: for the exterior approach with the high pressure jet and for high pressure foam.

Since there was room to conduct two additional experiments, it was decided to perform two offensive exterior approaches with a high pressure jet.

High pressure foam was tested only three times, because the use of high pressure foam made it virtually impossible to create the same starting conditions for a subsequent test. This is due to the fact that the foam also ends up on the walls and is then absorbed into the perforated walls with rock wool, which has an impact on the fire development in subsequent tests.

It was decided to diversify the tests with high pressure foam, because it turned out to be impossible to restore the building to its original state after the first test with high pressure foam. The three variations were:

1. First, cover the flames from the outside and subsequently cool the smoke gases (since the main purpose of high pressure foam is to create knockdown)
2. First, cool the smoke gases from the outside and subsequently create knockdown (the usual procedure for the fire department involved)
3. A conventional offensive interior approach with high pressure foam.

When interpreting the test results, it should be taken into account that the different approaches with high pressure foam were only tested once because of feasibility issues. Despite the limited testing of high pressure foam, it was decided to include the test results in the presentation of the data collected, merely for the purpose of comparison. However, additional research is required to determine with any certainty how effective high pressure foam is.

Each day six tests were performed: five tests of a technique for offensive exterior approaches and one test of an interior approach with a high pressure jet. All tests of a technique were performed by the same team. These teams consisted of two fire fighters who would use that particular technique in actual practise.

2.7 Safety

Construction safety
A prevention expert examined the building to determine whether the tests could be conducted safely. The expert calculated the maximum temperature the steel structure could have (core temperature) to still keep working safely.
On the expert's advice the most vulnerable parts of the building, the wind braces, were insulated with fire-resistant insulation. In addition to this, one of the thermocouples was positioned in such a way that it measured the steel construction's core temperature. It was decided beforehand to establish a no-play-procedure at the moment the steel construction reached its critical temperature.
As it turned out, the steel construction's temperature stayed well below the critical limit during all tests.
After each test the building was inspected visually for cracks, deformations and other indicators regarding construction safety.
As an extra precaution steel sheeting was installed above the pallet boxes to protect the construction (see figure 3) and to avoid direct radiation from the flames onto the beams as much as possible.

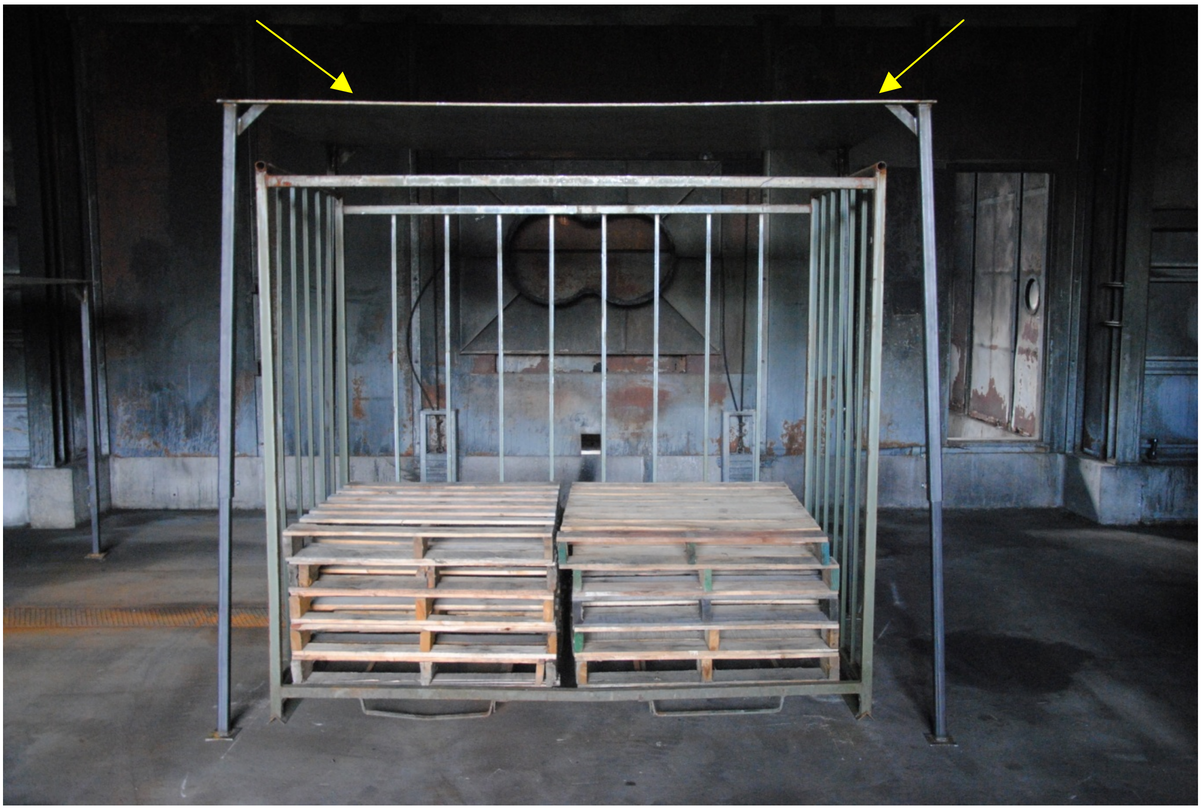

Figure 3: Steel sheeting above the fire load

Safety during operations
Beforehand, all combustible materials were removed from the hangar and the windows were welded shut to maximize safety during the operations and to prevent any impact on the tests.
The most risky approach, that is the interior approach with a high pressure jet, was always conducted by two individuals. In addition to this, a safety officer with a thermal imaging camera was inside the hangar during all tests. This officer was positioned in such a way, that he was out of reach of water and/or abrasive at all times and had a direct escape route to the outside. All parties were in contact with each other by walkie-talkies and there was a no-play-procedure in place.

During operations, spectators were kept at a distance and working circles with a diameter of approximately 5 metres were created.
All individuals who were or could be in the smoke during or after the tests wore breathing apparatus.

Safety while clearing out the fire room
As long as there was smoke in the building, the building was only entered by individuals who wore breathing apparatus, including the driver of the fork-lift truck. CO measurements were performed before individuals without breathing apparatus entered the fire room.

2.8 Method of registration

The following registrations were recorded during the tests.

Time registration
Time and duration were recorded with the aid of stopwatches. The computer system connected to the thermocouples registered time as well.

The following times or moments in time were registered:
- Time at which the starting temperature was reached
- Time at which the approach was started
- Time at which the smoke gas layer temperature was below 150°C.
- Time at which knockdown occurred
- Time at which extinguishing the fire with a high pressure jet started.

Temperature registration
Eight thermocouples were used for registering temperatures. Figure 4 contains a picture of one of the thermocouples.

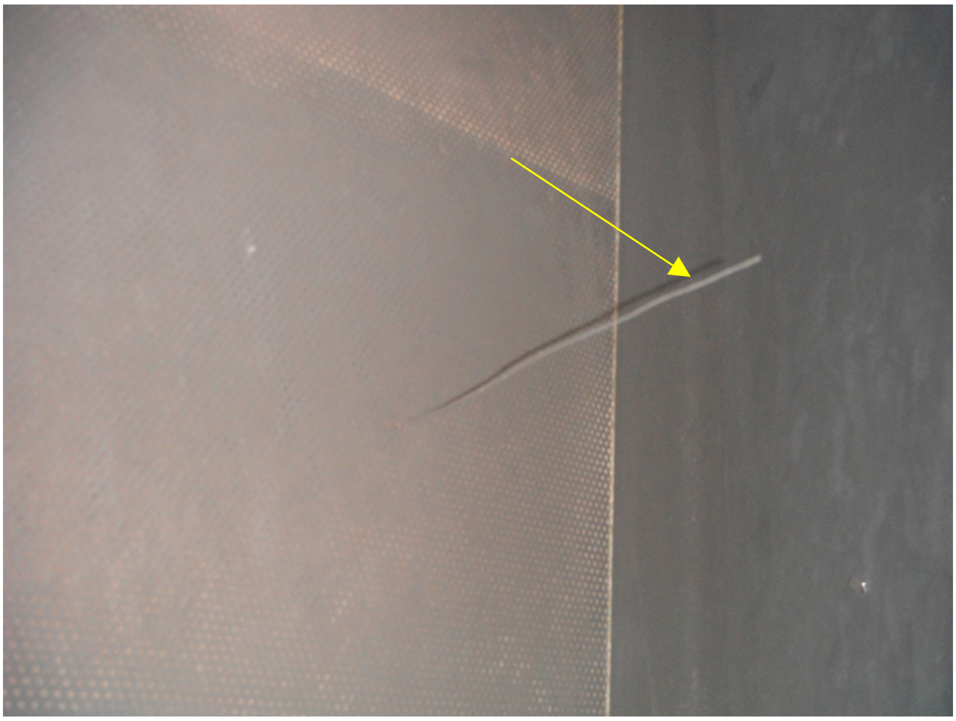

Figure 4: Thermocouple

The thermocouples were positioned at different locations in the building, at two heights: at 1 metre below the ceiling ('high') and 1.80 metres from the floor ('low'). See figure 5.

The thermocouples were positioned as follows:
- 4 regular thermocouples at a height where the temperature of the upper smoke layer was measured.
- 2 regular thermocouples at a height where a human being would be in the room, one of which close to the door through which the interior approach with a high pressure jet was conducted.
- 1 regular thermocouple, placed in isolation, to measure the core temperature of the steel construction.
- 1 thermocouple equipped with a metal plate, acquired from a Swedish research institute. In the end, this thermocouple was not used in the analysis.

The thermocouples were connected to a data logger with a measuring program. Therefore, all temperatures were available in real-time.

Video recording
A thermal imaging camera with a recording function was used to register what happened inside the building during the approach. This camera was operated by the safety officer (mobile camera in Figure 5)
A stationary thermal imaging camera (TIC in Figure 5) was placed inside to record the images inside. The approaches were also filmed from the outside of the building, with a regular camera.
Additionally, an industrial thermal imaging camera (Flir) was used to monitor the effects on the structure. This is a very accurate thermal imaging camera with a recording function, meant to be used on the outside.
Finally, there were the visual observations by the safety officer inside, which he recorded afterwards.

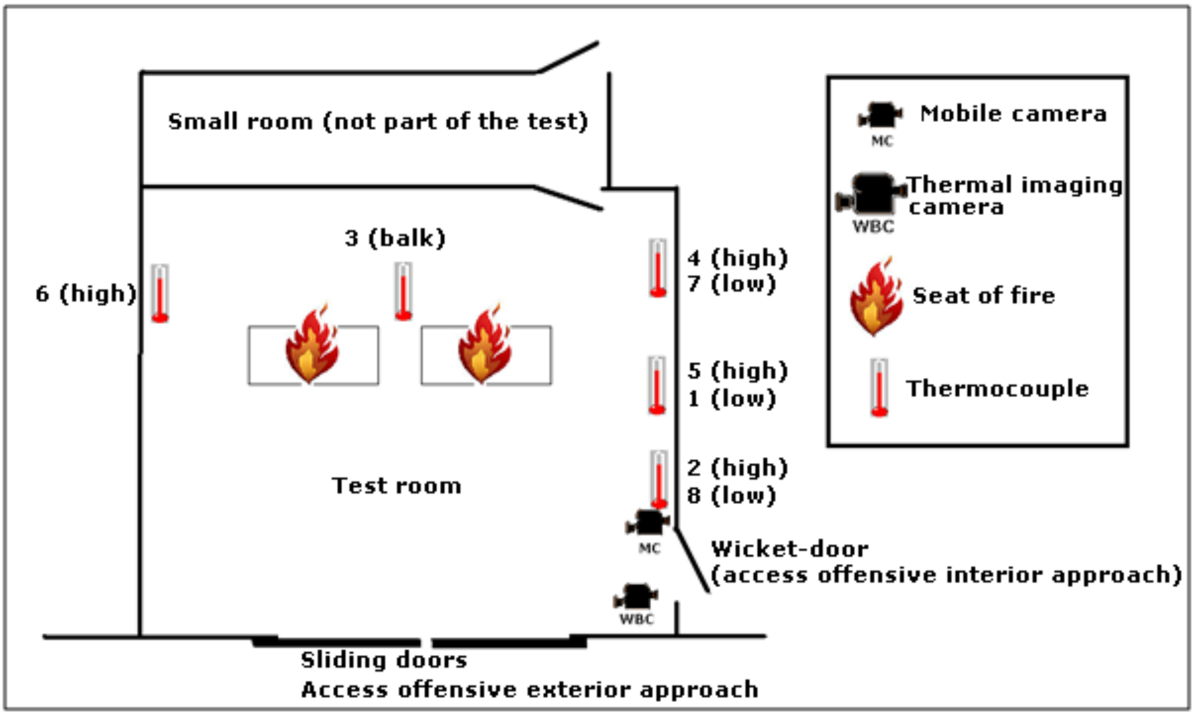

Figure 5: Schematic drawing of the test area

2.9 Test similarity

This particular test set-up was agreed upon, in order to be able to conduct the tests as similarly as possible. The set-up includes the use of a similar amount of water and wood, an identical method of ignition, the cooling of the room and removal of any excess water.
It proved to be difficult to recreate the same conditions for all tests, also due to local weather conditions and the fact that the test facility warmed up during the day.

To provide a picture of the similarity of the tests: below are some data on the fire development until the start of the approach (target temperature T = 430°C on thermocouple 5). Refer to Table 1.

Table 1: temperatures before starting the approach

	Minimum	Maximum	Average	Standard deviation
Test room temperature before igniting the fire	2	27	17	7
Time at which starting temperature was reached (seconds)	312	735	437	104
Temperature at the start of the test (°C)	374	435	418	15

A one way ANOVA analysis shows that there is no significant difference between the above-mentioned three variables per tested technique.

3 Test results

The findings from the high pressure foam tests are included in the presentation of the test results, even though the number of tests was very limited. It was decided to include the data to provide a more complete picture. However, the results of the test with high pressure foam should be interpreted with due caution.

3.1 Effectiveness of the techniques

It was examined to what extent the techniques were effective regarding smoke gas cooling and creating knockdown.

Smoke gas cooling

During the tests, the temperature of the smoke gas layer was measured. Figure 6 depicts per technique the average variation in temperature registered by thermocouple 6 (high in the room) against time. The tests with the fog nail, cold cut system and distributor nozzle show a steeper line than the interior approach with a high pressure jet.

Furthermore, it stands out that the cooling power of the fog nails is strongest at the beginning. At the moment of transition between innovative technique and extinguishing the fire with a high pressure jet (at 150°C), it is noteworthy that the temperature remains fairly constant in the fog nail tests, but keeps going down in the tests with the cold cut systems and the distributor nozzle. This can be explained by the fact that there is no reignition in the tests with the distributor nozzle and cold cut system, but in the fog nail tests the fire reignites during the transition to a high pressure jet.

In addition, it stands out that the variation in temperature in the interior approaches with a high pressure jet is very irregular. This is caused by human factors in the interior approach. Finally, it is also noteworthy that in the high pressure jet operation, the line descends most steeply after over 200 seconds. This can be explained by the fact that during the interior approach the focus of the operation shifted from smoke gas cooling to attacking the flame front, because the smoke gas cooling had insufficient impact on the temperature of the smoke gas layer.

The data also show that the exterior approach with high pressure foam[2] is relatively successful during its first 50 seconds as far as lowering the temperature is concerned. However, after that time the line flattens and high pressure foam ends up in last position in reaching the target temperature of 150°C.

[2] Note: the exterior approach with high pressure foam was only tested twice, in different set-ups. Additional research is required to determine its effectiveness with any certainty.

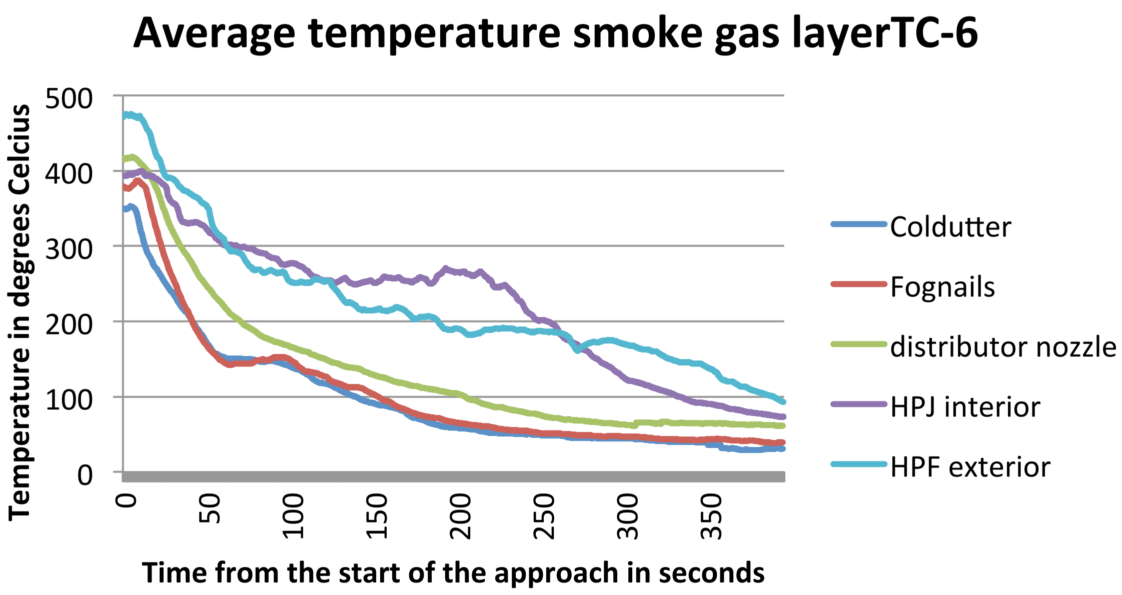

Figure 6: average temperature smoke gas layer TC-6

The steepness of the lines in the chart above was further analysed in order to determine the effectiveness of the techniques and also because the tests did not start at the exact same starting temperature. Linear regression analysis was applied: an analysis of the variations in temperature was conducted from t=0 until the moment the target temperature of 150°C had been reached. This analysis shows that the gradient coefficient for the average temperature development is the most negative in the fog nail tests (-0.49). This means that in this test set-up, the fog nails caused the strongest fall in temperature per unit of time. The fog nails are followed by the cold cut system (-0.31), the distributor nozzle (-0.24), exterior high pressure foam (-0.07) and the interior high pressure jet (-0.06), respectively.

Figure 7 depicts for the various techniques the temperature at breathing level (thermocouple 8).

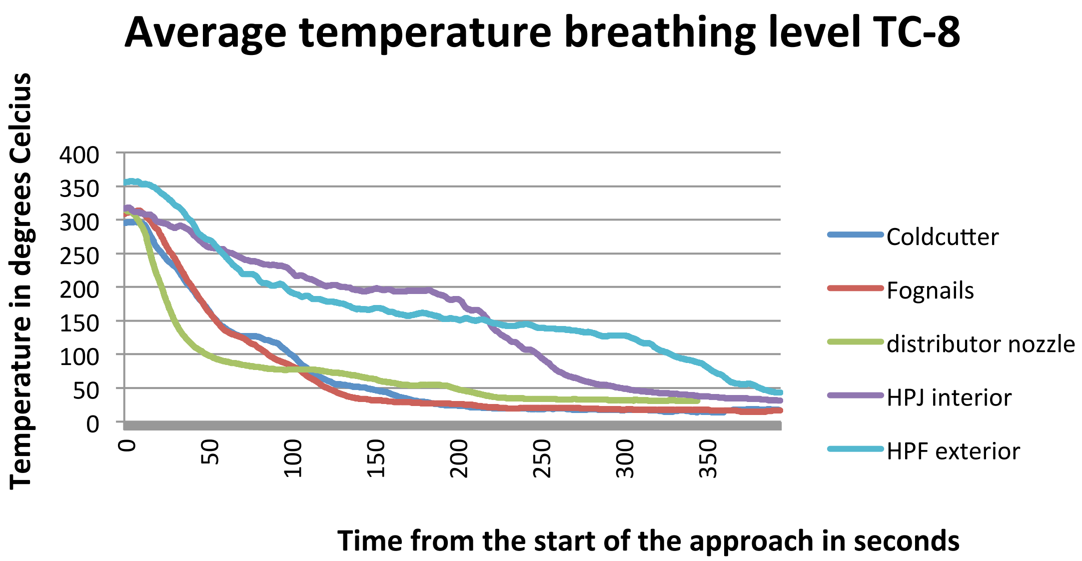

Figure 7: average temperature breathing level TC-8

What stands out is that the distributor nozzle generates a fast drop in temperature on thermocouple 8, compared to the previous chart. It must be pointed out that this thermocouple was situated next to the side door at a height of 1.80 metres (breathing level). Therefore, devices that have a cooling effect in the front part of the room, such as the distributor nozzle and fog nail, will perform well with regard to thermocouple 8. However, an analysis of the difference between thermocouple 7 (at the back of the room) and thermocouple 8 (next to the door at breathing level) shows no differences. The interior approach with a high pressure jet and the exterior approach with high pressure foam are far less effective than the exterior approaches with the cold cut system, fog nail and distributor nozzle.

The time it took for the smoke gas layer temperature to fall under 150°C (thermocouple 6) was also examined. The results are in the chart below (Figure 8).

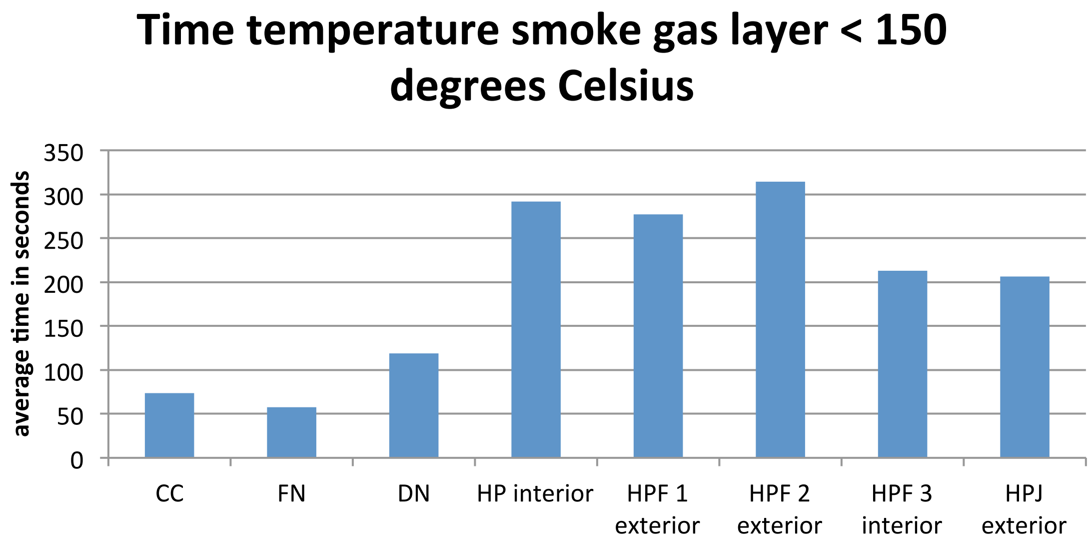

Figure 8: smoke gas layer < 150°C for the various systems

A statistical analysis using a t-test was carried out to determine the chance that the differences found, were coincidental. At a chance of coincidence smaller than 5% (a reliability level of 95%) there is said to be a significant difference. The results of these calculations are included in Appendix 2.

With regard to smoke gas cooling the following findings are noteworthy:

- Both the cold cut system and the fog nail perform significantly better than the other systems. No significant differences are found between the cold cut system and the fog nail.
- The distributor nozzle approach obtains significant better results than the high pressure foam approaches and the interior approach with a high pressure jet.
- The interior approaches with a high pressure jet perform significantly worse than the interior approach with high pressure foam. However, it must be noted that there was only one interior test with high pressure foam, so this cannot be determined with any certainty.
- There are no significant differences between the exterior approaches with a high pressure jet on the one hand, and the approaches with the fog nails, distributor nozzle, high pressure foam and interior approach with a high pressure jet on the

other hand. The significant differences between these systems cannot be explained any further, since only two exterior approaches with a high pressure jet were conducted, and the results thereof varied considerably.
- The differences between the approaches with high pressure foam cannot be determined statistically, since each test was only conducted once.

The maximum temperature reached during the tests - after the signal to start the offensive approach had been given - was also looked at. Figure 9 shows that the temperature continued to rise in the tests with the cold cut system and the high pressure foam techniques, which initially focussed on smoke gas cooling.

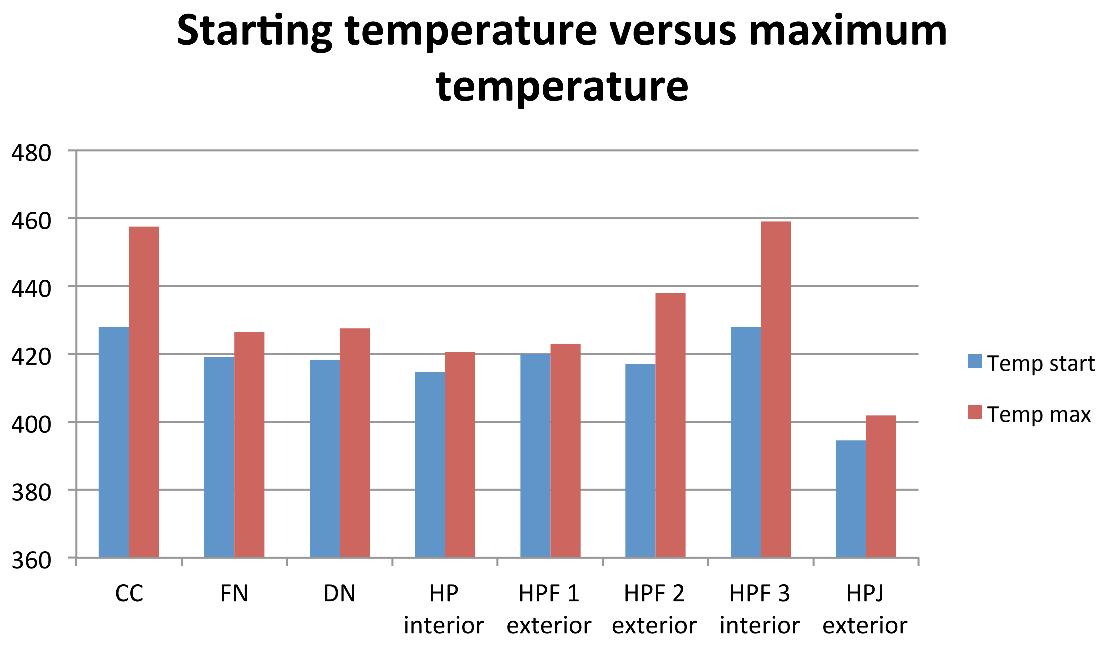

Figure 9: starting temperature versus maximum temperature reached

A possible explanation for this is that in the case of the cold cut system a hole had to be made at the beginning of the test (which takes time), whereas this was not necessary for the other techniques.
In the case of an approach with high pressure foam, an explanation could be that high pressure foam is suitable for smoke gas cooling only to a limited extent.

Knockdown
The observer inside the building registered whether knockdown occurred and at what moment, using a thermal imaging camera.
In all tests with offensive exterior techniques, knockdown occurred before the building was entered, with the exception of one approach with the distributor nozzle.
Figure 10 shows the average time at which knockdown occurred. It shows that initial knockdown took much longer to occur in the tests with the interior high pressure jet approach. This is caused by the fact that smoke gas cooling had to be performed first, to ensure the safety of the individuals inside the building.
The distributor nozzle created knockdown relatively fast compared to the other offensive exterior approaches. The exterior approaches with high pressure foam and the exterior approaches with the high pressure jet also did well, but because of the limited number of tests it cannot be determined with any certainty whether this can be attributed to the systems.

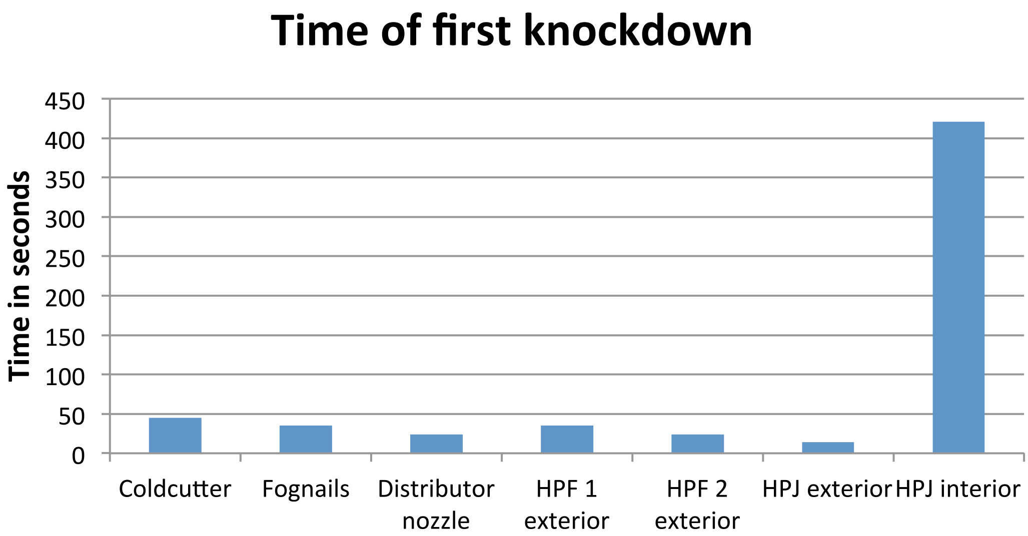

Figure 10: time until initial knockdown

Notable is that interior approaches with a high pressure jet show the greatest variation in the time at which the flames have disappeared. This means that an interior approach with a high pressure jet is very dependent on the operators[3]. The distributor nozzle approaches also show a relatively wide variation. This variation is one of the reasons it is not possible to demonstrate a significant difference at a reliability level of 95%.

At a smoke gas layer temperature of 150°C, the switch was made from an offensive technique to attacking the fire with a high pressure jet. It was looked at whether the fire would flare up after the moment of transition.

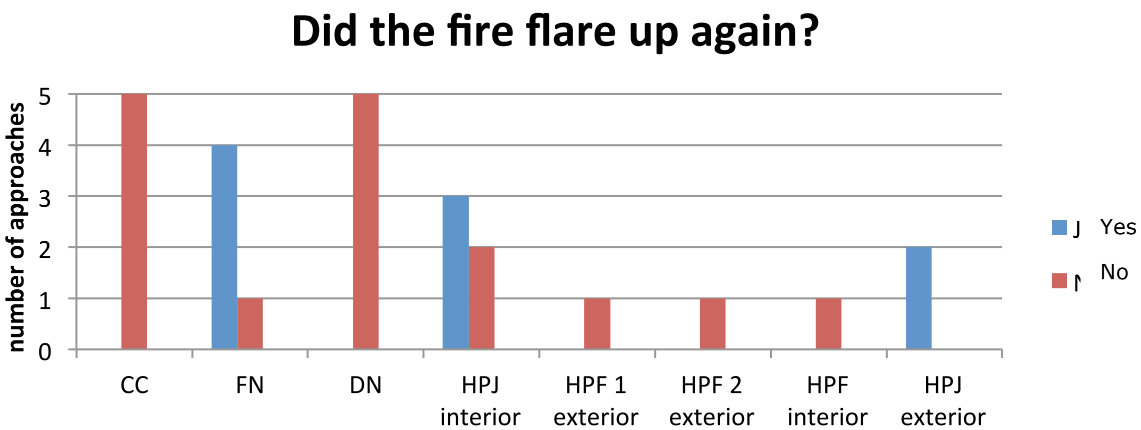

Figure 11: overview fire flaring up again per system

Figure 11 shows that the fire did not flare up in the tests with the cold cut system, the distributor nozzle and the high pressure foam. The fire did flare up in (some of) the

[3] Despite the fact that the interior approaches with a high pressure jet were executed by the same, very experienced fire fighters.

tests with the fog nails and the interior and exterior approaches with a high pressure jet.

When determining how long it took for the flames to definitely disappear with the three techniques last mentioned, it turns out that this took an average of 92 seconds for the fog nails, 361 seconds for the interior approach with a high pressure jet and an average 307 seconds for the exterior approach with a high pressure jet. It is not possible to demonstrate significant differences because of the limited number of exterior approaches with a high pressure jet and the great variation shown in the interior approaches with a high pressure jet.

3.2 Variation in temperature and the safety of firefighting personnel

After conducting a further analysis, where t=0 is the moment of entry, it becomes clear which temperatures the fire fighters had to face upon entering the building and how the temperature developed during the course of the operation.
Figure 12 shows that the temperature is considerably higher during the interior approaches with a high pressure jet, than during the exterior approaches with the cold cut system, fog nails, distributor nozzle and high pressure foam. That is only logical, since the choice was made to perform an interior approach instead of an exterior approach.

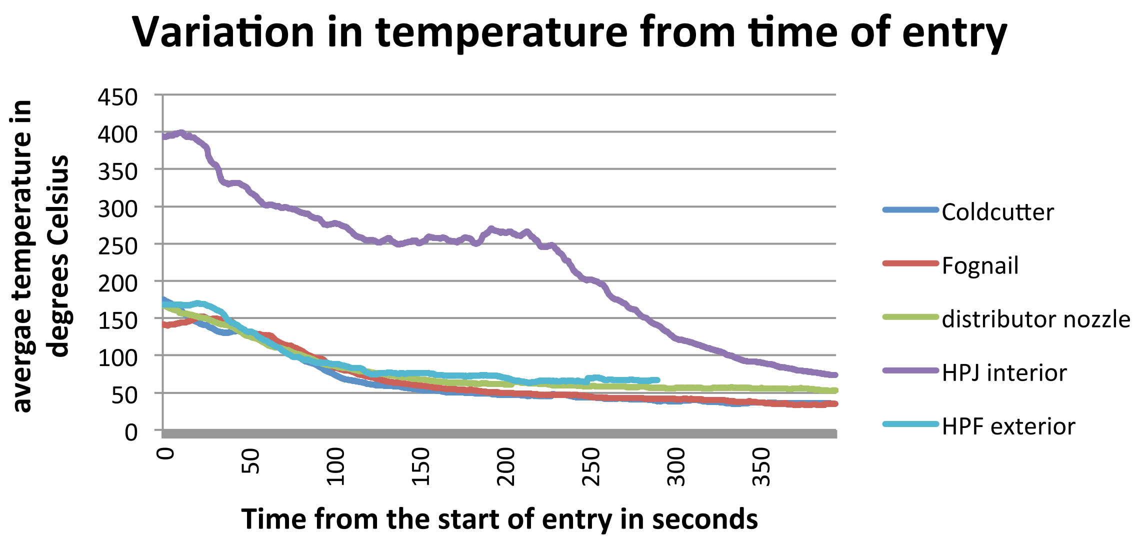

Figure 12: average temperature upon entering

During the offensive exterior approaches a switch was made to attacking the fire with a high pressure jet when the temperature of the smoke gas layer dropped below 150°C. There are not many differences between the various offensive exterior techniques when comparing the variation in temperature during exterior approaches, after the fire fighters entered the building with a high pressure jet (Figure 13). In none of the offensive exterior techniques a strong increase in temperature occurs after switching to an approach with a high pressures jet. Therefore, the interior approaches could be conducted relatively safe.

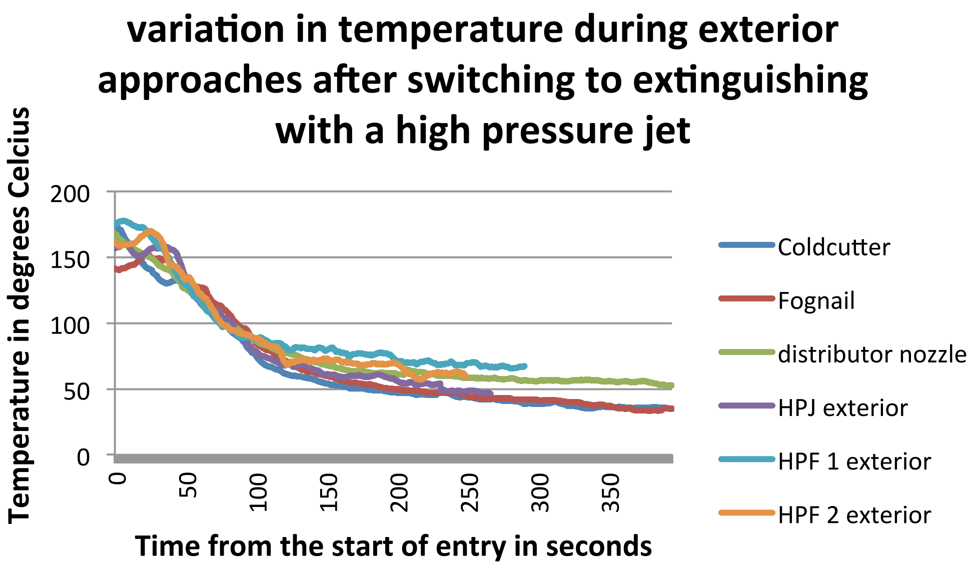

Figure 13: average temperature upon entering per exterior approach

3.3 Other measurements and observations

Water usage
The water usage during the tests has not been measured explicitly. However, a rough estimation of the average water usage was made based on the average duration of the operation and the theoretical flow rate of each technique. Table 2 depicts the results.

	Average duration (seconds)	Flow rate (litres/second)	Average water usage[4]
Cold cut system	74	1	74
Fognails	58	2.3	133
Distributor nozzle	119	5.6	660
High pressure foam - exterior	296	2.8	839
High pressure foam - interior	213	2.8	603
High pressure jet - interior	291	2.1	611
High pressure jet - exterior	207	2.1	435

Table 2: Estimated water usage.

It must be stressed that this is purely an estimate and valid exclusively for the tests conducted. Apart from that, average water usage is not an absolute predictor of collateral damage. Certain techniques can apply water more targeted than others, which also has an impact on collateral damage.
Finally, it must be noted that for each technique water usage is estimated for the period between the start of the approach (offensive exterior approach or interior approach with high pressure jet) and the moment the target temperature of 150°C is reached. The water usage for the subsequent extinguishing of the fires is not considered.

[4] For high pressure foam inclusive of foaming agent

System consistency
In addition, it was monitored whether the systems performed more or less the same during the tests. Any variations would say something about the predictability of the system and the possibility to influence its performance. Figures 14-17 show the results.

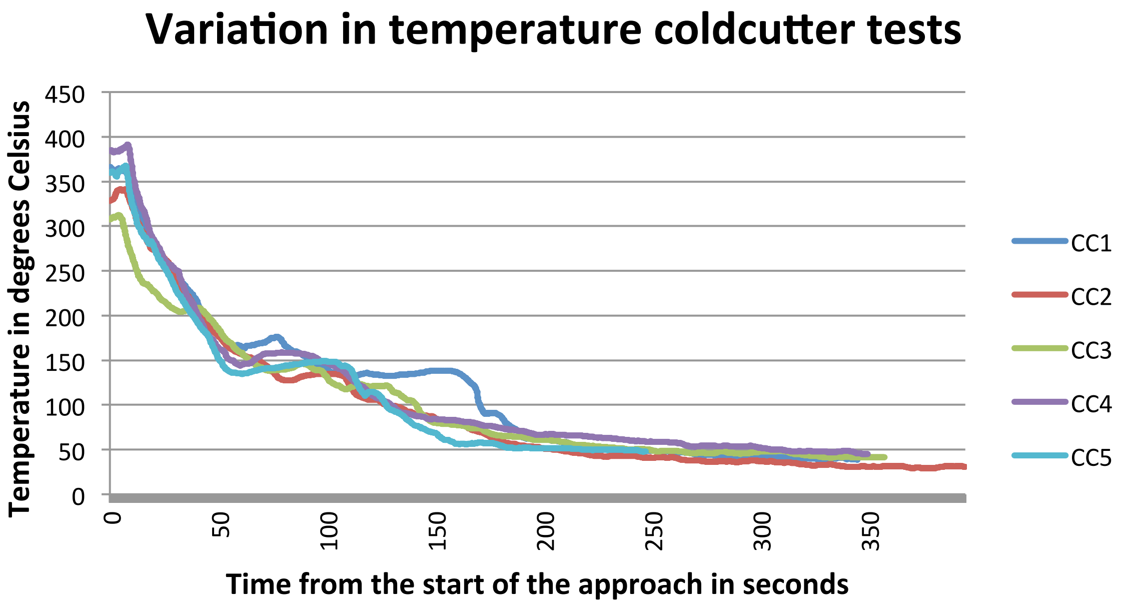

Figure 14: variation in temperature cold cut system tests

At the beginning of the test with the cold cut system, a hole had to be made by using the abrasive. For this, the results of the measurements are corrected with 2 seconds[5]. The slopes of the lines are more or less similar. The third test was different from the others, as is shown by the green line. In this test the nozzle of the cold cut system slipped twice. Subsequently a new access hole had to be created, which resulted in a temporary limited rise in temperature.
In conclusion: when used in the exact same way, the cold cut system performs consistently in smoke gas cooling. However, because of the tactics and technique, the effectiveness of the device is largely dependent on the skill of the operator.

[55] Determined by means of measurements from the video recordings

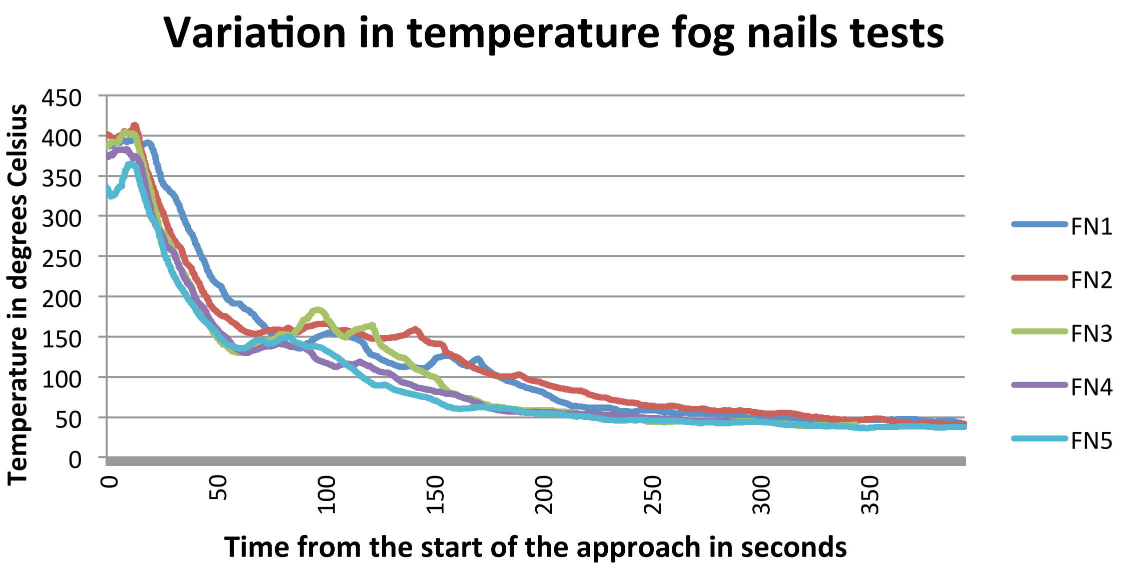

Figure 15: variation in temperature fog nail tests

When comparing the fog nail tests with each other, it is clear that there is little variation as far as smoke gas cooling is concerned. The performance of the fog nail approach was less dependent upon its operator in the tests. After all, the entry holes had already been created, the fog nails were already in place en the operator only had to open the valve. It is noteworthy that the variation increases after the moment of switching to attacking the fire with a high pressure jet (at 150°C). This is caused by the fact that the fire flared up again in some instances. In conclusion: of all tested techniques, the fog nails are the most consistent in cooling smoke gases. There is a greater variety in temperature development after switching to extinguishing the fire.

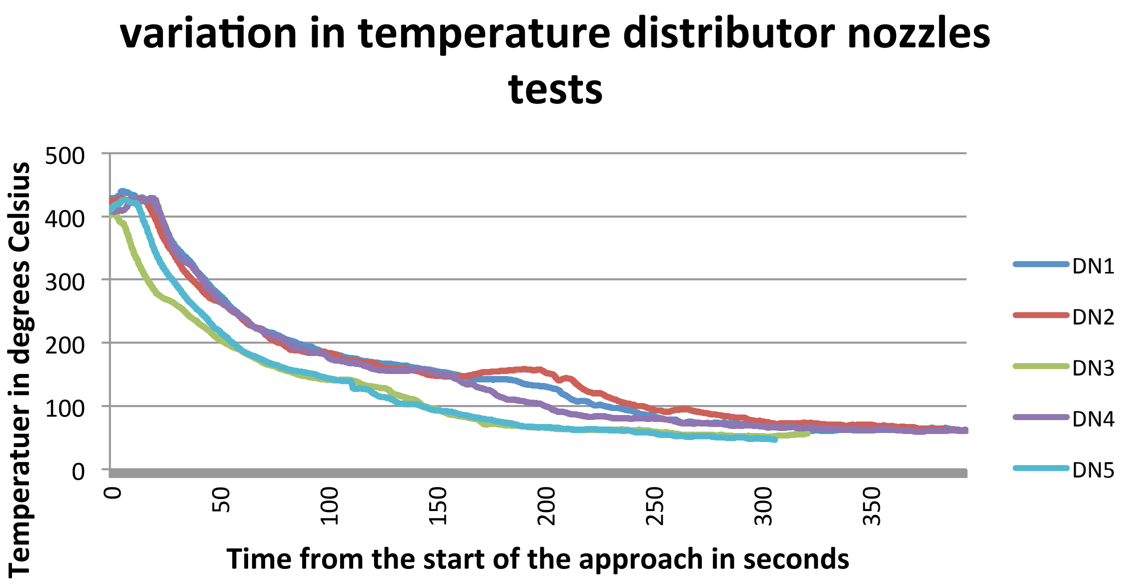

Figure 16: variation in temperature distributor nozzle tests

The distributor nozzle shows a relatively consistent picture with regard to variation in temperature.

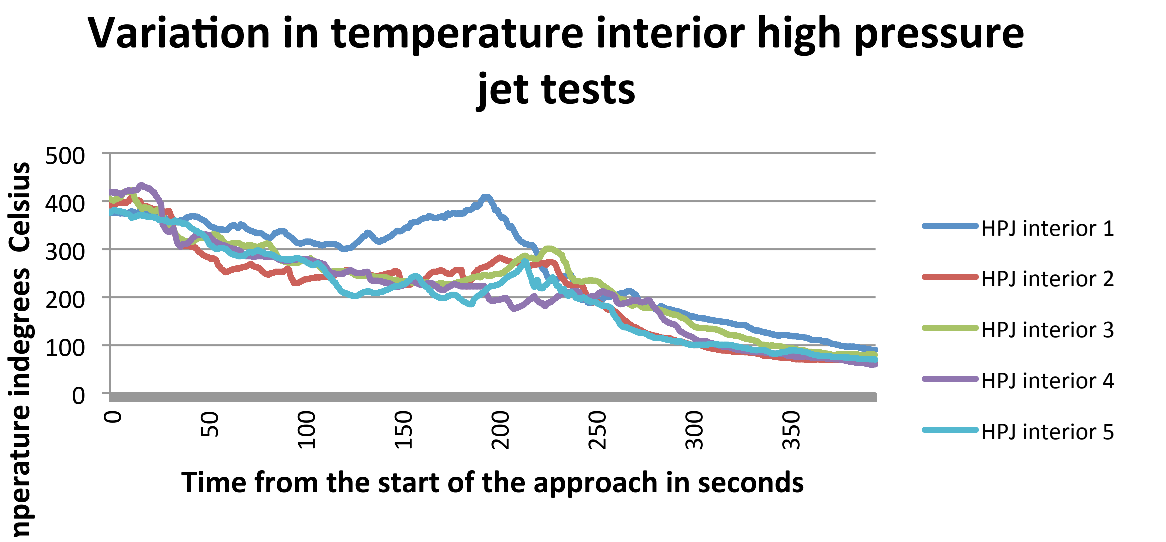

Figure 17: variation in temperature interior high pressure jet tests

The temperature development in the interior tests with a high pressure jet varies. Through smoke gas cooling alone, the smoke gas layer does not reach a temperature of 150°C. The temperature drops considerably only after switching to attacking the flame front. In conclusion: there are considerable differences in the variation in temperature. This can be explained by human factors and by the fact that during an interior operation there are various options to choose from.

Interior approaches
The variation in temperature during interior approaches was examined. Figure 18 seems to indicate that an interior approach with high pressure foam is most effective in lowering the temperature. However, the interior approach with high pressure foam was only performed once and as a result, does not provide any data regarding variation. Therefore, it is not possible to determine how an interior approach with a high pressure jet compares to an interior approach with high pressure foam.

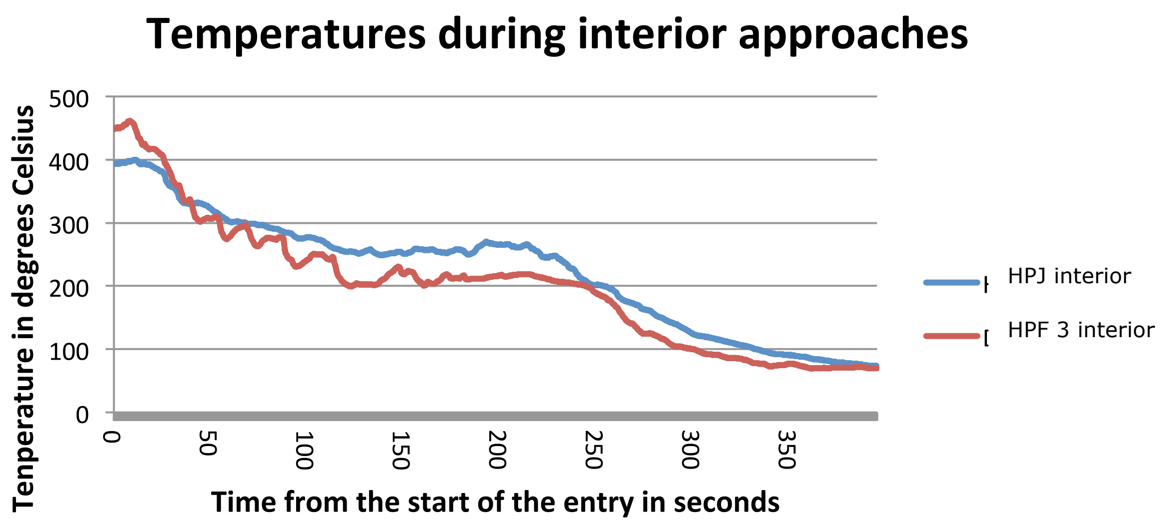

Figure 18: average temperature upon entering in interior approaches

High pressure foam operational tactics
Figure 19 does not show any major differences, even though there was only one test conducted for each of the high pressure foam tactics (exterior approach attacking the flame front, exterior approach smoke gas cooling and interior approach). However, it does seem that high pressure foam is more effective when used for attacking the flame front, as is shown by the blue line and the final part of the green line.[6] To be able to determine this with any certainty, more high pressure foam tests would have to be conducted, using different approaches.

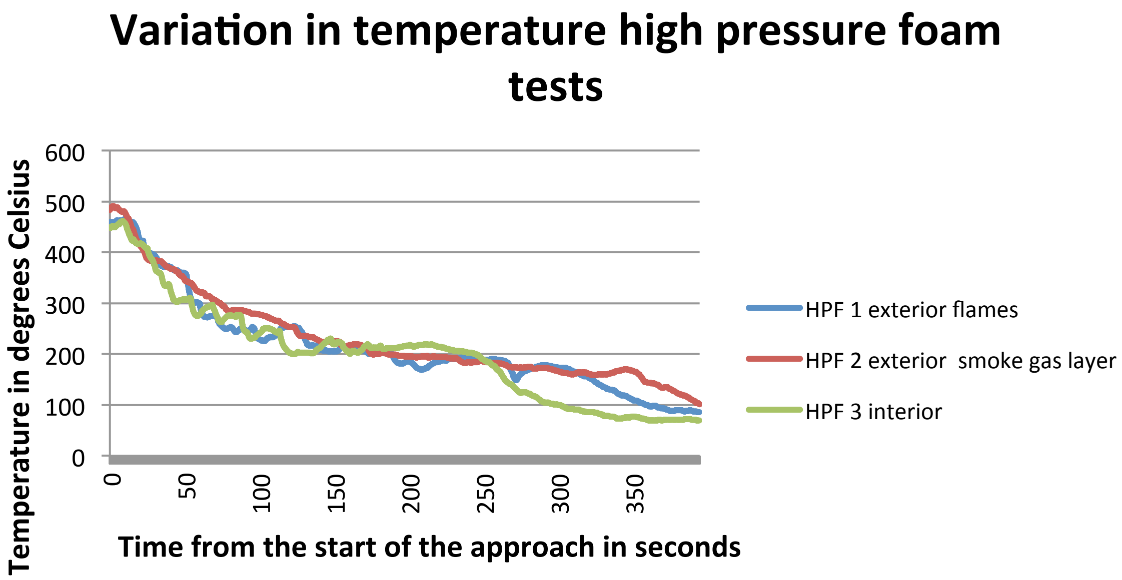

Figure 19: variation in temperature high pressure foam tests

Images thermal imaging camera
The approaches were recorded using a thermal imaging camera. The recordings of the approaches were examined. The images of the thermal imaging camera support the observations presented in this report, such as the observations on the effectiveness of creating knockdown and whether or not a fire flares up again.

[6] Initially, the interior approach was focussed on smoke gas cooling; after some time the focus shifted to attacking the flame front.

4 Conclusions

This chapter provides the answers to the research questions that were posed in the introduction.

Research question 1: How effective are the tested techniques with regard to smoke gas cooling and extinguishing a fire?
The fog nails, cold cut system, distributor nozzle and exterior approach with high pressure foam[7] are more effective with regard to smoke gas cooling than an interior approach with a high pressure jet.
The cold cut system and fog nail perform best and are equally good, the distributor nozzle performs a little less good, but still significantly better than the approaches with high pressure foam and the interior approach with a high pressure jet.
With the cold cut system and the distributor nozzle, the temperature of the smoke gas layer keeps dropping, even after stopping the offensive exterior approach. With the fog nails, the temperature rises somewhat due to the fire flaring up again. However, this does not result in a strong rise in temperature.
The variation in temperature during the interior approach with a high pressure jet is more irregular than with the fog nails, cold cut system and distributor nozzle. The exterior approach with high pressure foam is not very effective in lowering the temperature of the smoke gas layer. However, this comparison is difficult to make since high pressure foam was only tested three times, in three different ways, due to practical reasons.
The cold cut system, fog nails and distributor nozzle perform well regarding the temperature at breathing level, compared to the interior approach with a high pressure jet.

As far as attacking the flame front is concerned (knockdown), all systems perform considerably better than the interior approach with a high pressure jet. On average knockdown was first realised by the distributor nozzle. Significant differences cannot be demonstrated, due to the wide variation, particularly in the interior approaches with a high pressure jet.
The fires in the tests with the cold cut system, distributor nozzle and high pressure foam did not flare up again. The fire did flare up in (some of) the tests with the fog nails and the interior and exterior approaches with a high pressure jet. After switching to extinguishing the fire with a high pressure jet, the second knockdown was first reached in the fog nail test, considerably sooner than in the other tests. Significant differences cannot be demonstrated because of the limited number of exterior approaches with a high pressure jet and the wide variation in the interior approaches with a high pressure jet.

Research question 2: To what extent do the tested techniques contribute to the safety of firefighting personnel with regard to the variation in temperature from the moment of entry?
The temperature upon entry is considerably higher during the interior approach with a high pressure jet, than during the exterior approaches with the cold cut system, fog nails, distributor nozzle, high pressure foam. This is of course the result of the decision to perform an interior approach. The temperature in an interior approach with a high pressure jet is during the first three minutes after entering approximately 250°C higher than in the tested offensive exterior approaches with the fog nail, the cold cut system, distributor nozzle and high pressure foam.

[7] Note: For practical reasons, the approaches with high pressure foam were only tested once. In order to determine with any certainty how effective high pressure foam is, additional research is required.

After entering the building to extinguish the fire, there are hardly any differences in temperature development between the various exterior approaches.

Research question 3: Are there any other issues regarding effectiveness that became apparent when testing the techniques?
The largest amount of water/foam is deposited inside during the offensive exterior approaches with high pressure foam and the distributor nozzle. This can lead to collateral damage.
It must be noted however, that average water usage is not an absolute predictor of collateral damage. Certain techniques can apply water more targeted than others, which also has an impact on collateral damage.

The cold cut system uses the smallest amount of water and the floor of the building remained virtually dry.

The test results of the cold cut system, fog nails and distributor nozzle are similar when comparing the variation in temperature between tests with the same technique. The widest variation occurred between the tests where an interior approach with a high pressure jet was performed; these approaches are very dependent on the quality and choices of their operators. The greatest variation is seen in the smoke gas cooling phase.
Three high pressure foam tests were conducted, each with a different method: an exterior approach focussed on attacking the flame front, an exterior approach focussed on smoke gas cooling and an interior approach, initially focussed on smoke gas cooling and subsequently switching to attacking the flame front.
Due to the limited number of tests, it cannot be determined with any certainty, but it seems that there is hardly any difference in temperature development between the three tests. However, high pressure foam seems to be more effective when it is used for attacking the flame front. In order to determine this with any certainty, additional tests are required.

The interior approach with high pressure foam seems to be more effective with regard to variation in temperature than the interior approach with a high pressure jet.

Answer to the main question:
How does the effectiveness of some techniques for the offensive exterior approach compare to an interior approach with a high pressure jet when fighting fire in industrial buildings?

In the tests the cold cut system and fog nail performed best regarding smoke gas cooling. In the test scenario's, the distributor nozzle also performed well when used for smoke gas cooling. All tested systems perform better in achieving knockdown than an interior approach with a high pressure jet. The cold cut system and distributor nozzle prevented the fire from flaring up again. However, the fire did flare up in the fog nail tests, but only to a limited extent.
In the tests, high pressure foam performed well in achieving knockdown, but it does not seem very suitable for smoke gas cooling.

The offensive techniques that were tested were not only safer, but also more effective with regard to smoke gas cooling and attacking the flame front compared to interior approaches with a high pressure jet.

5. Recommendations

As mentioned before, the scope of the conducted tests was limited due to various reasons. That does not alter the fact that by conducting the test described in this report, a great amount of data has been gathered and considerable insight has been gained. To gain an even better insight into the effects and operational possibilities of the various techniques, additional testing is required. Suggestions are:

- Tests in more complex situations: greater distances, L- or Z-shaped rooms, rooms containing obstacles, etc.
- Tests with bigger fire loads / far higher temperatures of approximately 700°C
- Tests where fires can spread both inside the fire room and through detector plates into adjacent rooms
- tests where each high pressure foam scenario is tested several times
- Tests where atmospheric humidity and oxygen percentages are measured, serving as parameters for creating survivable circumstances (at a height of 1.80 and 0.50 metres).
- Tests with different scenarios to test and compare techniques (with considerable variation in for instance the connections between rooms and fire loads).

In this way a better understanding of the effectiveness of the various techniques and of their differences can be achieved, based on the underlying scenarios.

Appendices

Appendix 1: Registration form

Scenario code	
Time	
Starting time clock	
Starting temperature reached	
Start approach	
Knockdown offensive technique	
Interior approach high pressure jet	
Knockdown extinguishing / end of test	
Temperature	
Starting temperature room (TC5)	
Temperature at test start (TC5)	
Maximum temperature reached (TC5)	
Temperature < 150 degrees (TC6)	
Other	
Other remarks	

Appendix 2: Significance tests

There are significant differences:

- Cold cut system and distributor nozzle (t=-2.809; p=0.023)
- Cold cut system and high pressure jet (t=-16.793; p=0.000)
- Cold cut system and high pressure foam 1 exterior (t=-7.858; p=0.001)
- Cold cut system and high pressure foam 2 exterior (t=-9.288; p=0.001)
- Cold cut system and high pressure foam 3 interior (t=-5.386; p=0.006)
- Cold cut system and high pressure jet exterior (t=-2.944; p=0.032)
- Fog nail and distributor nozzle (t=-4.560; p=0.002)
- Fog nail and high pressure jet interior (t=-24.738; p=0.000)
- Fog nail and high pressure foam 1 exterior (t=-15.649; p=0.000)
- Fog nail and high pressure foam 2 exterior (t=-18,288; p=0,000)
- Fog nail and high pressure foam 3 interior (t=-11.084; p=0.000)
- Fog nail and high pressure jet interior (t=-12.087; p=0.000)
- Distributor nozzle and high pressure foam 1 exterior (t=-5.321; p=0.006)
- Distributor nozzle and high pressure foam 2 exterior (t=-6.565; p=0.0003)
- Distributor nozzle and high pressure foam 3 interior (t=-3.168; p=0.034)
- High pressure jet interior and high pressure foam 3 interior (t=4.256; p=0.013)