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When water goes up in smoke

Experimental research into the effect of the 3D pulse method and the arc method on smoke cooling

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Summary

Background

Opinions differ when it comes to the question of how to approach the seat of a fire that cannot be reached directly with the extinguishing agent, making it necessary for firefighters to progress through hot smoke. In the Netherlands, the '3D pulse method' (Appendix 1) is used as a smoke cooling technique. Instructors have noticed that this method is difficult to learn, requires a lot of practice and training and is rarely performed correctly. There is also evidence that the pulse method is seldom applied in practice. The general impression among the fire service community is that it is too complicated and should be simplified. Previous field experiments with smoke cooling showed that the 3D pulse method can jeopardize the fire attack team since, although the smoke gases are cooled locally, they can heat up again behind the fire attack team. This can cause the team members to become trapped, as it were. Furthermore, there are indications that casualties chance of survival deteriorates as a result.

This calls for a better understanding of the effect of the 3D pulse method on the environmental conditions in the building where the attack team and/or any casualties are located. More information on other possible smoke cooling methods which are also effective and which are easier to learn is also required. Consequently, this research compares the 3D pulse method used in the Netherlands to the arc method (Appendix 1) used in the United States of America. These methods are compared for both high pressure and low pressure systems. Because some Dutch fire brigades are equipped with CAFS OneSeven (Compressed Air Foam System), where foam is applied to the walls and ceiling, this extinguishing system has been included in this research as well. The effectiveness of the door procedure (Appendix 1) was also investigated.

The main research question is:

When using either the 3D pulse method or the arc method, to which extent are smoke gases cooled and what are the effects on the seat of the fire and on the safety of firefighters and casualties when firefighters progress to the seat of the fire in a dynamic smoke layer?

Research design

The different methods were only applied to a scenario with a dynamic smoke layer. This is because a static smoke layer occurs in a confined space in which the fire would self-extinguish due to a lack of oxygen and the temperature would quickly become too low. One base scenario was applied to all experiments:

A major fire in a living room (6 – 8 MW) where the door from the fire room to the corridor is open, smoke is flowing into the adjacent corridor and the front door to the residence is open; no fire attack.

All experiments were carried out in duplicate, as was the baseline measurement (the basic scenario), and with experienced firefighters.

In order to best approximate the real-life situation, the research was conducted in a brick building. The building was L-shaped, with the long part of the L-shape consisting of a 2-metre wide, 2.5 metre high and 20-metre long corridor. The fire room was located in the short part of the L-shape. This shape was chosen so that it would be impossible for the seat of the fire to be reached directly while carrying out the smoke cooling methods.

Various parameters were measured at different locations and/or heights inside and outside the building during the experiments. These parameters were the temperature, radiation, gas concentrations and footage inside and outside. The fire attack team's subjective perception was also measured by means of a questionnaire immediately after the attack.

The corridor was divided into different segments (longitudinal direction: position in the corridor relative to the entrance) and zones (height direction: hot and cold) for the analysis. In order to assess the effect of the different methods on the smoke gases, the temperature was measured in the different segments and zones in the corridor whilst progressing to the seat of the fire. The temperature readings in the individual zones and segments were averaged. The average temperature in a zone or segment is a measure of the cooling effect obtained by absorption of heat from the seat of the fire. The energy content was used mainly to assess whether there was an increase or decrease in energy in the zone or segment in question. The energy content was used together with the temperature to show whether there was a temporary or permanent cooling effect in a zone or segment. The measurement results were analysed for the duration of the attack, i.e. from the time of entering the corridor until the moment when the seat of the fire was reached. This did not include the final extinguishing of the seat of the fire.

An important aspect of the design of these experiments was the repeatability of the starting conditions. This was essential in order to enable the different methods to be compared. For this purpose, the baseline conditions were considered first. By using a similar fire load and a fixed protocol for each experiment, any variations in baseline conditions were minimized. The measurement results have shown that in general, the dispersion in results was limited (about 10%), indicating good reproducibility of the conditions.

Research results

Smoke cooling

In general, the cooling effect achieved by the arc method was found to be better than that of the 3D pulse method. The reach of forwards and backwards cooling when applying the arc method was also better than that of the 3D pulse method. There were some tests where the temperature increased behind the attack team when using the 3D pulse method, whereas the temperature remained low in all tests performed with the arc method. While the 3D pulse method is taught in standard fire fighter training in the Netherlands and the arc method was explained at the test site shortly before the experiments , the film footage showed that the arc method is easier to perform than the 3D pulse method and is less dependent on the nozzle operator.

Progressing to the seat of the fire

The temperature in the fire room and at the opening to the corridor decreased relative to the baseline measurement as the firefighters progressed during all fire attacks. This means that all fire extinguishing systems and methods have a cooling effect on the fire room while progressing.

Firefighters and casualties' safety

The heat radiation dose limit was not exceeded with any of the smoke cooling methods researched. The received dose was found to be generally slightly higher for the tests with the 3D method than with the tests with the arc method.

The average scores for the subjective perception of thermoregulation, discomfort and effort show that the attacks were not excessively strenuous for fire attack teams. The fire attack team experienced the most discomfort in the attack with LP 450 due to water vapour, the amount of water, no visibility, the force required to properly operate the nozzle and a lack of communication possibilities.

The deployment of fire attack teams will always have negative consequences for casualties due to an increase in CO values, regardless of the fire extinguishing system or method used, as compared to baseline. Life-threatening or even fatal situations arise for vulnerable and highly vulnerable casualties further down the corridor. No life-threatening situations arise for casualties in the general group, with one exception. Both baseline measurements, i.e. where no fire attack took place, showed that it took longer for a life-threatening situation to arise. However, in practice, an individual may have been in a dangerous situation for a unknown amount of time, as a result of which life-threatening or fatal situations may already have been reached before the arrival of the fire service.

Door procedure

A decrease in temperature was observed at all measuring points in the corridor, but it cannot be concluded that this was a direct consequence of the door procedure. Another possible explanation could be that, because both front doors were closed prior to the door procedure, the fire received less oxygen and became under-ventilated, decreasing the temperature even before the door procedure started. The design of the experiment may have also played a role since there was little or no flow of hot smoke gases past the thermocouples when the doors were closed. Furthermore, the measuring points on the outside above the door did not show any effect of the cold block over the door.

Answering the main question

As both methods cool the smoke gases and seat of the fire, carrying out smoke cooling is always better than no attack at all. The results of the arc method are more positive than those of the 3D pulse method, both as regards cooling along the height and length of the corridor, and as regards forwards and backwards cooling. The results of the arc method are also more consistent which seems to indicate that this method is easier to carry out. The reach of forwards and backwards cooling when applying the arc method is better than that for the 3D pulse method, as a result of which the first method offers firefighters increased safety. The time needed for the attack is also shorter when using the arc method (at least with the current test design).

All extinguishing systems and attack methods have a cooling effect on the fire room while progressing. The average scores of subjective perception of thermoregulation, discomfort and effort show that the experiments were not unduly strenuous for the attack team. The attacks with LP 450 were reported to produce the most discomfort. No unsafe situations for fire service personnel, either measured or reported, arose during the experiments. Conditions for potential casualties worsened by the use of the methods and extinguishing systems researched for smoke cooling. This might lead to life-threatening or fatal situations for vulnerable and highly vulnerable people. In general, the arc method worsened these conditions less than the 3D pulse method, specifically in the front section of the corridor. There are significant differences between the two tests for both methods and pressure systems in terms of survivability, indicating that the nozzle operator has a major influence on the conditions that determine survivability.

The analysis of the film footage has shown that, although the 3D method is the standard method taught, the arc method is easier to perform according to protocol and is less dependent on the nozzle operator.

Based on this research, it can be concluded that both the arc method and the 3D method are effective methods to cool smoke gases, but that the arc method provides more cooling, and is easier to learn and carry out.

Foreword

Here it is! The report which has been awaited with great anticipation both in the Netherlands and internationally. I am pleased and proud to present the report with the final results of unique research into smoke cooling methods and extinguishing systems.

Smoke cooling is a favourite topic of discussion among fire service experts and instructors all over the world. One might sometimes get the idea there are several different ‘doctrines’ when it comes to the best and most effective smoke cooling method: pulse techniques or a solid stream, surface cooling or 3D cooling? And just when you finally think you've got it, there is another new argument to bring it all into doubt. That is why the professorship of Fire Service Science of the IFV's Fire Service Academy decided to conduct this research. Rather than carrying out the experiments in a container, which tends to be the customary location for drills, a brick building was selected for the experiments so as to optimally simulate real-life circumstances. The experiments consisted of the application of different nozzle techniques and measuring which technique produced the best cooling effect.
This had never been done before, making this research unique.

Publishing this report took a long time because processing all the measurement data took much longer than we had anticipated. Not only did we have an enormous quantity of measurement data, but it was also quite difficult to present the results in a comprehensible manner. And we didn't cut any corners. Not only were the temperatures measured, but the cooling effect in terms of energy change was studied as well. This required the development of a completely new algorithm. The effect of the different methods on survivability for casualties was also considered and the impact of the different techniques on fire service personnel was studied, albeit to a limited extent.

The results and conclusions of this research are quite compelling and will lead to discussion, amazement and hopefully admiration all over the world. This research has enabled us to shed light on a difficult subject and further simplify techniques for firefighters in the field. We have had the report translated into English to present it to the international community for discussion. We are looking forward to the response.

The results have already been incorporated into the new e-learning environment on nozzle techniques for the Dutch ‘*Manschap*’ study programme for firefighters. Practice-oriented participatory research has thus been linked directly to teaching and study material. As far as I know, this is a global first, and it's something we can rightly be proud of.

This research is another fine example of the intensive collaboration between the Fire Service Academy researchers, Troned staff, instructors and firefighters from the field, and the *Brand* [Fire] Community of Practice. I would like to express my enormous gratitude to everyone who has contributed to this research. It would not have been possible without your efforts. A great achievement!

Enjoy reading this report.

Ricardo Weewer
Professor of Fire Service Science
Fire Service Academy (IFV)

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Introduction

Background

There were two reasons for carrying out this research. Firstly, there is an ongoing worldwide discussion about how to approach the seat of a fire that cannot be reached directly with the extinguishing agent, making it necessary for firefighters to progress through hot smoke. Secondly, instructors have observed that the 3D pulse method recommended in the Dutch teaching and study material (smoke cooling technique, appendix 1) is very difficult to learn, requires a lot of practice and training and is rarely performed correctly. And there is evidence that this method is seldom applied in practice. The general impression is that the current smoke cooling method is too complicated and should be simplified. Taking into account the basic principles of firefighting, smoke cooling actually only applies if the seat of the fire cannot be reached directly and the attack depth is small (or the room is less than 70 m^2 in size).

As stated, the Fire Service Academy's teaching and study material addresses a method which can be applied to cool smoke gases in a building, the ‘3D pulse method’. This is taught to instructors as a ‘standard method’ and they in turn pass on their knowledge to their students. Firefighting when entering is divided into three parts: door procedure, the smoke cooling phase and the actual firefighting phase. The 3D pulse method is the standard method in the Netherlands for the smoke cooling phase. An instructional video is also used for this.

The application of smoke cooling is based on the assumption that the risk of smoke gas igniting is reduced if the temperature is lowered (prevention of auto-ignition). This is achieved by applying an extinguishing agent (mainly water), which absorbs energy, effectively creating an inert gas mixture.. This is necessary to enable safe access to the burning structure to rescue people inside and/or to extinguish the fire.

Previous field experiments into smoke cooling (Fire Service Academy, 2013, 2015) reported that the standard smoke cooling method in the Netherlands (the 3D pulse method) can lead to dangerous situations for the fire attack team. The direct surroundings of the fire attack team are cooled during the smoke cooling phase, but the temperature behind the team can increase again, potentially trapping the team. Furthermore, smoke cooling may inadvertently have a negative effect on possible casualties nearby. The extent to which the introduction of water contributes to preventing the smoke layer from igniting was the subject of previous research (Fire Service Academy, 2020).

In order to safely apply smoke cooling a better understanding of the effect of the 3D pulse method on the environmental conditions in a building experienced by both the attack team and potential casualties is necessary. More information on other smoke cooling methods which are also effective and which are easier to learn than the current method is also required. Consequently, this research compares the 3D pulse method to the arc method used in the United States of America. Because some Dutch fire brigades are equipped with CAFS OneSeven (Compressed Air Foam System), this extinguishing system has been included in this research as well.

This field research is the final phase of the research into smoke cooling. Earlier phases consisted of a literature review (Fire Service Academy, 2018) and the aforementioned research into the prevention of smoke gas igniting (Fire Service Academy, 2020).

Purpose of the research

The purpose of this research is to determine how, and to what extent, different smoke cooling methods (the 3D pulse method and arc method) affect conditions in a space containing a hot smoke layer (i.e. decrease temperature and energy), the seat of the fire, the safety of firefighters and any casualties while progressing to the seat of a fire in a dynamic smoke layer.

Main and sub-questions

The main research question is:

When using either the 3D pulse method or the arc method, to what extent are smoke gases cooled and what are the effects on the seat of the fire and on the safety of firefighters and casualties[1] *when firefighters progress to the seat of the fire in a dynamic smoke layer?*

This main question is answered by means of the following sub-questions:

1. *When using the 3D pulse method and the arc method when progressing to the seat of the fire in a dynamic smoke layer, to what extent can smoke gases be cooled in terms of:*
    a. *temperature versus height?*
    b. *energy decrease?*
    c. *forward and backward cooling?*
2. *To what extent does the application of the 3D pulse method and the arc method make it possible to affect the seat of the fire while progressing to the seat of a fire in a dynamic smoke layer?*
3. *How does smoke cooling while progressing towards a seat of a fire in a dynamic smoke layer affect firefighters and casualties' safety?*
4. *How does the door procedure carried out from outside affect indoor conditions?*

[1] This is a common term in the fire service; anyone still inside is considered to be a casualty.

Scope

The research focused exclusively on smoke cooling methods using low pressure, high pressure and CAFS OneSeven. The 3D pulse method for smoke cooling as contained in the teaching and study material was carried out during the field experiments and compared to the arc method. The arc method is an American method which has led to good results there. Other fire extinguishing systems which might possibly be used for smoke cooling were not considered in this research.

In addition, the methods were only applied to a scenario with a dynamic smoke layer. This is because a static smoke layer occurs in a confined space in which the fire would self-extinguish due to a lack of oxygen and the temperature would quickly become too low. Furthermore, a dynamic smoke layer is a worst case scenario (maximum heating of the smoke layer).

The focus of the research was on an offensive interior attack from the moment the fire attack team arrives at the front door until the moment the seat of the fire is reached. Different stages of the research protocol, while performed in a fixed order, are considered separately.

Involvement of the fire service world

In order to make maximum use of the knowledge and experience available in the field, an expert group was formed to design and implement the research. The expert group consisted of members of the Dutch Fire Community of Practice. The members of the expert group established the research protocol together with researchers of the Fire Service Academy. In addition, firefighters from various safety regions formed the attack teams and provided other support during the experiments. The firefighters who carried out the high-pressure and low-pressure experiments have extensive experience of using the 3D pulse method. Firefighters trained and instructed on the use of CAFS OneSeven carried out the experiments with CAFS OneSeven.

1 Research design

This chapter describes the design of the research, starting with some general information. This is followed by a detailed description of the location, a summary of the fire load, the extinguishing systems researched (high pressure, low pressure 250 l/min, low pressure 450 l/min and compressed air foam (CAF)) and attack methods (3D pulse method and arc method), the field experiments and the measurement set-up. And finally, the protocol for the experiments, the data analysis and the quality of the research are discussed.

1.1 General information about the design

The field experiments were conducted from 14 to 18 October 2019. Four experiments were carried out each day, except on 16 and 18 October. Five experiments were conducted on 16 October and two on 18 October. A total of 19 experiments were carried out; see also Table 1.2 on page 21.

One base scenario was applied to all experiments:
A major fire in a living room (6 – 8 MW) where the door from the fire room to the corridor is open, smoke is flowing into the adjoining corridor and the front door to the residence is open; no fire attack.

This base scenario (the baseline measurement) was carried out twice (experiments 18 and 19, see table 1.2). The fire attack team was deployed during the other experiments and they used different fire extinguishing systems and attack methods (see section 1.4).

1.2 Location

The experiments were carried out in purpose-built structure at the Troned training centre for professional emergency services at Twente Airport in the Netherlands.
The L-shaped building has a 20-metre long, 2.5 metre high and 2-metre wide corridor. The corridor is constructed of sand-lime bricks (walls) and concrete hollow-core slabs (roof). Halfway down the corridor there is a safety door to the outside. The short part of the L is a modified steel shipping container in which the fuel was placed. This fire room, the total dimensions of which are 2.4 x 2.4 metres, has four doors and a sliding hatch (approx. 0.4 x 0.6 m) for ventilation. A 50-cm draft stop was installed over the doors of the corridor.
The floor plan of the location, the exterior view and the top view are shown in figure 1.1, figure 1.2 and figure 1.3.

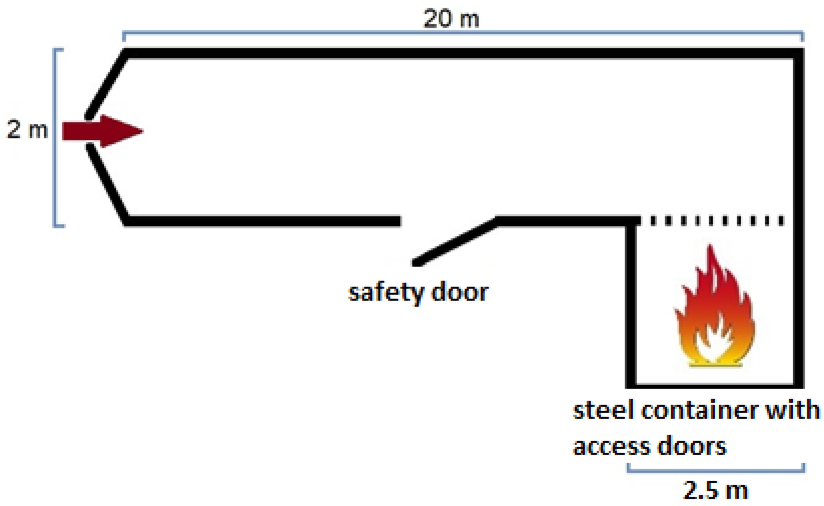


Figure 1.1 Floor plan of the test location

Figure 1.2 Exterior view of the test location

Figure 1.3 View from above the test location

There were seven thresholds in the building. The space between two consecutive thresholds was 3 metres, except between thresholds 6 and 7. These were 2 metres apart, see figure 1.4.

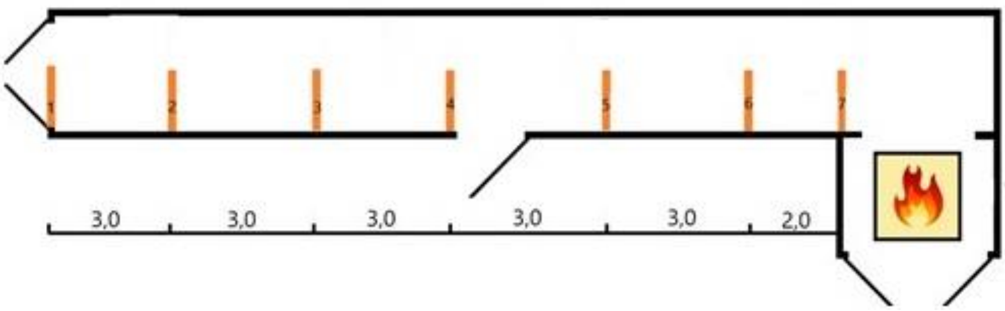


Figure 1.4 Locations of thresholds in the test location

1.3 Fuel

A representative fire load (pallets, chipboard and plastic) was used as fuel. The seat of the fire was positioned so that it could not be reached directly when attacking the fire through the corridor. The fuel was composed as follows (from top to bottom):

> chipboard (1220 x 1220 x 18 mm)
> 2 stringers of pallets
> chipboard
> 2 stringers of pallets
> chipboard
> 3 pallets
> chipboard
> foam block (100 x 100 x 21 cm)
> chipboard
> 5 pallets

Figure 1.5 Amount of fuel

Furthermore, sheets of chipboard were placed diagonally on both sides, with the lower end touching the seat of the fire, and against the ceiling over the seat of the fire. The fire was lit by spraying two softboard battens with lighter fluid. The battens were lit and slid into the second pallet from the bottom, one on the left and one on the right. The quantity of fuel is shown in figure 1.5. The total quantity of fuel is approx. 180 kg of pine wood, 143 kg of chipboard and 9 kg of foam. The potential heat release rate is between 6 and 8 MW, comparable to that of a fire in a living room.

1.4 Fire extinguishing systems and attack methods researched

The following fire extinguishing systems were the subject of this field research:

> High pressure (HP)
> Low pressure 250 l/min (LP 250)
> Low pressure 450 l/min (LP 450)
> CAFS OneSeven.

A summary of the fire extinguishing systems and their characteristics is provided in table 1.1.

Table 1.1 Fire extinguishing systems that were the subject of the research

Fire extinguishing system	Brand / type of extinguishing agent	Average flow rate, measured prior to the experiments	Pump pressure	Nozzle type
HP	Water	119 l/min	33 bar high pressure	Akron trigger
LP 250	Water	252 l/min	10 bar	TFT F06
LP 450	Water	433 l/min	12 bar	TFT F06
CAFS OneSeven	A-class OneSeven Addition as a percentage: 0.3%	130 l/min	9 bar low pressure 8 bar air pressure	TFT G-force fliptip

Two smoke cooling methods, the 3D pulse method and the arc method, were used with each fire extinguishing system except CAFS OneSeven. CAFS OneSeven was only used in combination with the arc method. The door procedure was carried out in two experiments. Brief descriptions of what the methods entail are given below. Step-by-step descriptions of the methods can be found in the deployment protocol in Appendix 1.

3D pulse method

The 3D pulse method as used in this research is based on the 2018 the Dutch *Manschap A* study programme (basic firefighting training). The nozzle operator discharged a three-second long pulse into the smoke layer, at a cone angle of 30 degrees, at the entrance to the corridor. After the pulse, the team began progressing towards the seat of the fire. Three-second pulses were discharged every three metres until the team had reached the seat of the fire, where the fire attack team switched to the "pencilling and painting method” described in the study programme to extinguish the seat of the fire.

Pencilling and painting

“Pencilling consists of spraying a straight stream towards the flames and making a sweeping motion. It's like colouring in a drawing with a pencil. So you use the pencilling method to extinguish the actual seat of the fire.
Painting is used to apply a thin layer of water to a surface. This is similar to a thin layer of paint being applied with a brush. You paint to prevent any non-combustible materials from burning or pyrolysing. In other words, you use the painting method in order to prevent new seats of fire” (E-module Af- en nablussing, Leergang Manschap A 1.0, 2018).

Arc method

The arc method is based on the ‘flow and move’ method which is used in the United States (Zevotek, Stakes, & Willi, 2018). The name is based on the movement made with the nozzle, i.e. a 1-2-3-4-3-2-1 pattern shown in figure 1.6.

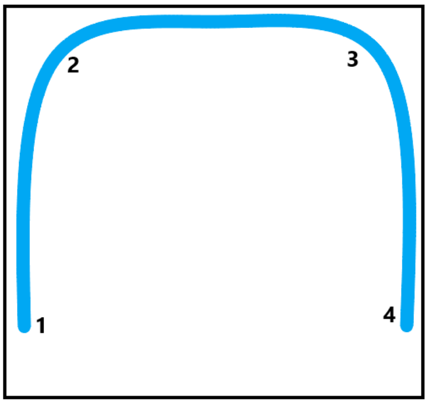


Figure 1.6 Arc pattern

The nozzle operator opens the nozzle at the entrance to the corridor. He starts by making the arc pattern with a solid stream keeping the nozzle open. While this pattern is made, over and over again, the team progresses to the seat of the fire. The nozzle operator starts cooling immediately in front of himself (1 metre) and gradually extends the cooling range while progressing. When the team has reached the seat of the fire, they start extinguishing it according to the 'pencilling and painting' method.

Door procedure and temperature check

The door procedure and temperature check as described in the teaching and study material which were part of the *Manschap A* (Manschap A 1.0) study programme at the time of the research (2019) were carried out prior to smoke cooling during two experiments (experiments 16 and 17).[2] The nozzle operator checks the door temperature by discharging a short pulse onto the upper part of the door. He then creates a cold block by discharging two short pulses onto the space at the top, between the door and the frame.

Cold block

"The door is opened to check for the presence of any fuel behind the door. Before the door is opened, the nozzle operator first discharges two short bursts of water mist above the door, first on the hinge side of the door and then on the handle side. This immediately cools and dilutes any fire gases escaping through the gap over the door. This is what we refer to as 'creating a cold block'" (E-module Verkenningstechnieken, Leergang Manschap A 1.0, 2018).

[2] In anticipation of this report, the teaching and study material was altered in Manschap A 2.0.

After the number two of the fire attack team has opened the door a little, the nozzle operator (number 1) crouches in the doorway and discharges a short one-second pulse into the room. Immediately after the pulse, the nozzle operator retreats and closes the door. The nozzle operator and the number two then discuss what they have seen. If there is any smoke, the temperature will have to be checked first before entering. When checking the temperature, the nozzle operator again discharges a short one-second pulse to see whether the water evaporates or pours down. After this pulse, the nozzle operator again retreats to discuss with the number two what they have seen and heard.

1.4.1 Summary of the experiments

table 1.2 shows a summary of all experiments conducted.

Table 1.2 Summary of field experiments

Experiment	Date	Extinguishing system (pressure/flow)	Attack method
1	14/10/19	HP	3D pulse method
2	14/10/19	LP 250	3D pulse method
3	14/10/19	LP 250	3D pulse method
4	14/10/19	HP	3D pulse method
5	15/10/19	LP 450	3D pulse method
6	15/10/19	HP	Arc method
7	15/10/19	HP	Arc method
8	15/10/19	LP 450	3D pulse method
9	16/10/19	LP 250	Arc method
10	16/10/19	LP 250	Arc method
11	16/10/19	CAFS OneSeven	Arc method
12	16/10/19	CAFS OneSeven	Arc method
13	16/10/19	CAFS OneSeven	Arc method
14	17/10/19	LP 450	Arc method
15	17/10/19	LP 450	Arc method
16	17/10/19	HP	Door procedure followed by 3D pulse method
17	17/10/19	LP 250	Door procedure followed by 3D pulse method
18	18/10/19	Baseline measurement	none

19	18/10/19	Baseline measurement	none

1.5 Measurement design

Several parameters were measured during the experiments. These parameters were the temperature, radiation, gas concentrations and footage inside and outside. The perception of the attack team (nozzle operator and number 2) was measured as well.

1.5.1 Temperature

During the experiments, the temperature was measured in several places using thermocouples (type K). Four measuring poles (B1 to B4) with a total of 28 thermocouples at different heights were placed in the corridor: 0.3 metres, 0.9 metres, 1.5 metres, 1.8 metres, 2 metres, 2.2 metres and 2.4 metres from the floor. Another five separate thermocouples were placed in the fire room to measure the temperature in at the seat of the fire.

Thermocouples were also placed on four flagpoles over the front doors. Each flagpole (2.5 metres in length) featured four thermocouples to measure the effluent smoke and gases and the effect of the door procedure. The data from all thermocouples was registered using the LabVIEW system.

The thermocouples were shielded from their environment by a steel tube with mineral wool insulation inside. This allows the hot junction of the thermocouple to measure the temperature of the hot gases flowing through the tube without being influenced by radiation or water. An example is shown encircled in red in figure 1.7.

1.5.2 Radiation

Two types of heat radiation meters were used in order to measure radiation: four water-cooled flux meters (Schmidt-Boelter) and four plate thermometer heat flux meters (PTHFM). The heat radiation meters were placed on measuring poles B1 to B4. The water-cooled flux meters are more sensitive and their measuring range is less extensive than that of the plate thermometer heat flux meters. Since less radiation was expected at lower heights, the water-cooled flux meters were placed at a height of 0.3 metres and the plate thermometer heat flux meters at a height of 1.5 metres. The heat radiation meter data was also registered using the LabVIEW system. The plate thermometer heat flux meter is encircled in green in figure 1.7.

Figure 1.7 Measuring pole with sensors

1.5.3 Gas concentrations

The gas concentrations, i.e. the oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x) concentrations, were measured using Testo measuring equipment. The Testo probe is encircled in yellow in figure 1.7. Gas measurements were taken at B1, B2 and B3 for temperature reasons. table 1.3 shows which parameter was measured, what was used to measure it and where it was measured. The data from the measuring equipment used can be seen in Appendix 2. The measurement locations are shown in figure 1.8 and figure 1.9.

Table 1.3 Summary of parameters, measurement methods and measurement locations

Parameter	Measurement method	Measurement location	Measuring height (m)
Temperature	Type K thermocouples	B1 - B4 Fire room Above the entrance	0.3 - 0.9 - 1.5 - 1.8 - 2.0 - 2.2 - 2.4 2.0 - 2.2 - 2.4 ≥ 2.5
Radiation	Plate thermometer heat flux meter (PTHFM) Water-cooled flux meter (SB)	B1 - B4 B1 - B4	1.5 0.3
Gas concentrations	Testo 350 flue gas analyser	B1 - B3	0.3

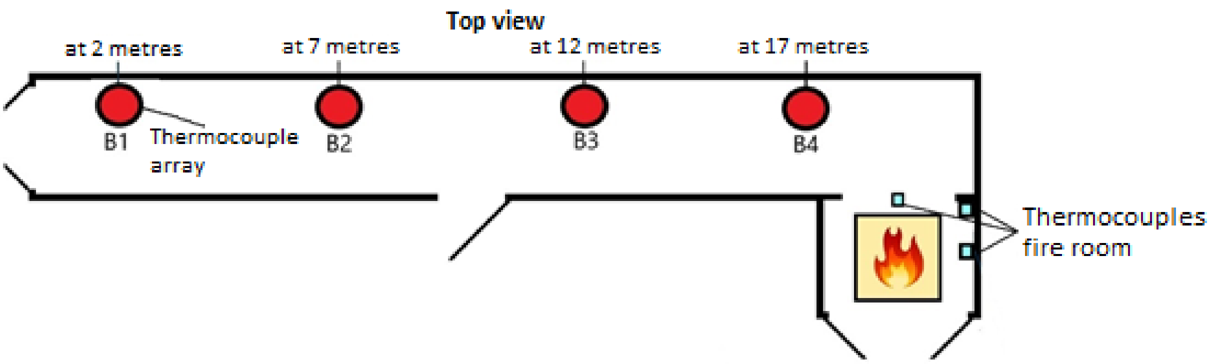


Figure 1.8 Floor plan (view from above) with locations of measuring equipment

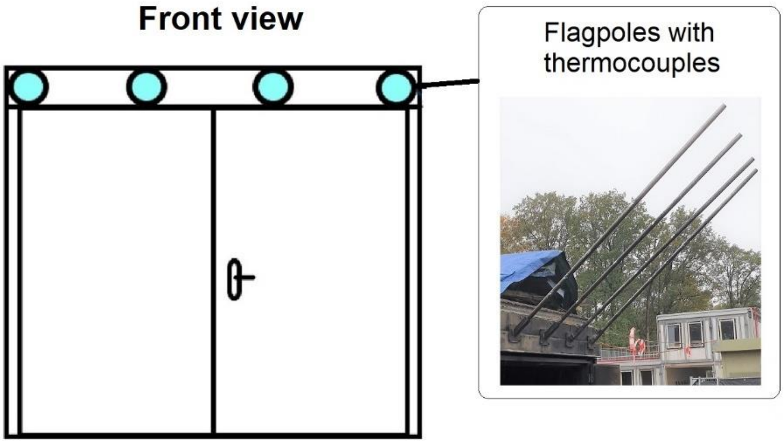


Figure 1.9 Front view of building with locations of measuring equipment

1.5.4 Camera footage

The experiments were recorded using ten video cameras: six Action cameras, three thermal imaging cameras and one FireCam. The FireCam was placed at the shortest distance from the seat of the fire since it can withstand temperatures of over 400 °C, albeit for a brief period. The camera footage was used to support the measurements.

Figure 1.10 Thermal imaging camera in a protective case

Seven cameras were placed on the floor in the corridor of the building. Another three cameras were placed outside. Two of them were directed at the doors of the corridor and one at the doors of the fire container. The locations of these cameras are shown in figure 1.11.

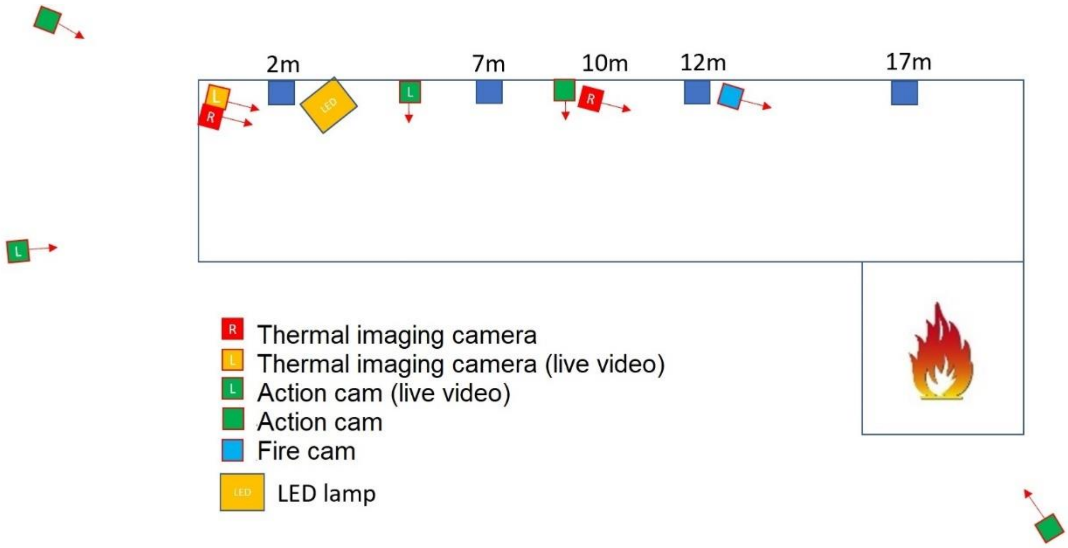


Figure 1.11 Floor plan showing the camera locations

1.5.5 Subjective perception of thermoregulation, discomfort and effort

In order to measure subjective perception, the nozzle operator and the number 2 filled in a short questionnaire about their perception of heat, any pain, skin humidity and effort during the attack. The questionnaire consisted of five scored questions and two open-ended questions. The questionnaire can be found in Appendix 3.

1.6 Experiment protocol

The fire was lit and was given sufficient oxygen by leaving all the doors of the container (fire room) open. Once the flames reached the block of foam, the upper two doors of the fire cabinet were closed, see figure 1.12.

Figure 1.12 Upper doors of the fire container closed

As soon as a 30 to 50 cm-thick smoke layer had formed at the safety door, the safety door (halfway down the corridor) was closed. The left-hand lower door of the fire container was closed when the seat of the fire was fully ablaze. The hatch in the door was kept open. Next, the temperature throughout the corridor was monitored by means of the temperature measurements. If the temperature throughout the corridor exceeded 100 °C, the right-hand lower door of the fire container was closed as well, see figure 1.13.

Figure 1.13 All the doors of the fire container closed

As soon the smoke layer at the beginning of the corridor was more than 50 cm thick, the left-hand door of the corridor was closed. The temperature was continuously monitored to check that it had reached over 200 °C at a height of 2.20 metres throughout the corridor. The attack could be started as soon as the temperature had been over 200 °C for more than one minute. The right-hand door of the corridor was kept open during the attacks.

3D pulse method

The fire attack team started at the first threshold in the corridor and discharged a three-second pulse from there. The team then progressed to the next thresholds. Whenever the next threshold was reached, the team reported this to the control room to enable the progress to be recorded. A three-second pulse was discharged at each threshold, except at threshold 7. Once threshold 7 was reached, this was also reported to the control room.

Arc method

The fire attack team started at the first threshold in the corridor. The nozzle operator opened the nozzle and started making the arc pattern. While making this pattern, the team continued progressing to the seat of the fire.

Extinguishing the seat of the fire

When threshold 7 was reached, the team started extinguishing the seat of the fire in accordance with the teaching and study material. When a knock-down[3] was reached, this was reported for recording.

Details of the various steps of the attack protocol containing both methods of smoke cooling have been included in Appendix 1.

[3] Knock-down: no more flames are visible, but the seat of the fire has been not extinguished.

1.7 Data analysis

Temperature measurements were the main tool for answering the main question. In order to enable any conclusions to be drawn on the effect of the attacks in the corridor, the corridor was divided into longitudinal segments. The boundaries between the segments are centrally between two measurement locations. This created two 5-metre-long segments (B2 and B3) where the measurement location was in the middle of the segments, and two segments where the measurement location was slightly off-centre, one segment being 4.5 m long (B1) and the other one 5.5 m (B4).

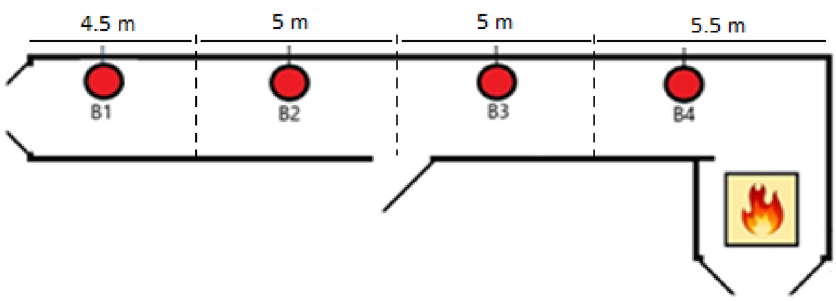


Figure 1.14 View from the top of the division of the corridor into vertical segments

1.7.1 Hot and cold zones

Besides the division of the corridor into longitudinal segments, zone modelling principles from Fire Safety Engineering (FSE) were used for the height orientation. A further division into hot and cold zones was applied here. These zones are the natural result of the fire producing hot smoke gases, heating up the air in the room and also drawing air towards the seat of the fire. Temperature differences lead to pressure differences which cause hot gases to flow out whereas, at the same time, the seat of the fire requires oxygen and this triggers an air flow from outside towards the seat of the fire. This creates a counter flow above and below the neutral zone, with the hot smoke gases air at the top (the hot zone) and the colder outdoor air being drawn in below (the cold zone).

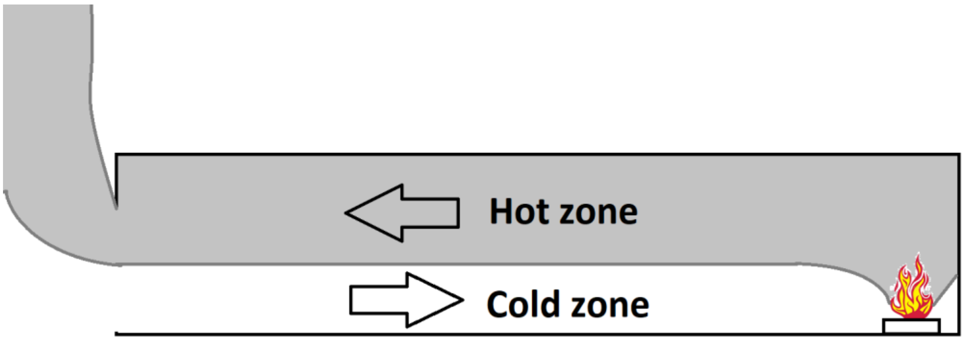


Figure 1.15 Side view of division into hot and cold zones

In order to study the effect of different attack methods on smoke cooling, it is necessary to know where the neutral zone is located. The neutral zone is located roughly at the underside of the smoke layer. The exact height of the smoke layer is difficult to define and it fluctuates during the attack. In practice, there is a gradual shift in temperature from the hot zone to the cold zone (also referred to as the 'mixed zone' in a three-zone model) around the neutral zone. Based on the measuring results, the decision was made to establish the boundary between the hot and cold zones at a fixed height for all experiments.

The controlled design of the experiments generally resulted in a consistent smoke layer where the greatest variation in temperature was observed between 1.5 and 0.9 m. Based on this and on visual observations, the boundary between the zones was established at 1.2 m, as shown in figure 1.16.
Since smoke still flows out of the fire room at segment B4, the temperature is still high at or just above floor level. Therefore the boundary between the hot and cold zones was continued all the way to the floor, instead of maintaining the height of 1.2 m here.

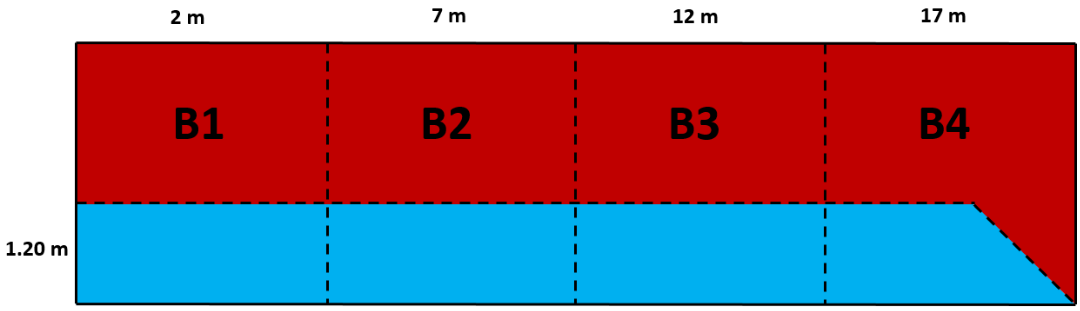


Figure 1.16 Side view of division of the corridor into vertical segments and horizontal hot (red) and cold zones (blue)

1.7.2 Smoke cooling

In order to assess the effect of the different methods on the smoke gases, the temperature in the different segments and zones in the corridor was measured whilst progressing to the seat of the fire. Because temperature is a local phenomenon, the temperature readings of multiple thermocouples in the individual zones and segments were averaged. However, the temperatures were measured locally and there could be several different temperatures in a zone or segment.

The average temperature in a zone or segment is a measure of the cooling effect obtained by absorption of heat from smoke layer. The energy content of a segment is a global property of the entire segment and this was mainly used to see if there was an energy increase or decrease in that segment. In principle, there is an energy balance. However, the various flows of energy to, for example, partition structures were not measured; only the energy content of the zone and/or the segment was considered. The energy content was used together with the temperature to show whether there was a temporary or permanent cooling effect in a zone or segment. The measurements were analysed for the duration of the attack, i.e. from the time of entering the corridor until the moment when the seat of the fire was reached (threshold 7). This did not include the final extinguishing of the seat of the fire. Since each combination of attack methods was carried out twice, the average values of each pair of experiments were used for the calculations and the standard deviation was established. Although carrying out each combination twice is not sufficient to provide a reliable value for the standard deviation in terms of quantity, it does give a good indication of the measure of dispersion in results between the two experiments.

Temperature versus height

The influence of smoke cooling on the temperatures at different heights was determined as follows: the difference in temperature at specific heights at consecutive thresholds which were reached while progressing through the corridor was considered. The sum of these differences is the net change while progressing. Next, the average values of these sums were calculated in order to arrive at an overall effect for the method used. Since the emphasis here is on the effect of smoke cooling at the different heights, the average values for the entire corridor are used here.

Energy decrease

The energy content of each segment and zone was determined in order to calculate the decrease in energy. A fixed height threshold was maintained so that the volume of each segment and zone would remain constant. The energy content of a segment then only depends on the temperature of the smoke layer in that specific segment at a specific time. The average value of all thermocouples of a segment is taken as the temperature of the smoke layer in the segment in question. The change in energy caused by progressing could be established by considering the energy content at different times while progressing. Equal volumes also made it possible to compare the changes in energy over the different experiments. The energy content was calculated based on the temperature and volume using the following equations.

$$Q = C_v \cdot M \cdot T$$

Here, Q is the energy, C_v is the specific heat capacity at constant volume - which depends on the temperature), M is the mass and T is the temperature. The specific heat capacity is determined by:

$$C_v(T) = a \cdot T + b$$

With temperature T in Kelvin and the constant a = 0.187 J/kg/K^2 and b = 665 J/kg/K (Nederlands Normalisatie-Instituut, 2011).
Mass was determined by specific mass (density) and volume. The volume was calculated on the basis of the boundary height established and the dimensions of the corridor. The relationship between specific mass and temperature follows from the following formula (Nederlands Normalisatie-Instituut, 2011):

$$\rho = \frac{1.293 \cdot 273}{T} = \frac{353}{T}$$

Together this gives:

$$Q = (0.187 \cdot T + 665) \cdot 353 \cdot V$$

Where Q is the energy in Joule, T the temperature in Kelvin and V the volume in m^3.

Forward and backward cooling

The temperatures at the individual measurement locations during the attack were considered in order to draw conclusions about forward and backward cooling. These temperatures were placed alongside the times when the thresholds were reached and, consequently, the team's position in the corridor. Here, any changes in temperature at the measurement locations in front of or behind the team at the moment when a specific threshold was reached were taken into consideration. Qualitative observations were made for each experiment to determine whether the temperature increased or decreased and for how long the effect continued to be noticeable; this was expressed in the number of 'thresholds progressed'. E.g.: a decrease in temperature in the hot zone was measured at B3 (at threshold 5, at 12 m) when the fire attack team reached threshold 2 (at 3 m). Forward cooling was therefore approximately 9 m (or three thresholds). If this was followed by an increase in temperature being measured at threshold 2 when the team had progressed to threshold 5, the backward cooling would also be about 3 thresholds. In other words, the temperature remained low up to about 9 m behind the fire attack team.

1.7.3 Seat of the fire

Measurements were carried out at the seat of the fire. Five thermocouples were used for this: one over the partition between the fire room and the corridor (the outflow opening, i.e. where smoke could flow out) and four on the walls inside the fire room. Again, the difference in temperature during the smoke cooling (progression) phase, i.e. from the start of the attack until when the seat of the fire (threshold 7) was reached, was considered. This did not include the actual extinguishing of the seat of the fire. The average values of the measurements of the four thermocouples in the fire room were calculated. The averages of the two experiments were determined for each extinguishing system.

1.7.4 Safety

Survivability is divided into three phases, see in figure 1.17.

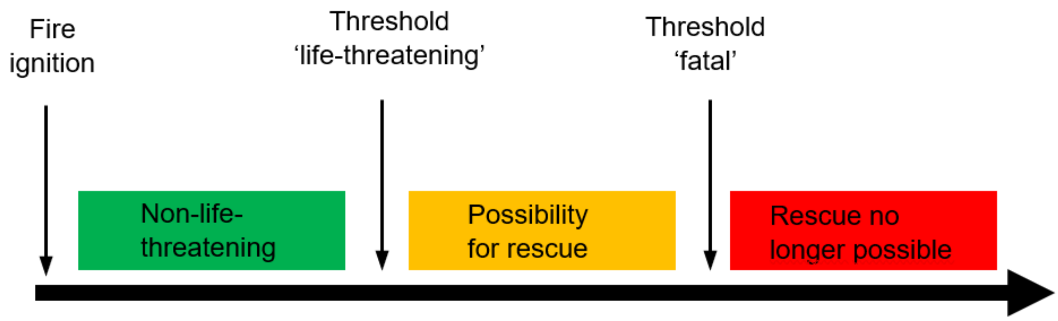


Figure 1.17 Diagram of survivability for casualties in the event of fire

The measurements at a height of 0.3 m were used in order to determine the survivability for any casualties (assumed to be unconscious on the ground). Gases and heat radiation were measured here. According to the relevant ISO standard (ISO 13571, 2012) and the SFPE Handbook (Purser & McAllister, 2016), the following methods are important for determining survivability.

> The Fractional Effective Concentration (FEC) or Fractional Irritant Concentration (FIC). This is the ratio between the concentration of a particular substance and the concentration that endangers survivability.

> The Fractional Effective Dose (FED) or Fractional Lethal Dose (FLD). This is the ratio between the dose – the concentration and the duration of exposure – of a certain substance and the dose that endangers of survivability.

In order to determine the FED/FLD or FEC/FIC value at which exposed people can no longer escape safely or survive, a threshold value has been established. This threshold value depends on the vulnerability of the people in question and the fire conditions to which they are exposed. The SFPE manual makes a distinction between three population groups: ‘highly vulnerable’, ’vulnerable’ and ‘general’ as shown in table 1.4.

Table 1.4 Summary of the threshold values according to the SFPE handbook

Fire condition	Method	Life-threatening			Fatal		
		Highly vulnerable	Vulnerable	General	Highly vulnerable	Vulnerable	General
Irritant gases	FIC/FLD	0.5	1.5	5.0	0.1	0.3	1.0
Asphyxiant gases	FED_{IN}	0.1	0.3	1.0	0.2	0.6	2.0
Heat	FED_{heat}	0.8	2.4	8.0	1.2	3.6	12.0

These threshold values were used to determine which threshold for a specific method was first exceeded in each experiment. Graphs of all experiments and all methods can be found in Appendix 9 Safety of Casualties.

There are no standardised methods for determining the safety conditions for fire service personnel as there are for casualties. The radiation part of the FED_{heat} method was used to develop a formula for determining exposure(Appendix 8 Safety of fire service personnel). This formula is based on the exposure to heat radiation according to the following tolerance (Brandweeracademie, 2016):

- Maximum radiation load of 3 kW/m^2 for 20 minutes
- Maximum radiation load of 4.6 kW/m^2 for 5 minutes

A FED of 1.0 is reached for both tolerances with the developed formula. The radiation measured at a height of 1.5 m was used to determine the actual exposure. This height can be considered to be the maximum height (top of the helmet) when progressing through the corridor in a crouched position.
This method and the formula that was developed should not be considered to be an exact method to determine heat radiation exposure of fire service personnel. They merely served as a method to make a relative comparison of the different techniques as part of this research.
In order to determine the team's exposure to heat radiation while progressing, the measurement readings of the individual measurement locations were broken down to reflect the moments when fire attack team passed and added together as shown in Figure 18. When the team was between threshold 1 and threshold 2, they were in the blue area and the radiation of measurement location B1 was used; between threshold 2 and threshold 4 the radiation of B2 was used, etc. This enabled the overall dose to be calculated for the entire corridor, divided into four sections. The exposure to heat radiation while extinguishing the fire was not taken into consideration because this research focuses on smoke cooling between entering a building and reached the seat of the fire.

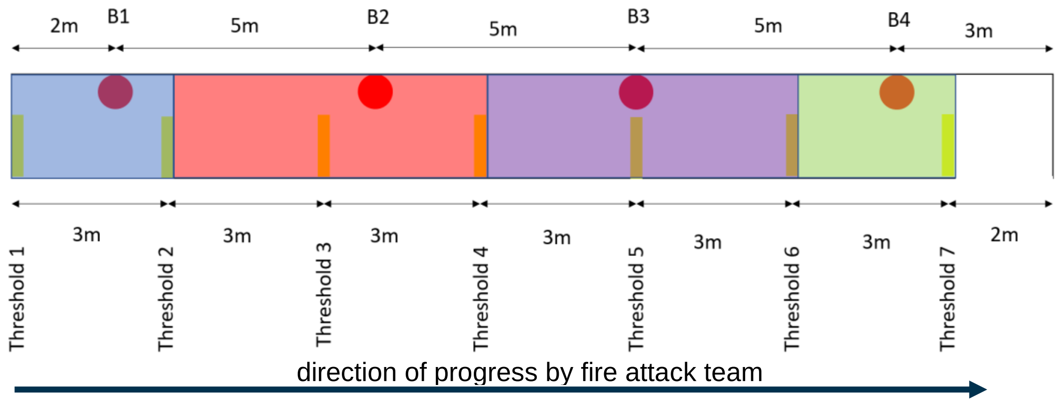


Figure 18: Distribution of measurements for calculating the fire attack team's exposure to radiation

1.7.5 Door procedure

The door procedure was examined in two experiments. Each time, the door procedure was carried out three times before continuing with a normal attack. The temperatures in the hot and cold zones and of the individual measurement locations were calculated for each experiment. This was followed by assessing whether there was any change in temperature while carrying out the door procedure. The measurement results of the escaping smoke, measured by thermocouples over the doors, were assessed at the same time.

1.8 The quality of the research

The quality of the research is determined to a major extent by how much attention is paid to uniformity and reliability prior to and during the research. This section first addresses the uniformity of the conditions during the experiments, followed by the reliability.

1.8.1 Uniformity of the conditions during the experiments

It is important to attempt to achieve uniformity of conditions during the experiments in order to rule out, or at least minimise, the influence of any undesirable variables on the experiments. The following measures were specifically taken to ensure that the conditions during the experiments would be as uniform as possible.

> Promoting uniform fire growth by:
  – Limiting the number of experiments on one day so that the building could be cleared of smoke and the temperature of the building could drop sufficiently - to approximately the ambient temperature - before each experiment to ensure an equivalent starting situation for all experiments.
  – Placing the same amount of fuel in the exact same location in the fire room and igniting it in the same way.
  – Keeping the ventilation profiles and door seals identical.

> Facilitating uniform conditions, including uniform baseline conditions, which enabled smoke cooling to take place by:

- Installing windbreaks to minimise any effect of wind on smoke development and smoke cooling, although it was obviously not possible to completely shield the building from all wind.
- Strictly describing which doors should be closed at the start of and during the experiment, and implementing and checking this.
- Making sure that the temperature at 2.2 m throughout the corridor was higher than 200 °C for a period of more than one minute prior to each experiment.
- Checking the positions and operation of all sensors and cameras prior to each experiment.
- Cleaning the corridor as thoroughly as possible and removing any residue or debris left by the fire, water and/or foam after each experiment.

> Facilitating uniform conditions with regard to the intervention by the attack team by:
  - Using a protocol describing which actions were to be conducted before, during, and after an experiment.
  - Giving instructions about the protocol and practising it prior to the actual attack.

> Facilitating a uniform analysis by using computerised data processing tools.

1.8.2 Reliability

The reliability of research is about whether the same results can be achieved if the research is carried out again in exactly the same way. Concessions were actually made to this by changing nozzle operators between experiments. However, the benefits of changing nozzle operators for achieving the aim of the research were considered to be of greater importance. For instance, changing nozzle operators prevented any systematic errors in the operation. And changing operators also meant a lesser burden on human resources on days when experiments were carried out. The effects this had on repeatability are described in section 2.2.

The following points were applied to the rest of the design and implementation of the experiments and the use of the measuring equipment in order to ensure optimum reliability of the research.

> The design and implementation of the experiments:
  - The research team which designed the experiments also designed and built the measurement set-up and supervised the operation. This ensured a high degree of consistency in the various phases of the research.
  - A small, compact research team and a fixed team/sub-team was used for every aspect of the research (including measuring equipment, data collection and analysis), reducing the risk of different interpretations during the experiments.
  - An experiment (pre-test) was carried out a couple of months prior to the experiments to test the research design and the measuring equipment.
  - All variants were carried out at least twice, for the purpose of repeatability.
  - All variants were conducted according to clearly defined protocols.
  - A logbook was kept, recording all crucial moments during an experiment. Any deviations from the research protocol were also noted.

> Measurements and measuring equipment:

- All measuring equipment was checked prior to each experiment to ensure it would operate correctly and record the measurement results properly.
- Measurements were conducted at several positions in the corridor and at several heights for all the experiments.
- The results of the measurements were linked to the camera footage, based on time stamps and visual observation.

1.8.3 Course of the research

Although the measuring equipment was checked prior to each experiment, the gas measuring programme failed during one experiment with LP 450 when the 3D pulse method was being used (experiment 5). The consequence of this was that only the gas measurements of experiment 8 LP 450 using the 3D pulse method was considered in the research.

2 Results

This chapter discusses the results of the field experiments. The repeatability of the experiments is discussed first (section 2.1). Sections 2.2 to 2.5 describe the results.

2.1 Repeatability

An important aspect of the design of these experiments was the possibility of producing repeatable results. For this purpose, the starting conditions were considered first. By using a similar fire load and a fixed protocol for each experiment, any variations in starting conditions were minimized from the start. Accordingly, each experiment was started in a similar situation, enabling the different extinguishing systems and attack methods to be compared as objectively as possible. The temperature distribution measured in the corridor at the start of the attack showed the extent to which similar starting conditions were achieved.

table 2.1 shows the average values for the temperatures and standard deviations for each location and height at the start of the attack. The locations are indicated as the number of metres from the entrance of the corridor, i.e. the seat of the fire was at 20 m (around the corner at the end of the corridor).

Table 2.1 Average temperatures at the start of the attacks for all experiments per location and per height

Height / location	B1 (2 m) [°C]	B2 (7 m) [°C]	B3 (12 m) [°C]	B4 (17 m) [°C]
2.4 m	221 ± 15	265 ± 24	352 ± 26	462 ± 30
2.2 m	217 ± 13	265 ± 28	339 ± 16	478 ± 34
2.0 m	206 ± 14	219 ± 25	317 ± 34	449 ± 37
1.8 m	160 ± 19	202 ± 23	267 ± 23	393 ± 40
1.5 m	105 ± 19	122 ± 14	145 ± 18	259 ± 32
0.9 m	42 ± 10	29 ± 7	39 ± 13	53 ± 13
0.3 m	23 ± 2	23 ± 3	28 ± 8	46 ± 4

The general dispersion in results is 10-12% of the measured value, which indicates good reproducibility of the conditions. The graphs of the starting conditions can be found in Appendix 4.

2.2 The influence of smoke cooling on temperature and energy

This section describes the influence of smoke cooling on the temperature (a local phenomenon) and the energy content (hot and cold zones along the entire corridor). The reach of smoke cooling is addressed as well, assessing how far ahead of the fire attack team the smoke gases were cooled and whether the temperature of the smoke gases behind the fire attack team increased or decreased after the application of smoke cooling.

2.2.1 Temperature across height

Although the conditions were designed and constructed with the aim of maximising reproducibility (see section 1.8.1), the individual experiments did not all start with identical temperatures. The changes in temperature at each height between the start of the attack and the moment when the fire room was reached were therefore measured. The average increase or decrease in temperature for all measurement locations was determined. This gave an average change in temperature for each height and for each extinguishing system and attack method.

Hot zone

The coloured parts in figure 2.1 indicate the heights that are considered to be part of the hot zone, between 1.5 m and the ceiling.

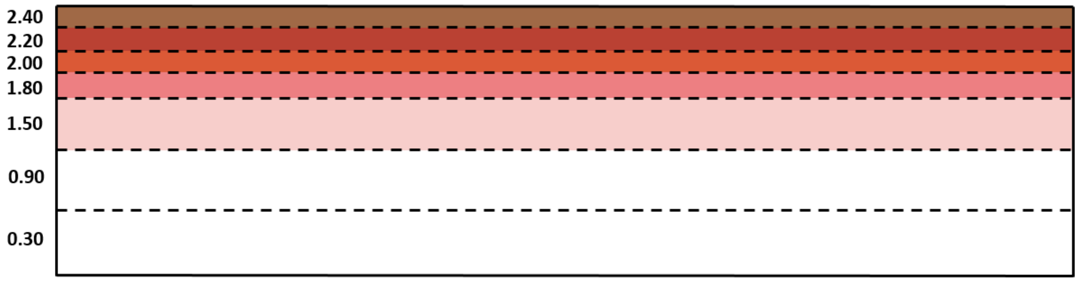


Figure 2.1 Distribution of the hot zone along identical heights (coloured parts)

The results for the change in temperature are shown in figure 2.2 figure 2.3 and table 2.2. The only differences between the figures are the sequence of the fire extinguishing system and the method, facilitating visual comparison. A measure for the dispersion in values is also shown in the two graphs and in the table. This is the standard deviation based on the measurements of all measurement locations of the two experiments for each extinguishing system. The graphs also include the baseline measurements to show what happens if there is no attack by the fire service. Appendixes 5 and 6 feature the graphs for the individual baseline measurements and the extinguishing systems or attack methods.

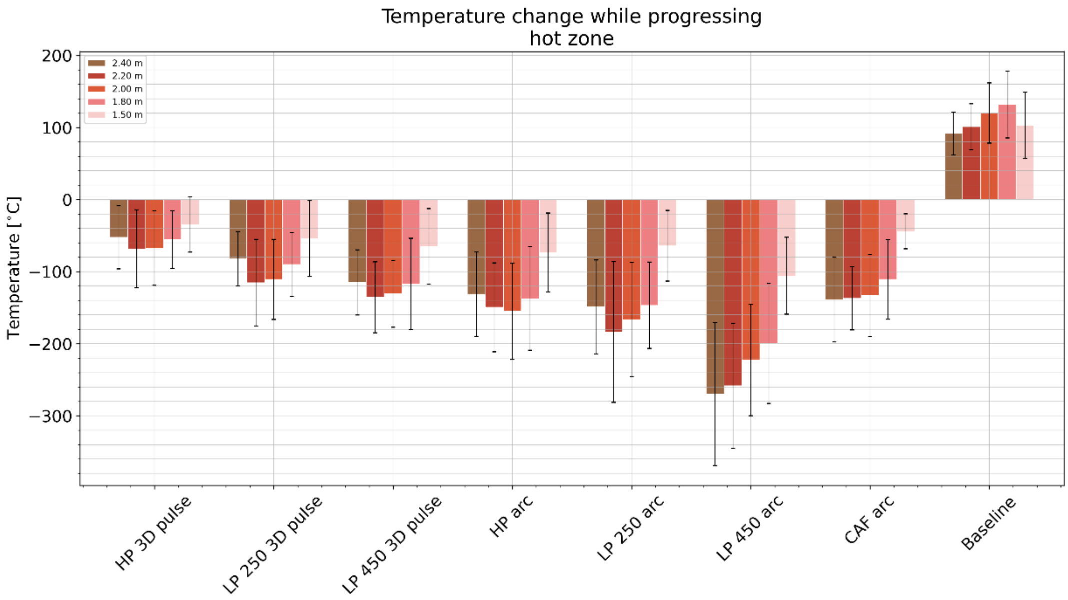


Figure 2.2 Changes in temperature for each fire extinguishing system and attack method in the hot zone, grouped by attack method

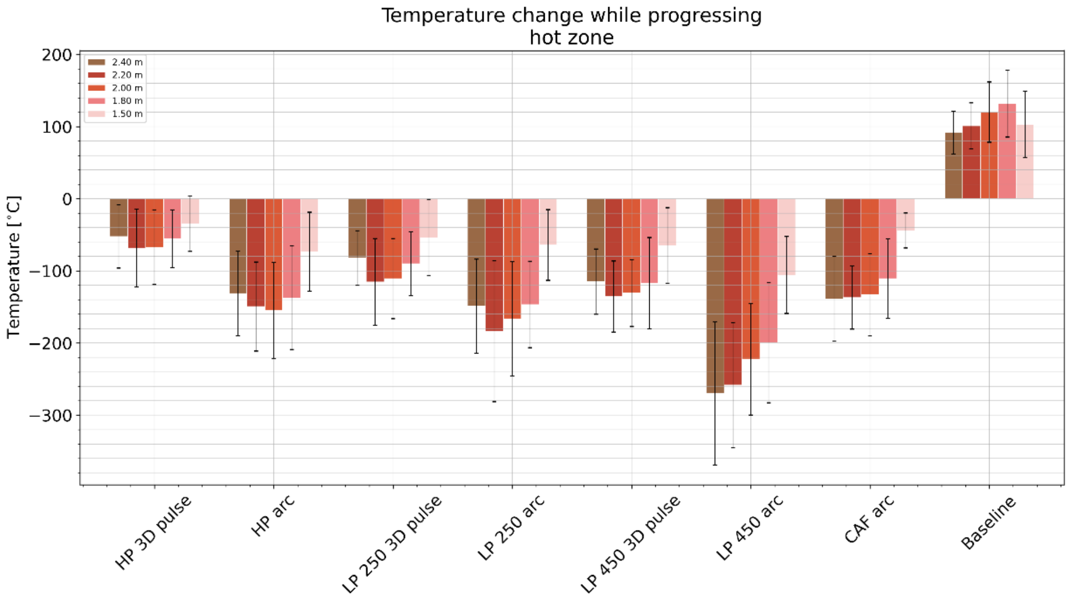


Figure 2.3 Changes in temperature for each fire extinguishing system and attack method in the hot zone, grouped by extinguishing system

Table 2.2 Changes in temperature for each fire extinguishing systems and for each measurement height

Fire extinguishing system	Temp (2.4 m) [°C]	Temp (2.2 m) [°C]	Temp (2.0 m) [°C]	Temp (1.8 m) [°C]	Temp (1.5 m) [°C]
HP 3D pulse method	-52 ± 44	-68 ± 54	-67 ± 52	-55 ± 40	-35 ± 38
HP arc method	-131 ± 59	-149 ± 62	-155 ± 67	-137 ± 72	-73 ± 55
LP 250 3D pulse method	-82 ± 38	-115 ± 60	-111 ± 55	-90 ± 44	-54 ± 53
LP 250 arc method	-149 ± 65	-184 ± 98	-166 ± 79	-147 ± 60	-64 ± 49
LP 450 3D pulse method	-115 ± 45	-136 ± 49	-131 ± 46	-117 ± 63	-65 ± 52
LP 450 arc method	-270 ± 99	-258 ± 87	-222 ± 77	-200 ± 83	-106 ± 53
CAFS OneSeven arc method	-139 ± 59	-137 ± 44	-133 ± 57	-111 ± 55	-44 ± 24
Baseline measurement	92 ± 30	101 ± 32	120 ± 42	132 ± 46	103 ± 46

Analysis of the hot zone

All experiments showed a negative change in temperature in the hot zone during the attacks. This means that the hot zone was cooled during all attacks. As expected, the change in temperature for the baseline situation was positive, i.e. the temperature in the hot zone increased in the situation when no attack was carried out. The temperature changes increases with height, but in most instances, the change in temperature at 2.4 m was lower than at 2.2 m. The flow velocity at the ceiling is lower because of vortices there. Furthermore, the fact that the thermocouples were shielded may also have played a role. The shielding might have slowed down or influenced the flow or the vortices. Heat is also dissipated to the structure at the ceiling, resulting in lower temperatures and therefore also lower changes in temperature. figure 2.2 shows that the arc method caused the temperature to decrease more than the 3D pulse method did. A higher flow rate also led to a greater decrease in temperature. The relative decrease when applying the arc method is also greater that of the 3D pulse method.

Figure 2.3 shows that, in general, the decrease in temperature increases with higher flow rates. For instance, when using the 3D pulse method, LP 250 led to a greater decrease in temperature than HP, but the decrease in temperature when using LP 450 did not differ much from LP 250. Possible explanations for this are:

- Although more water is used, saturation led to little if any extra water evaporating.
- Not all pulses were discharged parallel to the corridor.

> A combination of the above.

The results with CAFS OneSeven are comparable to those with HP using the arc method. The greatest decrease in temperature was measured in the attacks using the LP 450 in combination with the arc method.

table 2.2 on the previous page quantifies the results of figure 2.2 and figure 2.3.

Cold zone
The temperatures between the floor and a height of 0.9 m (figure 2.4) were considered for the cold zone.

Figure 2.4 Distribution of the cold zone along identical heights

The results for the change in temperature are shown in figure 2.5, figure 2.6 and table 2.3. The only differences between the figures are in the sequence of the fire extinguishing system and the method, facilitating visual comparison. A dispersion measure is also shown in the two graphs and in table 2.3. This is the standard deviation based on the measurements of all measurement locations in the two experiments for each extinguishing system.

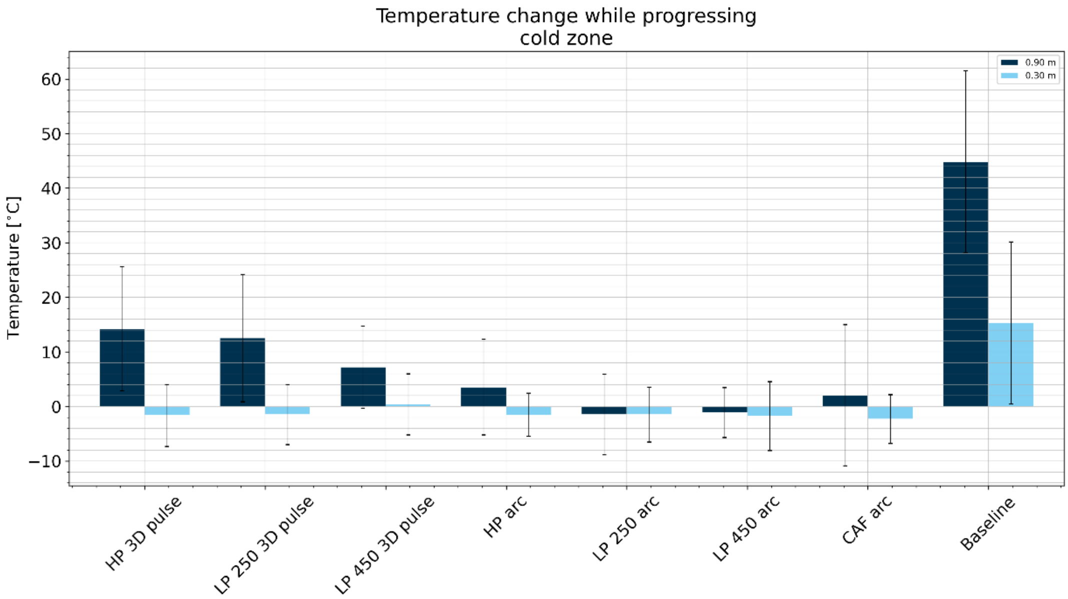


Figure 2.5 Changes in temperature for each fire extinguishing system and attack method in the cold zone, grouped by attack method

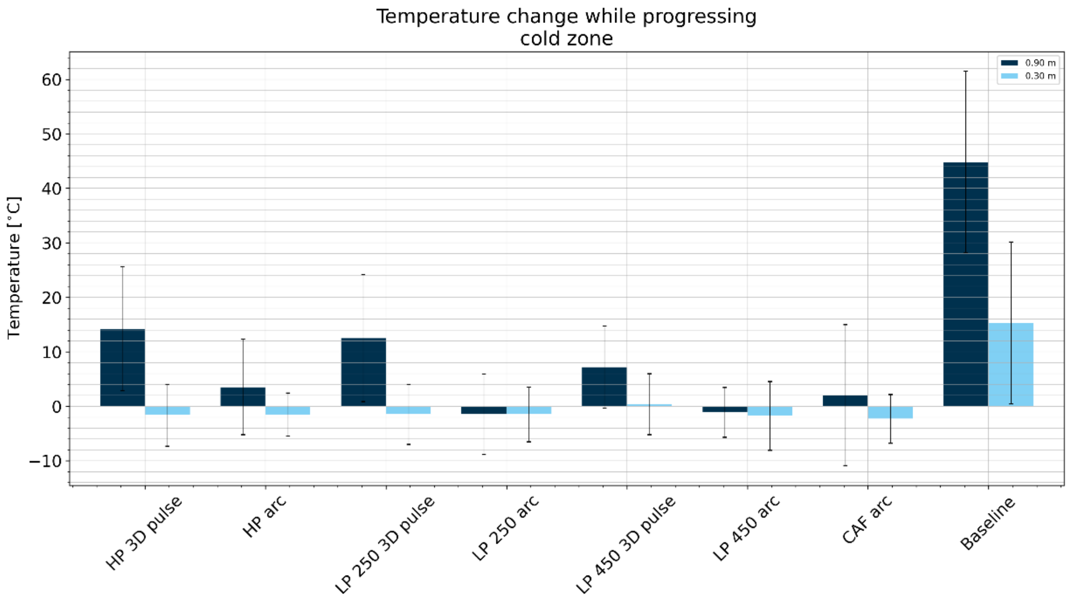


Figure 2.6 Changes in temperature for each fire extinguishing system and attack method in the cold zone, grouped by extinguishing system

Table 2.3 Changes in temperature for each fire extinguishing systems and for each measurement height

Fire extinguishing system	Temp (0.9 m) [°C]	Temp (0.3 m) [°C]
HP 3D pulse method	14 ± 11	-2 ± 6
HP arc method	4 ± 9	-2 ± 4
LP 250 3D pulse method	13 ± 12	-1 ± 6
LP 250 arc method	-1 ± 7	-1 ± 5
LP 450 3D pulse method	7 ± 8	0 ± 6
LP 450 arc method	-1 ± 5	-2 ± 6
CAFS OneSeven arc method	2 ± 13	-2 ± 4
Baseline measurement	45 ± 17	15 ± 15

Analysis of the cold zone

As figure 2.5 shows, the changes in temperature in the cold zone are much less than those in the hot zone. The baseline measurement showed an increase in the temperature in the cold zone by several dozens of degrees. The maximum change in temperature at a height of 0.3 m is only a couple of degrees for all fire extinguishing systems. Most changes in temperature at 0.9 m were positive, indicating that the temperature in the cold zone increases during smoke cooling. However, all attacks showed that this increase was less than the increase measured with the baseline measurement. The temperature at a height of 0.9 m increased more when using the 3D pulse method than was the case with the arc method. There was little if any increase in temperature in the cold zone with the arc method. In fact, carrying out the arc method with LP 250 and LP 450 resulted in a decrease in temperature of a couple of degrees at the height of 0.9 m.

figure 2.6 shows that the increase in temperature at the height of 0.9 m decreased as the flow rate was increased when using the 3D pulse method. The arc method showed a minimum increase for HP, but a higher flow rate turned this into a slight decrease. The LP 250 and LP 450 arc methods had the least effect on the cold zone. There was a very limited temperature decrease in the cold zone.

table 2.3 quantifies the results of figure 2.5 and figure 2.6.

2.2.2 Energy decrease

The energy content per zone was considered in order to determine the decrease in energy as a consequence of smoke cooling. This concerns the segments B1 to B4 as indicated in figure 1.14 in section 1.7. As was the case for temperature, the change in energy between the start of the attack and the moment when the fire room was reached was considered. The average values of the changes in energy were calculated for all segments of the corridor and for both experiments.

Hot zone

The segments between 1.2m and the ceiling were considered to be part of the hot zone, as indicated by figure 2.7.

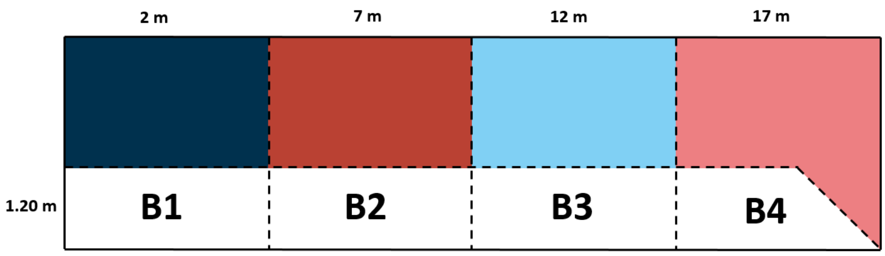


Figure 2.7 Distribution of the hot zone for each measurement location

The average change in energy for each fire extinguishing system is shown in figure 2.8, figure 2.9 and table 2.4. The only differences between the figures are in the sequence of the fire extinguishing systems and the attack methods, facilitating visual comparison. The heights of the bars indicate the decrease in energy and thus the effectiveness. A dispersion measure is also shown in the two graphs and in the table. This is the standard deviation based on the measurements of all thermocouples in a segment and of the two experiments for each extinguishing system.

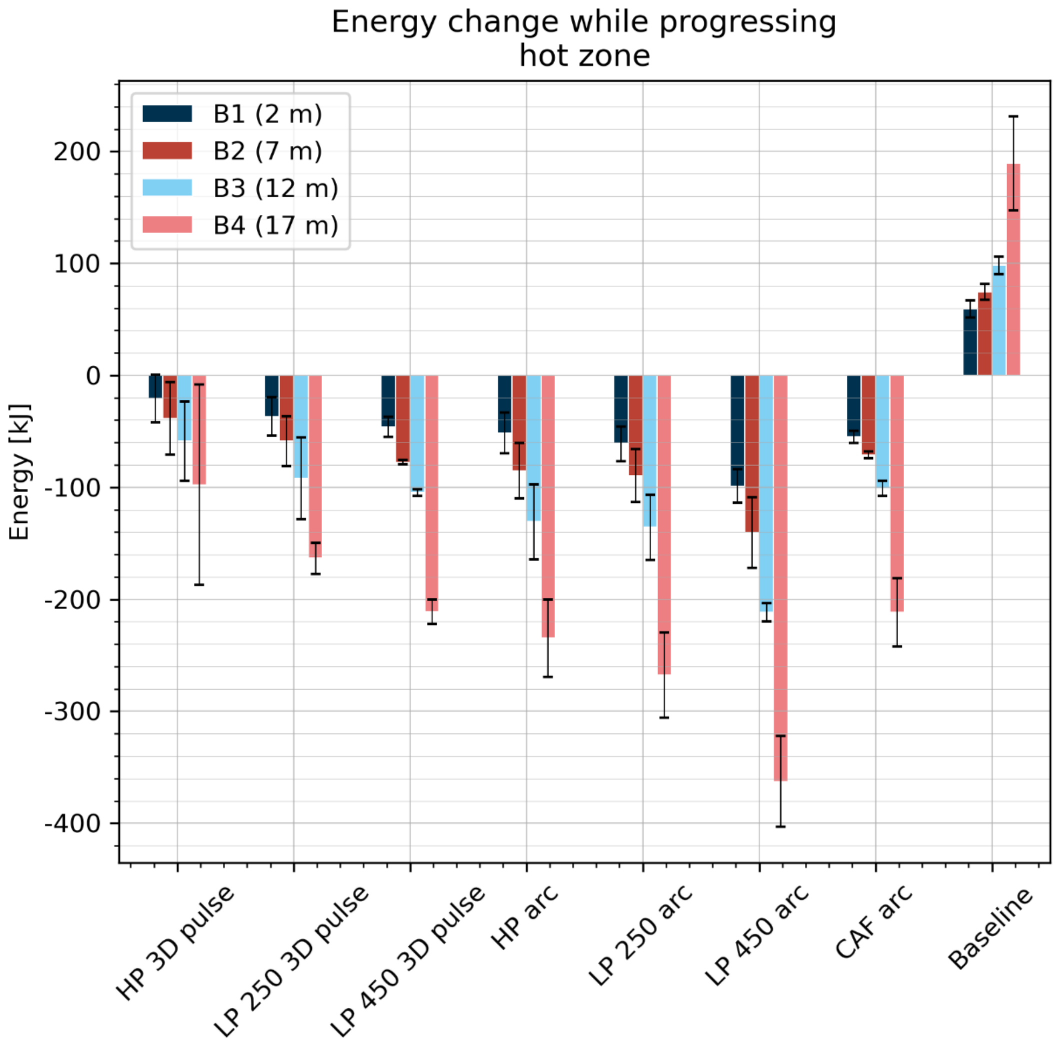


Figure 2.8 Changes in energy for each fire extinguishing system and attack method in the hot zone, grouped by attack method

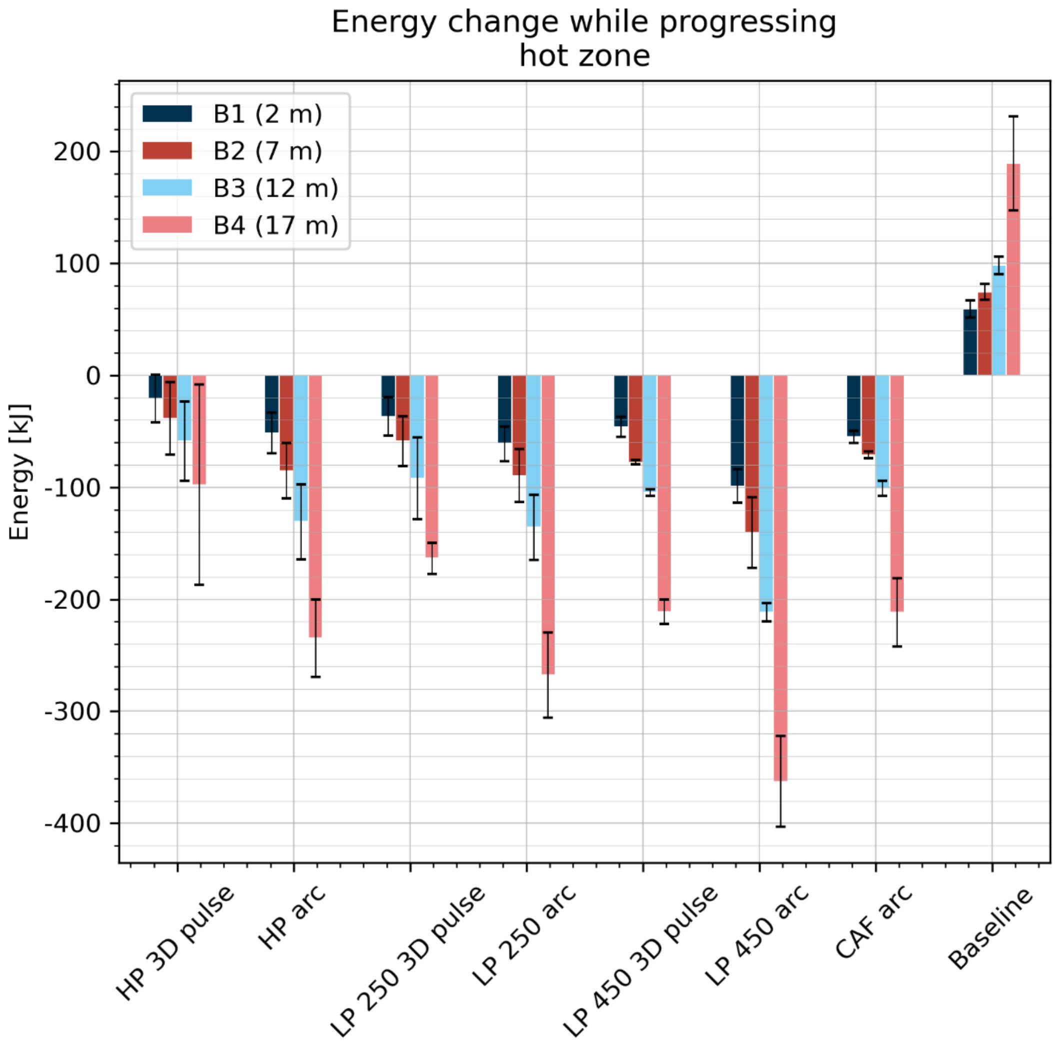


Figure 2.9 Changes in energy for each fire extinguishing system and attack method in the hot zone, grouped by extinguishing system

Table 2.4 Change in energy of the different fire extinguishing systems at the individual measurement locations

Fire extinguishing system	B1 (2 m) [kJ]	B2 (7 m) [kJ]	B3 (12 m) [kJ]	B4 (17 m) [kJ]
HP 3D pulse method	-21 ± 21	-38 ± 32	-59 ± 35	-98 ± 90
HP arc method	-51 ± 18	-85 ± 25	-131 ± 33	-235 ± 35
LP 250 3D pulse method	-37 ± 17	-59 ± 22	-92 ± 37	-163 ± 14
LP 250 arc method	-61 ± 15	-90 ± 24	-136 ± 29	-268 ± 38
LP 450 3D pulse method	-46 ± 9	-78 ± 2	-105 ± 3	-211 ± 11
LP 450 arc method	-99 ± 15	-140 ± 31	-212 ± 8	-363 ± 41
CAFS OneSeven arc method	-55 ± 5	-71 ± 3	-101 ± 7	-212 ± 30
Baseline measurement	59 ± 8	74 ± 7	98 ± 8	189 ± 42

Analysis of hot zone

All attacks showed that the energy decreased in all segments in the hot zone during the attack, in contrast to the baseline measurement which showed that the energy increased in all segments (figure 2.8). In general, the decrease in energy in the hot zone further down the corridor increased. The temperature was also higher there, enabling more energy to be absorbed by the water. When expressed as a percentage, there was also a greater decrease in energy further down the corridor. The decrease in energy in the hot zone when using the arc method exceeded that of the 3D pulse method in all segments of the corridor. Another remarkable finding is that the spread (SD) decreased as the flow rate increased.

The decrease in energy in the hot zone increased as the flow rate increased, as shown in figure 2.9. Thus, both the 3D pulse method and the arc method showed a greater decrease in energy for the HP, LP 250 and LP 450 fire extinguishing systems successively. The greatest decrease in energy was reached with the attacks using the LP 450 and arc method. The results with CAFS OneSeven are comparable to those with HP using the arc method.

table 2.4 quantifies the results of figure 2.8 and figure 2.9.

Cold zone

The segments between the floor and 1.2m were considered to be part of the cold zone, as indicated by figure 2.10.

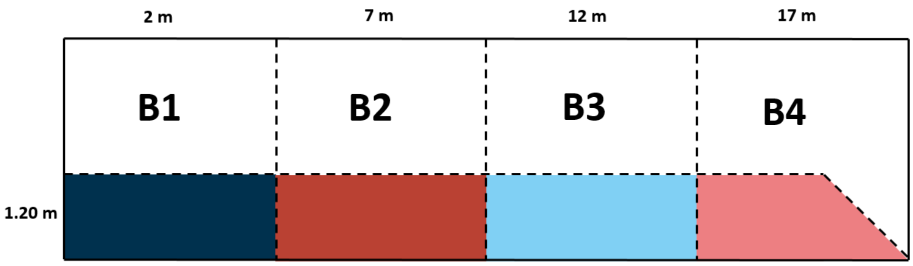


Figure 2.10 Distribution of the cold zone for each measurement location

The average change in energy for each fire extinguishing system is shown in figure 2.11, figure 2.12 and table 2.5. The only differences between the figures are in the sequence of the fire extinguishing systems and the attack methods, facilitating visual comparison. The heights of the bars indicate the decrease in energy and thus the effectiveness. A measure for the spread is also shown in the two graphs and in the table. This is the standard deviation based on the measurements of all thermocouples in a segment and of the two experiments for each extinguishing system.

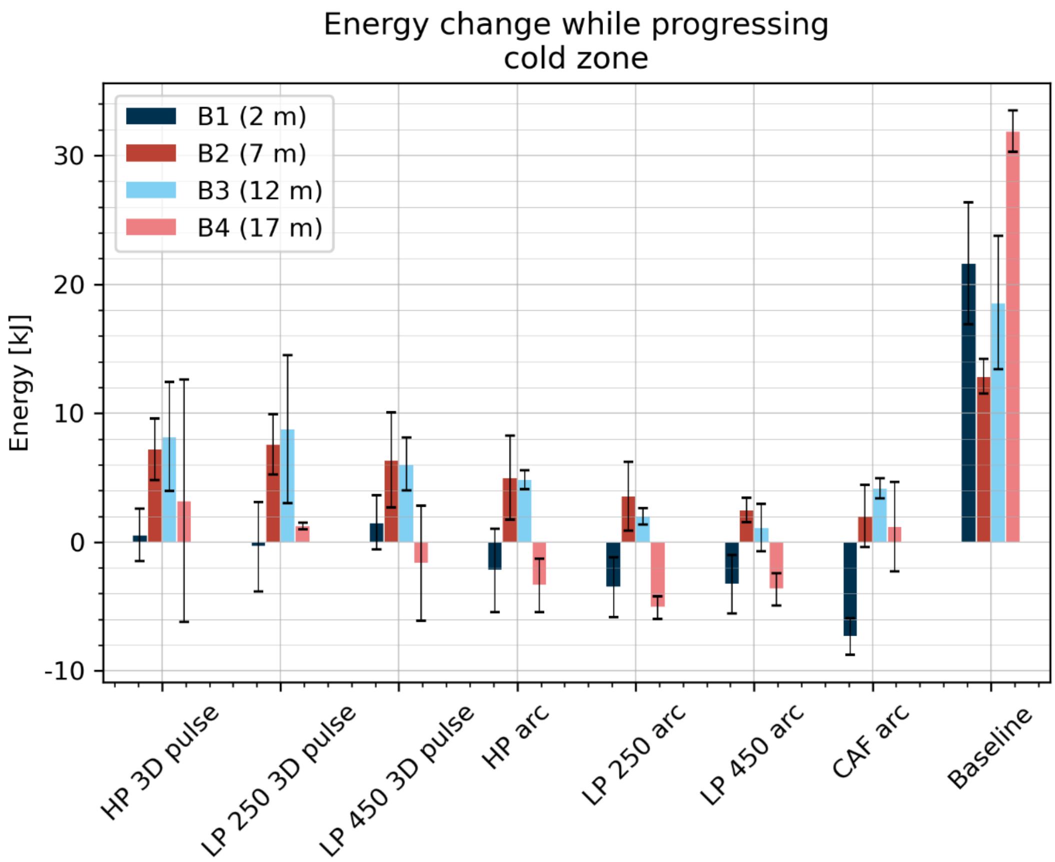


Figure 2.11 Change in energy in the cold zone while progressing for each fire extinguishing system and attack method, grouped by attack method

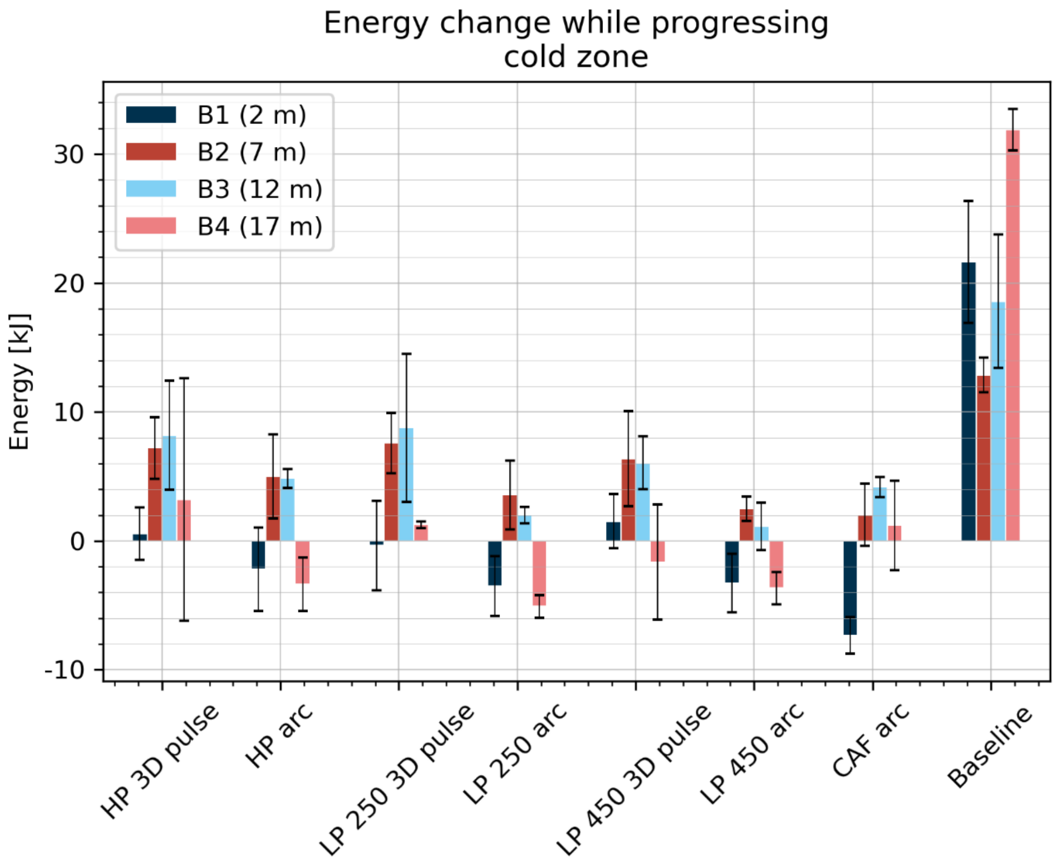


Figure 2.12 Change in energy in the cold zone while progressing for each fire extinguishing system and attack method, grouped by fire extinguishing system

Table 2.5 Change in energy of the different fire extinguishing systems at the individual measurement locations

Fire extinguishing system	B1 (2 m) [kJ]	B2 (7 m) [kJ]	B3 (12 m) [kJ]	B4 (17 m) [kJ]
HP 3D pulse method	1 ± 2	7± 2	8 ± 4	3 ± 9
HP arc method	-2 ± 3	5 ± 3	5 ± 1	-3 ± 2
LP 250 3D pulse method	0 ± 3	8 ± 2	9 ± 6	1 ± 0
LP 250 arc method	-4 ± 2	4 ± 3	2 ± 1	-5 ± 1
LP 450 3D pulse method	2 ± 2	6 ± 4	6 ± 2	-2 ± 4
LP 450 arc method	-3 ± 2	2 ± 1	1 ± 2	-4 ± 1
CAFS OneSeven arc method	-7 ± 1	2 ± 2	4 ± 1	1 ± 3

Baseline measurement	22 ± 5	13 ± 1	19 ± 5	32 ± 2

Analysis of the cold zone

As shown by figure 2.11, the baseline measurement showed an increase in energy in all segments in the cold zone as well, but much less than was the case in the hot zone. The use of extinguishing systems also led to an increase in energy in the cold zone in the middle of the corridor (segments B2 and B3). This may have been due to vortices between the hot and cold zones during the attack (caused by the smoke layer being mixed). The 3D pulse method showed a slightly greater increase in energy in the middle of the corridor than the arc method did. However, the differences are so slight that it cannot be judged with certainty that this is a significant difference. Decreases in energy were achieved with the arc method at the beginning and end of the corridor (segments B1 and B4), whereas little or no decrease was achieved there when using the 3D pulse method. As the sample size was only 2, the standard deviations in the values measured, save those of the baseline measurement, were so large (sometimes >100%) that it cannot be judged with certainty that there were any increases or decreases in energy in the cold zone. This was the case specifically for the 3D pulse method, demonstrating that this method leads to less clear-cut results than the arc method. When CAFS OneSeven was applied, a distinct decrease in energy was achieved at the entrance, but this effect was negligible further down the corridor.

Figure 2.12 shows that the decreases in energy at the entrance and the end of the corridor do not seem to depend very strongly on the flow rate, but that the increases in energy in the middle of the corridor do decrease as the flow rate increases, both when applying the 3D pulse method and when applying the arc method. table 2.5 quantifies the results. A negative average means a decrease in energy in the cold zone; the opposite is true for a positive average.

2.2.3 Forward and backward cooling

Forward cooling is determined as the reach of the cooling effect on the smoke gases in front of the fire attack team for each fire extinguishing system and attack method. Backward cooling is determined as the extend of lingering of the cooling effect as the attack team passes a given location. After applying smoke cooling, the temperature of the smoke gases behind the fire attack team can increase or decrease. Here, the emphasis was on reach rather than on the level of decrease (or increase). table 2.6 shows a summary of the assessments for the individual extinguishing systems. The distances were determined on the basis of the measurement locations and the moments in time when the team reached a certain threshold and are therefore only approximate values. See Appendix 7 for further details. The distances were determined in multiples of 3 m (the distance between the thresholds), except for the seventh threshold which is 17 m from the entrance. A value of > 17 m indicates that the reach was at least the maximum number of thresholds.

Table 2.6 Reach of smoke cooling in front of and behind the fire attack team

Fire extinguishing system	Forward cooling*	Backward cooling*
HP 3D pulse method	3 m	9 m
HP arc method	9 m	> 17 m

LP 250 3D pulse method	6 m	> 17 m
LP 250 arc method	9 m	> 17 m
LP 450 3D pulse method	6 m	9 m
LP 450 arc method	15 m	> 17 m
CAFS OneSeven arc method	15 m	> 17 m

**all distances are approximate values*

For clarification, the two figures (see figure 2.13 and 2.15) and two graphs (figure 2.14 and Figure 2.16) below give details of the reach of smoke cooling during with the 3D pulse method and the arc method, both using HP. The HP attack with the 3D pulse method shows that the smoke gases were cooled as far as approximately 3 metres ahead of the fire attack team. The smoke gases continued to be cooled up to approx. 9 metres behind the fire attack team. The temperature of the smoke gases at a greater distance behind the fire attack team increased again. The hot smoke gases are highlighted in red; the smoke gases which were cooled in front of the fire attack team and continued to be cooled behind the fire attack team are marked in blue. This is also shown by Figure 2.14 where the temperature shows a 'sawtooth' pattern. The graphs show the temperatures of the hot zone at all four measurement locations from the start of the attack until the moment when the end of the corridor was reached.

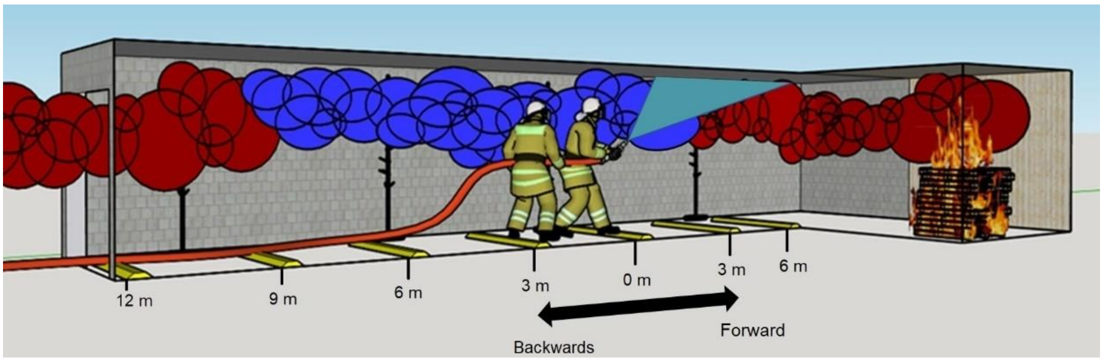


Figure 2.13 Smoke cooling in front of and behind the fire attack team when carrying out an HP attack using the 3D pulse method

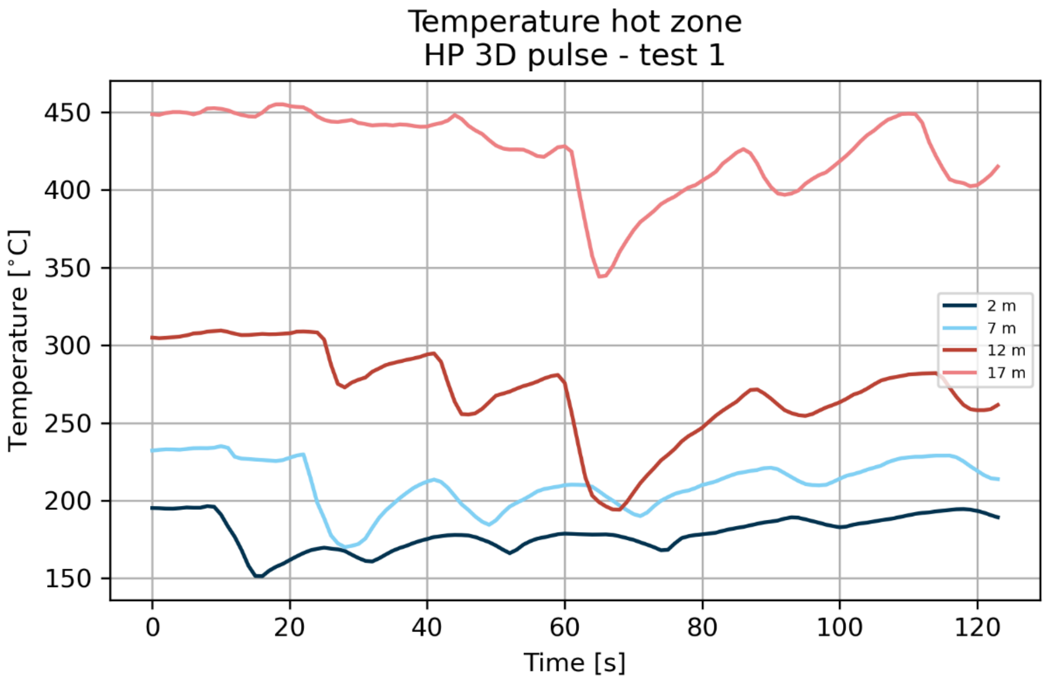


Figure 2.14 Temperatures in the hot zone while progressing at different distances in the corridor

During the attack where the combination of HP and the arc method was applied, the smoke gases were cooled up to approx. 9 metres ahead of the fire attack team. The smoke gases in the rest of the corridor behind the fire attack team stayed cool and their temperature did not increase again.

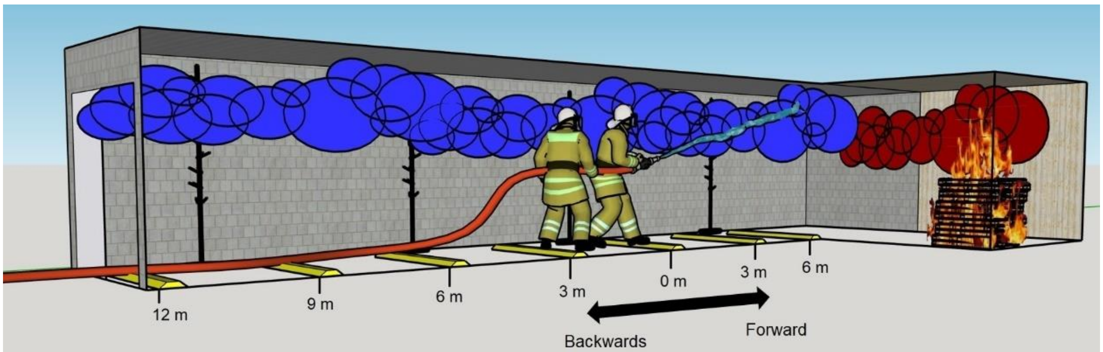


Figure 2.15 Smoke gas in front of and behind the fire attack team with an HP attack with the arc method

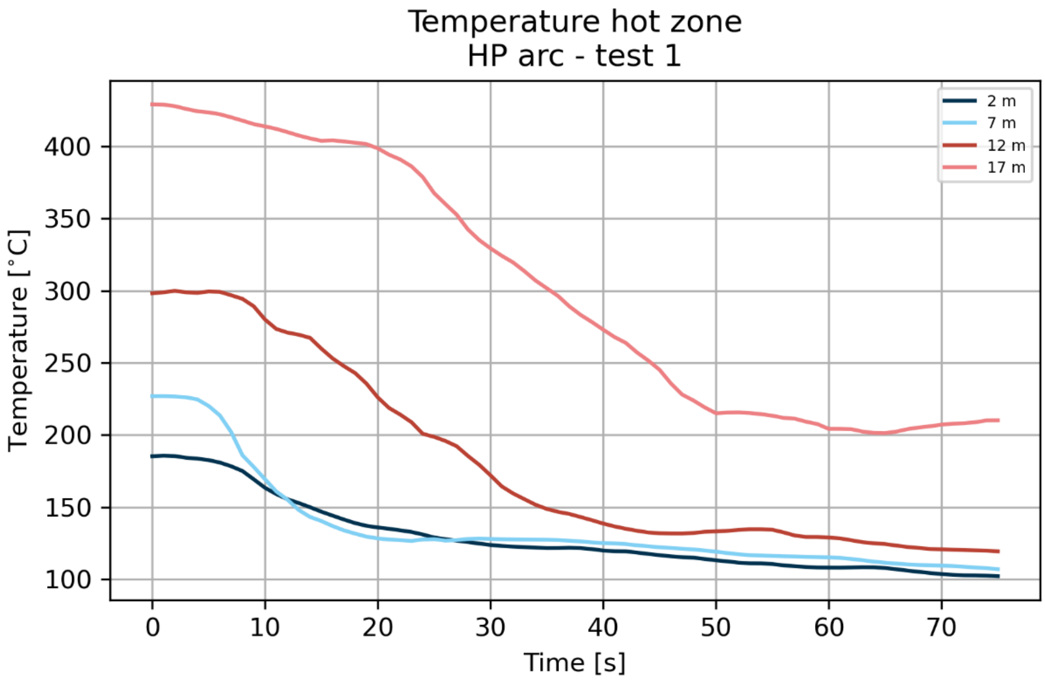


Figure 2.16 Temperatures in the hot zone while progressing at different distances in the corridor

Analysis

The analysis of forward and backward cooling shows that the temperature behind the team consistently remained the lowest with all flow rates when applying the arc method, whereas the use of the 3D pulse method sometimes led to a rise in temperature behind the team, as has been concluded in section 2.2.2 above,. The arc method had a longer forward cooling reach than the 3D pulse method; this was true for all flow rates. The cooling effect of the 3D pulse method is temporary because of the inflow of new hot smoke gases in between two pulses. The arc method provides a constant supply of cooling capacity and thus continuously cools the smoke gases. This is the most noticeable when applying HP, where a low flow rate combined with the 3D pulse method leads to limited forward and backward cooling. What is remarkable is that the degree of backward cooling of the LP 450 3D pulse method equals that of the HP 3D pulse method. However, the results show that the backward cooling effect of both these methods is less than that of the LP 250 3D pulse method. The most likely explanation for this is that, although the flow rate of LP 450 is higher, leading to a higher cooling capacity, the speed of progressing is slower due to the counterpressure and the weight of the hose. The consequence of this is that there is more time between two pulses, enabling the smoke layer to build up again. Although the cooling capacity of HP (per pulse) is lower, the speed of progression is higher, leading to shorter intervals between two pulses. This gives the same net effect in this particular test design. The combination of the speed of progression and the cooling capacity of the LP 250 3D pulse method results in the best backward cooling with the 3D pulse method, where the temperature behind the fire attack team does not increase.

2.2.4 Execution

The results above also list the standard deviation of the experiments that were carried out in duplicate; this value is a measure of the spread of the results. However, since the standard deviation was established by doing only two experiments, this is not a sufficiently reliable result to enable any quantitative conclusions to be drawn. A remarkable finding however is that the standard deviation of the 3D pulse method is generally greater than that of the arc method. This means that the arc method leads to more consistent results. Although the experiments were carried out by experienced teams, the 3D pulse method is more complex to implement than the arc method. The 3D pulse method consists of several actions (such as aiming, determining the correct aiming angle and pulse durations, adjusting the nozzle), making it more prone to error. As a result, the nozzle operator and the manner in which the 3D pulse method technique is carried out have a relatively major effect on the effectiveness of smoke cooling when compared to the arc method. Furthermore, the standard deviation decreased as the flow rate increased. This means that besides ensuring more cooling capacity, it is less affected by how the technique is performed, but it does not necessarily lead to a greater cooling effect. The effectiveness of smoke cooling therefore depends mostly on the way the method is carried out in the 3D pulse method with low flow rates and is least dependent on how the method is carried out in the arc method or the 3D pulse method with high flow rates.

An analysis of the film footage confirms that the 3D pulse method is more complex to execute. The footage shows that, when the 3D pulse method was executed, not all pulses were discharged completely parallel to the corridor. As a result, some pulses partly hit the wall directly, see figure 2.7. There was also some variation in the duration of the pulses.

Figure 2.17 Thermal imaging camera footage showing the pulse hitting the left-hand wall during the 3D pulse method

The arc method was not always carried out according to protocol either. The protocol stipulates that the walls must be hit to just above floor level. However, the footage of the experiments shows that the arc motion was not continued to just above the floor but stopped halfway down the height of the wall in some experiments. In spite of the nonconformities in applying the arc method, the difference in decreases in temperature was less than for the nonconformities in applying the 3D pulse method. This is probably because the hot layer did not reach a level lower than 1.2 metres from the floor in these experiments. This means that the arc motion did not have to be continued until just above the floor in order to cool the hot smoke gases, since there were no hot smoke gases at a level lower than 1.2 metres from the floor. The influence of the actual execution is therefore less significant for the arc method.

2.2.5 Summary

The results for temperature across height and the decrease in energy show that the arc method produced a greater local decrease in temperature and energy than the 3D pulse method. The reach of forwards and backwards cooling when applying the arc method was also better than that of the 3D pulse method. There were some situations where the temperature increased behind the attack team when using the 3D pulse method, whereas the temperature remained low in all situations tested using the arc method. While the 3D pulse method is taught as the standard smoke cooling method in the Netherlands , the film footage showed that the arc method is easier to perform according to protocol than the 3D pulse method and is less dependent on the nozzle operator.

Increases in energy in the middle of the corridor were also found in all attacks; this was probably caused by mixing. This increase was less significant for the arc method than it was for the 3D pulse method. In addition, it was found that, when applying the arc method, the energy in the cold zone decreased at the beginning and the end of the corridor, whereas during almost all 3D pulse method tests the energy increased.

All techniques only have a minimal effect on the temperature at a height of 0.3 m in the cold zone along the entire length of the corridor, but increases in temperature were noticeable at the height of 0.9 m, particularly when applying the 3D pulse method. The temperature effect was the lowest when applying the LP 250 and LP 450 arc methods, which means that the temperature conditions for possible casualties neither improve nor deteriorate at this location.

This shows that the arc method gives more, and more consistent, cooling than the 3D pulse method, both along the length and across the height of the corridor. A higher flow rate also gives more consistent results and decreases the influence of how the technique is executed. The effectiveness of smoke cooling therefore depends most on the way the method is carried out in the 3D pulse method with low flow rates and is least dependent on how the method is carried out in the arc method and the 3D pulse method combined with high flow rates. The greatest cooling effect and decrease in energy were reached by the combination of the arc method and the highest flow rate, LP 450.

2.3 Influence of smoke cooling on the seat of the fire

The change in temperature in the fire room between the start of the attack and the moment when the end of the corridor was reached was examined in order to assess the influence of smoke cooling on the seat of the fire. Fully extinguishing the fire was not included in this. Figure 2.18 shows a diagram of the design of the seat of the fire in the fire room.

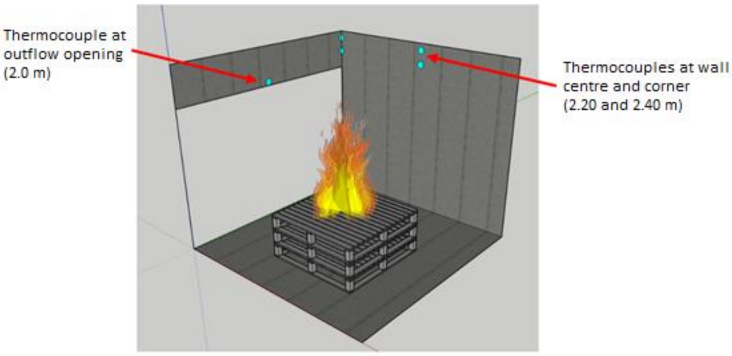


Figure 2.148 Diagram of the design of the seat of the fire in the fire room

2.3.1 Changes in temperature in the fire room

Figure 2.19 shows the changes in temperature in the fire room while progressing. The average values were established for the four thermocouples on the walls. A negative number means a net decrease in temperature.

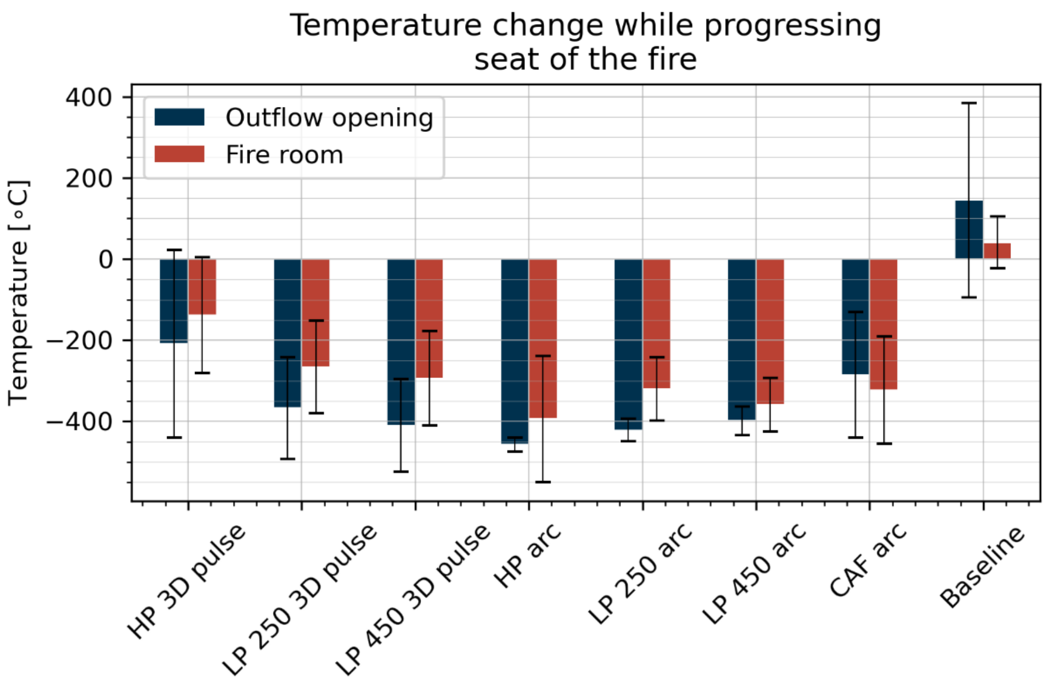


Figure 2.19 Changes in temperature in the fire room for the individual fire extinguishing systems and attack methods while progressing

Table 2.7 Changes in temperature for the individual extinguishing systems and measurement locations

Fire extinguishing system	Outflow opening [°C]	Fire room [°C]
HP 3D pulse method	-208 ± 231	-138 ± 144
LP 250 3D pulse method	-367 ± 125	-266 ± 102

LP 450 3D pulse method	-410 ± 114	-294 ± 108
HP arc method	-457 ± 17	-394 ± 137
LP 250 arc method	-421 ± 27	-320 ± 71
LP 450 arc method	-399 ± 35	-359 ± 63
CAFS OneSeven arc method	-286 ± 154	-323 ± 129
Baseline measurement	145 ± 239	41 ± 65

Analysis

The temperature at the opening where the smoke flowed out (the 'outflow opening') and in the fire room decreased relative to the baseline measurement as the firefighters progressed during all experiments. The arc method generally showed a greater decrease in temperature than the 3D pulse method. For the 3D pulse method, a greater decrease was found as the flow rate increased, whereas for the arc methods the decrease was less dependent on the flow rate. The greatest decrease in temperature was achieved when applying the HP arc method, probably because this method enables a high progressing speed whilst still providing sufficient cooling capacity.

The standard deviations for the arc method are smaller than for the 3D pulse method, which means that the results of the arc method are more consistent than those of the 3D pulse method. The effect on the seat of the fire depends on several factors, such as the flow profiles at the time of the experiment, the nozzle operator's technique and atmospheric conditions.

table 2.7 quantifies the results of the change in temperature in the fire room. A negative average means a decrease in temperature and a positive average means an increase in temperature.

2.3.2 Summary

All techniques led to the seat of the fire being cooled relative to the baseline measurement while progressing. The arc method led to greater cooling than the 3D pulse method.
The 3D pulse method increases cooling as the flow rate increases. The arch method gives the best results when combined with HP, which can probably be explained by the fact that HP enables a high speed of progression through the corridor.

2.4 Influence of smoke cooling on the safety of fire service personnel and casualties

This section addresses the influence of smoke cooling on the safety of fire service personnel and casualties in the building. In addition to temperature, radiation and gas concentrations were measured to get an idea of the conditions in the corridor during smoke cooling.

2.4.1 Fire service

Figure 2.20 shows the exposure to heat radiation (dose) while progressing for each experiment. The horizontal axis shows the time in seconds since the attack started. The FED was well under the threshold values (1.0) throughout all experiments. The greatest increase in FED occurred near the end of the corridor, when the team was nearing the seat of the fire.

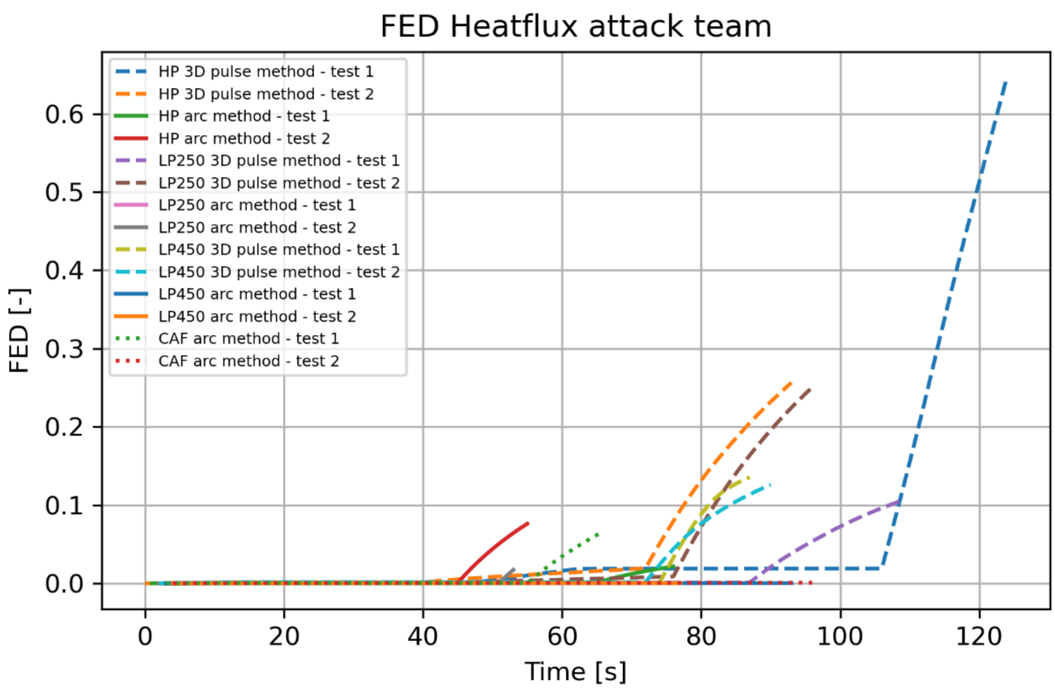


Figure 2.20 Cumulative radiation over time during attacks

Subjective perception of thermoregulation, discomfort and effort

In order to get an initial idea of subjective perception, the nozzle operator and the number 2 filled in a short questionnaire about their perception of heat, any pain, skin humidity and effort. The questionnaire consisted of five scored questions and two open-ended questions. The answers to the scored questions can be found in table 2.8.

Table 2.8 Scores for subjective perception of thermoregulation, pain and effort

Fire extinguishing system	Thermal sensation	Thermal comfort	Skin moisture	Sensation of pain	Effort perceived
HP 3D pulse method	Not hot, not cold	Neutral	Slightly moist	No pain	Extremely light
HP arc method	Slightly warm	-	Quite moist	No pain	Somewhat strong
LP 250 3D pulse method	Slightly warm	Slightly uncomfortable	Moist	No pain	Somewhat strong
LP 250 arc method	Slightly warm	Slightly uncomfortable	Moist	No pain	Very light

LP 450 3D pulse method	Hot	-	Moist	No pain	Between light and somewhat strong
LP 450 arc method	Not hot, not cold	Neutral	Moist	No pain	Somewhat strong
CAFS OneSeven arc method	Not hot, not cold	Neutral	Moist	No pain	Between extremely light and very light

The average scores for the subjective perception of thermoregulation, discomfort and effort show that the experiments were not excessively strenuous for the subjects. However, the fact that they had previous experience of such conditions should be taken into account.

The nozzle operators' and number twos' answer to the first open-ended question, i.e. when did they perceive the most heat, was that, when applying the arc method, they had experienced the most heat near the seat of the fire (threshold 7). As regards the 3D pulse method, one half of all nozzle operators and number twos indicated that they had perceived most heat at the entrance, whereas the other half had perceived most heat at the seat of the fire.

The second question was about what caused the most discomfort during the attack. In connection with the arc method, fully extinguishing the seat of the fire was generally indicated as the cause of most discomfort. Most discomfort was experienced by the nozzle operators and number twos during the attacks where the LP 450 arc method was implemented. They indicated that the water vapour, the amount of water, the lack of visibility, the strength needed to properly operate the nozzle and lack of ability to communicate caused discomfort during the attack.
In general, less discomfort was experienced when carrying out the 3D pulse method than was the case with the arc method. The only discomfort mentioned in connection with the 3D pulse method was the hard work involved in progressing while carrying out the LP 250 3D pulse method.

Analysis of the influence of smoke cooling on firefighters' safety

The safe exposure level used for exposure to heat radiation (dose) was not exceeded in any of the smoke cooling methods researched. In general, exposure to heat radiation was found to be slightly higher for the tests with the 3D method than for the tests with the arc method. The questionnaire shows that the fire attack teams did not perceive the experiments as being unduly strenuous. All techniques applied showed a decrease in heat radiation in the corridor compared to the baseline measurement. This means that the smoke cooling techniques which were the subject of the research improve safety while progressing compared to an attack where no smoke cooling is applied. As indicated before, no conclusion can be drawn as to the actual safety of fire service personnel since only a relative comparison was made.

2.4.2 Casualties

For all experiments the only threshold values that were exceeded were for FED_{in}. This means that any life-threatening conditions were caused by the asphyxiant gases, which was CO in all cases. This section only expands on the results for the asphyxiant gases since no threshold values were exceeded for the irritant gases and heat radiation measured as part of this study. Figures for all methods and all experiments can be found in Appendix 9.
Figures 2.21 to 2.29 show summaries of the effect of each attack on the survivability for each population group and measurement location. The graphs start at the moment when the seat of the fire was ignited and are limited to 15 minutes. Only the baseline measurements actually continued until this time; for the actual experiments the seat of the fire was fully extinguished immediately after the smoke cooling. Fully extinguishing the seat of the fire has not been included in these graphs. No measurements were recorded for LP 450 study materials 3D test 1 due to the measuring equipment failing; only the moment of the start of the attack is shown for this test.

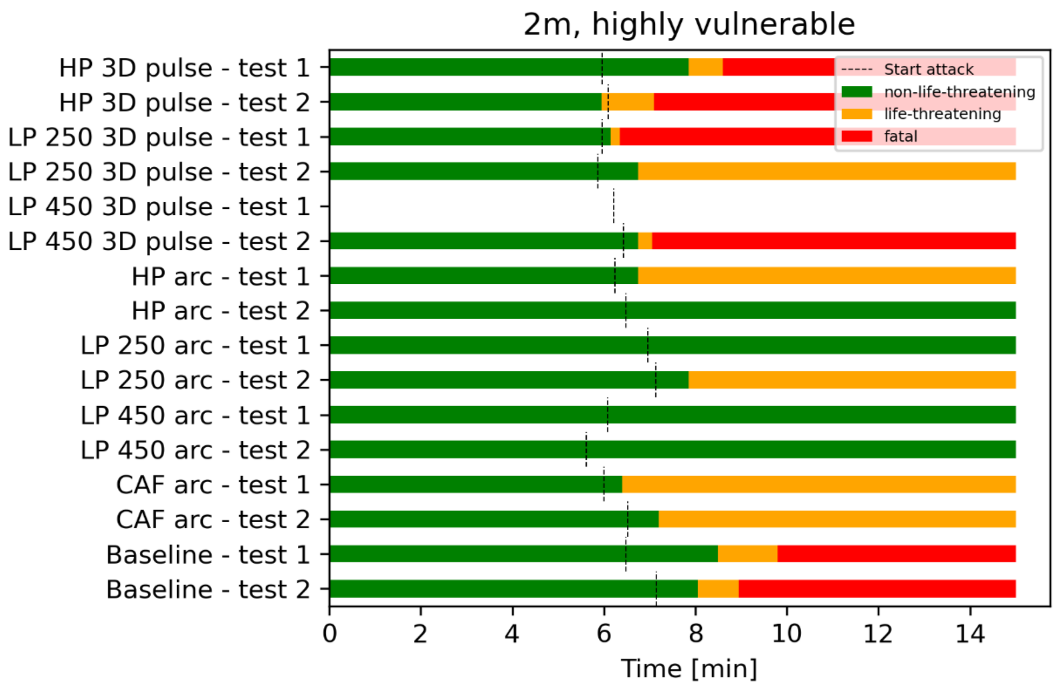


Figure 2.21 Survivability times for the highly vulnerable group at 2 metres down the corridor

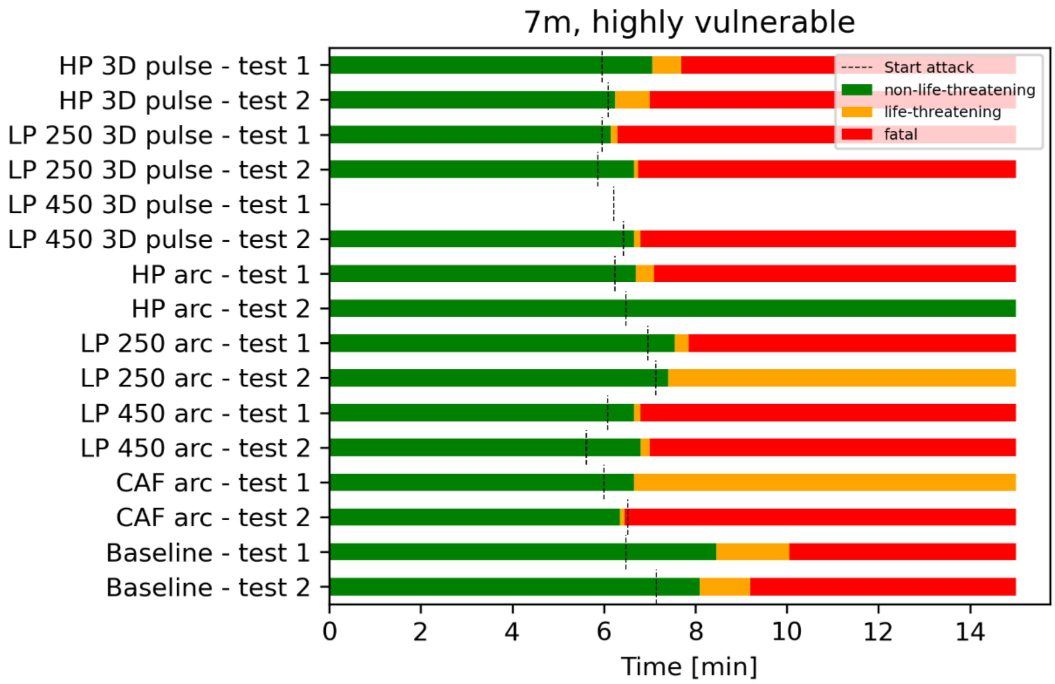


Figure 2.22 Survivability times for the highly vulnerable group at 7 metres down the corridor

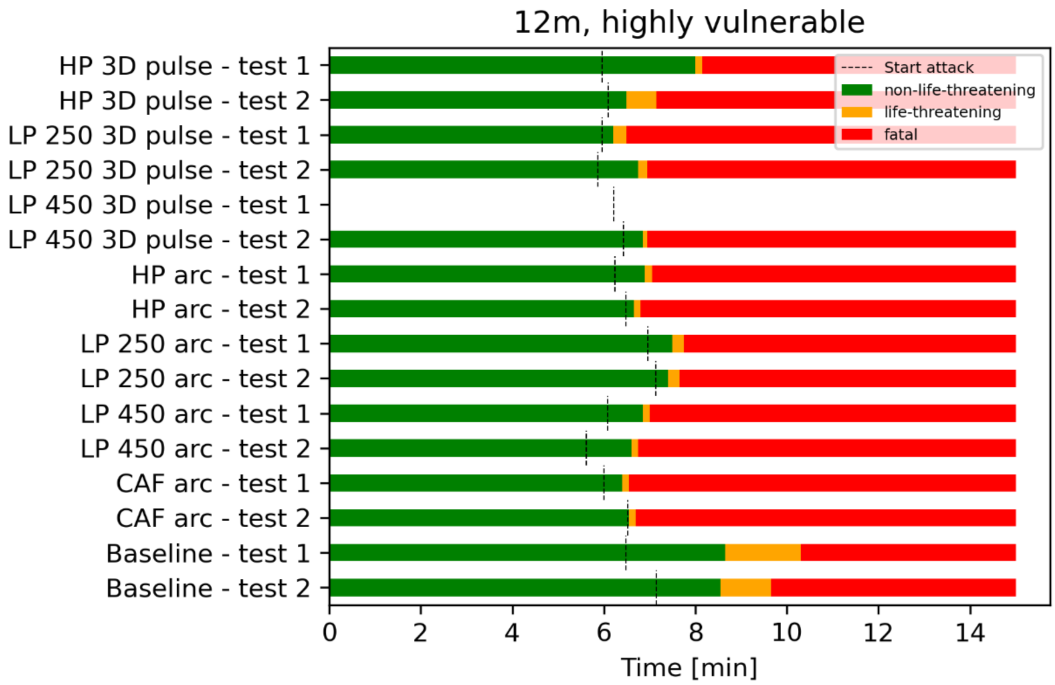


Figure 2.23 Survivability times for the highly vulnerable group at 12 metres down the corridor

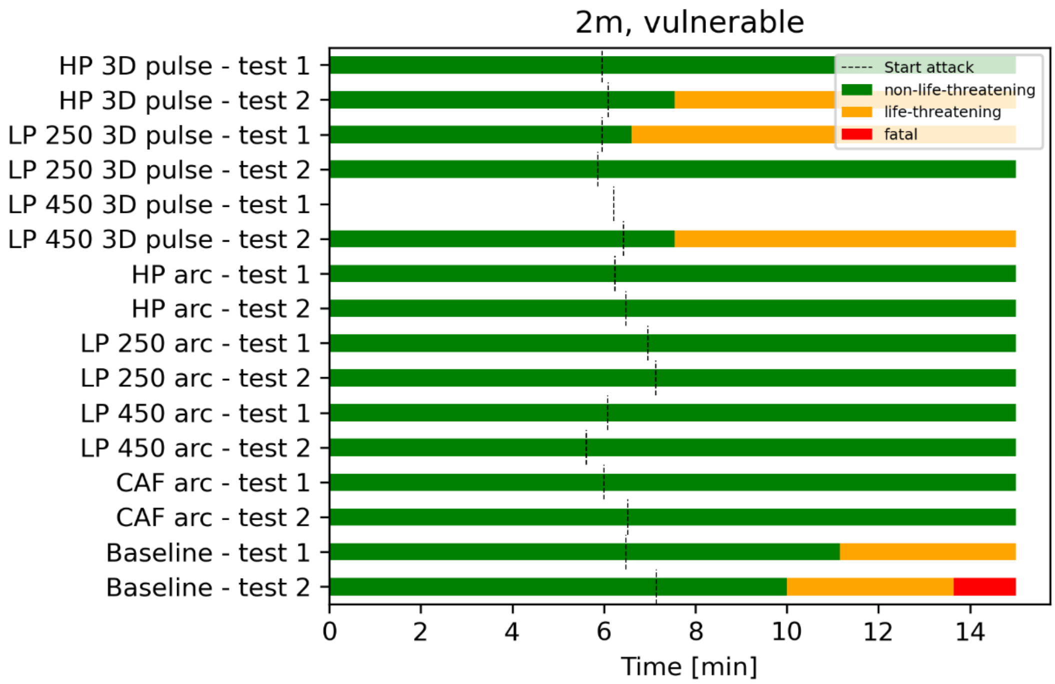


Figure 2.24 Survivability times for the vulnerable group at 2 metres down the corridor

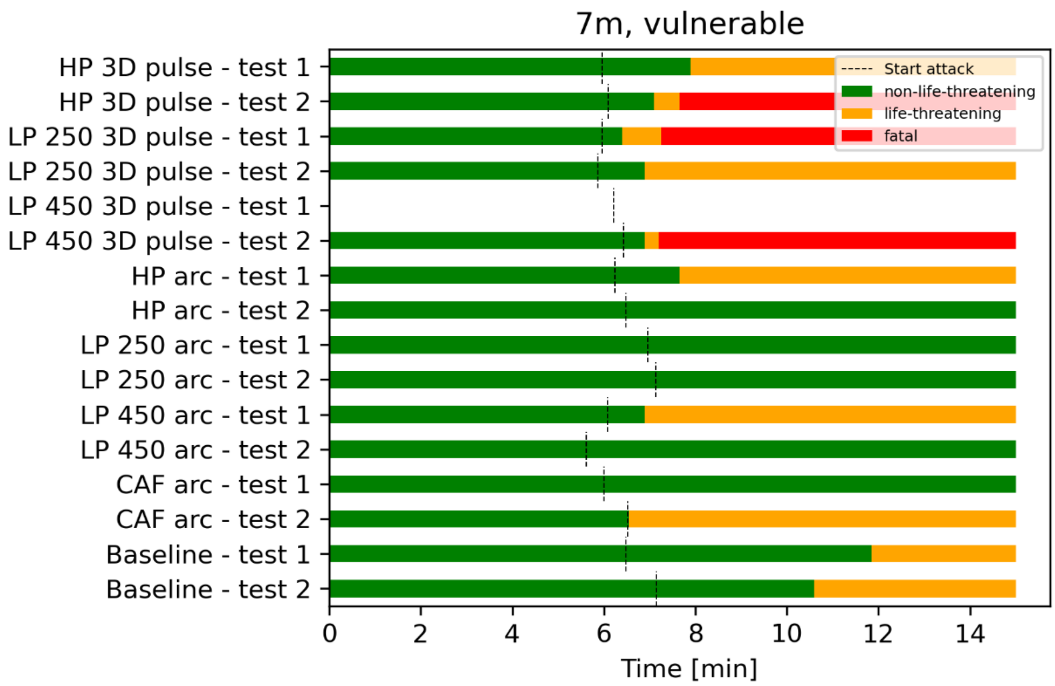


Figure 2.25 Survivability times for the vulnerable group at 7 metres down the corridor

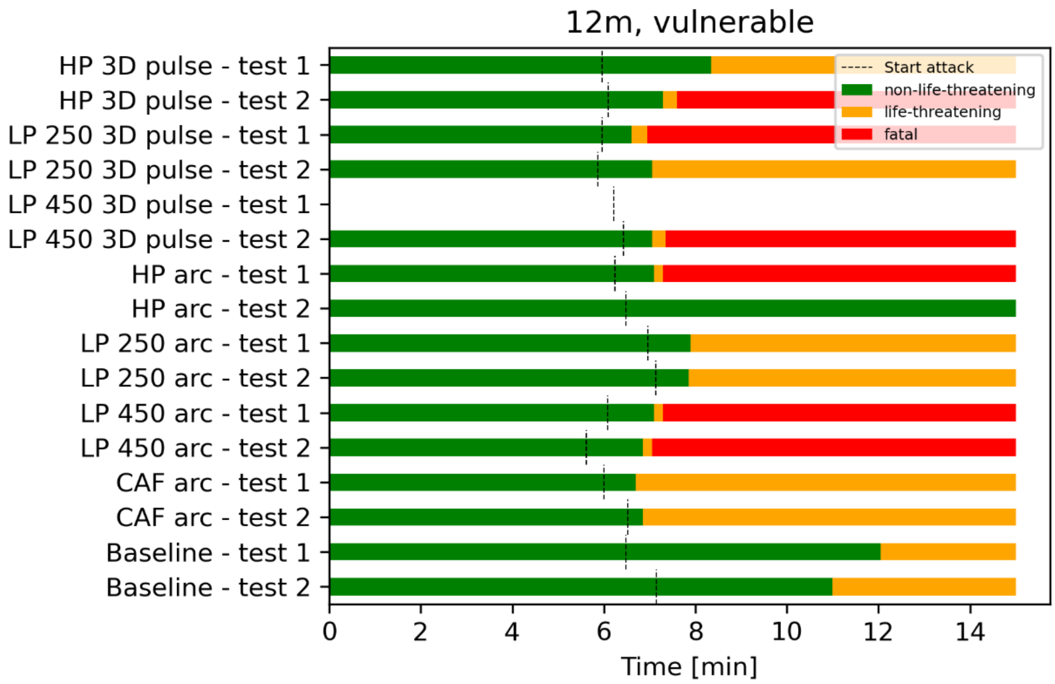


Figure 2.26 Survivability times for the vulnerable group at 12 metres down the corridor

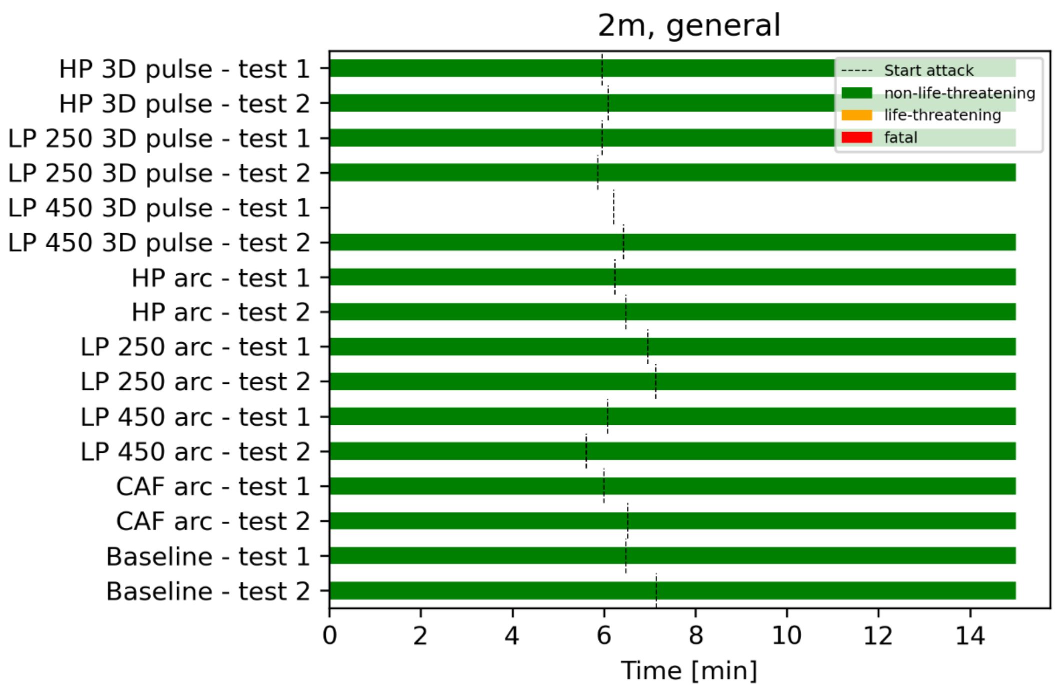


Figure 2.2715 Survivability times for the general group at 2 metres down the corridor

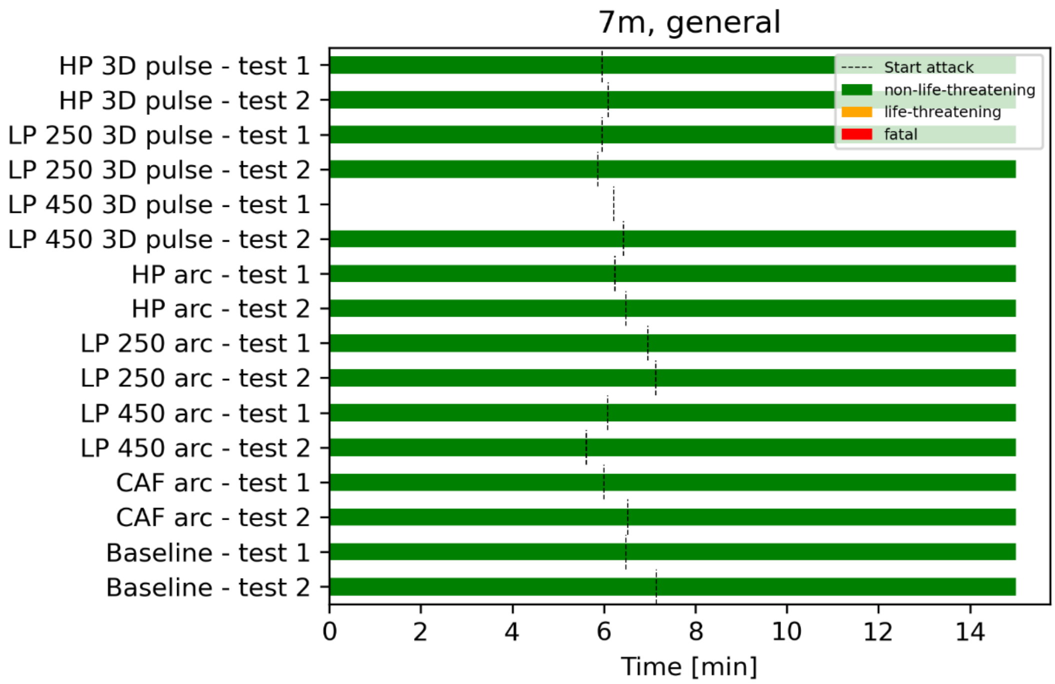


Figure 2.28 Survivability times for the general group at 7 metres down the corridor

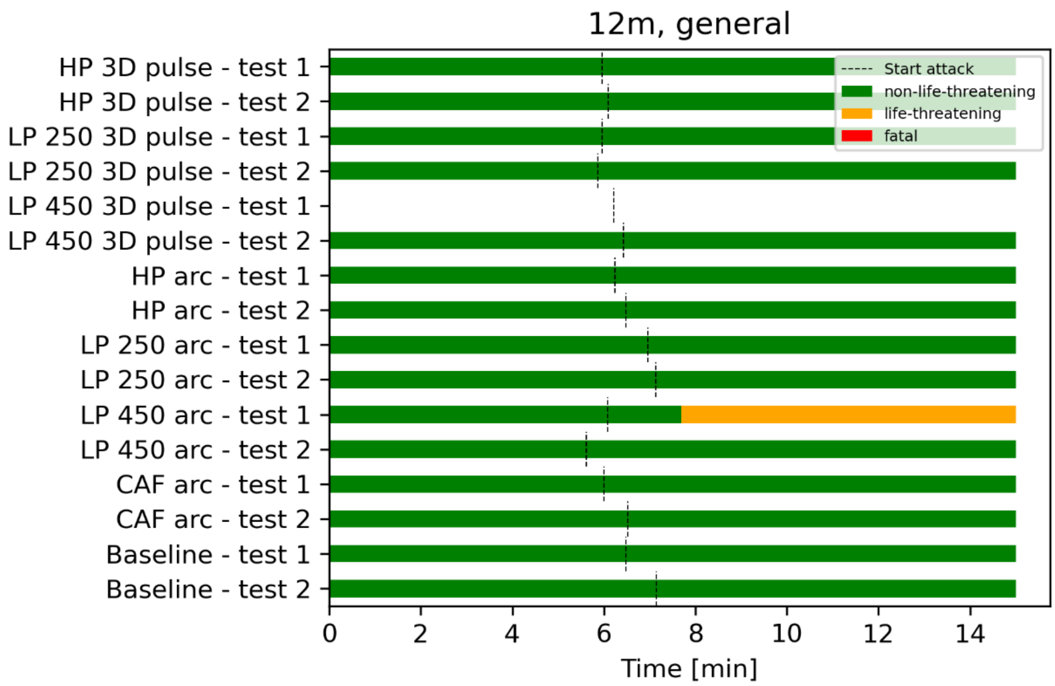


Figure 2.29 Survivability times for the general group at 12 metres down the corridor

Analysis of the influence of smoke cooling on firefighters' safety

The time between the moment the fire started and the attack in these experiments is approx. 6.5 minutes. In reality this time would be longer: approx. 13 minutes (time of the alert + response time + preparing for the attack). Since this time is relevant for any casualties, a relative comparison between the experiments and the baseline measurement is made here.

The techniques have been assessed on the basis of an improvement or a deterioration of the conditions compared to the baseline measurements.

The results show that, as regards the general group, a threshold value was only exceeded in LP 450 test 1 where the arc method was applied. Conditions continued to be survivable for this group throughout the corridor during the baseline measurements and the other tests. The conditions for the vulnerable to highly vulnerable groups worsen from 12 m into the corridor for basically every attack. The baseline measurements show that the situation became life-threatening for the vulnerable group throughout the corridor in 13 minutes. In general, the arc method worsened these conditions less than the 3D pulse method, specifically in the front section of the corridor near the entrance. There are significant differences between the two tests for the individual extinguishing systems in terms of survivability, indicating that the nozzle operator has a major influence on these conditions.

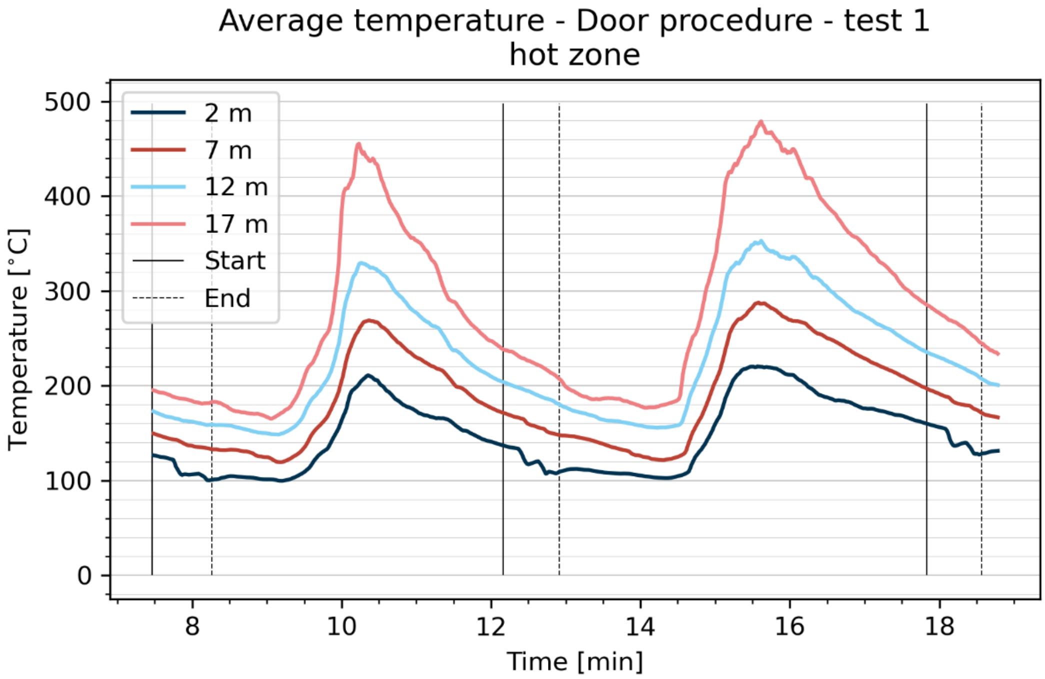
2.4.3 Summary

Based on the exposure method used, the safe exposure level for fire service personnel was not exceeded with any of the smoke cooling methods researched. However, the radiation dose received by the attack teams when applying the 3D pulse method is higher than when applying the arc method. The average scores for the subjective perception of thermoregulation, discomfort and effort show that none of the attacks was excessively strenuous for the teams. The team perceived the most discomfort during the attack with LP 450. The reasons mentioned for this were: the water vapour, the amount of water, lack of visibility, the strength needed to properly operate the nozzle and the lack of ability to communicate.

The actions of the fire attack teams will always have negative consequences for highly vulnerable to vulnerable casualties, regardless of the fire extinguishing system or method used. This is because any cooling action disturbs the smoke layer, leading to an increase in CO values at casualty level which is noticeable as soon as the attack starts. Life-threatening and even fatal situations arose in all experiments, specifically for the casualties lying 7 metres or 12 metres down the corridor. No life-threatening situations arose for casualties in the general group, with one exception.
Both baseline measurements, i.e. where no fire attack took place, showed that it took longer for a life-threatening situation to arise for casualties.

2.5 Influence of the door procedure

The door procedure was carried out three consecutive times during two experiments, with the smoke layer being built up every time until its temperature was at least 200 °C at a height of 2.2 m along the entire corridor for more than one minute. A cold block, as described in section 1.4, was applied before each execution of the door procedure. This means that the two front doors were opened in the meantime, enabling the smoke production and consequently the smoke layer to increase again. The graphs below show the average temperature in the corridor and in the fire room while the successive door procedures, marked 'Start' and 'End', were carried out. Brief temperature changes of 10-20 degrees were only observed directly behind the door (2 m into the corridor). The thermocouples on the flagpoles measured temperatures above the door of a maximum of 50 degrees when the door was opened.



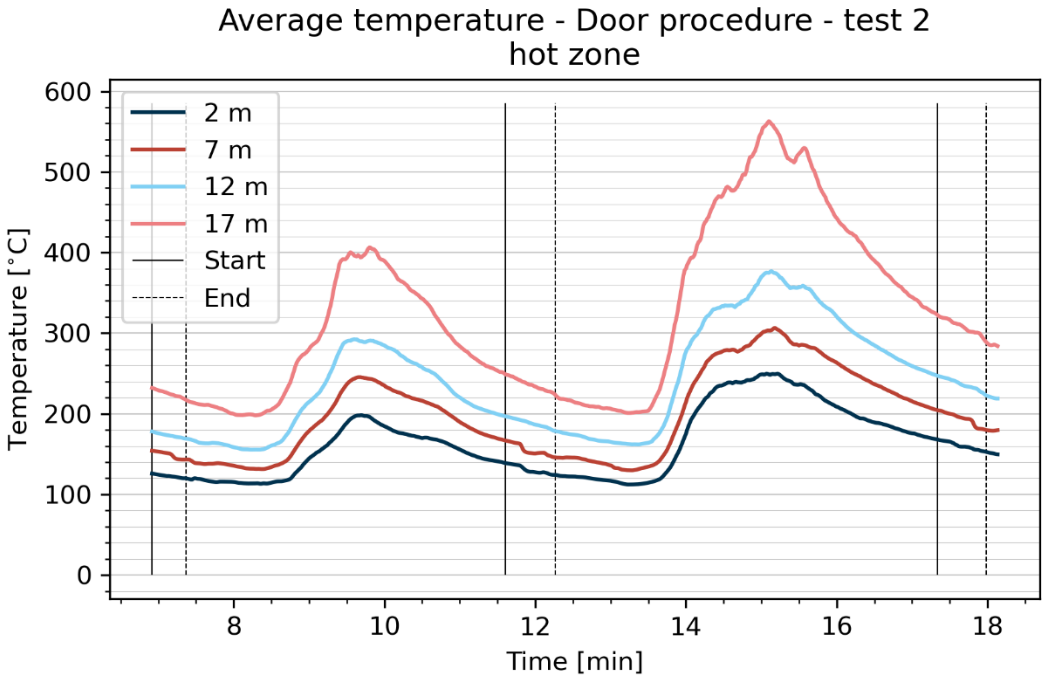


Figure 2.30 Average temperature development in the hot zone during the door procedures

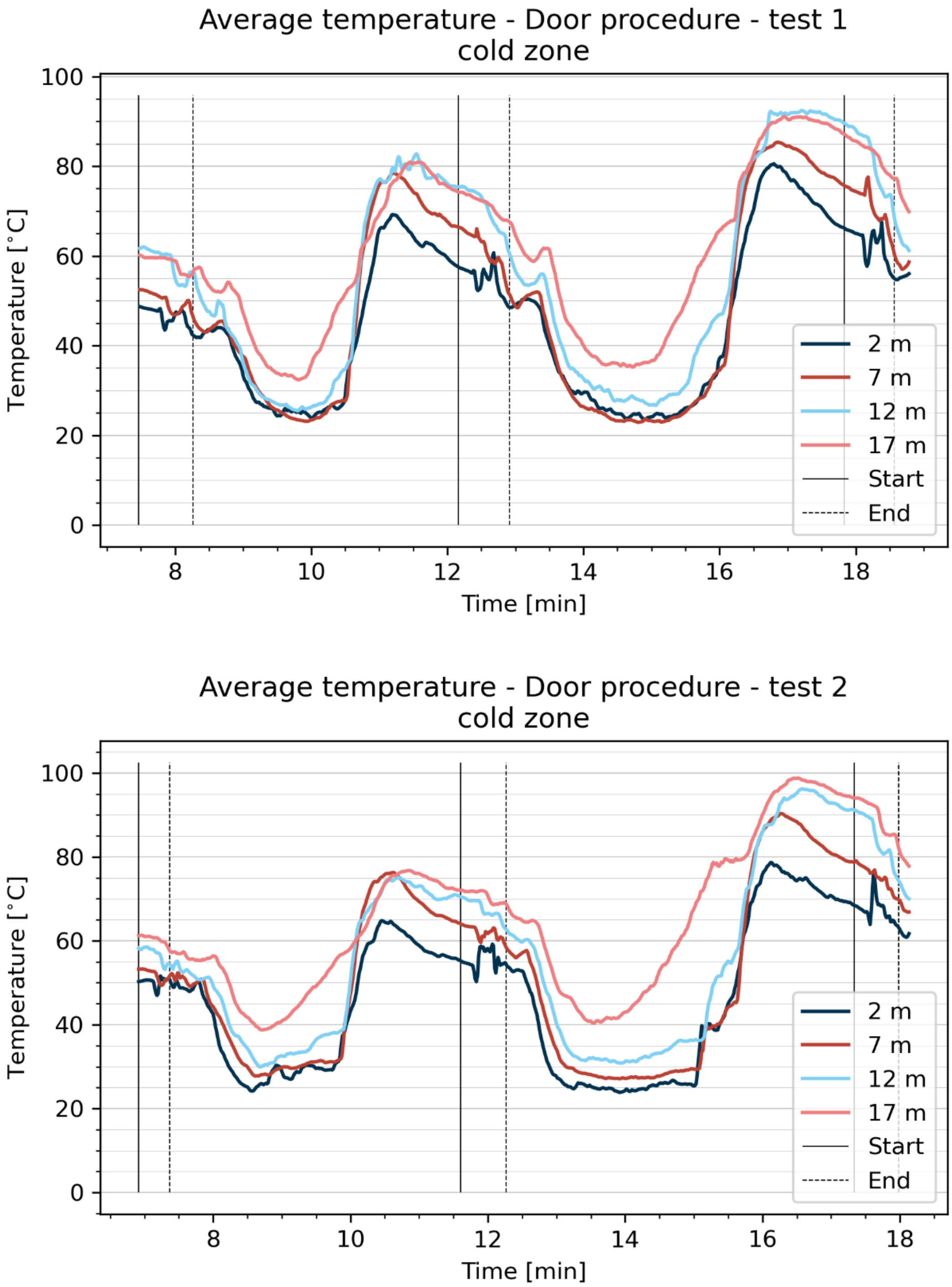


Figure 2.31 Average temperature development in the cold zone during the door procedures

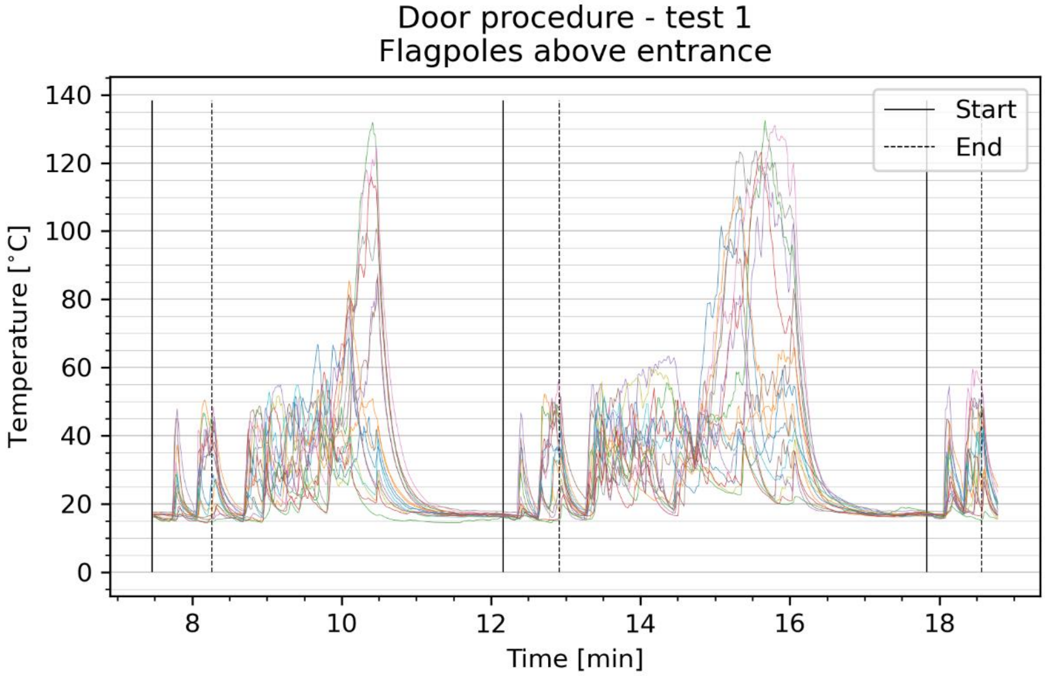


Figure 2.32 Temperature development above the front door during door procedure 1

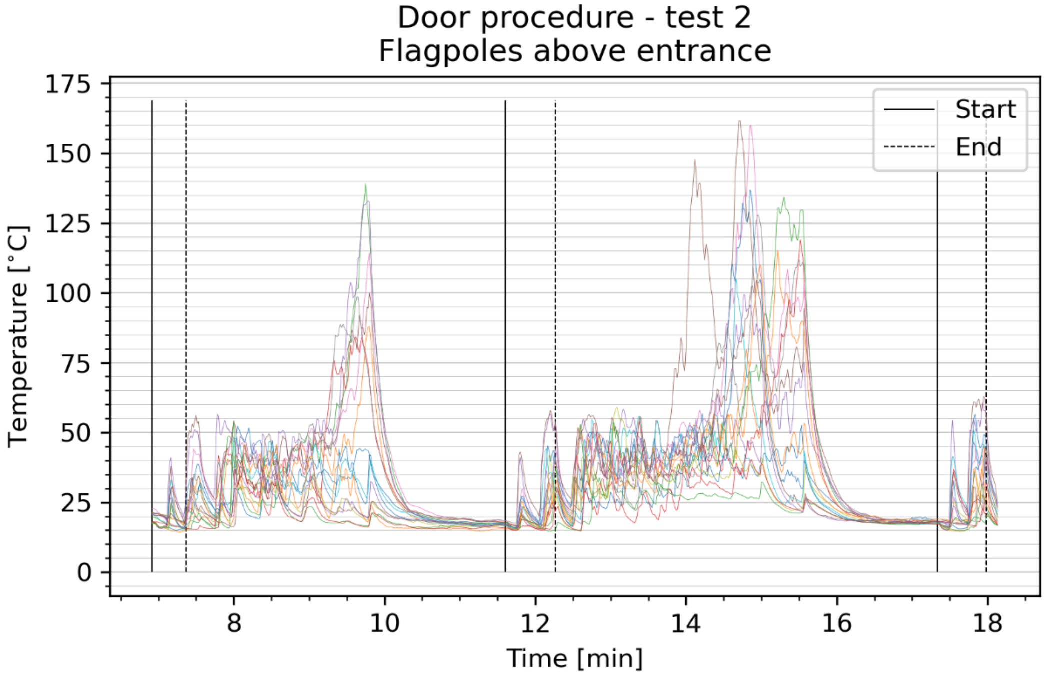


Figure 2.33 Temperature development above the front door during door procedure 2

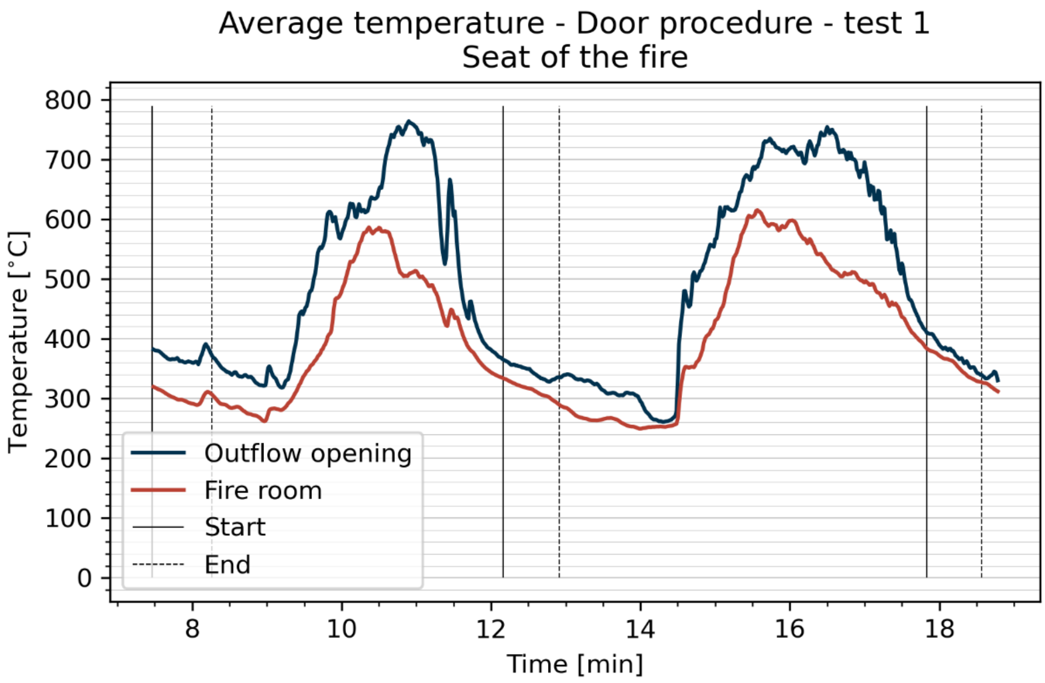


Figure 2.34 Temperature in the fire room during door procedure 1

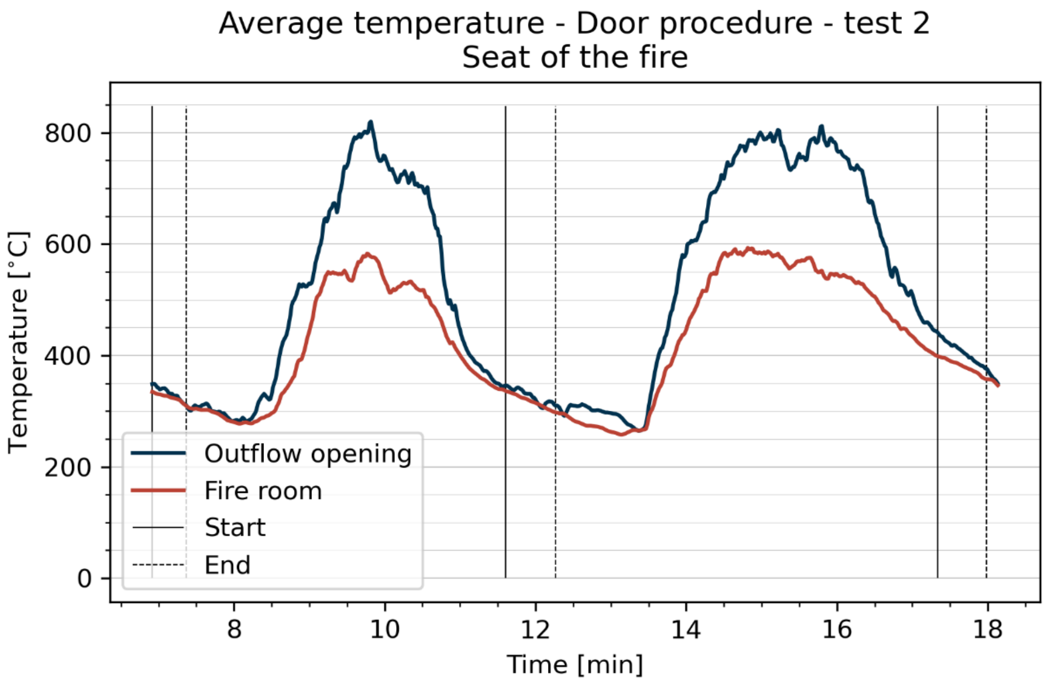


Figure 2.35 Temperature in the fire room during door procedure 2

Analysis

The results do not show any clear effect of the individual implementation of the cold block or the door procedure. The front doors were opened in order to achieve the correct conditions and they were closed again before the door procedure was carried out. As the graphs show, the temperature at the seat of the fire decreases as the fire became under-ventilated. The succession of actions is too fast to be able to properly interpret the changes in temperature. When carrying out the tests, it was found that at the flagpoles, temperatures were poor indicators of the temperature of the smoke layer. The smoke layer was immediately diluted and dispersed in the open air. Although measures were taken to reduce the influence of wind, it still had a significant effect on the measurements. Because the smoke was sometimes blown away from the flagpoles, reliable measurements of its temperature were not possible.

2.6 Attack duration and water consumption

Table 2.9 Attack durations until the seat of the fire was reached and water consumption

Extinguishing method	Attack time in seconds until the seat of the fire was reached	Water consumption in litres
HP 3D pulse method	90	40
HP arc method	66	135
LP 250 3D pulse method	102	70
LP 250 arc method	62	275
LP 450 3D pulse method	88	130
LP 450 arc method	78	550
CAFS OneSeven arc method	80	175

Execution

The attack durations are based on the average value of two measurements (except the LD450 arc method where only one measurement was available). The duration is based on the time in seconds from the start of the attack until the moment when the seat of the fire (threshold 7) was reached. The flow measurements were carried out by filling a water tank and repeatedly measuring the weight for 10, 30 and/or 60 seconds. The ratio of 1 kg = 1 litre was presumed.

The water consumption of the pulse method is based on the average of two measurements, with a 6*3-second pulse multiplied by the flow rate per second measured. There is some uncertainty here due to the actual speed of counting by the nozzle operator. This uncertainty is estimated to be of an order of magnitude of 10 litres.

The water consumption of the arc method is based on the average of two measurements (except the LD450 arc method where only one measurement was available). The measurement is based on the attack time multiplied by the flow rate per second measured. This involves some uncertainty due to the actual opening and closing times and the moment when these times were communicated. This uncertainty is estimated to be of an order of magnitude of 20 litres.

The CAFS OneSeven flow measurement is not exact because it is a water/foam/air mixture. Since the exact mixture at the time of the experiments is not known, a ratio of 1 kg = 1 litre was presumed here as well.

Analysis

In general, the arc method can be presumed to consume at least three times as much water as the 3D pulse method (not considering CAFS OneSeven) while progressing towards the seat of fire (distance of 20 m).

3 Conclusion

This chapter answers the main question and the sub-questions as described in the introduction. The individual sub-questions are answered first (sections 3.1.1 to 3.1.4). The main question is answered last (section 3.2).

3.1 Answers to the sub-questions

3.1.1 When using the 3D pulse method and the arc method when progressing to the seat of the fire in a dynamic smoke layer, to what extent can smoke gases be cooled in terms of:
a. temperature across height?
b. energy decrease?
c. forward and backward cooling?

Temperature across height

All experiments showed a decrease in temperature in the hot zone during the attacks. This means that the hot zone was cooled during all attacks. The arc method achieved a greater decrease in temperature cooling than the 3D pulse method. Another finding was that the 3D pulse method showed a higher increase in temperature in the cold zone than the arc method. This is remarkable since the arc method was expected to stir up and mix the smoke layer more which in turn would lead to an increase in temperature in the cold zone.

If the flow rate is higher, the temperature decrease in the warm zone is also higher. But the difference between the HP arc method and the LP 250 arc method is less significant that was expected on the basis of the flow rate. The same goes for the difference between the LP 250 3D pulse method and the LP 450 3D pulse method. The results with CAFS OneSeven are comparable to those with the HP arc method. The highest decrease in temperature was measured with the attacks using the LP 450 and arc method.

Energy decrease

The relative change in energy in the warm zone decreased in all segments during all attacks, contrary to the baseline measurement where the energy increased in all segments, as expected. The decrease in energy further down the corridor was greater in the hot zone. The temperature was also higher there, enabling more energy to be absorbed by the water. Furthermore, the decrease in energy in the hot zone when using the arc method exceeded that of the 3D pulse method in all segments of the corridor.

The decrease in energy in the hot zone increased as the flow rate increased. Thus, both the 3D pulse method and the arc method showed a greater decrease in energy for the HP, LP 250 and LP 450 fire extinguishing systems successively. The highest decrease in energy was reached with the experiments using the LP 450 arc method. The results with CAFS OneSeven are comparable to those with the HP arc method.

The energy increased in all segments in the cold zone for the baseline measurement, but this increase was much less than in the hot zone. The different attacks showed that the energy sometimes increased in the cold zone as well. This is particularly true in the middle of the corridor. The 3D pulse method led to a greater increase in energy in the middle of the corridor than the arc method did. This may have been due to mixing of the hot and cold zones during the attack. The standard deviations in the values measured were so significant (sometimes >100 %) that it cannot be judged with certainty that there were any increases or decreases in energy in the cold zone. When CAFS OneSeven was applied, a distinct decrease in energy was achieved at the entrance, but this was negligible further down the corridor.

Forward and backward cooling

The analysis of forward and backward cooling shows that the temperature behind the fire attack team consistently remained the lowest with all flow rates when applying the arc method, whereas the use of the 3D pulse method sometimes led to a rise in temperature behind the team again. The arc method had a longer forward cooling reach than the 3D pulse method; this was true for all flow rates. The cooling effect of the 3D pulse method was mainly localised and of shorter duration due to hot smoke gases coming from the fire room. This is the most noticeable when applying HP, where a low flow rate combined with the 3D pulse method leads to short-term forward and backward cooling.

3.1.2 To what extent does the application of the 3D pulse method and the arc method enable the seat of the fire to be influenced when progressing to the seat of a fire in a dynamic smoke layer?

All methods showed a decrease in temperature at the outflow opening and in the fire room relative to the baseline measurement as the firefighters progressed. This means that all fire extinguishing systems and attack methods have a cooling effect on the fire room while progressing. The extent to which smoke cooling has an effect on the seat of the fire depends on several factors, such as the flow profiles at the time of the experiment, the nozzle operator's technique and atmospheric conditions. The arc method achieved greater cooling than the 3D pulse method. With the 3D pulse method, a notable increase in cooling as the flow rate increases was observed. The arc method gives the best results when combined with HP, which can probably be explained by the fact that HP enables a high speed of progression through the corridor, while the arc method provides enough cooling capacity.

3.1.3 How does smoke cooling while progressing towards a seat of fire in a dynamic smoke layer influence firefighters and casualties' safety?

Safety of firefighters

Based on the exposure method used (heat radiation dose), the safe exposure level was not exceeded in any of the smoke cooling methods researched. However, whilen applying the 3D pulse method, the dose received is higher than with the arc method.
The average scores for the subjective perception of thermoregulation, discomfort and effort show that the attacks were not excessively strenuous for fire attack teams. The fire attack team experienced the most discomfort due to water vapour, the amount of water, the lack of

visibility, the force required to properly operate the nozzle and a lack of ability to communicate in the attack with LP 450 arc method.

Safety of casualties

The intervention by fire attack teams will always have negative consequences for casualties in the vulnerable and highly vulnerable population groups, regardless of the fire extinguishing system or method used. This is because any intervention disturbs the smoke layer, leading to an increase in CO values at casualty level is noticeable as soon as the attack has started. Life-threatening and even fatal situations arose in all experiments, specifically for the casualties lying 7 metres or 12 metres down the corridor. No life-threatening situations arose for casualties in the general group, with one exception. Both baseline measurements, i.e. where no fire attack took place, showed that it took longer for a life-threatening situation to arise for casualties.

3.1.4 How does a door procedure carried out from outside influence indoor conditions?

A decrease in temperature was observed at all measuring poles, but it cannot be concluded that this was a direct consequence of the door procedure. The decrease might also be due to the fact that, because both front doors were closed prior to the door procedure, the fire received less oxygen, decreasing the temperature even before the door procedure started. Since no further effect of the cold block or the door procedure was observed, further research is recommended.

3.2 Answering the main question

The main research question was:

When using either the 3D pulse method or the arc method, to which extent are smoke gases cooled and what are the effects on the seat of the fire and on the safety of firefighters and casualties when firefighters progress to the seat of the fire in a dynamic smoke layer?

Since both methods cool the smoke gases, implementing smoke cooling is always better than not attacking at all. The results of the arc method are more positive than those of the 3D pulse method, both as regards cooling up to the height and along length of the corridor, and as regards forwards and backwards cooling. The results of the arc method are also more consistent which seems to indicate that this method is easier to carry out.

The reach of forwards and backwards cooling when applying the arc method was better than that of the 3D pulse method. The time needed for the attack is also shorter when using the arc method (at least with the current test design).

All extinguishing systems and attack methods have a cooling effect on the fire room while progressing. The average scores of subjective perception of thermoregulation, discomfort and effort show that the experiments were not unduly strenuous for the teams. The attacks with LD 450 were reported to produce the most discomfort. No unsafe situations for fire service personnel arose during the experiments.

The use of the methods and extinguishing systems researched for smoke cooling did however worsen the conditions for potential casualties. This might lead to life-threatening or fatal situations for vulnerable and highly vulnerable people. In general, the arc method worsened these conditions less than the 3D pulse method, specifically in the front section of the corridor. There are significant differences between the two tests for the individual extinguishing systems in terms of survivability, indicating that the nozzle operator has a major influence on these conditions.

The analysis of the film footage has shown that, although the 3D method is the standard method taught, the arc method is easier to perform according to protocol and is less dependent on the nozzle operator.

Based on this research, it can be concluded that both the arc method and the 3D method are effective methods to cool smoke gases, but that the arc method provides more cooling, and is easier to learn and carry out.

4 Discussion

The results of, and conclusions from, this research concern the test design, fire load and ventilation profile described. Different geometries, fire loads and/or ventilation profiles may lead to different results and conclusions. Since only two methods were compared, i.e. the 3D pulse method and the arc method with a continuously opened straight stream, it cannot be ruled out that another method might lead to better results, and therefore due care should be observed when drawing any general conclusions from the research results.
Furthermore, each test was only carried out twice, limiting the scope of the quantitative results. However, the marginal dispersion in results measured demonstrates the reliability and practicability of the experiments.

Four measuring poles with sensors for temperature, radiation and gas concentrations were placed in the building. Thermocouples were used to measure the temperature. The thermocouples were shielded with tubes as much as possible to minimise any contact with the extinguishing agent during attacks which might influence the measurement results. Nevertheless, the data shows that some thermocouples were directly hit by the stream in several experiments, leading to a sudden decrease in temperature. This mainly happened during the attacks with CAFS OneSeven. The foam stuck to the protective casing and around the thermocouples and as a result the measurement could no longer reliably represent the temperature in the environment.. However, this affected the results to a limited extent only, since we looked at the average temperatures of several thermocouples and at several measurement locations.

A conscious decision was made in advance to change nozzle operators between the experiments. This was decided because this would enable a better understanding of the degree of complexity of the implementation of the smoke cooling method. However, there was a disadvantage to changing nozzle operators since the nozzle operator and the way in which the smoke cooling methods are carried out has a relatively large influence on the effectiveness of smoke cooling. This was specifically relevant for the 3D pulse method.

Furthermore, the experiments were carried out with a dynamic smoke layer. A test design with a static smoke layer where the room remains closed might yield different results.

The L-shape of the building made it impossible to apply water or foam directly to the seat of the fire. However, the experiments showed that indirect cooling of the fire room was possible. The degree to which the attack influences the fire room may affect the flow in the corridor.

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Appendix 1 Attack protocol for smoke cooling experiments

The following abbreviations are used in the protocol:

RL	Research Leader
ME	Measurement and data acquisition team
ST	Stokers
NO1	Fire attack team position 1: nozzle operator
NO2	Fire attack team position 2: feeding the hose & monitoring the operation
NO3	Fire attack team position 3: feeding the hose & holding position halfway down the corridor
NO4	Fire attack team position 4: supplying the hose outside the building.

3D pulse method

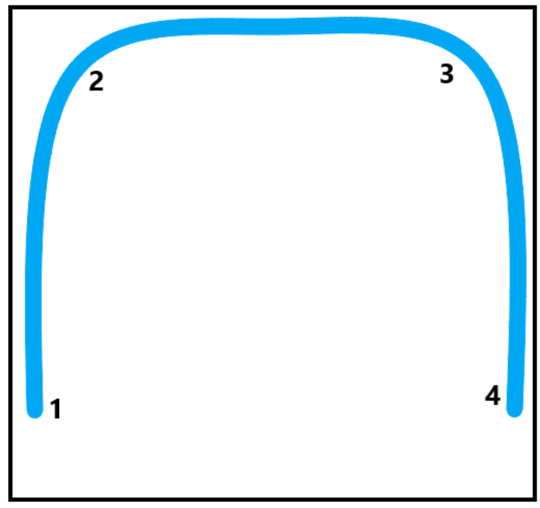
Step	Who	What	Command
1	RL	Attention signal for the fire attack team that the condition (>200°C above the ceiling) has been achieved along the entire length of the corridor and that the attack will start in one minute, provided the temperature remains stable.	Attention, one minute
2	RL	The RL gives the start signal for the attack on the ME's instruction.	Start attack
3	NO1 and 2	NO1 and 2 crouch down and move towards the first threshold in the first threshold in the corridor. As soon as NO1 feels the threshold, he shouts 'threshold'. The ME records the time when the threshold is reached.	Threshold
4	NO1	NO1 discharges a long pulse into the corridor. He does this by spraying diagonally through the corridor/room. The cone angle and spray angle are determined by the geometry of the room; the walls and ceiling should be hit as little as possible. As soon as NO1 opens the nozzle he counts out loud 'twenty-one, twenty-two, twenty-three, CLOSE! 'CLOSE' indicates the moment when NO1 closes the nozzle. *Settings: cone angle of 10°-30°, spray angle of 30°-60° in the direction of the far corner of the corridor, maximum flow rate, 3-second duration.*	Twenty-one, twenty-two, twenty-three, CLOSE
5	NO1, 2 and 3	When NO1 has completed the long pulse, he gives the 'progress' command to indicate that he is going to progress towards the seat of the fire. NO1 and 2 crouch down and move towards the next threshold. They keep to the right of the corridor. NO3 supplies the hose from outside. NO3 keeps a distance from the inflow opening so as to not impede the inflow/outflow of air.	Progress

<table>
<tr><th>Step</th><th>Who</th><th>What</th><th>Command</th></tr>
<tr><td>6</td><td>NO1 and 2</td><td>NO1 and 2 repeat step 3. As soon as NO1 feels the threshold, he loudly says ‘threshold’. The ME records the time when the next threshold is reached.</td><td>Threshold</td></tr>
<tr><td>7</td><td>NO1</td><td>NO1 and 2 repeat step 3 by discharging a long pulse</td><td>Twenty-one, twenty-two, twenty-three, CLOSE</td></tr>
<tr><td>8</td><td>NO1, 2 and 3</td><td>NO1, 2 and 3 repeat step 5 by progressing.</td><td>Progress</td></tr>
<tr><td>9</td><td>NO3 and 4</td><td>As soon as NO1 has given the ‘progress’ command for the fourth time, NO3 enters and progresses directly to the fourth threshold. NO3 starts supplying the hose from this position. NO4 takes over NO3's exterior position and supplies the hose from the outside. NO4 takes up a position a distance from the inflow opening so as to not impede the inflow/outflow of air.</td><td></td></tr>
<tr><td>10</td><td>NO1 and 2</td><td>As soon as NO1 and 2 have reached the last threshold (threshold 7, with a view of the seat of the fire), NO1 reports this by shouting the ‘seat of the fire’ command.</td><td>Seat of the fire</td></tr>
<tr><td>11</td><td>NO1</td><td>As soon as NO1 starts extinguishing the seat of the fire and cooling the surrounding materials, NO1 gives the ‘fully extinguish’ command.</td><td>Fully extinguish</td></tr>
<tr><td>12</td><td>NO1</td><td>1. Start by discharging two short pulses above the seat of the fire to cool the smoke gases.
The pulses serve to cool the smoke gases to prevent them from igniting.
Settings: cone angle of 30°, spray angle of 10°-20° towards the ceiling and the seat of the fire, maximum flow rate.
2. If any flames are visible in the seat of the fire: pencil once or twice:
Apply short bursts of water to the seat of the fire with a straight stream. The nozzle operator does this by very briefly opening the nozzle halfway and closing it as soon as the stream of water hits the seat of the fire, aimed at the core of the seat of the fire. This technique introduces cooling capacity into the seat of the fire. What is important here is that the force of the stream is not such that this breaks up the seat of the fire.
The purpose of pencilling is to extinguish the flames at the seat of the fire.
Settings: cone angle of 0°-10°, spray angle towards the seat of the fire, half-capacity flow rate.
3. If any materials next to or over the seat of the fire are burning or if there is any evaporation from such materials: paint:
Use a straight stream and apply a ‘line’ of water over the</td><td></td></tr>
</table>

	evaporating surfaces in a sweeping motion. **The purpose of painting is to cool materials and to prevent/reduce pyrolysis.** *Settings: cone angle of 0°-10°, spray angle towards any evaporating surfaces, 10-25% flow rate (flush).*

Step	Who	What	Command
13	NO1	As soon as no more flames or glow are visible, NO1 gives the ‘knockdown’ command. The team waits for 30 seconds to check that the fire does not reignite. NO1 repeats step 12 if the fire does reignite.	Knockdown
14	RL	If the seat of the fire does not re-ignite after 30 seconds, the RL gives the ‘end of experiment’ command.	End of the experiment
15	NO1 2,3,4	NO1 and 2 retreat through the corridor and/or the safety door. NO 3 retreats through the entrance. NO4 moves some distance away.	
16	NO1 2,3,4	NO1, 2, 3 and 4 immediately report to the researchers to answer a short series of questions about the comfort or discomfort they have perceived.	

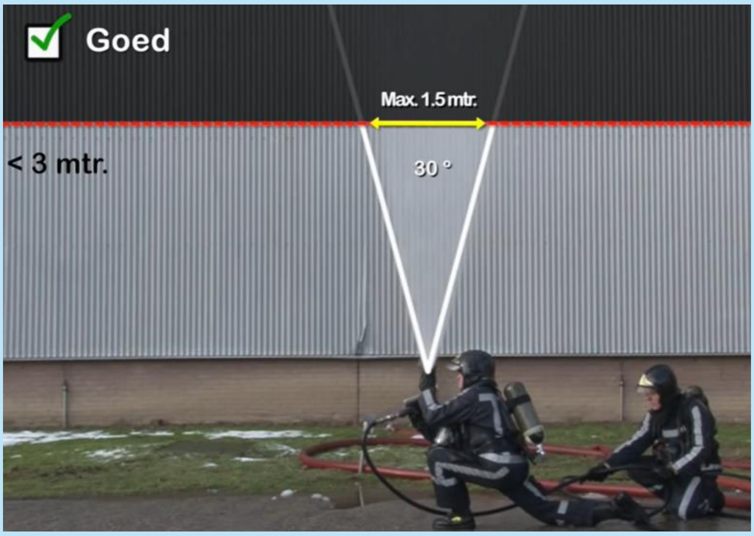
Arc method

Step	Who	What	Command
1	RL	Attention signal for the fire attack team that the condition (>200°C above the ceiling) has been achieved along the entire length of the corridor and that the attack will start in one minute, provided the temperature remains stable.	Attention, one minute
2	RL	On the ME’s instruction, the RL gives the start signal for the attack.	Start attack
3	NO1 and 2	NO1 and 2 crouch down and move towards the first threshold at the entrance. As soon as NO1 feels the threshold, he shouts ‘threshold’. The ME records the time when the threshold is reached.	Threshold
4	NO1	NO1 opens the nozzle. He starts to continuously make the arc pattern with the nozzle open. NO1 makes the arc pattern by continuously following the 1-2-3-4-3-2-1 pattern with a straight stream.  While making this pattern, he continues progressing to the seat of the fire. NO1 starts cooling at a relatively short distance in front of him (1 m) and extends this distance as he progresses further. *Settings: cone angle of 0°-10°, maximum flow rate.*	Open
5	NO1	As soon as NO1 feels the threshold, he shouts ‘threshold’. The ME records the time when the threshold is reached. NO1 does not stop at the threshold but continues with the arc pattern and progresses further towards the seat of the fire.	Threshold
6	NO3 and 4	As soon as NO1 has given the ‘progress’ command for the fourth time, NO3 enters and progresses directly to the fourth threshold. NO3 starts supplying the hose from this position. NO4 takes over NO3's exterior position and supplies the hose from the outside. NO4 takes up a position a distance from the inflow opening so as to not impede the inflow/outflow of air.	

Step	Who	What	Command
7	NO1 and 2	As soon as NR1 and 2 have reached the last threshold (threshold 7, with a view of the seat of the fire), NR1 indicates this by shouting the ‘seat of the fire’ command. **NO1 immediately stops extinguishing when the last threshold is reached** and closes the nozzle.	Seat of the fire
8	NO1	As soon as NO1 starts extinguishing the seat of the fire and cooling the surrounding materials, NO1 gives the ‘fully extinguish’ command.	Fully extinguish
9	NO1	1. Start by discharging two short pulses above the seat of the fire to cool the smoke gases. **The pulses serve to cool the smoke gases to prevent them from igniting.** *Settings: cone angle of 30°, spray angle of 10°-20° towards the ceiling and the seat of the fire, maximum flow rate.* 2. If flames are visible in the seat of the fire: pencil once or twice: Apply short bursts of water to the seat of the fire with a straight stream. The nozzle operator does this by very briefly opening the nozzle halfway and closing it as soon as the stream of water hits the seat of the fire, aimed at the core of the seat of the fire. This technique introduces cooling capacity into the seat of the fire. What is important here is that the force of the stream is not such that this breaks up the seat of the fire. **The purpose of pencilling is to extinguish the flames in the seat of the fire.** *Settings: cone angle of 0°-10°, spray angle towards the seat of the fire, half-capacity flow rate.* 3. If there are burning materials next to or over the seat of the fire or if there is any evaporation from such materials: paint: Use a straight stream and apply a ‘line’ of water over the evaporating surfaces in a sweeping motion. **The purpose of painting is to cool materials and to prevent/reduce pyrolysis.** *Settings: cone angle of 0°-10°, spray angle towards any evaporating surfaces, 10-25% flow rate (flush).*	
10	NO1	As soon as no more flames are visible, NO1 gives the ‘knockdown’ command. The team waits for 30 seconds to check that the fire does not reignite. NO1 repeats step 12 if the fire does reignite.	Knockdown
11	RL	If the seat of the fire does not reignite after 30 seconds, the RL gives the ‘end of experiment’ command.	End of the experiment
12	NO1 2,3,4	NR1 and 2 retreat through the corridor and/or the safety door. NO 3 retreats through the entrance. NO4 moves some distance away.	

13	NO1 2,3,4	NO1, 2, 3 and 4 immediately report to the researchers to answer a short series of questions about the comfort or discomfort they have perceived.	

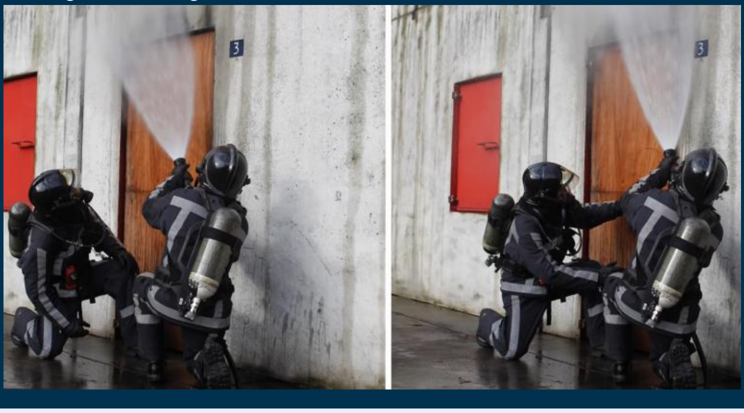
Temperature check

Step	Who	What	Command
1	NO1 and 2	Start the temperature check by carrying out the door procedure from step 6 to step 9 (open the door, short pulse).	
2	NO1	NO1 assumes a kneeling position and enters the room and moves a short distance (1 step) into the room in this position. NO1 points the nozzle straight up and discharges a short pulse of 1 sec. towards the ceiling. The aim is to hit a surface with a maximum diameter of 1.5 metres on the ceiling. Pay attention to whether the water evaporates or pours down audibly. *Settings: cone angle of 10- 30°, spray angle of 0° towards the ceiling, maximum flow rate.*  	
3	NO1 and 2	The nozzle operator retreats immediately after the temperature check and NO2 closes the door. After the door is closed, NO1 and NO2 discuss what they have seen and heard. - If the water pours down, the temperature is not very high and the team can enter. - If the water evaporates on the ceiling, **defensive smoke cooling** must be started.	
4	RL	When completing the temperature check OR the progression into the room OR offensive smoke cooling, the RL will give the 'end of exercise' command. If a sufficient fire load has remained, the RL may decide to carry out a second 'door procedure' experiment immediately after the experiment that has just been carried out.	End of the experiment

5	NO1 and 2	NO1, 2, 3 and 4 immediately report to the researchers to answer a short series of questions about the comfort or discomfort they have perceived.

Door procedure

Step	Who	What	Command
1	RL	Attention signal for the fire attack team that the condition (>200°C above the ceiling) has been achieved along the entire length of the corridor and that the attack will start in one minute, provided the temperature remains stable.	Attention, one minute
2	RL, ST	When the ‘close access’ command is given, the stoker closes the entrance door to the corridor.	Close access
3	ME	The ME starts a two-minute countdown. The ME will indicate when there are only 30 seconds remaining until the two minutes have elapsed.	
4	RL	The RL gives the start signal for the attack on the ME’s instruction.	Start attack
5	NO1 and 2	NO1 checks the door temperature by discharging a short pulse onto the upper part of the door. NO2 looks at the direction in which the door turns and the position of the door handle and passes on this information (turning toward the team or away from the team, handle on the left/right). *Settings: cone angle of 30°, maximum flow rate.* 	
6	NO1 and 2	NO1 takes up position on the handle side of the door and NO2 on the hinge side. They both crouch down. NO2 is ready to open the door and the nozzle operator has set the nozzle correctly.	

7	NO1	NO1 places a cold block: discharge two short pulses onto the space between the top of the door and the frame. Start on the hinge side and then continue to the other side. *Settings: cone angle of 30°, maximum flow rate.* 	
8	NO2	When the 'open' command is given, NO2 sets the door ajar, opening it just far enough that the nozzle operator fits through exactly. NO2 looks at the flow and smoke that may be escaping and holds the door with his foot.	Open
9	NO1 and 2	The nozzle operator sits in the doorway and discharges a short one-second pulse into the room. The nozzle operator retreats immediately after the pulse. When NO1 gives the 'close' command, NO2 closes the door. *Settings: cone angle 30°, spray angle 45°, maximum flow rate.*	Closed
10	NO1 and 2	After closing the door, NO1 and 2 discuss what they have seen: did they see any fuel (smoke), flow and/or flames? - If no fuel (smoke) was seen, the team can enter. - If there is fuel, a **temperature check** will have to be carried out first when entering. - If any glow or flames were seen, **offensive smoke cooling** must be started. 	

Appendix 2 Measuring equipment

Temperature

Type K thermocouples (a nickel - chrome and nickel - aluminium alloy) (Reotemp, 2018)) of 0.75 mm thick were used for the field experiment. The reasons for this are the wide temperature range (-270°C to 1260°), fast response time (0.06-1.8 s)[4] and low cost. Type K thermocouples are also often used for fire tests (Zevotek, Stakes, & Willi, 2018; Guillaume, Didieux, Thiry, & Bellivier, 2014). The thermocouples used and their properties are shown tables B2.1 and B2.2 respectively.

Table B2.1 Summary of the thermocouples used

Item number	Type	Length	Diameter
405-279	K RVS 1.4841	1000 mm	0.75 mm
405-280	K RVS 1.4841	1500 mm	0.75 mm
405-282	K RVS 1.4841	2000 mm	0.75 mm
405-283	K RVS 1.4841	3000 mm	0.75 mm

Table B2.2 Summary of properties of the thermocouples used

Property	Value
Type	K RVS 1.4841
Response time	0.06 – 1.8 s
Sensitivity	2.2 °C or 0.75 of the value measured (whichever is greater)
Resolution	0.01°C
Measuring range	< 1100 °C
Operational range	< 135 °C (connector)
Supplier	TCDirect

Thermocouples produce a voltage difference if there is a change in temperature. Since the relationship between the voltage and the temperature is known, the voltage measured can be converted into a temperature.

[4] https://www.omega.com/en-us/resources/thermocouples-response-time.

Radiation

Two types of heat radiation meters were used for the field experiments. Water-cooled Schmidt-Boelter flux meters were used at measurement locations where a low radiation load (<5 kW/m^2) was expected and plate thermometer heat flux meters (PTHFM) were used at measurement locations where a high radiation load (5 -15 kW/m^2) was expected. The measurement location at 17 m into the corridor was an exception. A high-range Schmidt-Boelter flux meter (50 kW/m^2) was used here because of its direct proximity to the seat of the fire. Tables B2.3 and B2.4 show summaries of the heat radiation meters used and their properties respectively.

Table B2.3 Summary of the heat radiation meters used.

Sensor	Type	Calibration value
19230802	PTHFM	4067[5] µV
19230803	PTHFM	4067[5] µV
19230804	PTHFM	4062[5] µV
19230806	PTHFM	4063[5] µV
12530	Schmidt-Boelter	0.455 ± 0.030 µV/(W/m^2)
12420	Schmidt-Boelter	0.529 ± 0.035 µV/(W/m^2)
12536[6]	Schmidt-Boelter	0.434 ± 0.028 µV/(W/m^2)
12537	Schmidt-Boelter	0.415 ± 0.027 µV/(W/m^2)
1630	Schmidt-Boelter	0.161 ± 0.010 µV/(W/m^2)

Table B2.4 Summary of properties of the heat radiation meters used

Property	PTHFM	Schmidt-Boelter	Schmidt-Boelter
Response time	1 - 10 s	< 0.45 s	< 0.25 s
Sensitivity	(of thermocouple)	See table B2.3	See table B2.3
Resolution	(of thermocouple)	See table B2.3	See table B2.3
Type	PLATT-TERMOMETER K	SBG01-005-02	SBG01-100
Range	(of thermocouple)	0 – 5 kW/m^2	0 – 50 kW/m^2
Operational range	< 850 °C < 200 °C (cable)	< 400 °C (cable)	< 400 °C (cable)
Supplier	Pentronic	Hukseflux	Hukseflux

[5] Criterion 4096 ± 62 µV (@ 100 °C)
[6] Replaced by 12537 due to damage after the first day of testing.

Just like thermocouples, these sensors produce a voltage difference with the relationship between the voltage and the heat radiation being known.

Gas concentrations

Table B2.5 gives a summary of the gas concentration measuring equipment used. Table B2.6 gives a summary of the properties of the measuring equipment used.

Table B2.5 Summary of the gas concentration measuring equipment used

Property	Testo 350
Supplier	Testo BV
Quantity	3
Operational range	-5 – 45 °C 0 – 70% RH
IP rating	IP40

Table B2.6 Properties of the Testo measuring equipment used

Gas	Measuring range	Resolution	Sensitivity	Response time
O_2	0-25 %Vol	0.01 %Vol	± 0.2 %Vol	< 20 s
CO	0-10000 ppm	1 ppm	± 10 ppm (< 199 ppm) ± 5 %[7] (200 - 2000 ppm) ± 10 %[7] (> 2000 ppm)	< 40 s
COlow	0-500 ppm	0.1 ppm	± 2 ppm (< 40 ppm) ± 5 %[7] (> 40 ppm)	< 40 s
NO	0-4000 ppm	1 ppm	± 5 ppm (< 100 ppm) ± 5 %[7][7] (100 - 2000 ppm) ± 10 %[7] (> 2000 ppm)	< 30 s
NOlow	0-300 ppm	0.1 ppm	± 2 ppm (< 40 ppm) ± 5 %[7] (> 40 ppm)	< 30 s
NO_2	0-500 ppm	0.1 ppm	± 5 ppm (< 100 ppm) ± 5 %[7] (> 100 ppm)	< 40 s
SO_2	0-5000 ppm	1 ppm	± 5 ppm (< 100 ppm) ± 5 %[7] (100 – 2000 ppm) ±10 %[7] (> 2000 ppm)	< 30 s
CO_2	0-50 %Vol	0.01 %Vol (< 25 %Vol) 0.1 %Vol (> 25 %Vol)	± 0.3 %Vol ± 1 %[7] ± 0.5 %Vol ± 1.5 %[7]	< 10 s

[7] of the value measured.

Table B2.7 gives a summary of the measurement locations of the Testo measuring equipment.

Table B2.7 Summary of the gas meters used

Sensor	Measurement location	Height (m)
G1	B1	0.30
G2	B2	0.30
G3	B3	0.30

Camera footage

To identify how smoke spreads in practice, camera footage was collected by placing cameras in several locations and having them record during the tests. Cameras can record actively or passively:

> Active: the footage recorded is sent directly to a recording computer (via a wired or wireless connection).
> Passive: the cameras save the footage to a storage medium which is read out after a test.

The advantage of active recording is that it allows the footage to be watched live while the test is being carried out. The disadvantages are that extra cables need to be laid or that wireless connections need to be arranged and that the footage must be stored immediately in a central location. This requires a lot of processing power, depending on the number of cameras and the image quality.
The advantages of passive recording are that the footage is stored immediately and no extra facilities are required. The disadvantages are that this footage can only be checked after a test and that storage capacity is often limited.

It was decided to use two types of cameras during the experiments (see table B2.8 on the next page):

> FireCam: this camera was placed at a short distance from the seat of the fire since it can withstand temperatures of over 400 °C, albeit for a brief period.
> Actioncam: these dust and water resistant cameras were used in all other locations.

Considering the conditions during a test, it was decided to have all cameras record passively. Whenever a test was completed, the camera's batteries were replaced by new ones, enabling the old batteries to be charged. All the cameras recorded their footage on micro-SD cards.

Table B2.8 Summary of the types of camera used

Cameras	FireCam	Actioncam
Make	FireCam	Nikkei
Type	4k Wi-Fi	Extreme X8S
Supplier	SpectraCam	Coolblue
Battery life	Unknown	1.5 hours
Storage medium	Micro-SD card	Micro SD card
Capacity	16Gb	32Gb
Image quality	4K/Full HD/HD	4K/Full HD/HD
Angle of view	150°	170°
Camera	5 megapixels	16 megapixels

Measuring systems

The various sensor signals can be measured, read and stored in several ways. Because of the number of sensors and their diversity, it was decided to use two measuring systems in parallel:

> Testo measuring system to record gas concentrations measured by Testo devices. Uses the software supplied with the system.
> Measuring system for temperature and radiation.

The Testo measuring system uses Testo hardware and software (see Figure B2.1), connected to a recording computer. The Testo hardware consists of a gas analyser and a smoke gas probe which takes gas samples.

Figure B2.1 Left: Testo 350 gas analyser. Right: Testo smoke gas probe[8]

[8] https://www.testo.com/nl-NL/testo-350/p/0632-3510.
https://www.testo.com/nl-NL/modulaire-rookgassonde-insteekdiepte-335-mm-incl-conus-t/p/0600-8764.

The gas analysers communicate by means of a CAN bus signal and can pass on each other's signals ('daisy-chaining'). Because of practical limitations, two signal chains were set up, each comprising of five gas analysers.

The Fire Service Academy had previous experience of using a DAQ (data acquisition) system for measuring temperature and radiation. A DAQ system can store signals for later analysis (offline) or can relay them to a computer with recording software for live monitoring (online). Its use requires thorough knowledge of the system, but on the other hand it offers a great deal of flexibility (a DAQ system can be purpose-built and expanded). The temperature and radiation sensors were connected to the National Instruments' Compact DAQ system in combination with National Instruments' LabVIEW software. The NI DAQ system consists of modules in a chassis (see figure B2.2) connected to a computer with registration software.

Figure B2.2 Left: Some DAQ modules.[9] Right: A DAQ chassis with four slots for modules

The modules filter, amplify and collate the sensor signals and the chassis can forward them by means of a USB or Ethernet signal. A chassis that can forward the signals by means of an Ethernet signal was chosen to enable online monitoring of the measurements. Ethernet enables signal transmission over longer distances than USB.

Table B2.9 Summary of the modules used and their properties

Module	NI 9202	NI 9212
Channels	16	8
Signal type	Volt	Temperature
ADC	24 bit	24 bit
Resolution	0.6 µV	0.01°C
Operational range	-40 – 70 °C 10 - 90% RH	-40 – 70 °C 10 - 90% RH

Table B2.10 Summary of the chassis used and their properties

[9] http://sine.ni.com/nips/cds/pages/image?imagepath=/images/products/us/03211720_l.jpg&title=cDAQ-9185&oracleLang=i https://www.ni.com/nl-nl/shop/select/c-series-voltage-input-module.

Chassis	NI 9185
Slots	4
Ethernet	10/100/1000 Mbps (auto)
Maximum signal cable length	100 m
Resolution	32 bits
Operational range	-20 – 55 °C 10 - 90% RH

The chassis used can pass on each other's signals in a chain (daisy-chaining). The advantage of this is that less cabling is required, but the disadvantage is that if one cable or chassis in the chain fails, all subsequent signals are also lost. That is why it was decided to connect each chassis to an Ethernet switch and then to the recording computer (star topology). Purpose-developed scripts were used for testing, synchronising and recording all sensors of the DAQ system.

In order to protect all signal cables, power supply cables and air hoses of the various systems against damage, they were laid on the floor, i.e. where the lowest temperatures were expected, if possible and installed under a cable duct. If placing them in a cable duct was not possible, they were wrapped in aluminium foil or aluminium tape. The connections were inspected regularly and any damaged cables were replaced.

Measurement configurations

A ‘thermocouple tree’ is a common way to attach several different sensors in fire experiments. This is a ‘measuring pole’ which enables thermocouples and other sensors to be attached at several different heights. Since the lowest temperatures were expected near the floor, a sealed and insulated space was designed for the DAQ chassis at the base of the measuring pole. This provided optimum protection of the DAQ chassis against the influences of temperature, radiation, smoke, water and/or steam. These measuring poles were then placed in measurement locations B1 to B4. Table B2.11 lists the sensors attached to each measuring pole for each measurement location.

Table B2.11 List of measuring poles and parameters measured

Measuring pole	Location	Parameter	Height (m)
B1	2 metres into the corridor	Temperature	0.30 - 0.90 - 1.50 - 1.80 - 2.00 - 2.20 - 2.40
		Radiation	0.30 - 1.50
		Gas concentrations	0.30
		Visibility distance	0.90

B2	7 metres into the corridor	Temperature	0.30 - 0.90 - 1.50 - 1.80 - 2.00 - 2.20 - 2.40
		Radiation	0.30 – 1.50
		Gas concentrations	0.30
		Visibility distance	0.90
B3	12 metres into the corridor	Temperature	0.30 - 0.90 - 1.50 - 1.80 - 2.00 - 2.20 - 2.40
		Radiation	0.30 – 1.50
		Gas concentrations	0.30
		Visibility distance	0.90
B4	17 metres into the corridor	Temperature	0.30 - 0.90 - 1.50 - 1.80 - 2.00 - 2.20 - 2.40
		Radiation	0.30 – 1.50

Possible measurement errors

As described in the research design, each sensor has a certain sensitivity and resolution. A sensor's sensitivity indicates the degree of reliability of a measurement. For example, if a thermocouple with a sensitivity of 1.6 °C is exposed to a temperature of 100 °C, the thermocouple can indicate a temperature between 98.4 and 101.6 °C. A sensor's resolution represents the smallest change that a sensor can measure. For example, a thermocouple with a resolution of 0.1 °C will not be able to record a 0.02 °C change in temperature.

Furthermore, each sensor has a response time, which is the time the sensor needs to react to a change in signal. This time depends to a significant extent on the type of sensor and there are several different definitions for it.

The sensitivity, resolution and response times of all sensors should be sufficiently low or short to enable the desired processes to be measured. Since this experiment mainly compared scenarios, sensitivity and resolution were less important. As the processes researched in this experiment occurred on very different time scales, the results were converted into time periods expressed in minutes. Sensor response times can be up to 1 minute. This means, especially for results based on gas concentrations, that the reported times may have been overestimated and should therefore be considered to be maximum times.

The sensitivity of the thermocouples used was 2.2 °C or 0.75% of the value measured (whichever is higher) and their resolution was 0.1 °C. The highest temperatures measured were approx. 400 °C. This means that, at these temperatures, the measuring error was approx. 3 °C. The thermocouples measured temperatures in the range of 20 °C to 400 °C. A 0.1 °C resolution is more than sufficient in this range. The maximum response time of the thermocouples used was 1.8 s. Since time periods in minutes were used in the analysis, the delay in the thermocouple signal measured is negligible.

The plate thermometer heat flux meters have the same properties as the thermocouples used because these radiation meters use the same type K thermocouple. The effects of the sensitivity and resolution of the thermocouples are continued via the radiation formula used, leading to a sensitivity and resolution of << 1 W/m^2. The plate thermometer heat flux meters measured radiation within an 0.45 to 10 kW/m^2 range. This means that the measurement error is negligible here. The response time of plate thermometer heat flux meters is actually longer than that of the thermocouples due to the heat capacity of the plate. However, this does not significantly influence the results, since it does not affect the way in which people perceive radiation.

The Schmidt-Boelter flux meters each have their own sensitivity and resolution. Their maximum sensitivity is approx. 1 W/m^2. The resolution of these meters is mainly determined by the measuring system and was approx. 1 W/m^2. The Schmidt-Boelter flux meter measured radiation within a 0 to > 1000 W/m^2 range. This means that the measurement error is negligible here as well. The response time of the Schmid-Boelter flux meter is < 1 s making it negligible as well.

The Testo measuring equipment has different sensitivities and resolutions for different gases. The threshold values of these gases for calculating survival conditions are so high that the influence of resolution and sensitivity on the measurement results is negligible. The Testo equipment has different response times for different gases. They can be up to 40 s which means that there is a delay in the gas concentrations measured.

Data processing and data transformation

LabView

The raw data was first checked by verifying that all sensors had been connected to the correct channels and that the channels had the correct designations for further analysis. Next, the data was read using purpose-developed scripts, which were developed using Python 3.7.0. A sliding average was applied to the voltage data. This introduced a delay in the data, which means that the data was 'pushed back' by the width of the average. The average values used are shown in table B2.12.

Table B2.12 Sliding averages used

Sensor	Sliding average (in measuring points)
Radiation (Schmidt-Boelter)	101

The next step consisted of combining the data files and converting them into the correct units.
The temperature data had already been measured in the correct unit, but radiation and voltages were converted into radiation (kW/m^2), using the calibrations and reference files of the specific sensors. A summary is provided below for the individual quantities.

Radiation

The calculation of the radiation ϕ in W/m² at a certain time for the plate thermometer heat flux meters is shown in equation 1 (Wickström, Anderson, & Sjöström, 2019):

$$\phi = \left(5.67037 \cdot 10^{-8} \cdot {T_{pt}}^{4}\right) - \left(76 \cdot \left(0.5\left(T_{pt} + T_{air}\right)\right)^{-0.66}\right) \cdot \frac{\left|T_{pt} - T_{air}\right|^{1/3}}{\varepsilon} \cdot \left(T_{air} - T_{pt}\right)$$

Equation 1 Conversion of plate temperature into radiation

Here, T_{pt} and T_{air} are the temperatures of the plate and, respectively, the ambient temperature in Kelvin.
 is the emission coefficient according to the following formula (see equation 2):

$$\varepsilon = \min\left(1.03 - 0.436 \cdot 10^{-3} \cdot T_{pt}, 1\right)$$

Equation 2 Emission coefficient formula

T_{air} is the temperature of the thermocouple at the same height as the plate thermometer heat flux meter.

The calculation of the radiation ϕ in W/m² at a certain time for the Schmidt-Boelter radiation meters is shown in equation 3 :

$$\phi = \frac{U}{S}$$

Equation 3 Conversion of water-cooled radiation meters

Here, *U* is the voltage measured (in Volt) and *S* is the sensitivity of the meter. They are shown in table B2.13.

Table B2.13 Sensitivity for each individual radiation flux meter

Radiation meter	Sensitivity *S* (V/W/m²)
B1 – 0.30 m (SB1.2)	$4.55 \cdot 10^{-6}$
B2 – 0.30 m (SB2.2)	$5.29 \cdot 10^{-6}$
B3 – 0.30 m (SB3.2)	$4.34 \cdot 10^{-6}$[10] $4.15 \cdot 10^{-6}$
B4 – 0.30 m (SB4.2)	$1.61 \cdot 10^{-6}$

LabView processing procedure

[10] Only for day 1 (HP 3D pulse – test 1 & 2 and LP 250 3D pulse – test 1 & 2).

Finally, all the data was reconfigured into a measurement frequency of 1 Hz (1 measurement per second) to create a complete file for each experiment. This file was used for further analysis. The LabVIEW data processing procedure is shown as a diagram in figure B2.3.

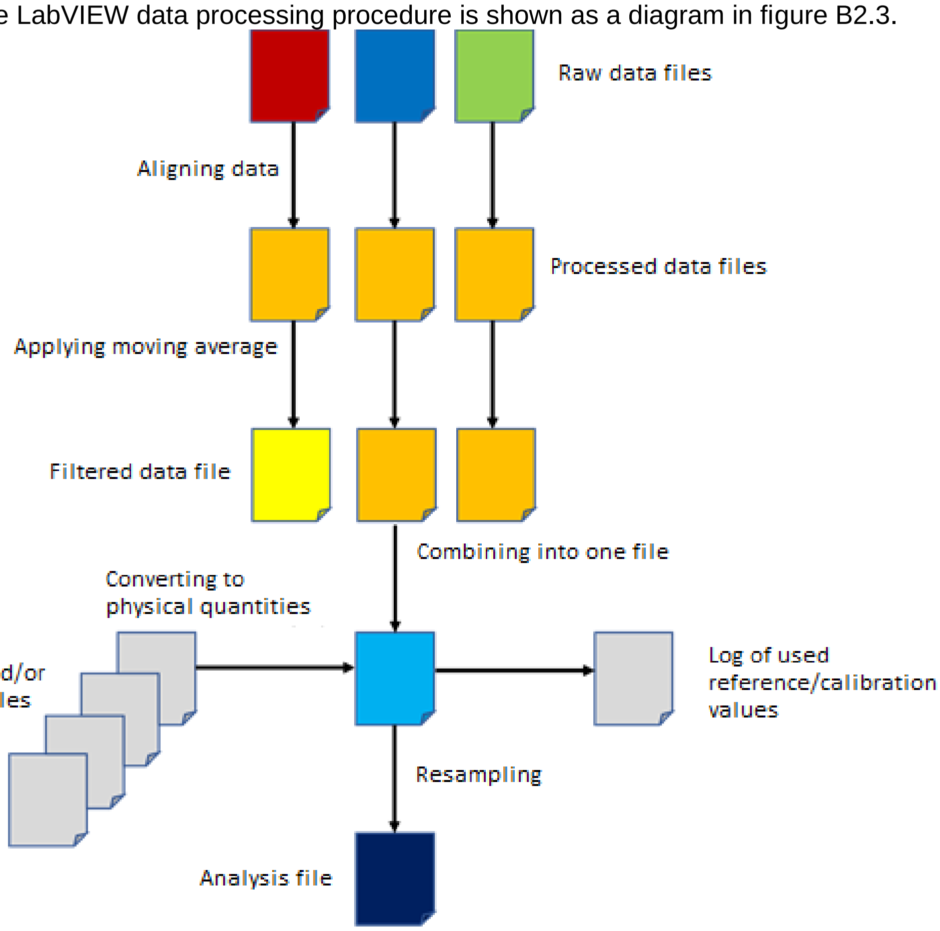


Figure B2.3 Diagram of the processing of LabVIEW data

Testo data processing procedure

The Testo measuring equipment in the configuration used has a measuring frequency of 1/3 Hz (1 measurement every 3 seconds) (Testo SE & Co, KGaA, 2005). As this might cause a difference of max 1 s between the measurements of the two configurations, the raw data was read using a purpose developed script (developed in Python 3.7.0) and was first reconfigured into the nearest 1/3 Hz point in time after the start of the test. This enabled the two configurations to be combined and compared. This combined file was used for further analysis. The Testo data processing procedure is shown as a diagram in figure B2.4.

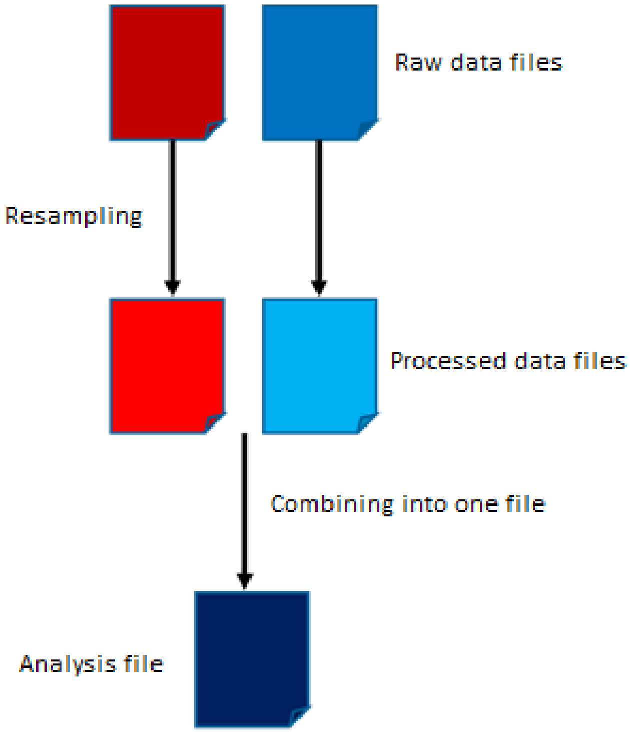


Figure B2.4 Diagram of the processing of Testo data

Appendix 3 Questionnaire on subjective perception of thermoregulation, pain and effort

1. Thermal sensation
   How hot are you feeling?

-3	-2	-1	0	1	2	3	4	5
Cold	Cool	Slightly cool	Not warm, not cold	Slightly warm	Warm	Hot	Very hot	Unbearably hot

2. Thermal comfort
   How do you rate the degree of comfort or discomfort due to heat at this moment?

0	1	2	3	4
Neutral	Slightly uncomfortable	Uncomfortable	Very uncomfortable	Very, very uncomfortable

3. Sensation of skin moisture
   How moist does your skin feel now?

0.0	0.5	1.0	1.5	2.0	2.5	3.0
Neutral (not dry, not wet)		Moist		Wet		Very wet

4. Sensation of pain:
   Are you feeling any pain; if so, how much?

0	1	2	3	4
No pain	Slightly painful	Painful	Very painful	Very, very painful

5. Effort perceived
   How much effort are you perceiving?

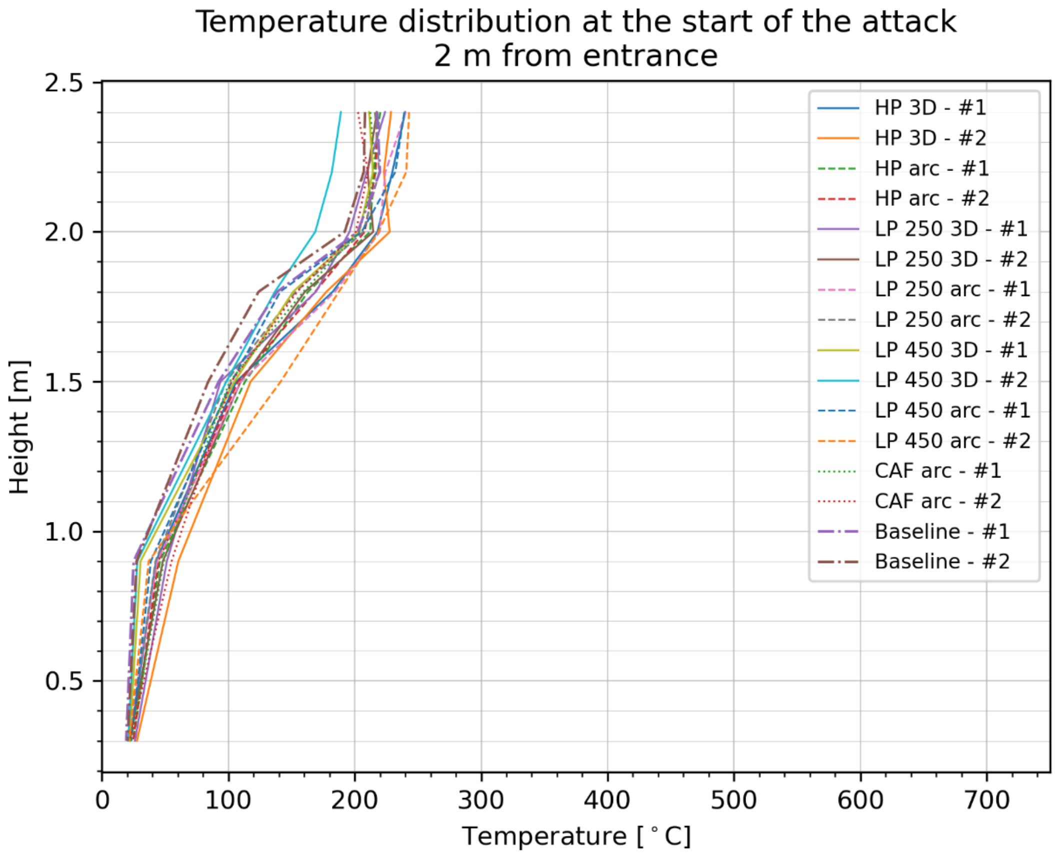
6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
No effort at all	Extremely light		Very light		Light		Somewhat strong		Strong		Very strong		Extremely strong	Maximum

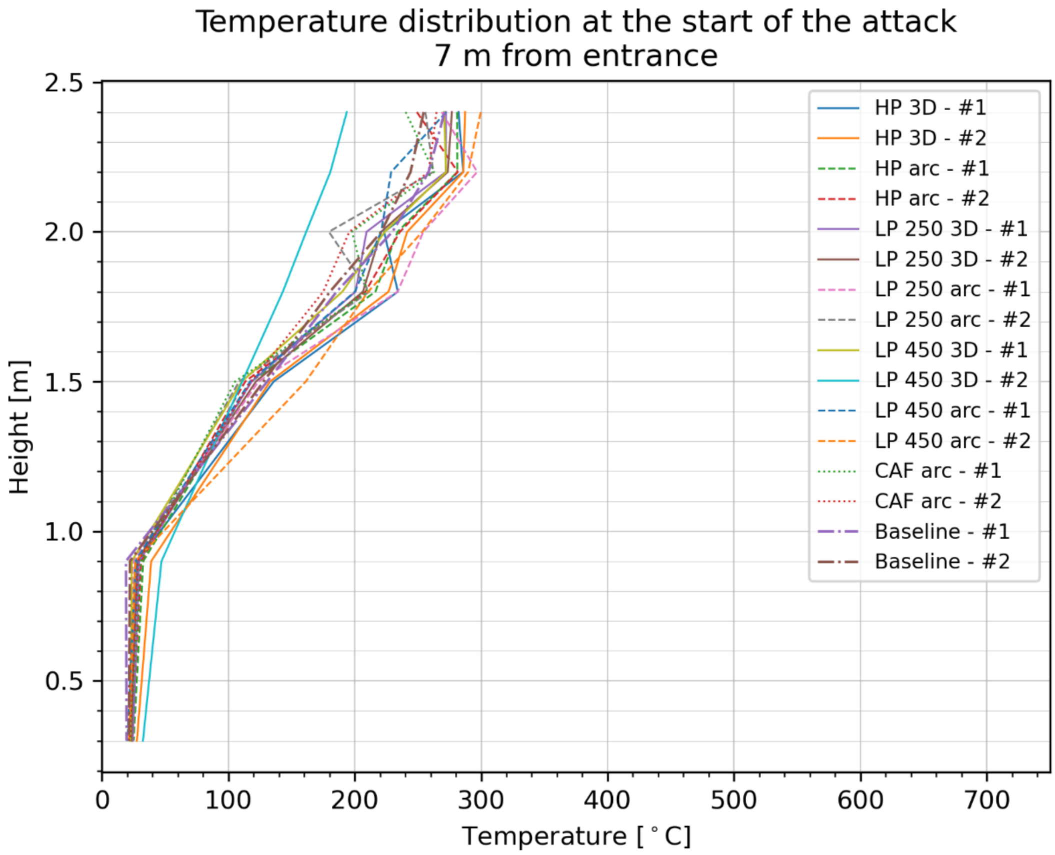
6. **When did you perceive the most heat?**
   Open-ended question

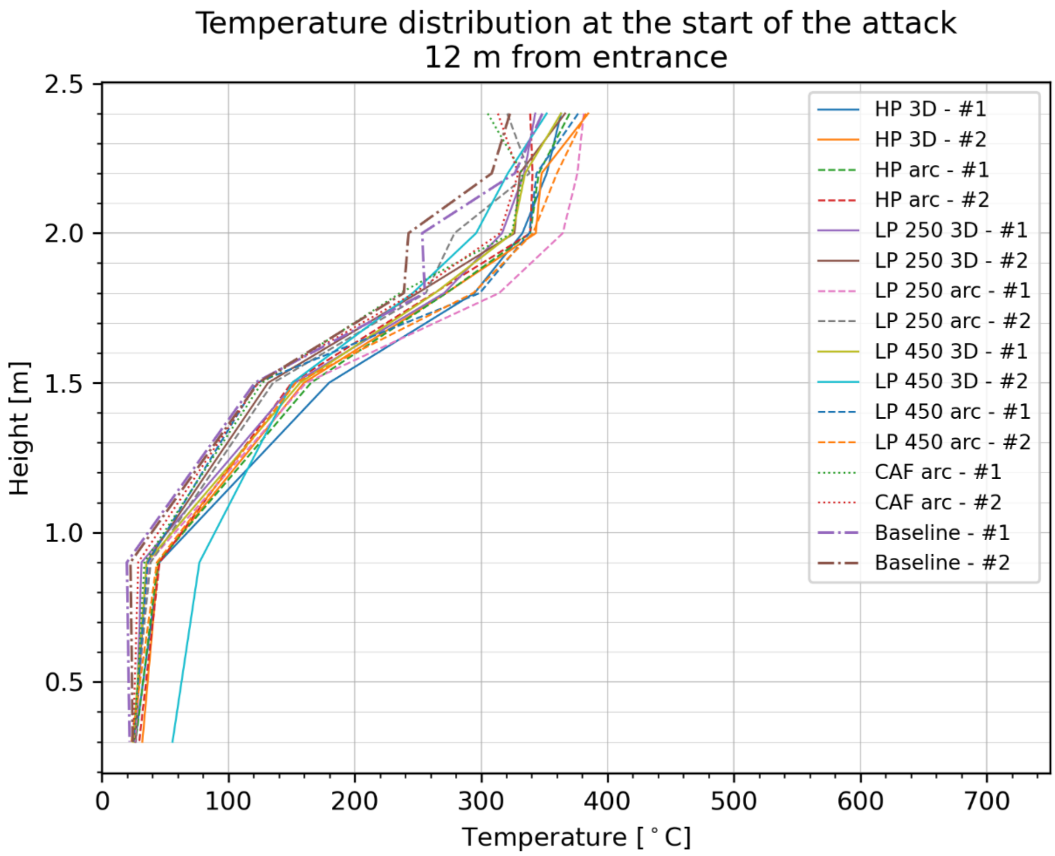
7. **What do you think causes the most discomfort?**
   Open-ended question

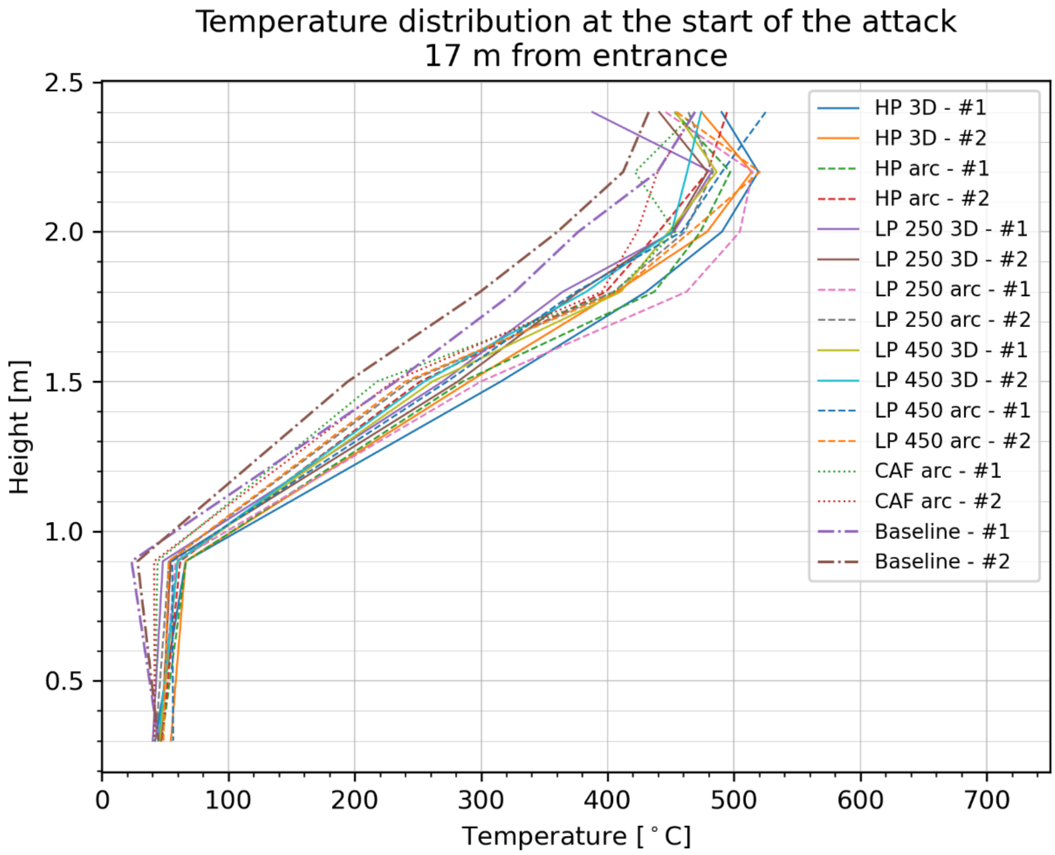
Appendix 4 Repeatability

The figures below show the temperature distribution as a function of the height for all experiments at the time when the attack was started. Each measurement location is shown separately. The temperature distributions between the heights of 1.20 m and 2.40 m are close to each other which means that the starting conditions are comparable. However, distinct differences between the measuring locations in the corridor can be seen. For instance, the temperatures are higher closer to the seat of the fire, resulting in greater differences in temperature distribution.



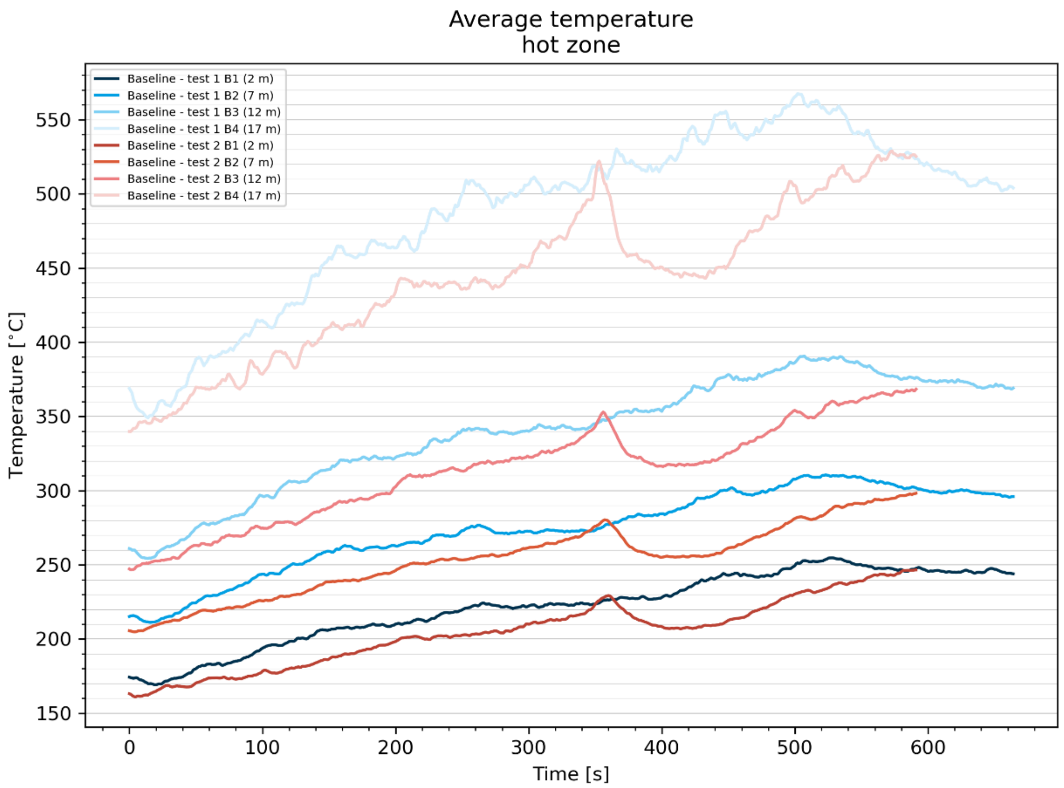

Temperature distribution at the start of the attack
7 m from entrance
Height [m]
Temperature [°C]
HP 3D - #1
HP 3D - #2
HP arc - #1
HP arc - #2
LP 250 3D - #1
LP 250 3D - #2
LP 250 arc - #1
LP 250 arc - #2
LP 450 3D - #1
LP 450 3D - #2
LP 450 arc - #1
LP 450 arc - #2
CAF arc - #1
CAF arc - #2
Baseline - #1
Baseline - #2

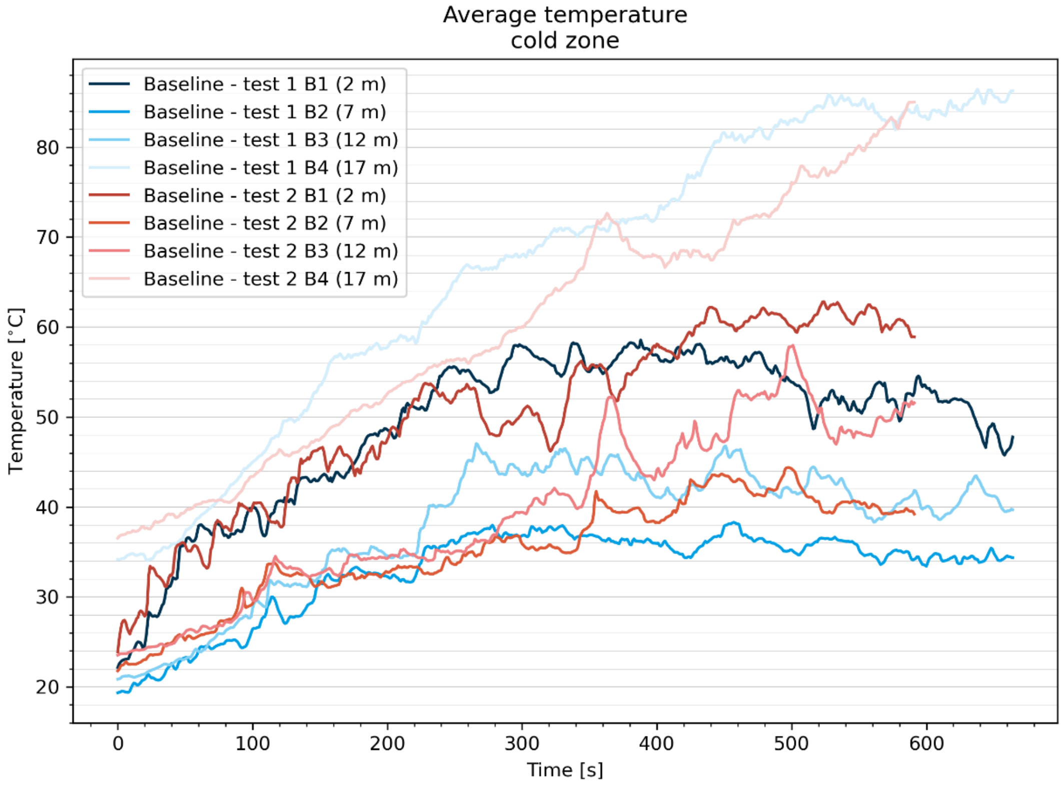

Temperature distribution at the start of the attack
12 m from entrance
Height [m]
Temperature [°C]
HP 3D - #1
HP 3D - #2
HP arc - #1
HP arc - #2
LP 250 3D - #1
LP 250 3D - #2
LP 250 arc - #1
LP 250 arc - #2
LP 450 3D - #1
LP 450 3D - #2
LP 450 arc - #1
LP 450 arc - #2
CAF arc - #1
CAF arc - #2
Baseline - #1
Baseline - #2


Temperature distribution at the start of the attack
17 m from entrance
Height [m]
2.5
2.0
1.5
1.0
0.5
0
100
200
300
400
500
600
700
Temperature [$^\circ$C]
HP 3D - #1
HP 3D - #2
HP arc - #1
HP arc - #2
LP 250 3D - #1
LP 250 3D - #2
LP 250 arc - #1
LP 250 arc - #2
LP 450 3D - #1
LP 450 3D - #2
LP 450 arc - #1
LP 450 arc - #2
CAF arc - #1
CAF arc - #2
Baseline - #1
Baseline - #2

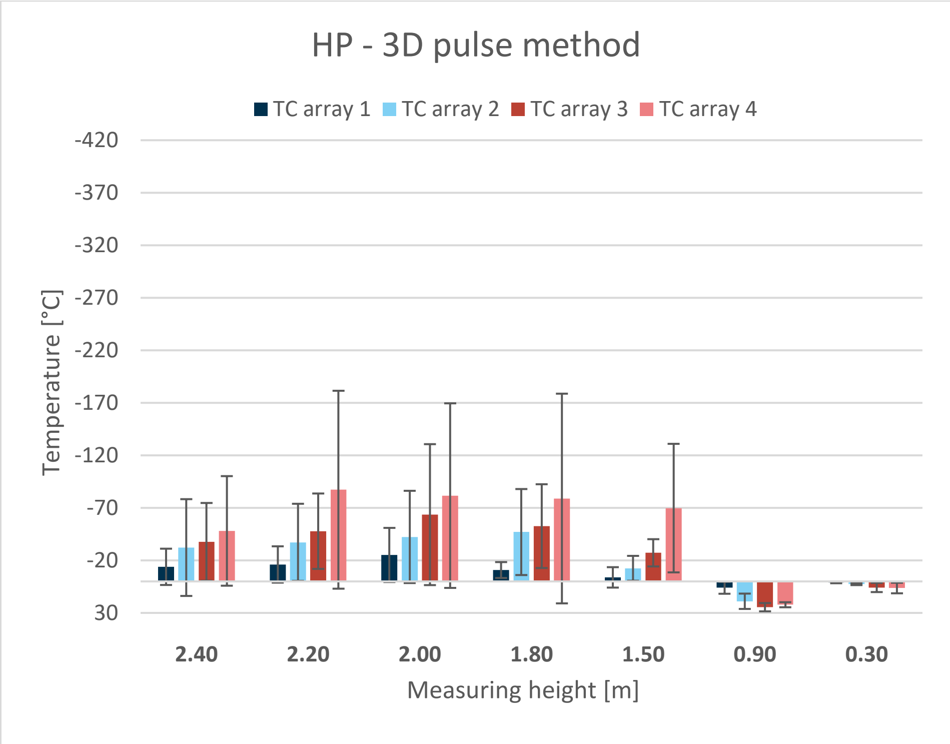
Appendix 5 Baseline measurement

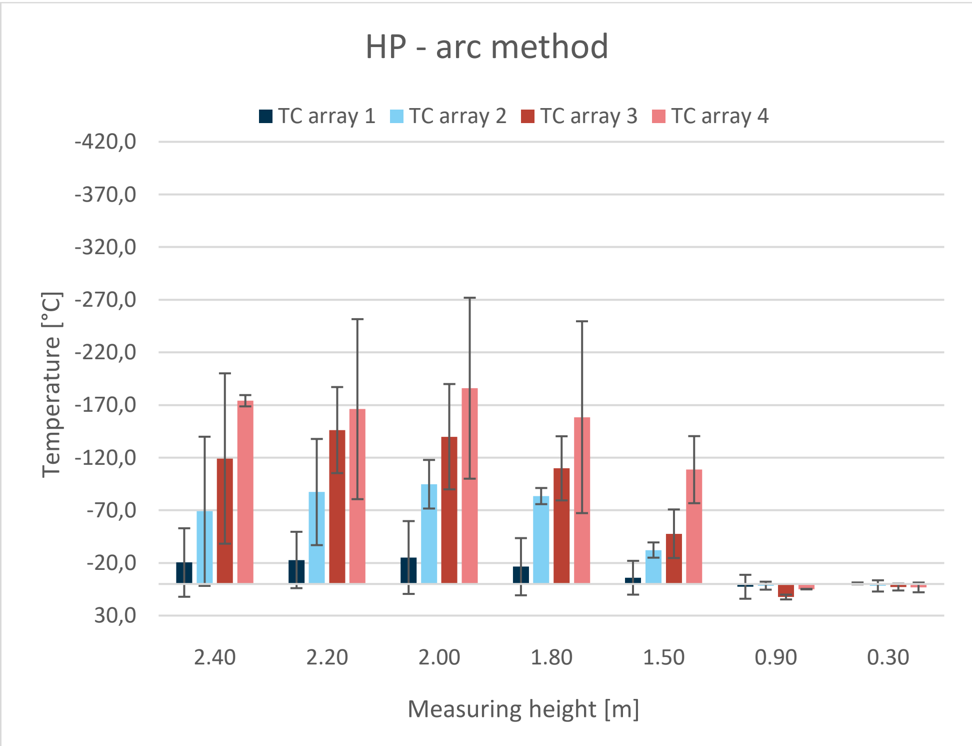
In order to determine whether the effects measured were caused by the different attack techniques, two baseline measurements were carried out. These baseline measurements were conducted to determine what the result would be if no intervention, which includes no smoke cooling, was carried out. As expected, the temperature, and thus the energy, increased everywhere during the baseline measurement.

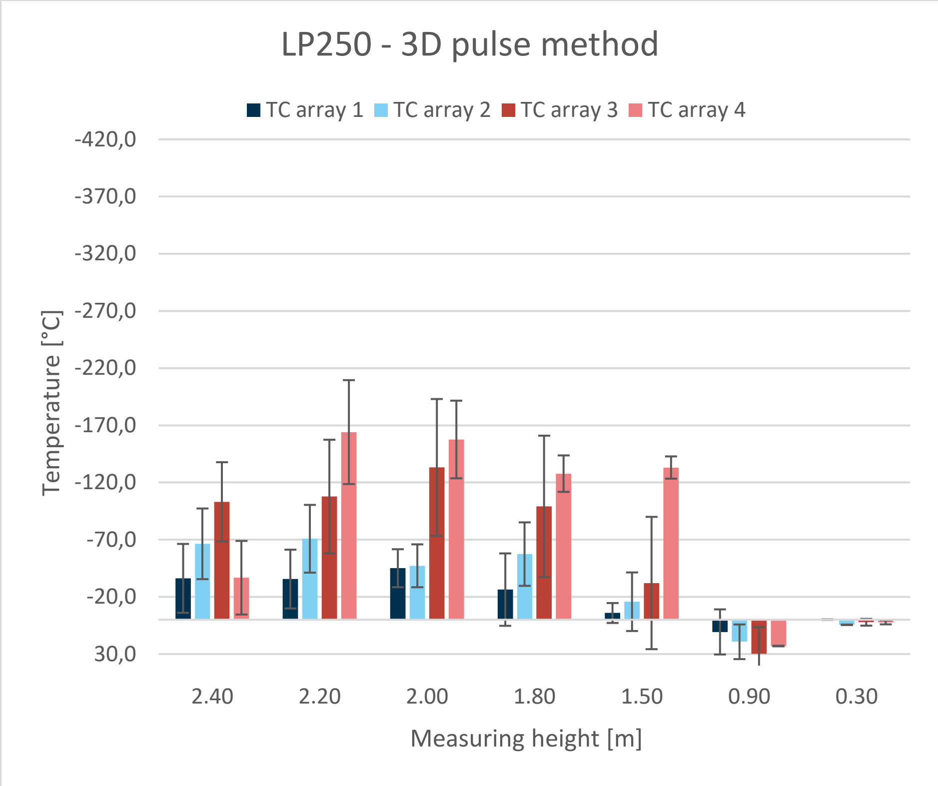


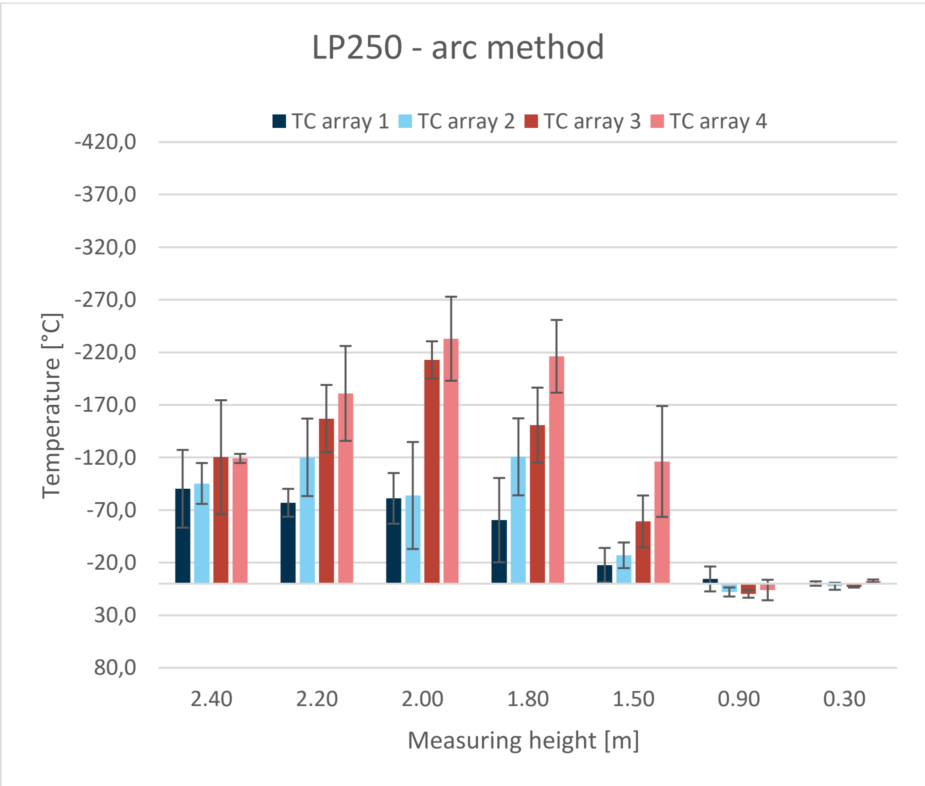

Average temperature
cold zone
Baseline - test 1 B1 (2 m)
Baseline - test 1 B2 (7 m)
Baseline - test 1 B3 (12 m)
Baseline - test 1 B4 (17 m)
Baseline - test 2 B1 (2 m)
Baseline - test 2 B2 (7 m)
Baseline - test 2 B3 (12 m)
Baseline - test 2 B4 (17 m)
Temperature [°C]
Time [s]
20
30
40
50
60
70
80
0
100
200
300
400
500
600

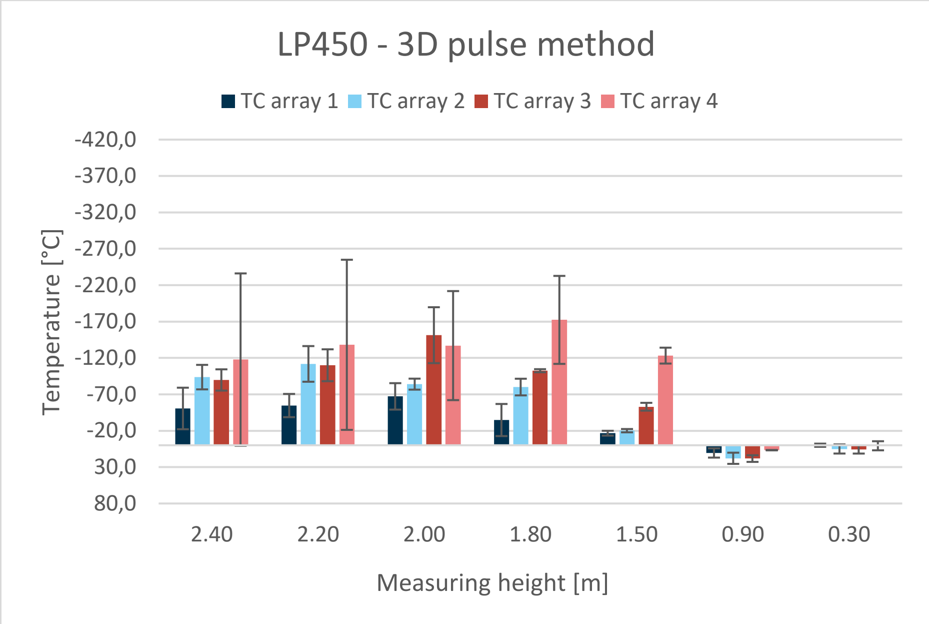
Appendix 6 Temperature versus height



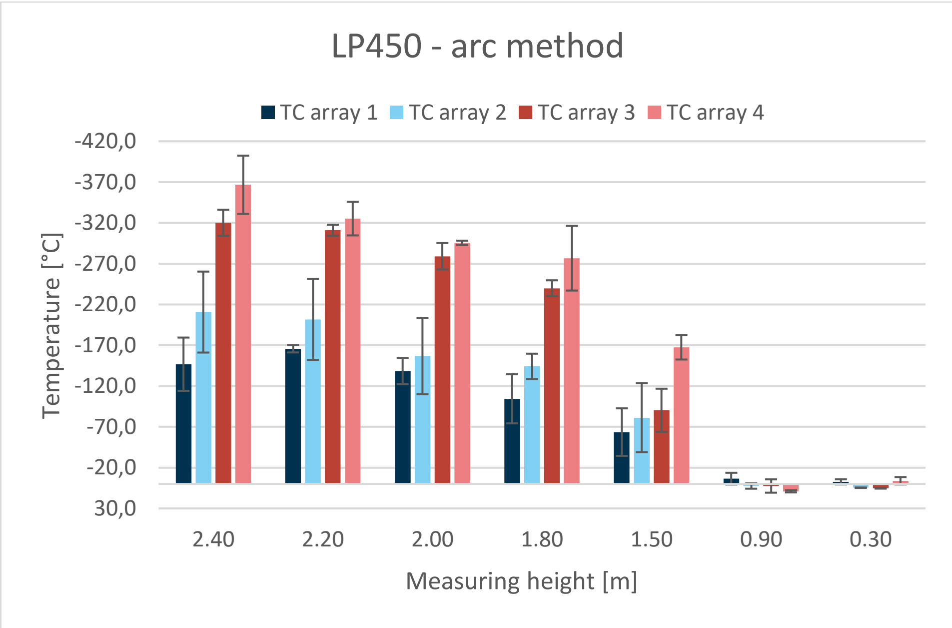



LP250 - 3D pulse method
TC array 1 TC array 2 TC array 3 TC array 4
Temperature [°C]
-420,0
-370,0
-320,0
-270,0
-220,0
-170,0
-120,0
-70,0
-20,0
30,0
2.40
2.20
2.00
1.80
1.50
0.90
0.30
Measuring height [m]

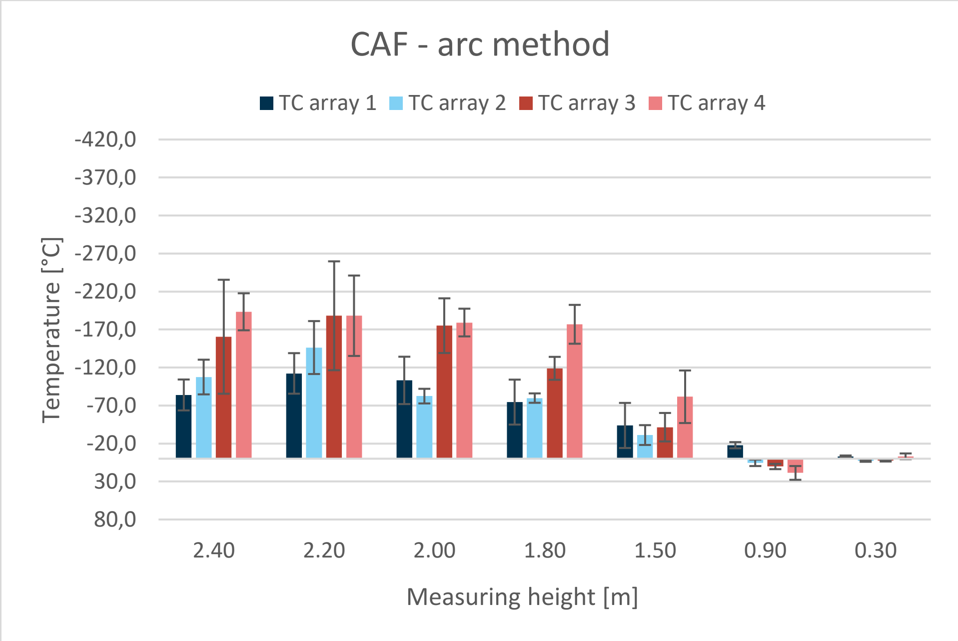

LP250 - arc method
TC array 1 TC array 2 TC array 3 TC array 4
Temperature [°C]
-420,0
-370,0
-320,0
-270,0
-220,0
-170,0
-120,0
-70,0
-20,0
30,0
80,0
2.40
2.20
2.00
1.80
1.50
0.90
0.30
Measuring height [m]



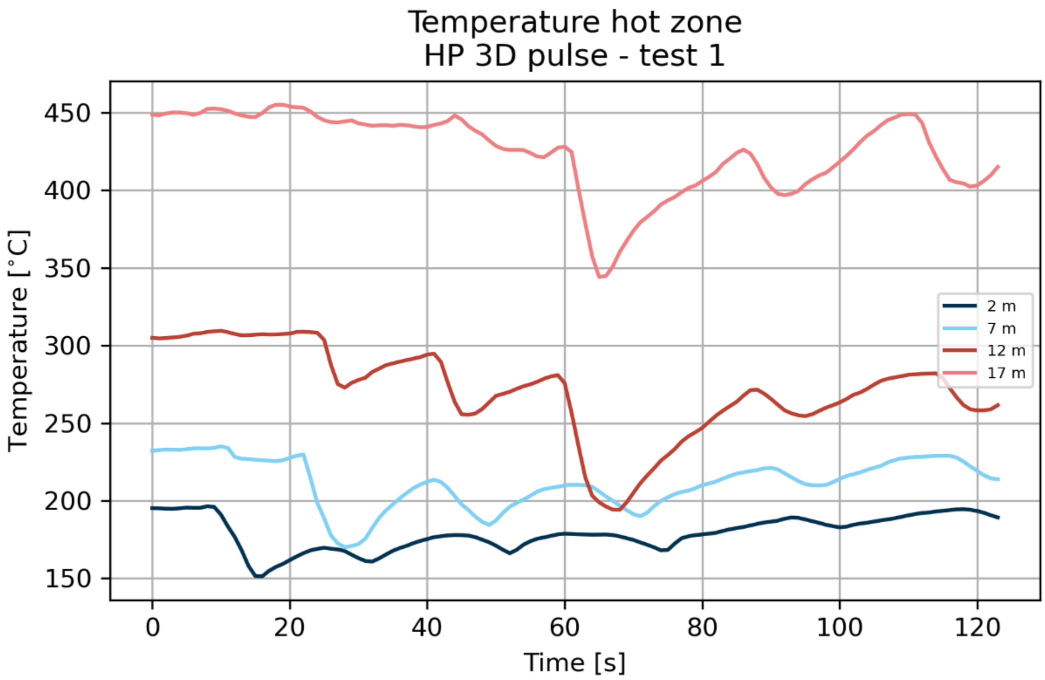
LP450 - 3D pulse method
TC array 1 TC array 2 TC array 3 TC array 4
-420,0
-370,0
-320,0
-270,0
-220,0
-170,0
-120,0
-70,0
-20,0
30,0
80,0
Temperature [°C]
2.40
2.20
2.00
1.80
1.50
0.90
0.30
Measuring height [m]

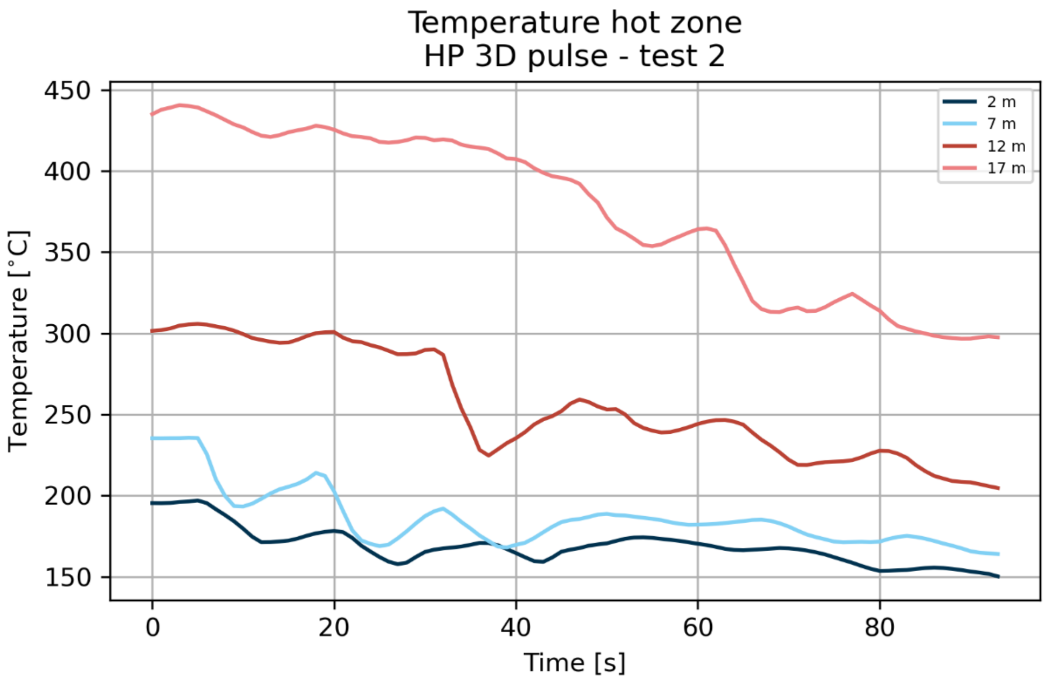


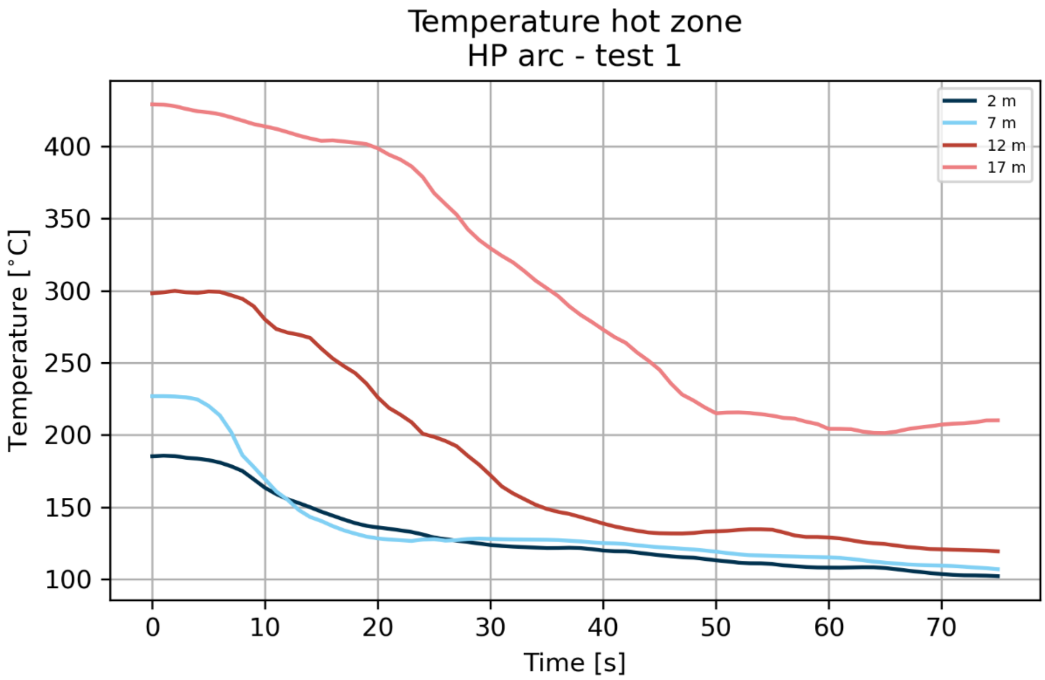
LP450 - arc method
TC array 1 TC array 2 TC array 3 TC array 4
-420,0
-370,0
-320,0
-270,0
-220,0
-170,0
-120,0
-70,0
-20,0
30,0
Temperature [°C]
2.40
2.20
2.00
1.80
1.50
0.90
0.30
Measuring height [m]

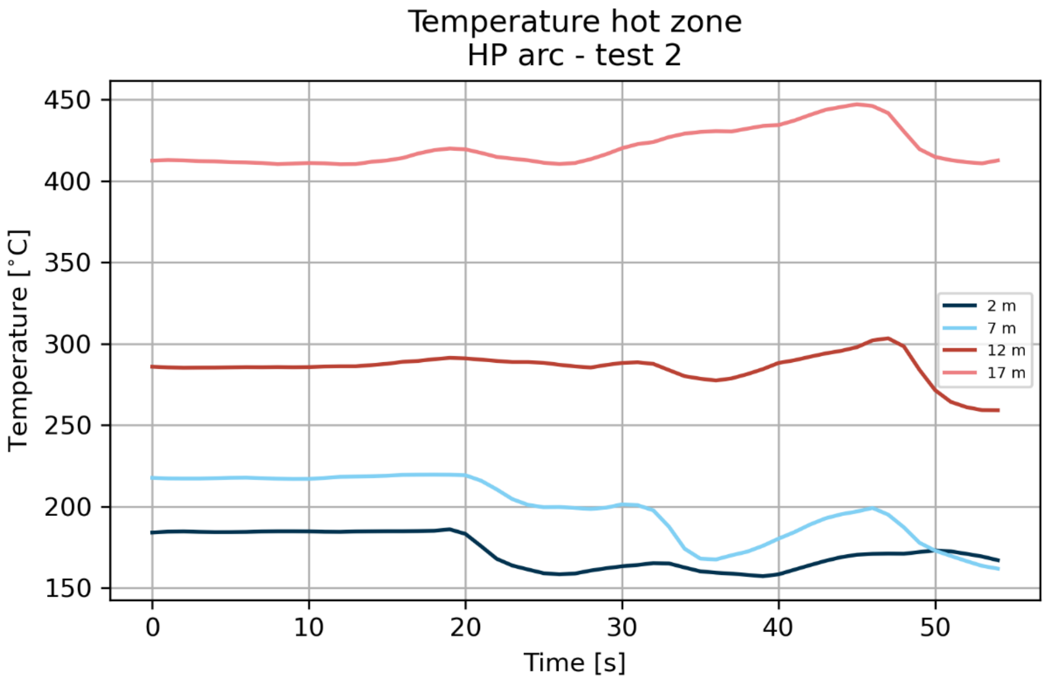

CAF - arc method
TC array 1
TC array 2
TC array 3
TC array 4
-420,0
-370,0
-320,0
-270,0
-220,0
-170,0
-120,0
-70,0
-20,0
30,0
80,0
Temperature [°C]
2.40
2.20
2.00
1.80
1.50
0.90
0.30
Measuring height [m]

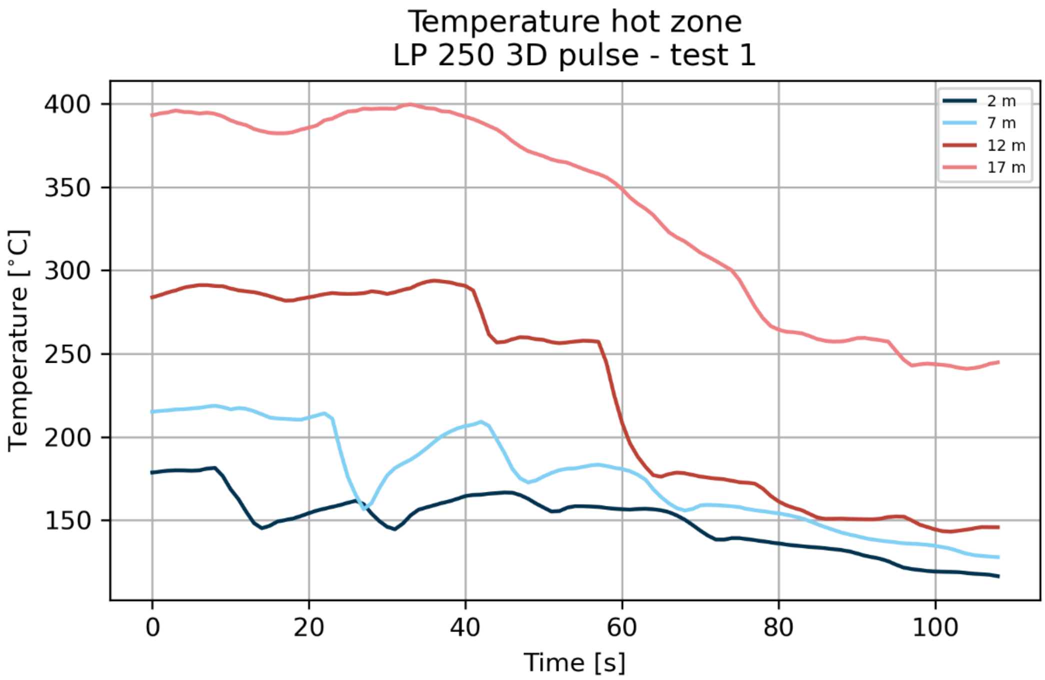
Appendix 7 Forward and backward cooling

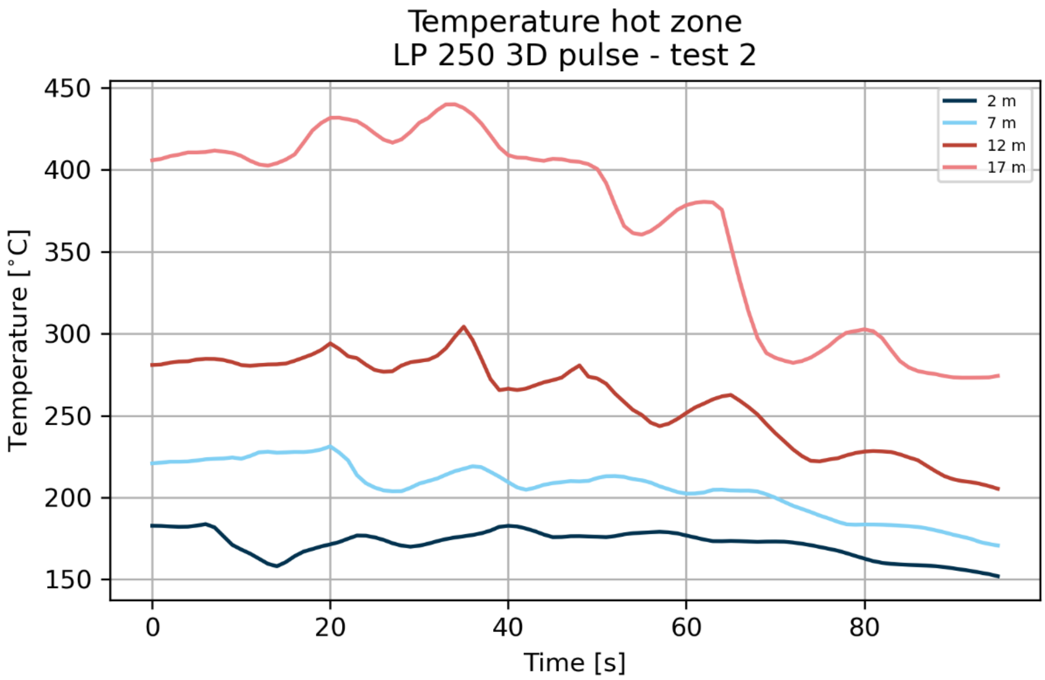


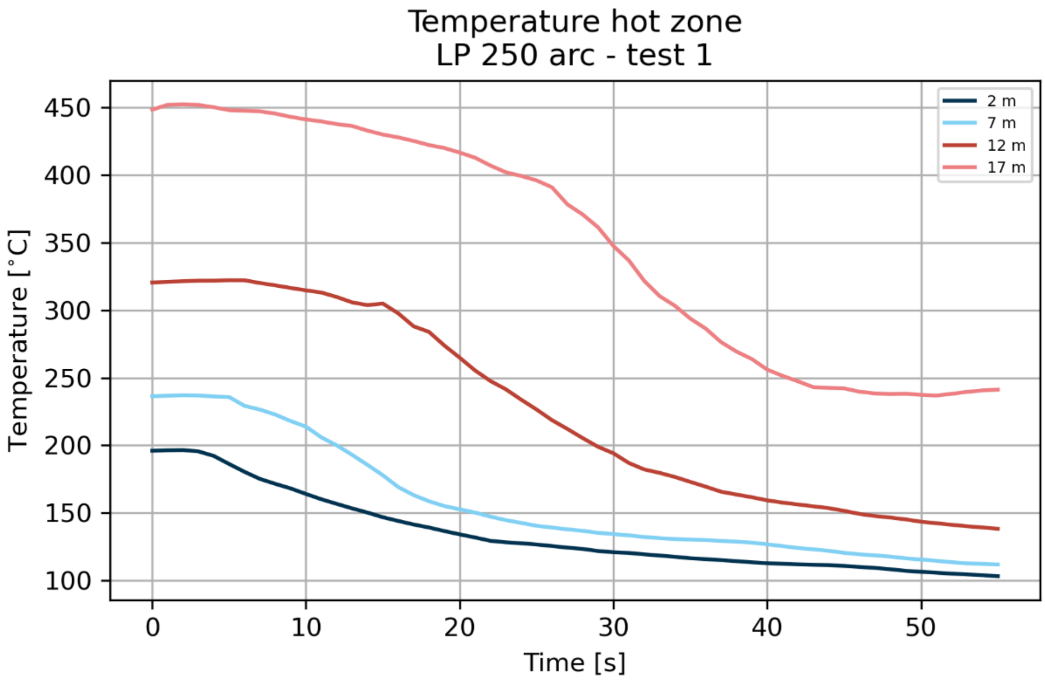


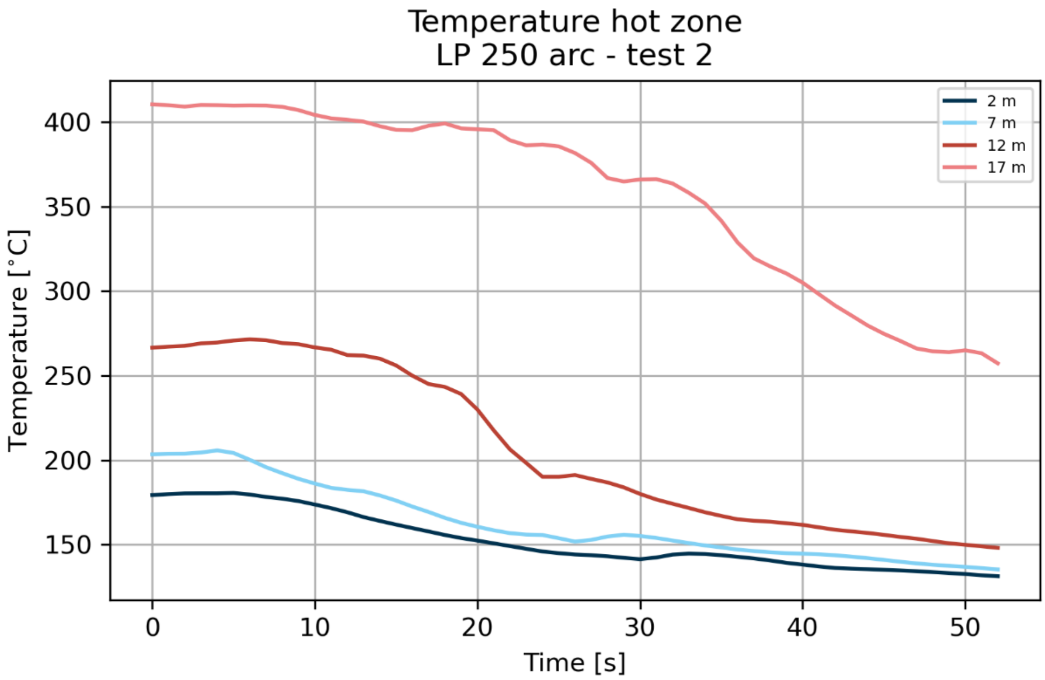

Temperature hot zone
HP arc - test 1
2 m
7 m
12 m
17 m
Temperature [°C]
Time [s]

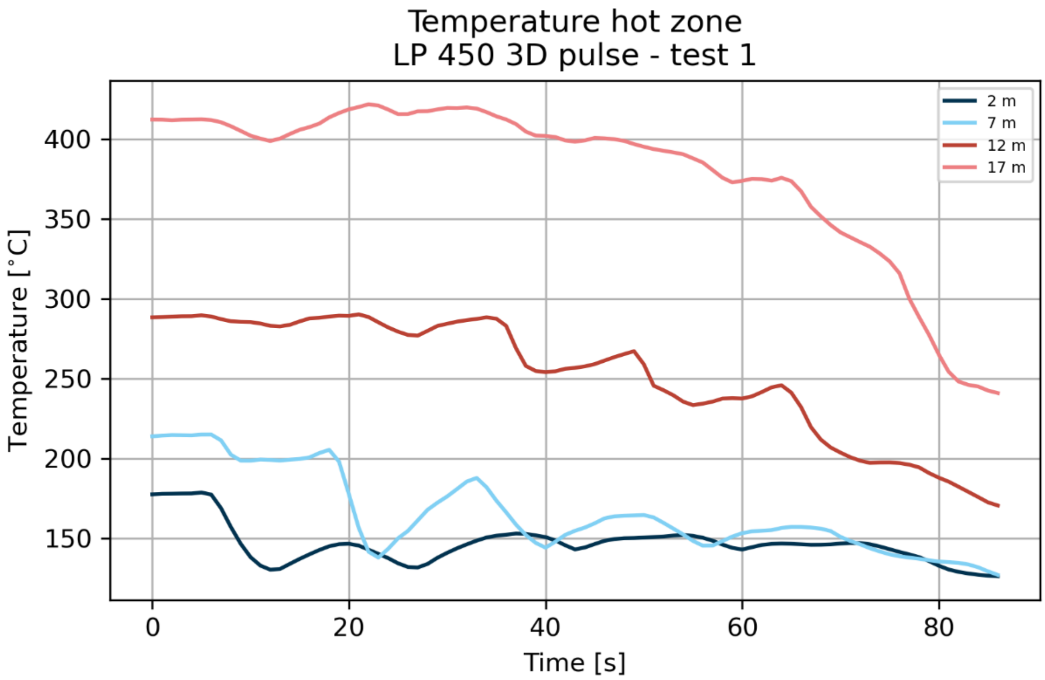

Temperature hot zone
HP arc - test 2
2 m
7 m
12 m
17 m
Temperature [°C]
Time [s]

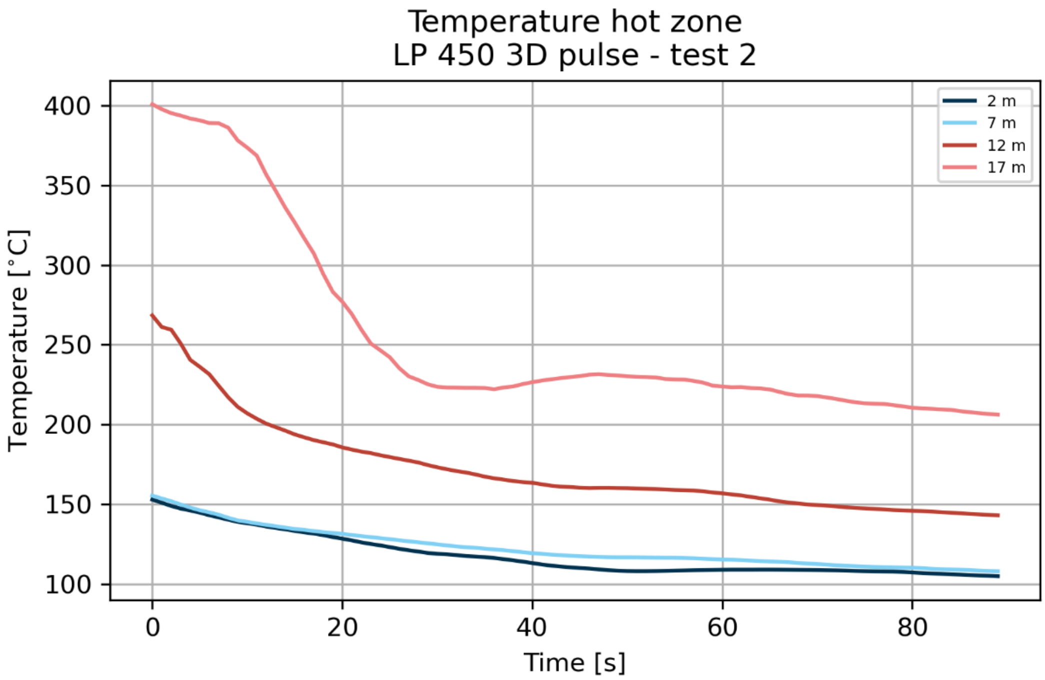

Temperature hot zone
LP 250 3D pulse - test 1
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m
400
350
300
250
200
150
0
20
40
60
80
100

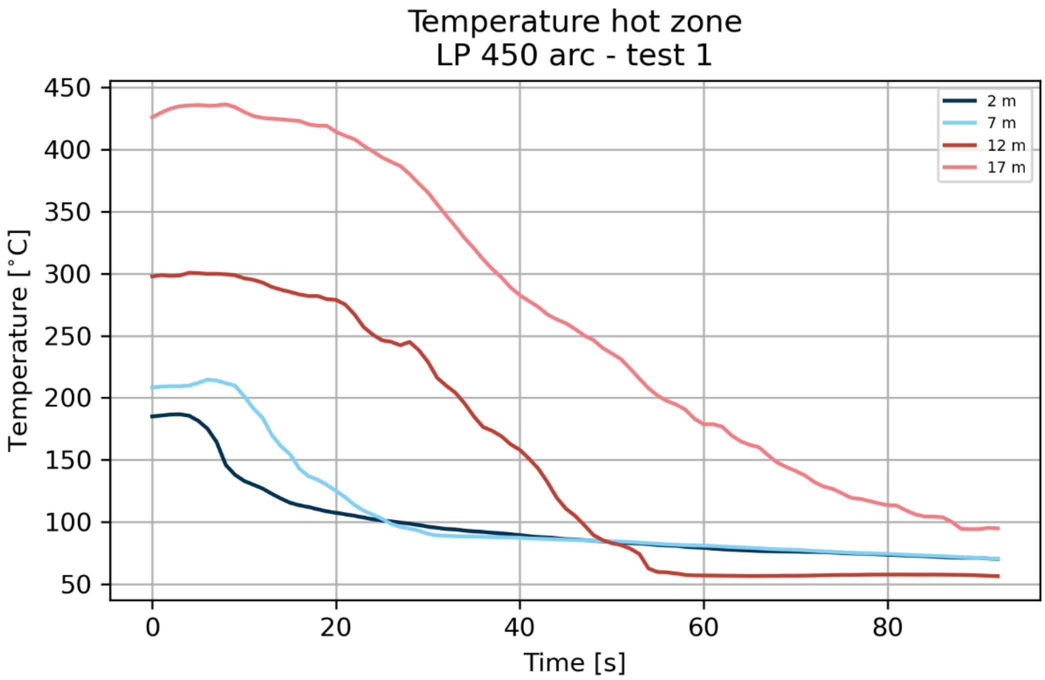

Temperature hot zone
LP 250 3D pulse - test 2
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m
450
400
350
300
250
200
150
0
20
40
60
80

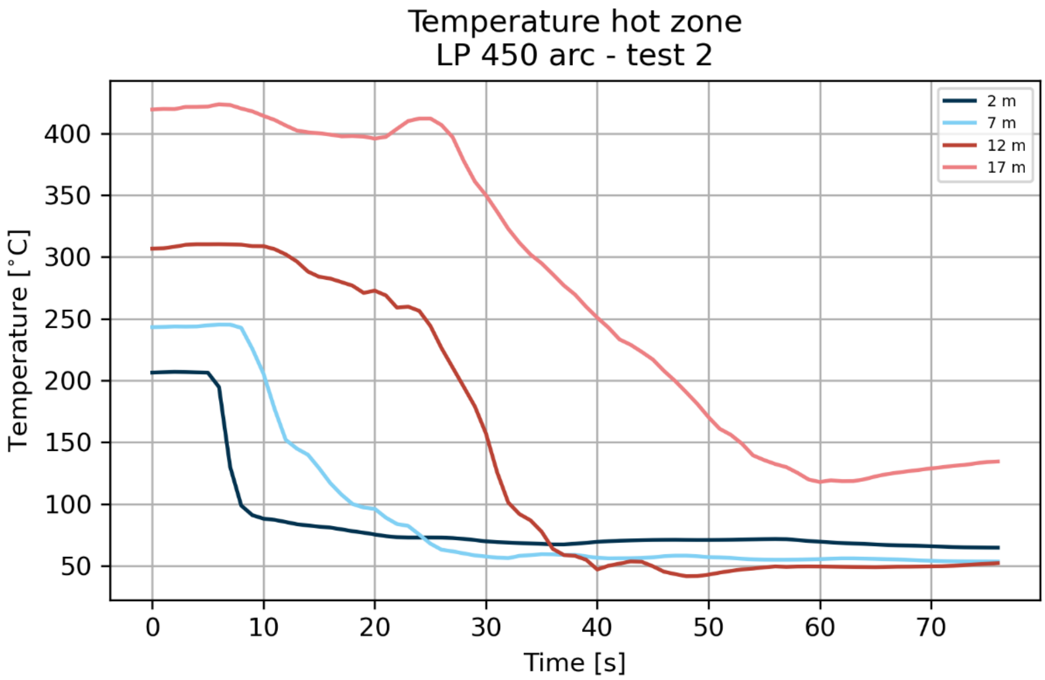

Temperature hot zone
LP 250 arc - test 1
2 m
7 m
12 m
17 m
Temperature [°C]
Time [s]
450
400
350
300
250
200
150
100
0
10
20
30
40
50

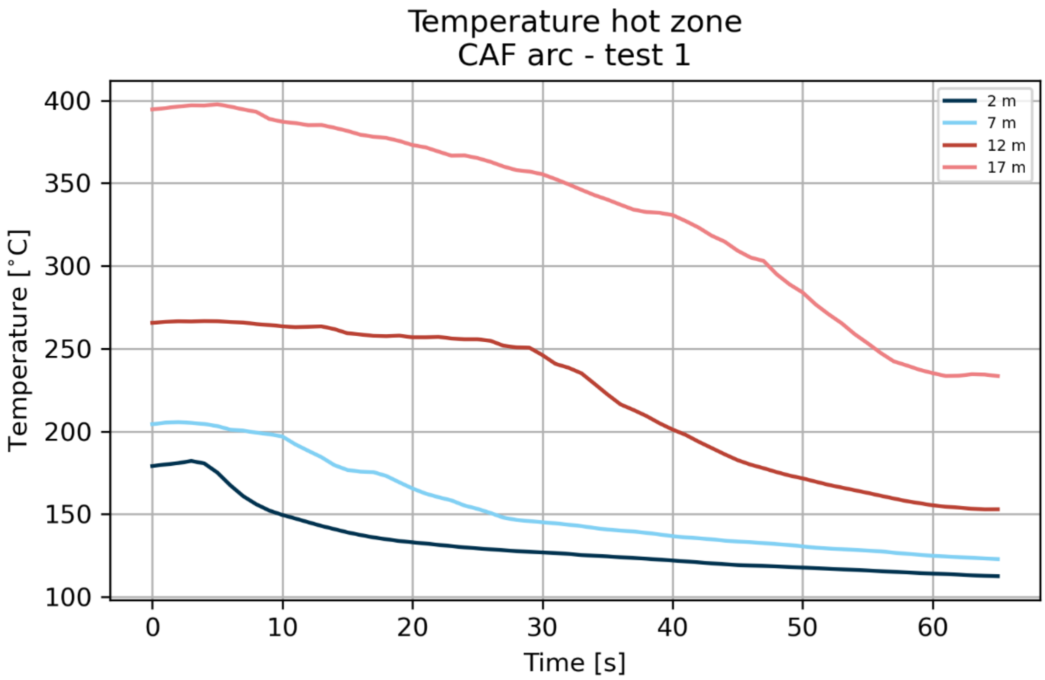

Temperature hot zone
LP 250 arc - test 2
2 m
7 m
12 m
17 m
Temperature [°C]
Time [s]
400
350
300
250
200
150
0
10
20
30
40
50

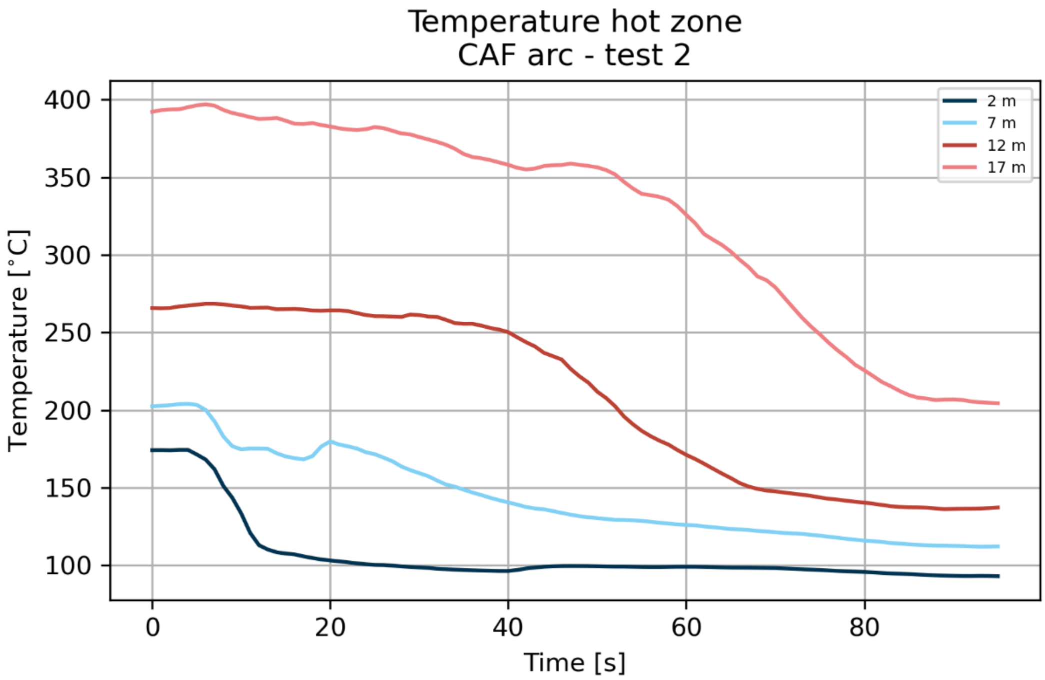

Temperature hot zone
LP 450 3D pulse - test 1
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m


Temperature hot zone
LP 450 3D pulse - test 2
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m


Temperature hot zone
LP 450 arc - test 1
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m
450
400
350
300
250
200
150
100
50
0
20
40
60
80


Temperature hot zone
LP 450 arc - test 2
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m
400
350
300
250
200
150
100
50
0
10
20
30
40
50
60
70


Temperature hot zone
CAF arc - test 1
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m


Temperature hot zone
CAF arc - test 2
Temperature [°C]
Time [s]
2 m
7 m
12 m
17 m

Appendix 8 Safety of firefighters

To examine firefighters' safety, the radiation part of the FEDheat method was used and a formula for determining exposure was developed. This formula is based on the exposure to radiation heat according to the following tolerance (Brandweeracademie, 2016):

- Maximum radiation load of 3 kW/m^2 for 20 minutes
- Maximum radiation load of 4.6 kW/m^2 for 5 minutes

These two points were used to develop a formula with the equation:

$$t_{irad} = a \cdot q^b$$

Here, t_{irad} is the time in minutes for the radiative component of radiation, q is the radiation in kW/m^2, and a and b are the coefficients to be determined.
This enables the following system of equations to be solved:

$$20 = a \cdot 3^b$$
$$5 = a \cdot 4{,}6^b$$

From this, it follows that:

$$a = \frac{5}{4{,}6^{\left(\frac{\log\left(\frac{20}{5}\right)}{\log\left(\frac{3}{4{,}6}\right)}\right)}} \approx 705{,}405$$

$$b = \frac{\log\left(\frac{20}{5}\right)}{\log\left(\frac{3}{4{,}6}\right)} \approx -3{,}243$$

From this, it follows that:

$$t_{irad} = 705{,}405 \cdot q^{-3{,}243}$$

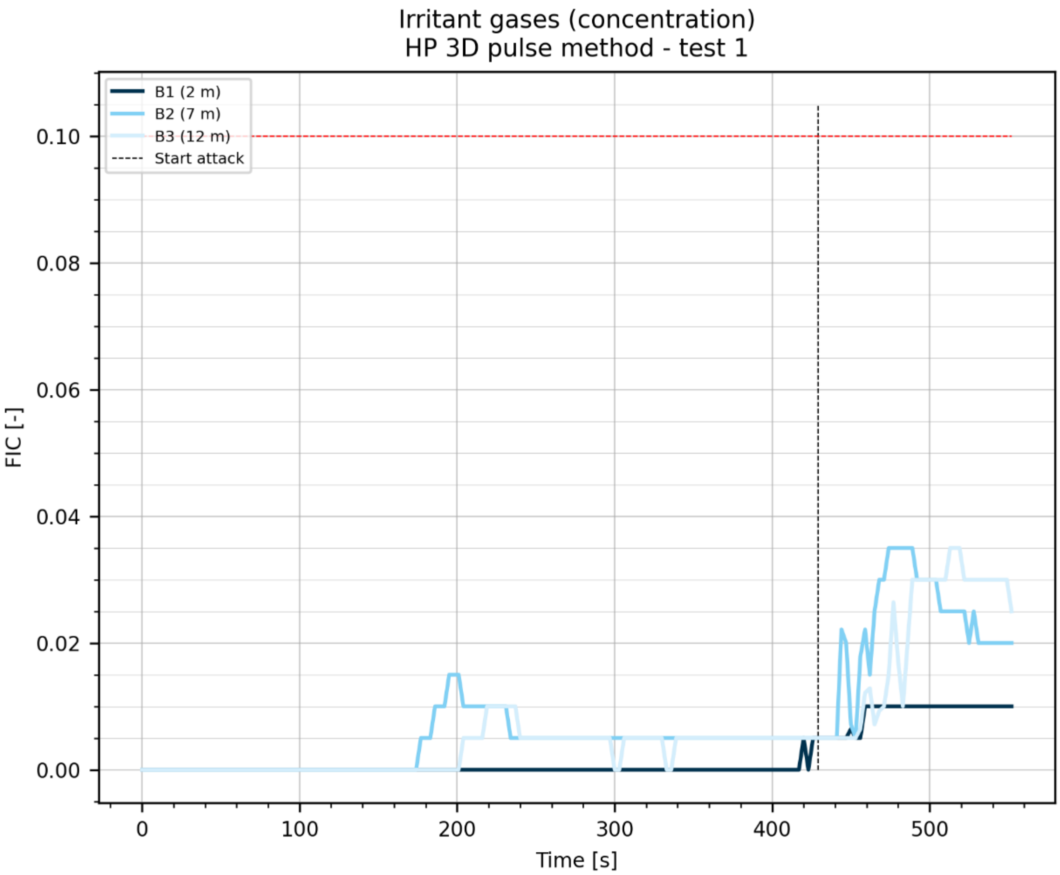
The dose at time T is then calculated by means of:

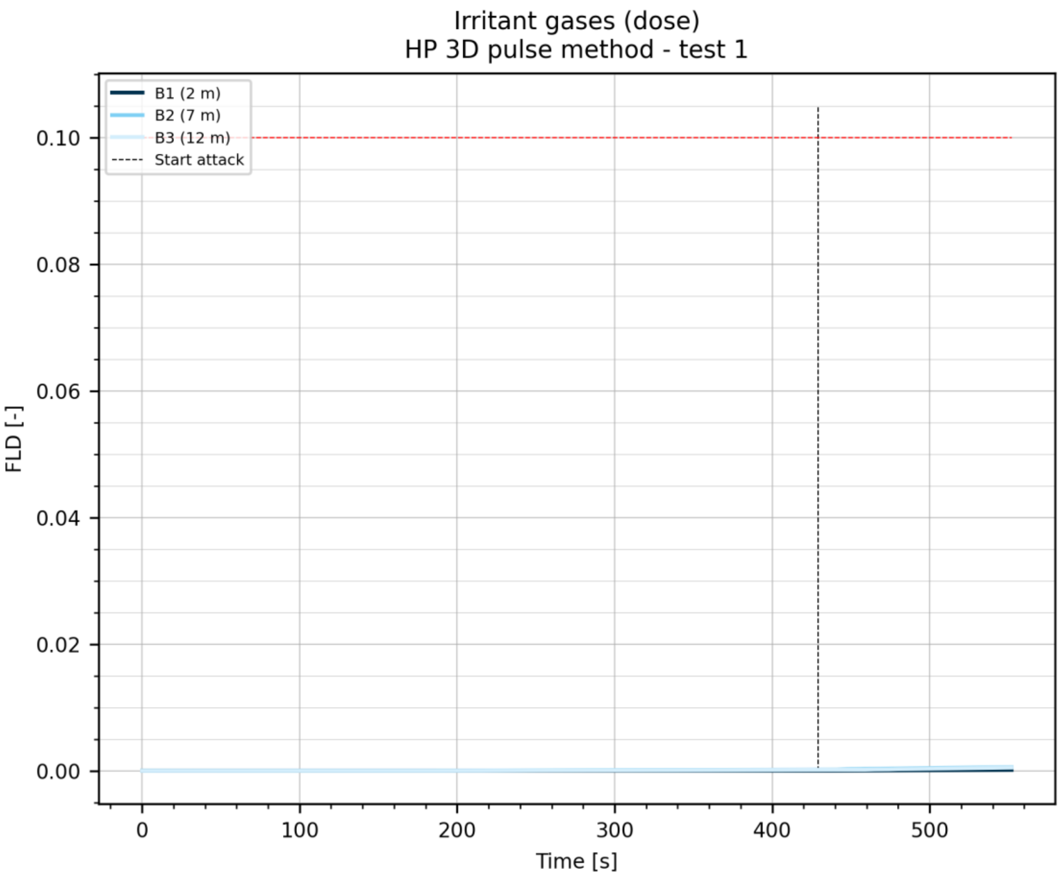
$$FED_{heat} = \sum_{t_i}^{t_2} \frac{1}{t_{irad}} \Delta t$$

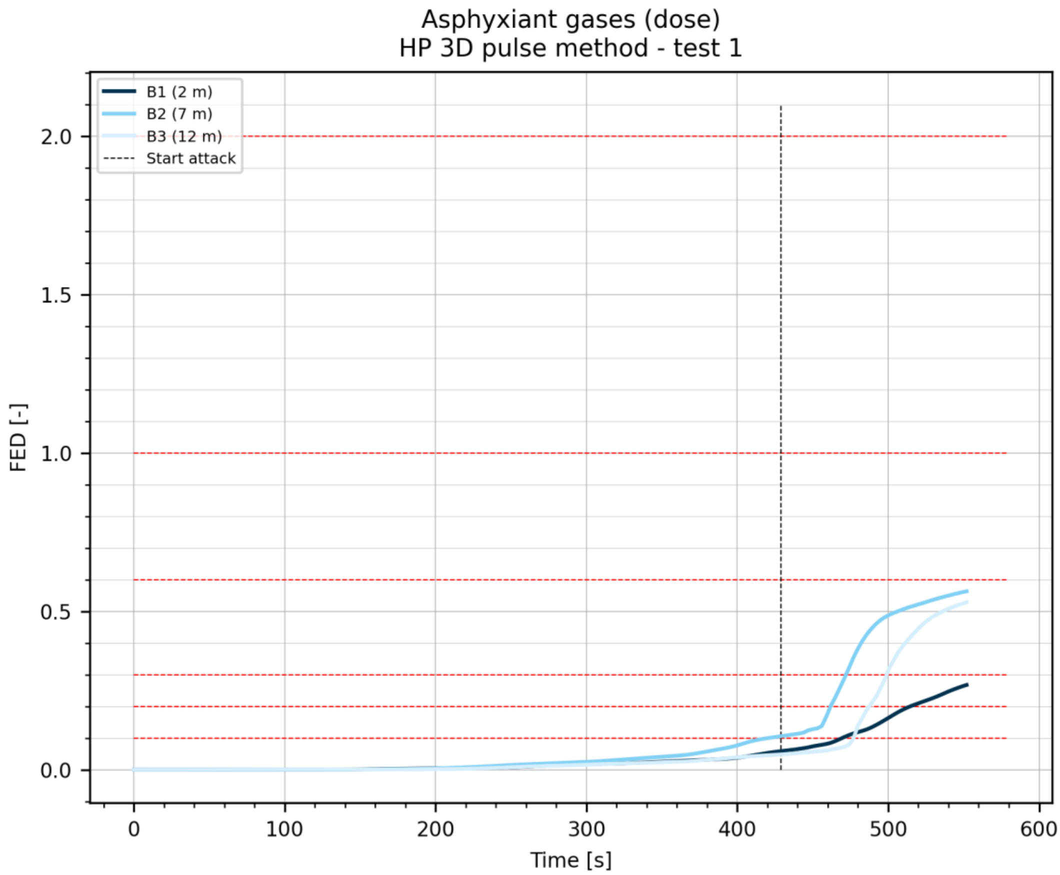
Appendix 9 Safety of casualties

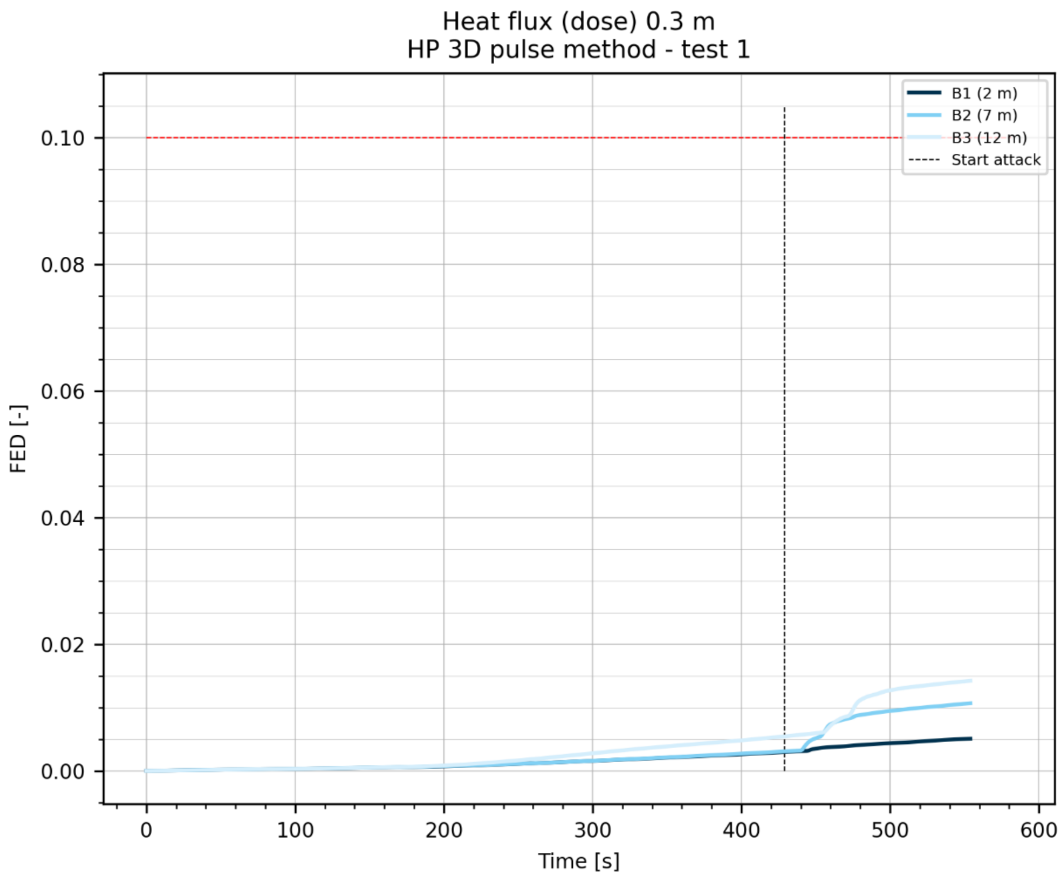
This Appendix lists all methods for calculating the safety of casualties from the SFPE manual (Purser & McAllister, 2016) for all experiments.

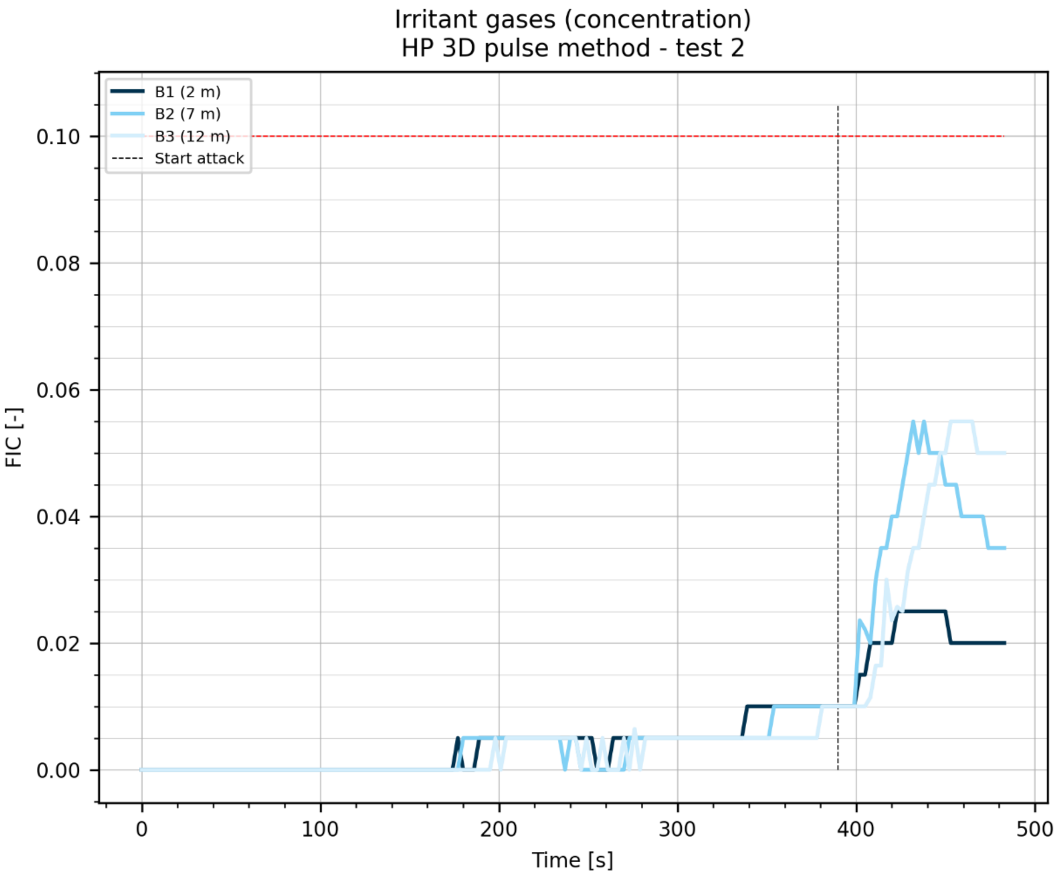
The red horizontal dotted lines indicate the threshold values for the different groups (see also Table 1.4 Summary of the threshold values according to the SFPE handbook). The fire is ignited at t = 0 s.

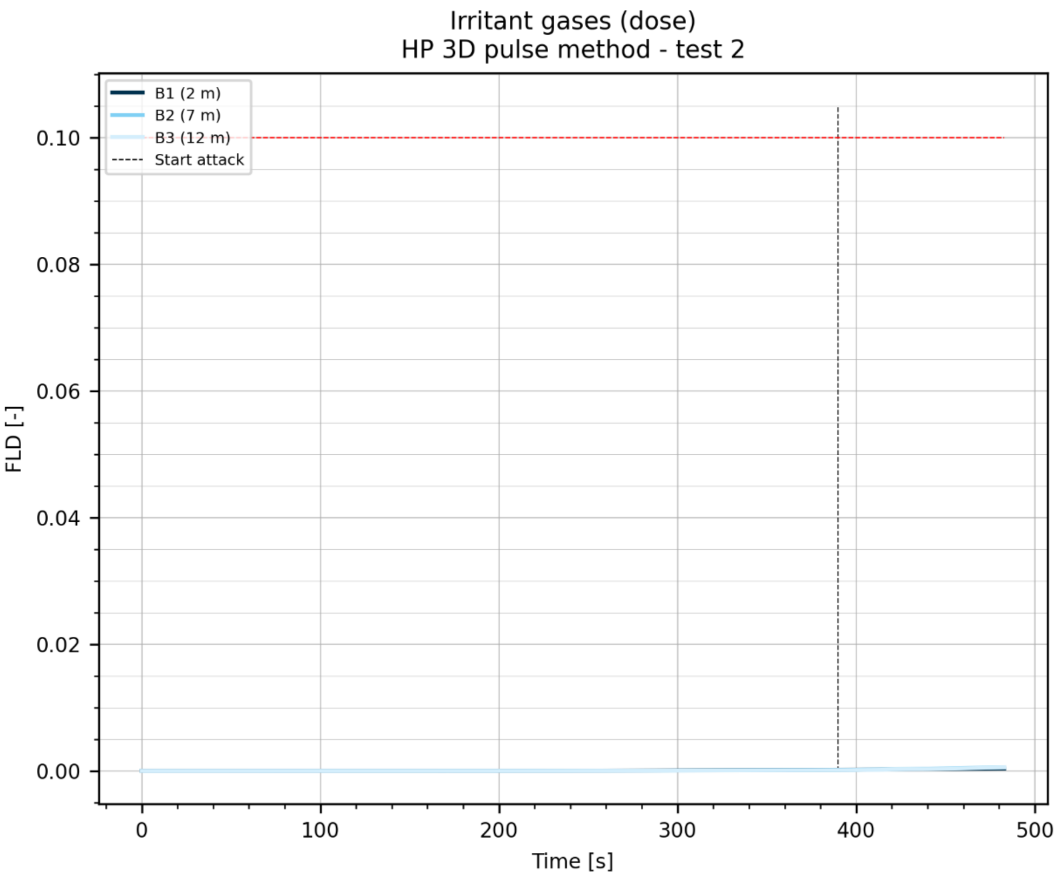

Irritant gases (concentration)
HP 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
0.10
0.08
0.06
0.04
0.02
0.00
FIC [-]
0
100
200
300
400
500
Time [s]

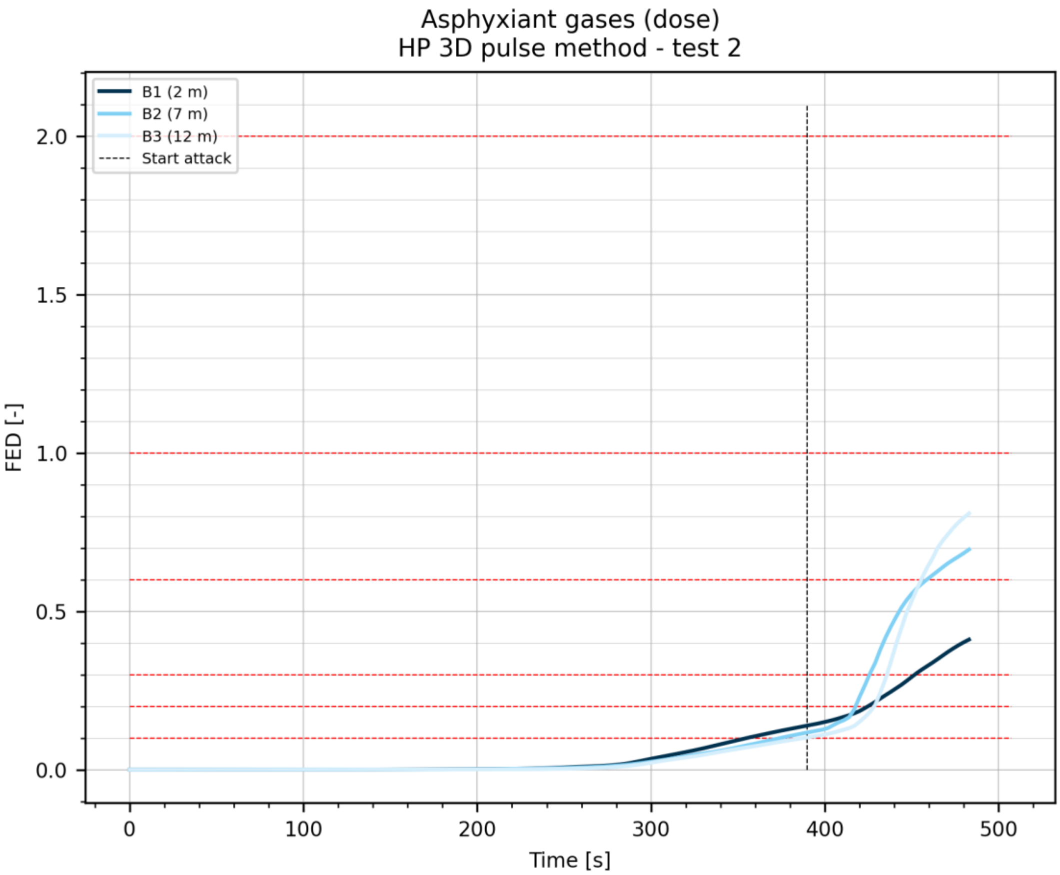

Irritant gases (dose)
HP 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
0.10
0.08
0.06
0.04
0.02
0.00
FLD [-]
0
100
200
300
400
500
Time [s]

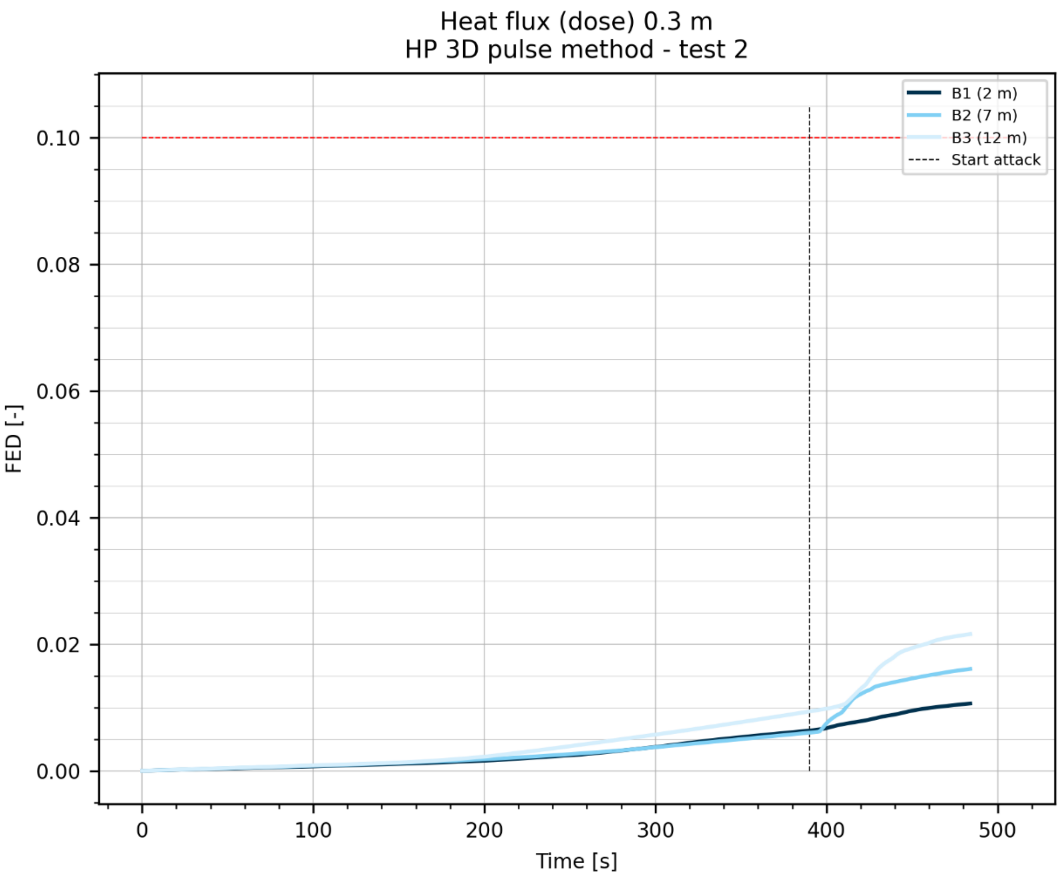

Asphyxiant gases (dose)
HP 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500
600

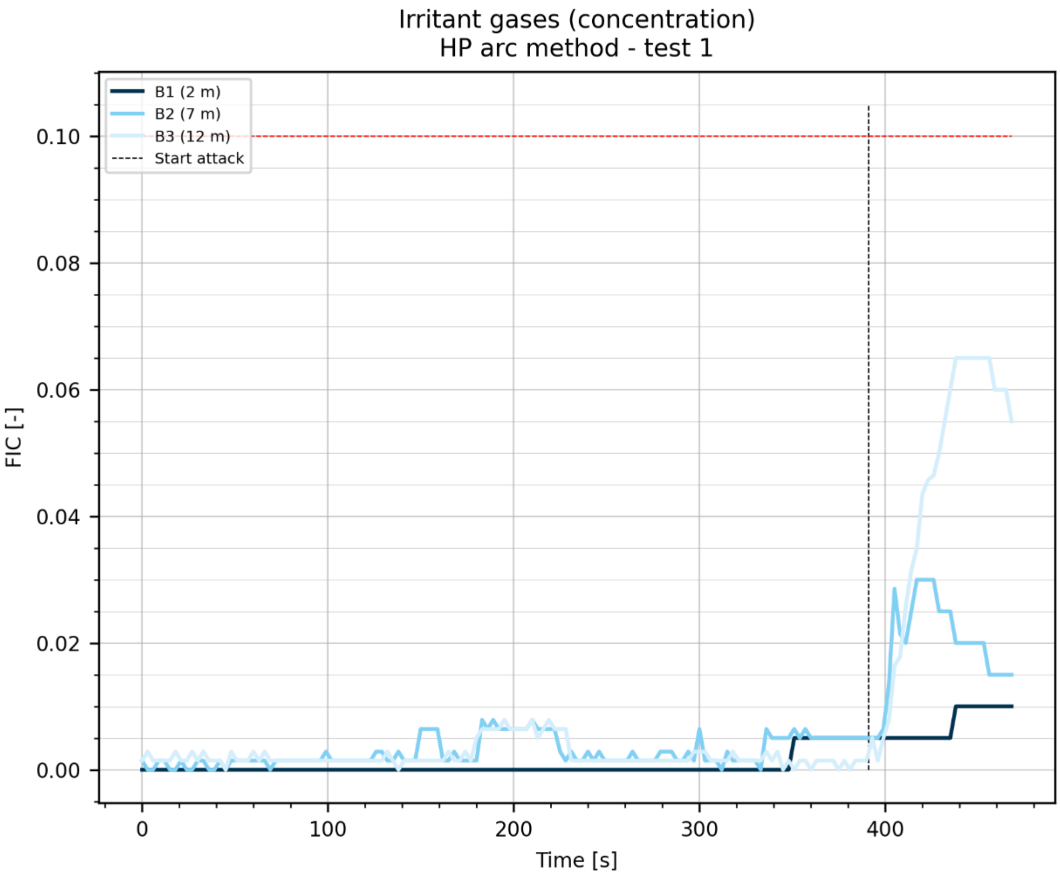

Heat flux (dose) 0.3 m
HP 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500
600

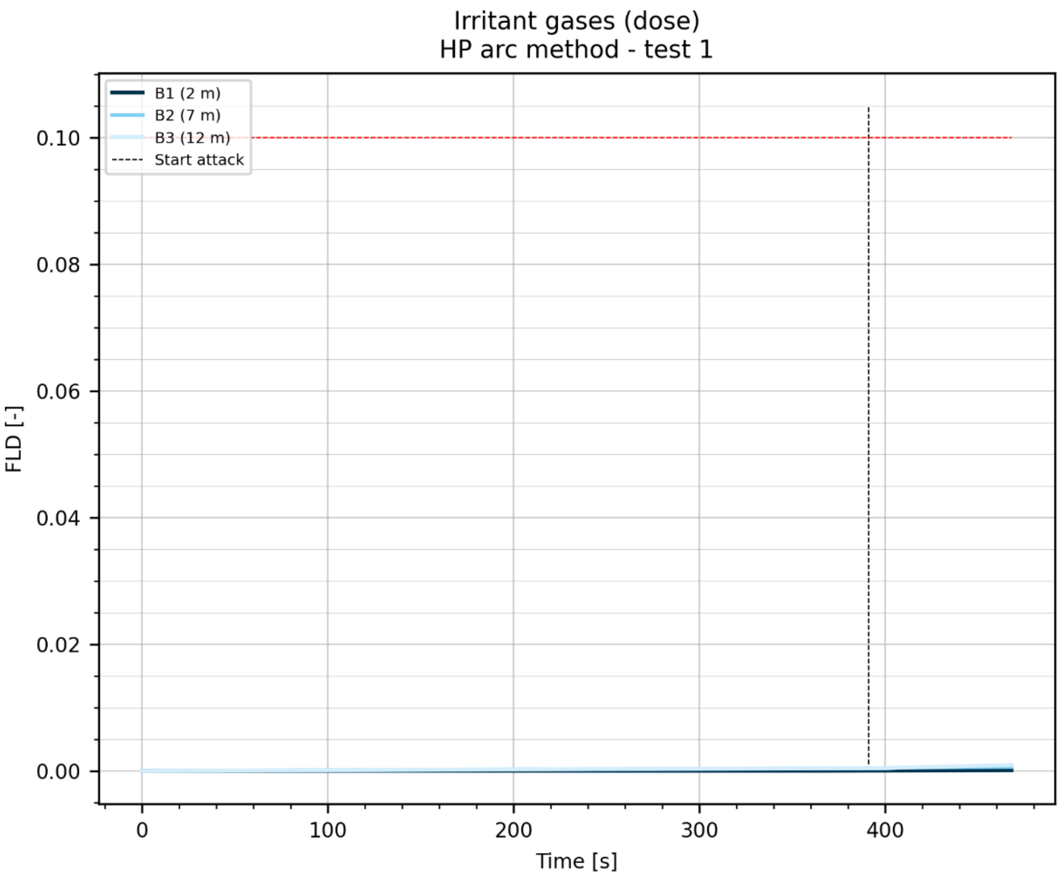

Irritant gases (concentration)
HP 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500
Time [s]

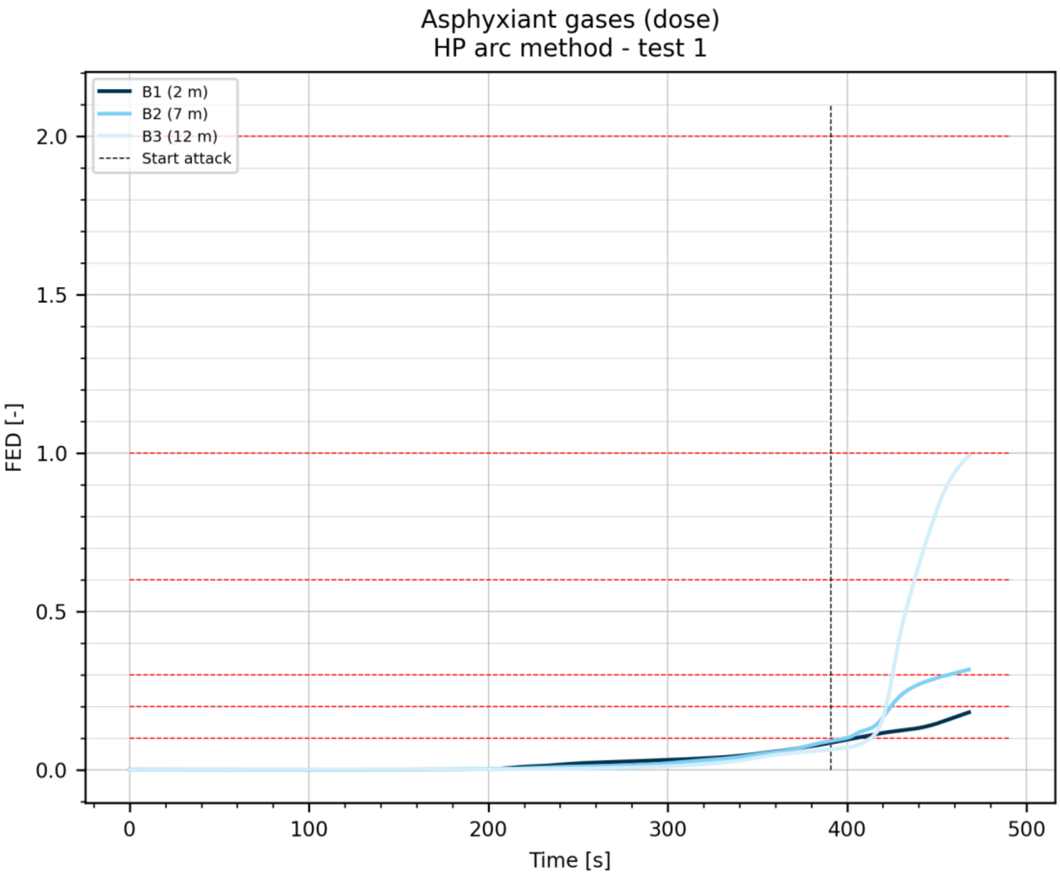

Irritant gases (dose)
HP 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500
Time [s]


Asphyxiant gases (dose)
HP 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500

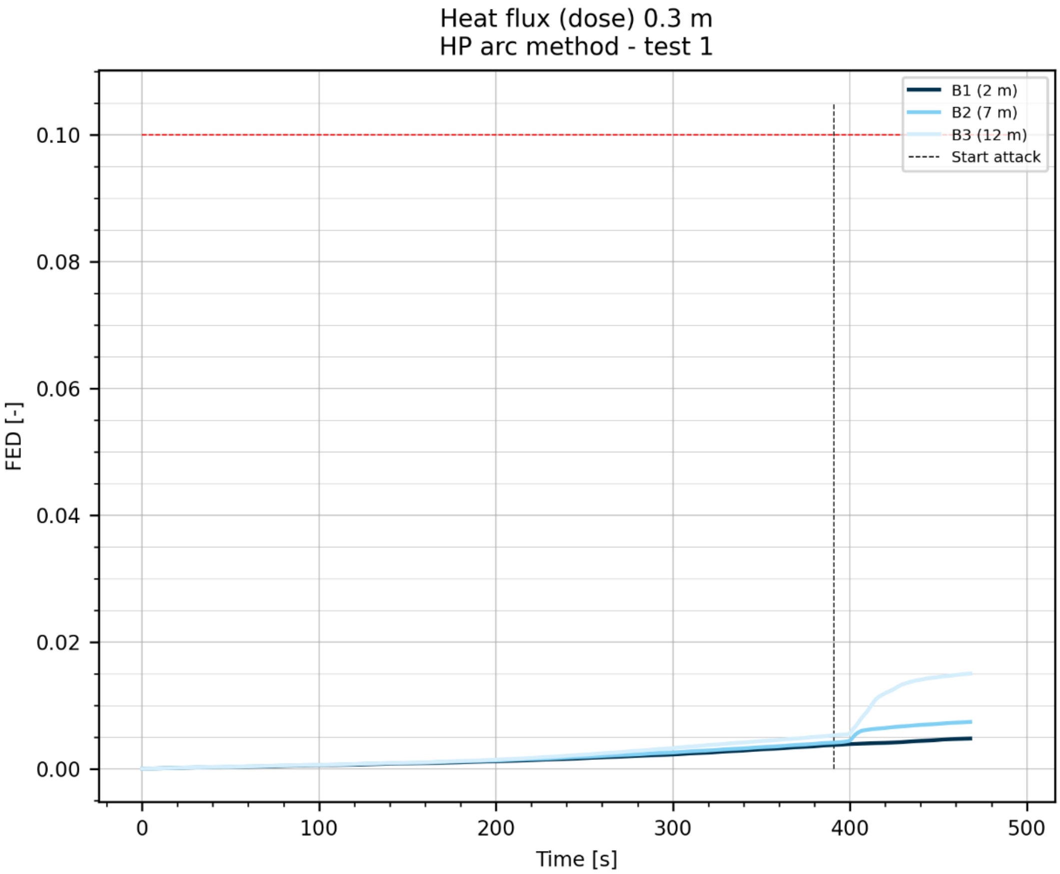

Heat flux (dose) 0.3 m
HP 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500


Irritant gases (concentration)
HP arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

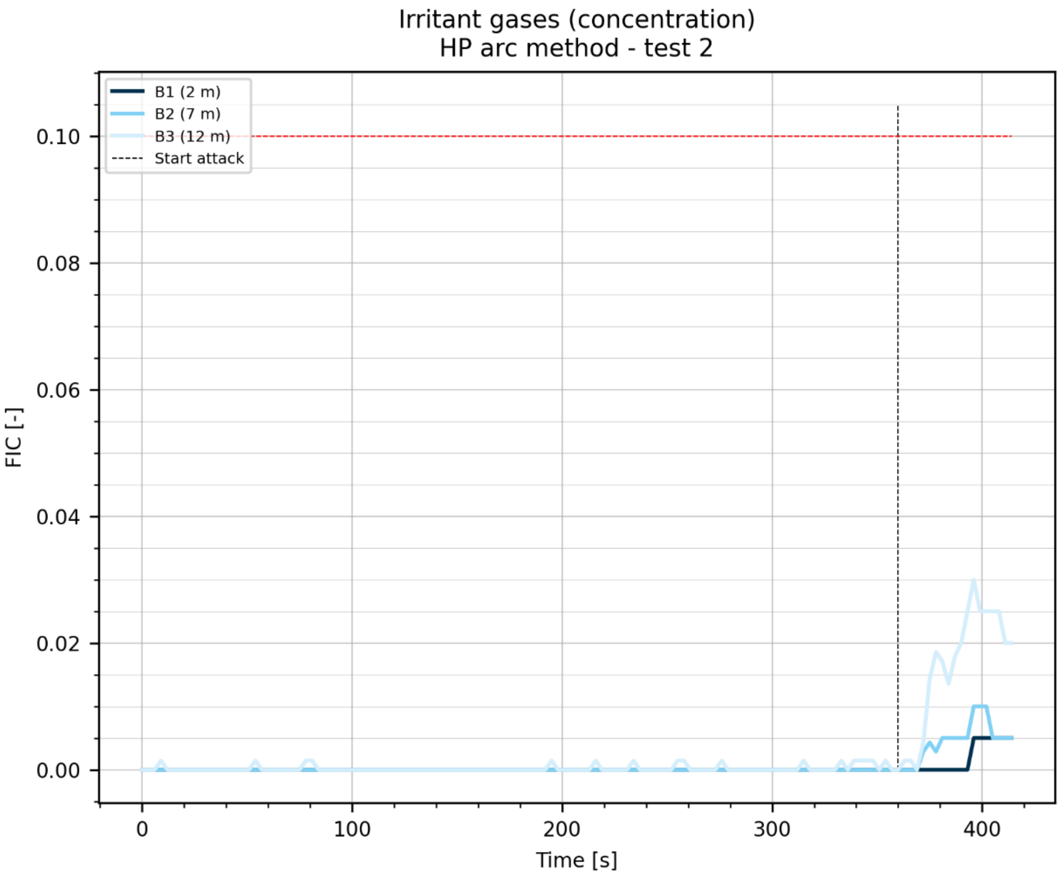

Irritant gases (dose)
HP arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

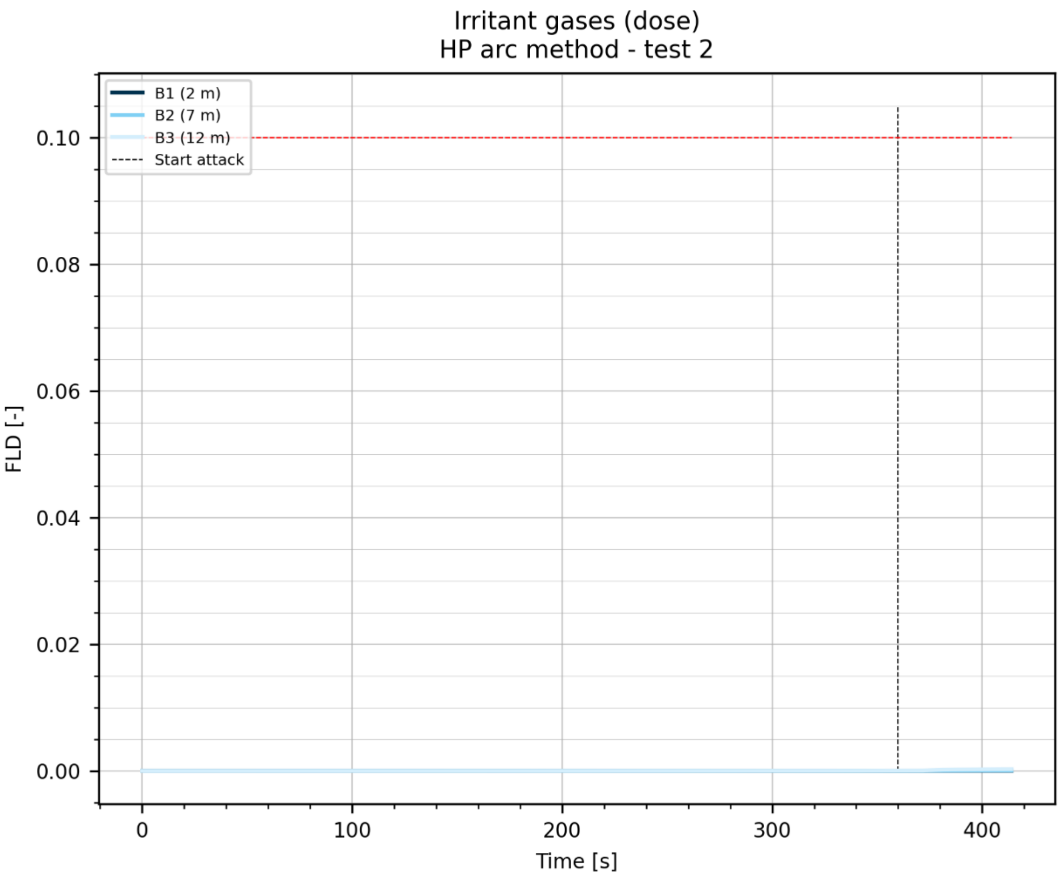


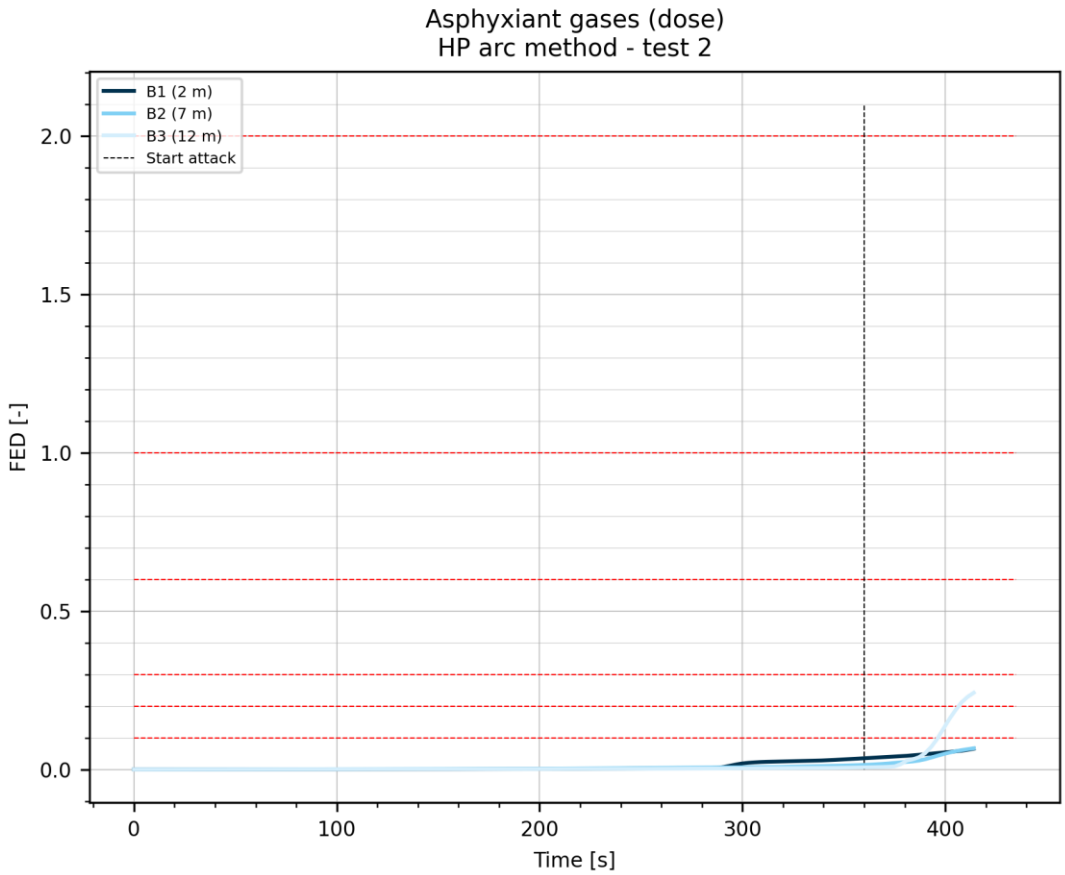
Asphyxiant gases (dose)
HP arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
2.0
1.5
1.0
0.5
0.0
FED [-]
0
100
200
300
400
500
Time [s]



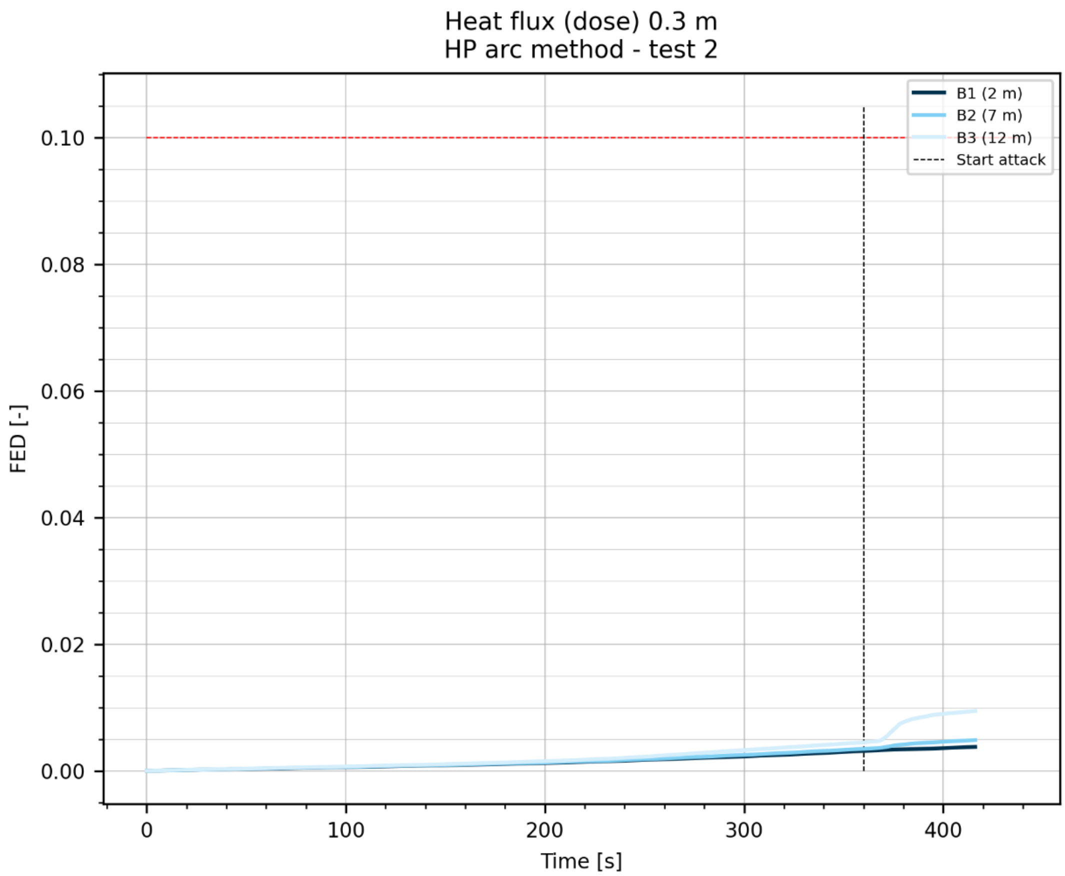
Heat flux (dose) 0.3 m
HP arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
0.10
0.08
0.06
0.04
0.02
0.00
FED [-]
0
100
200
300
400
500
Time [s]


Irritant gases (concentration)
HP arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

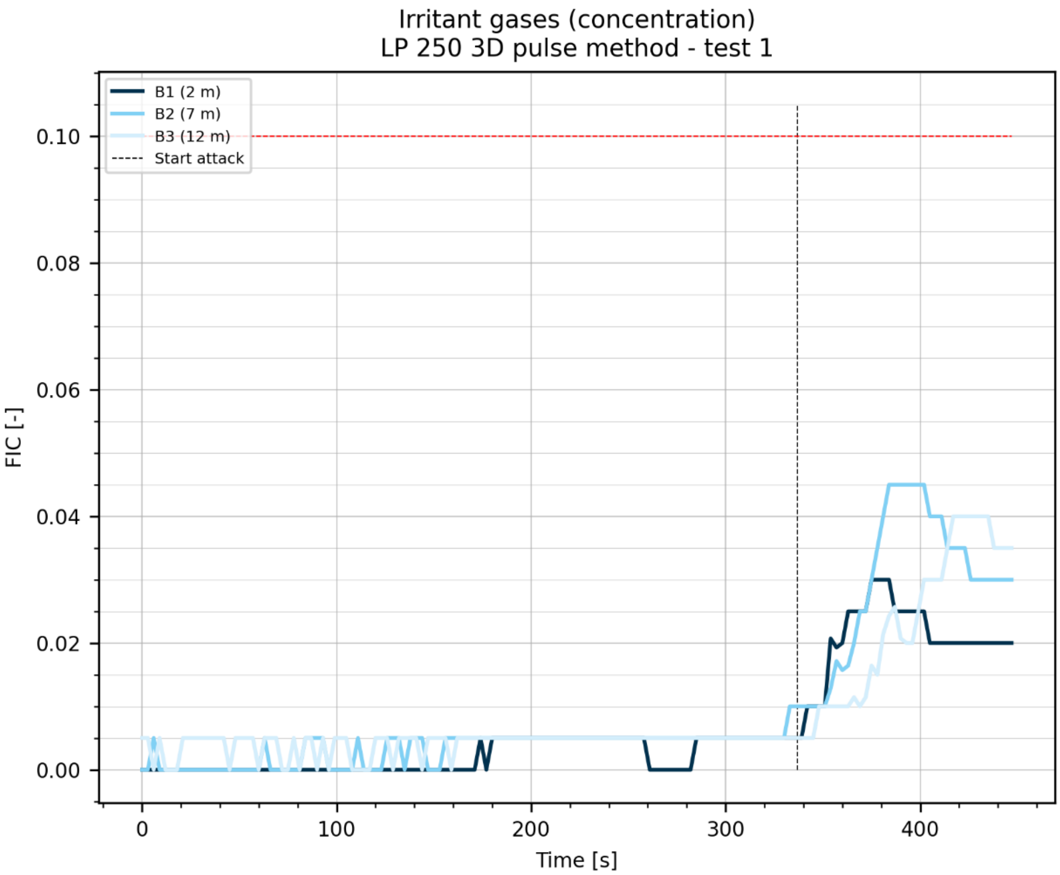

Irritant gases (dose)
HP arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

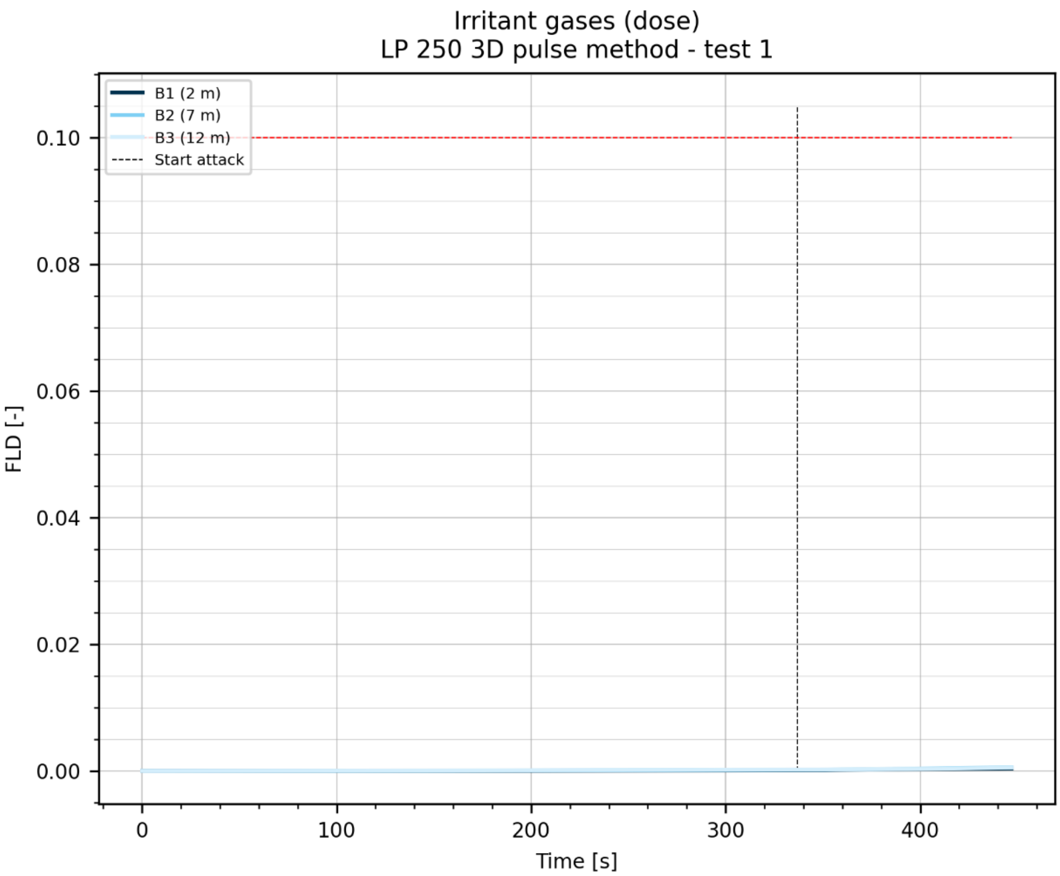


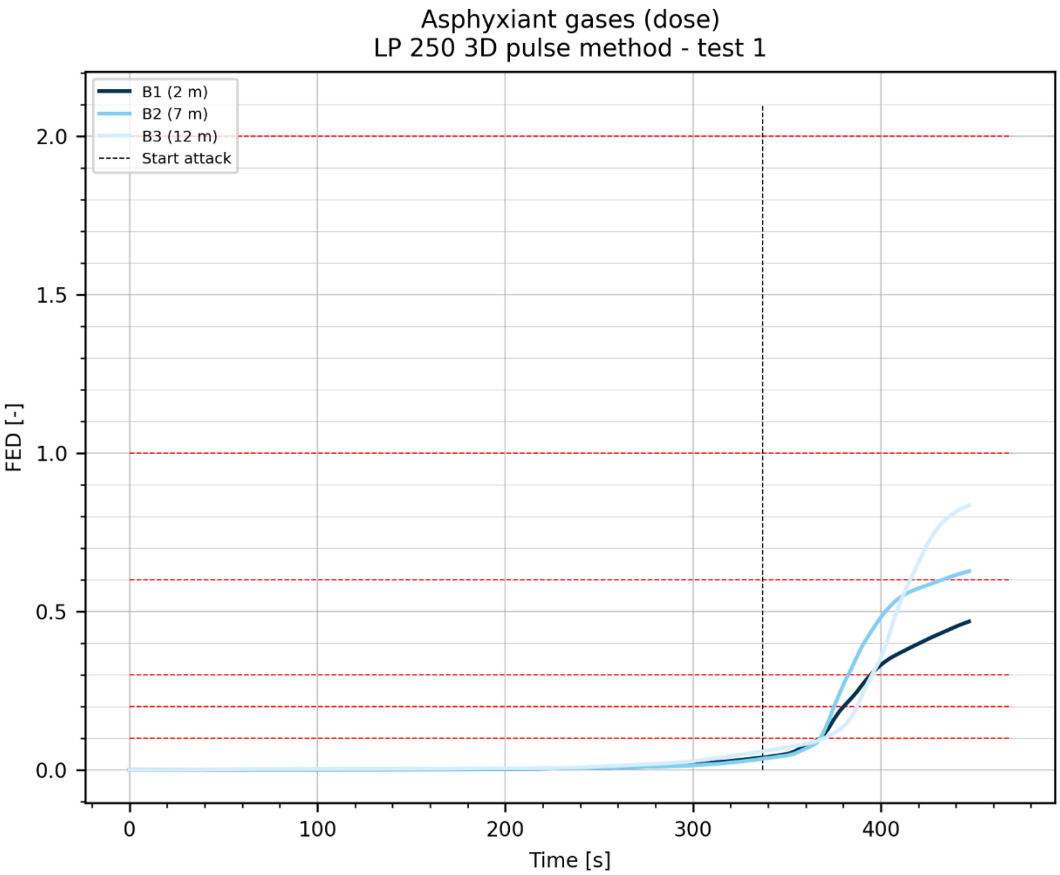
Asphyxiant gases (dose)
HP arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
Time [s]

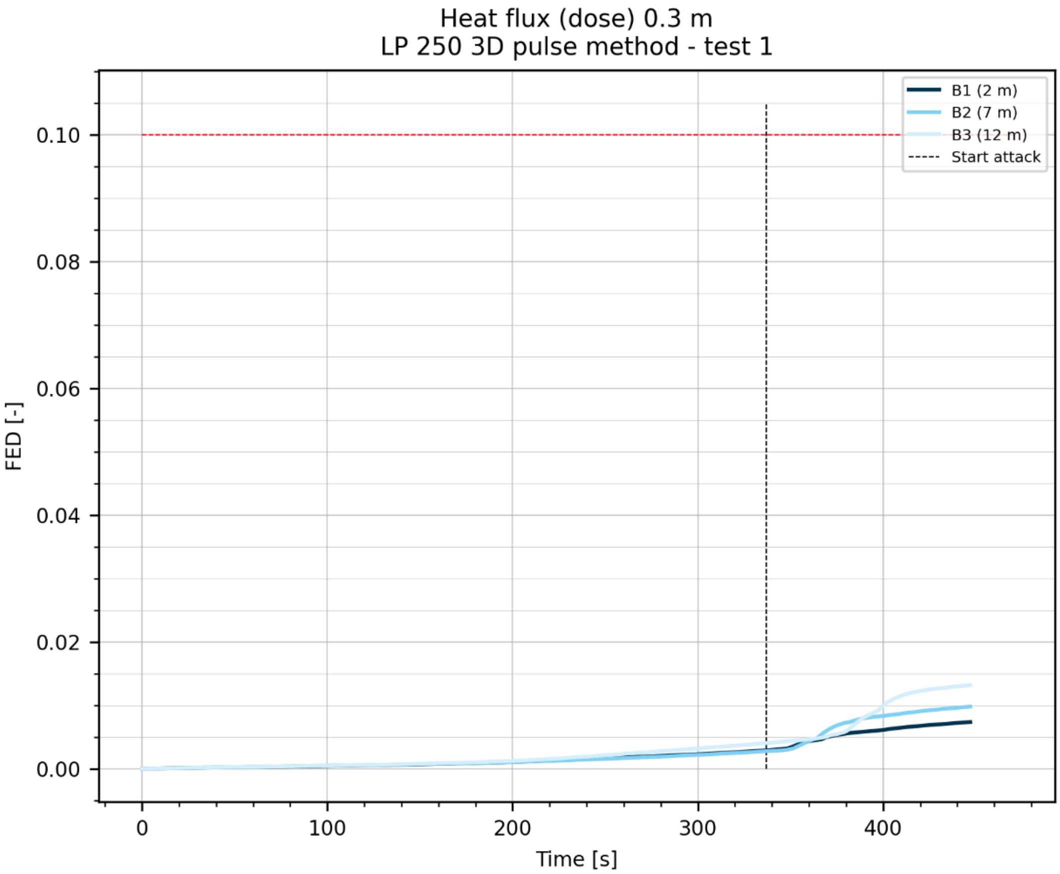


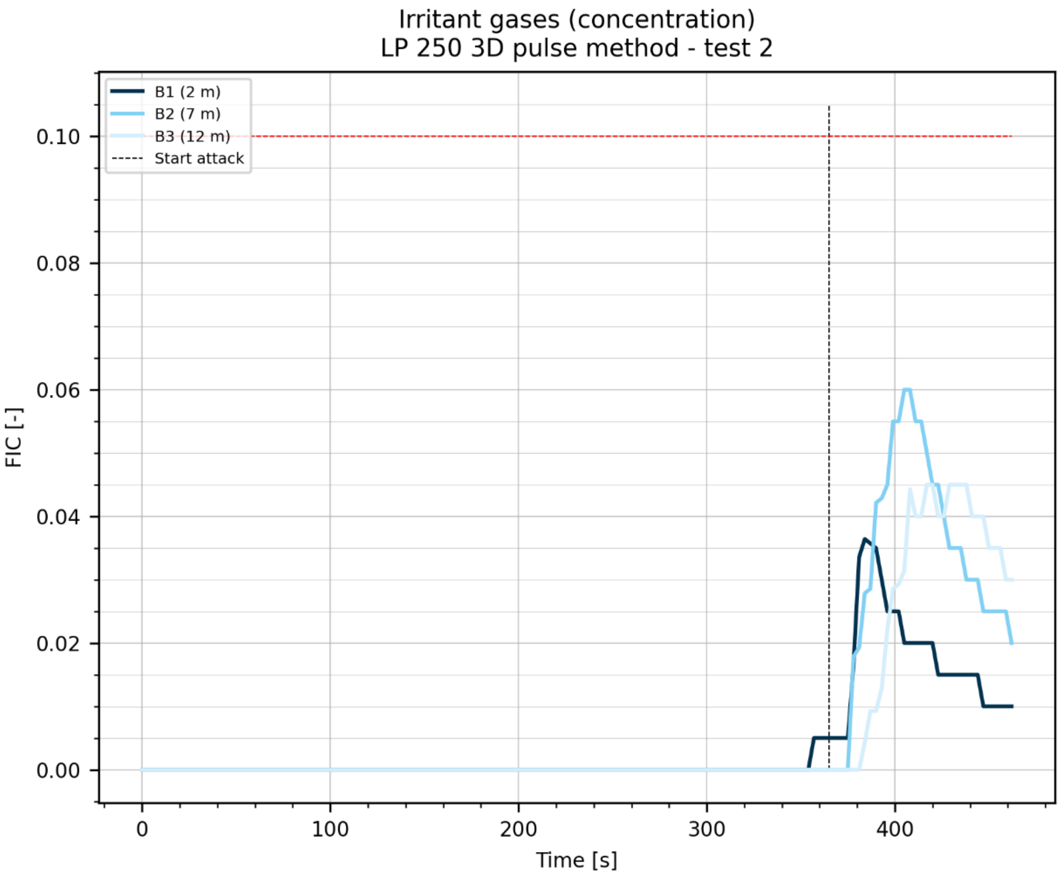
Heat flux (dose) 0.3 m
HP arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
Time [s]

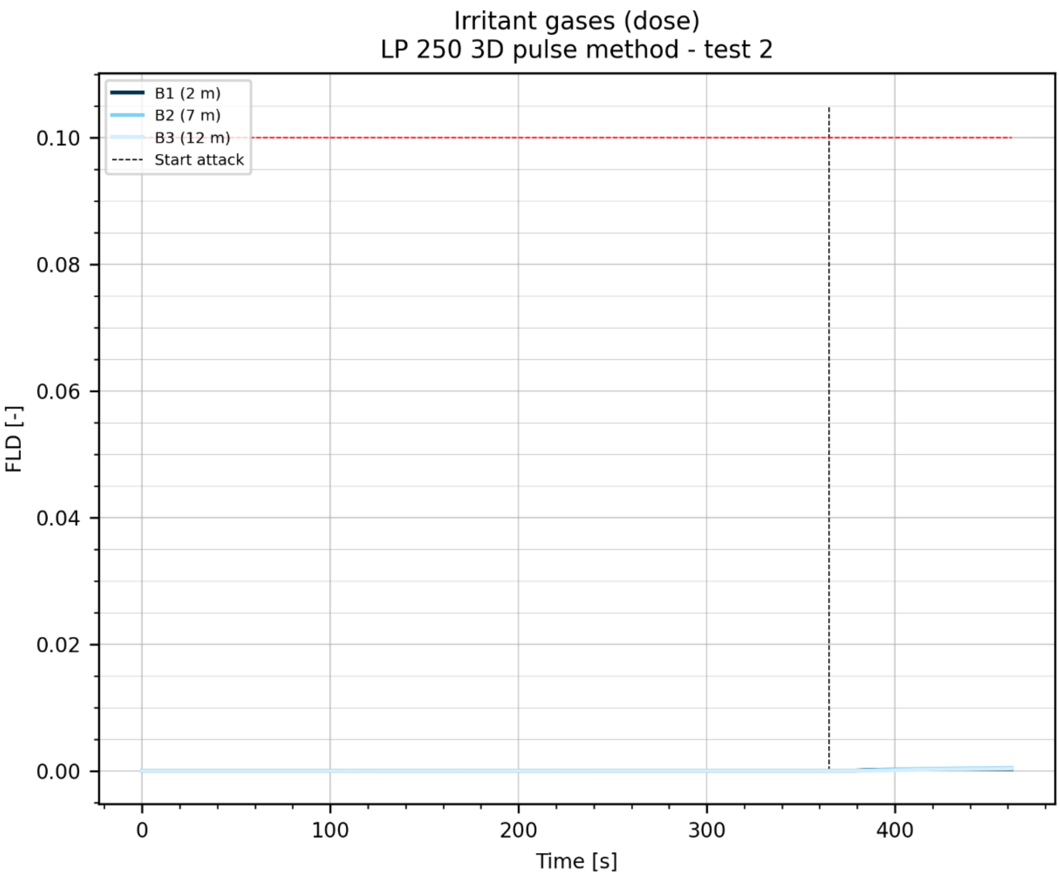

Irritant gases (concentration)
LP 250 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
Time [s]

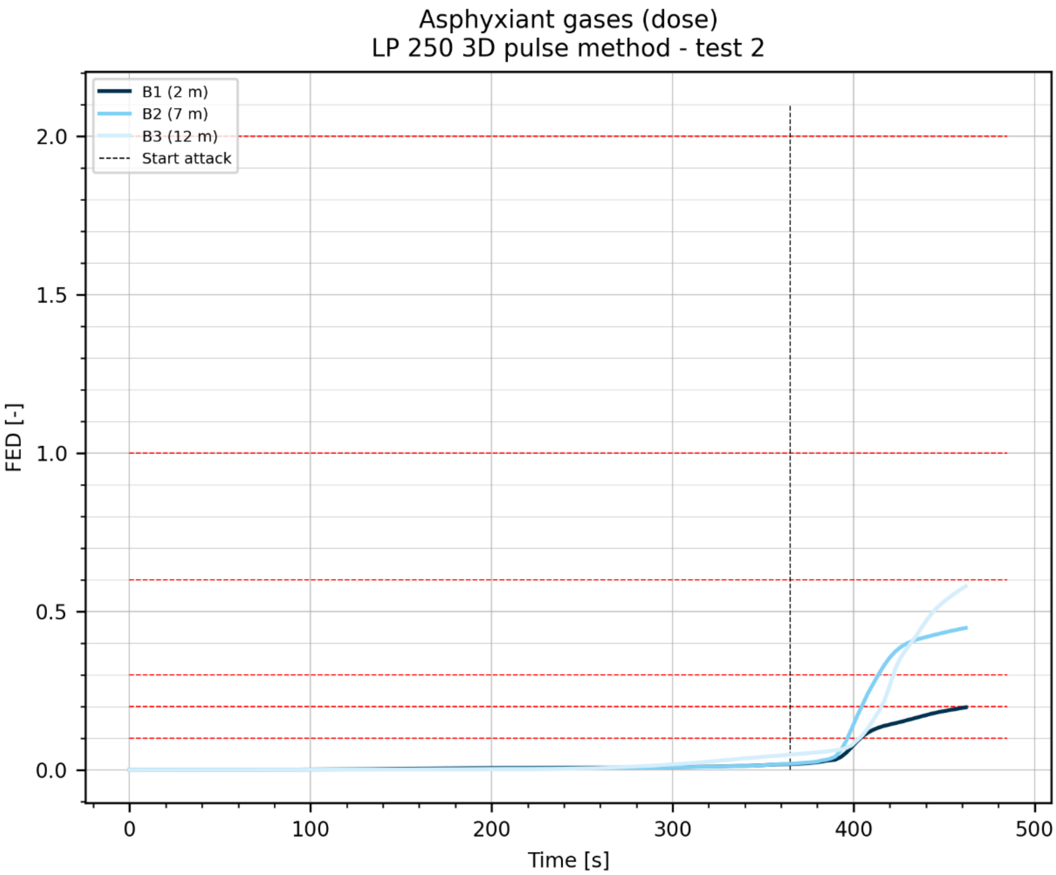

Irritant gases (dose)
LP 250 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
Time [s]

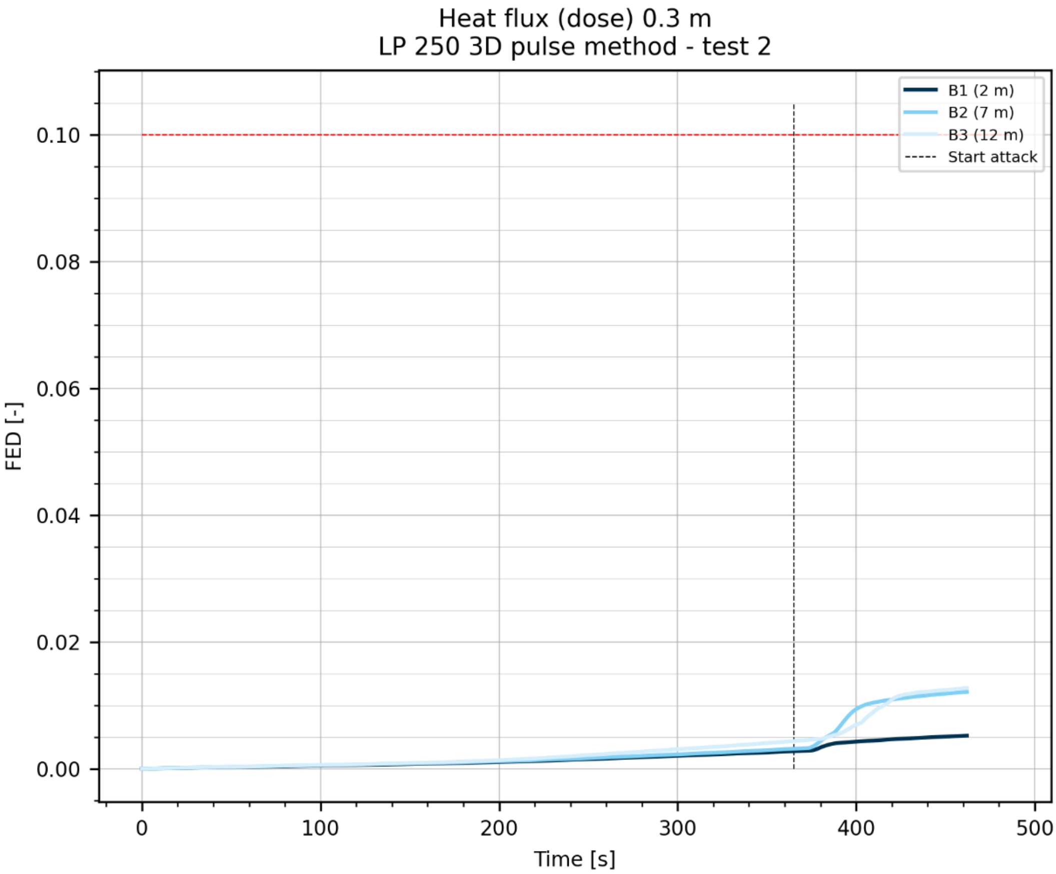

Asphyxiant gases (dose)
LP 250 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]

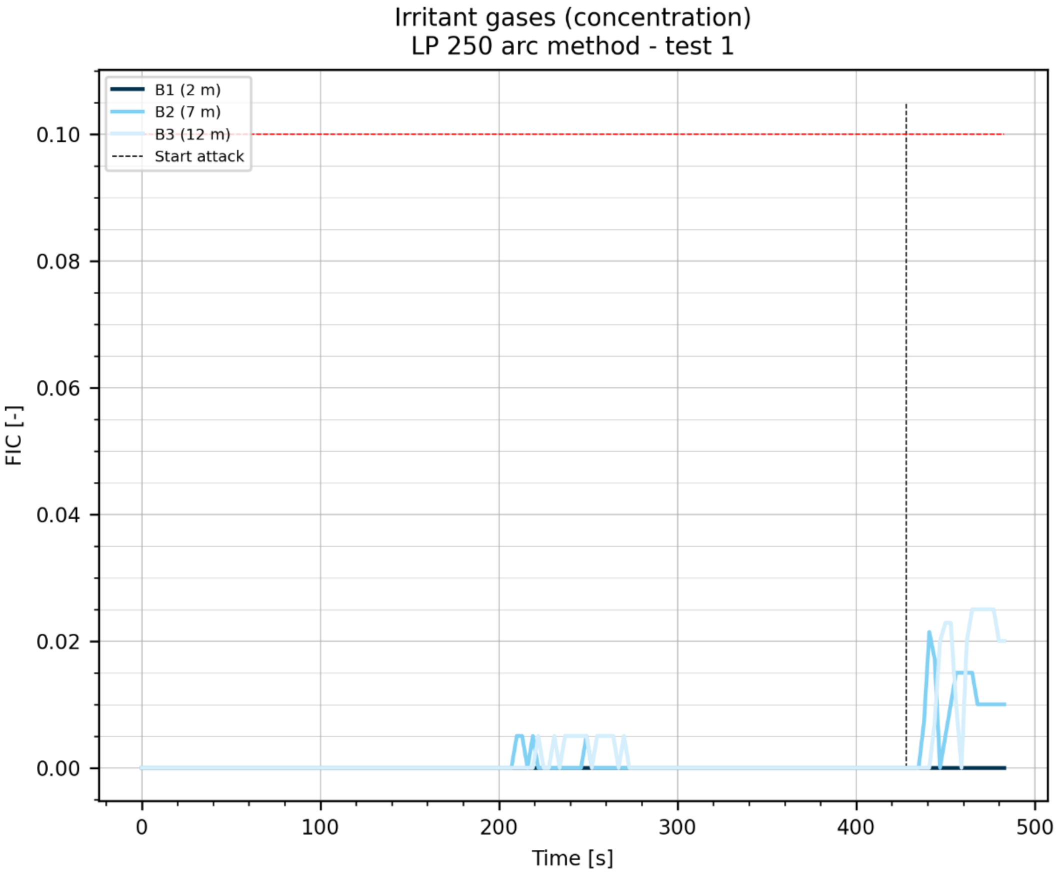

Heat flux (dose) 0.3 m
LP 250 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]

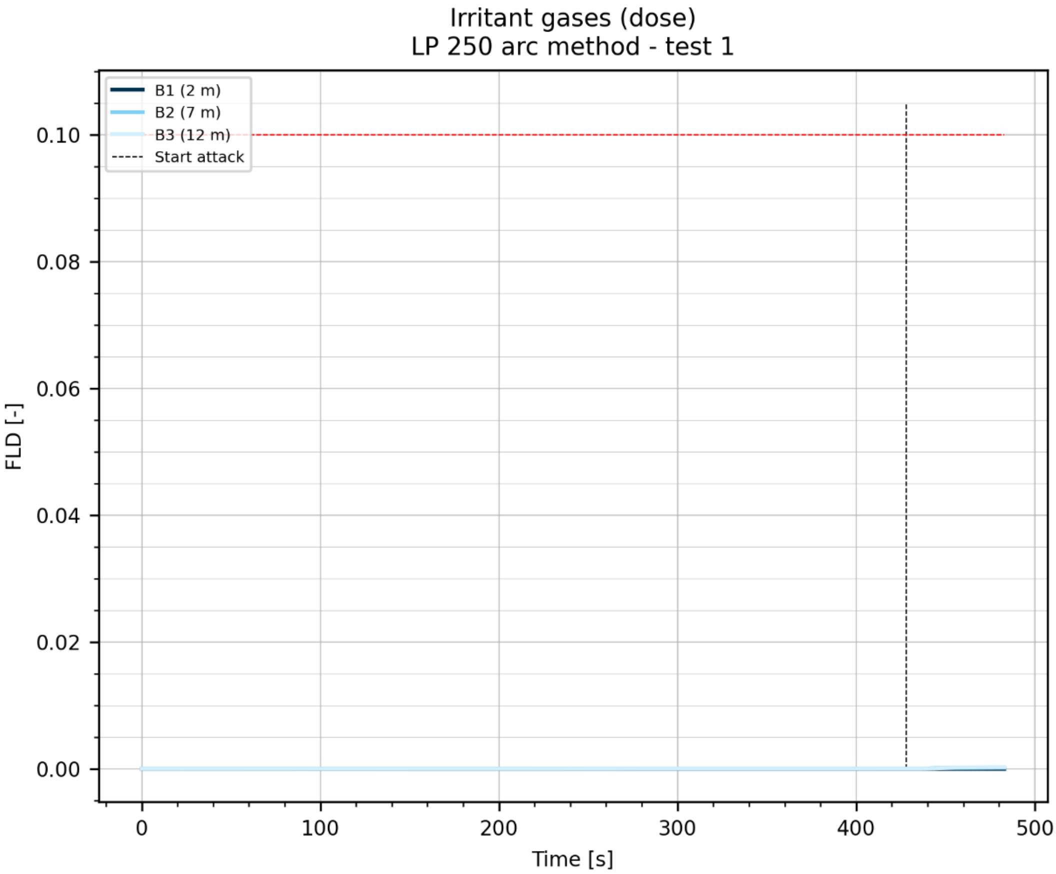

Irritant gases (concentration)
LP 250 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

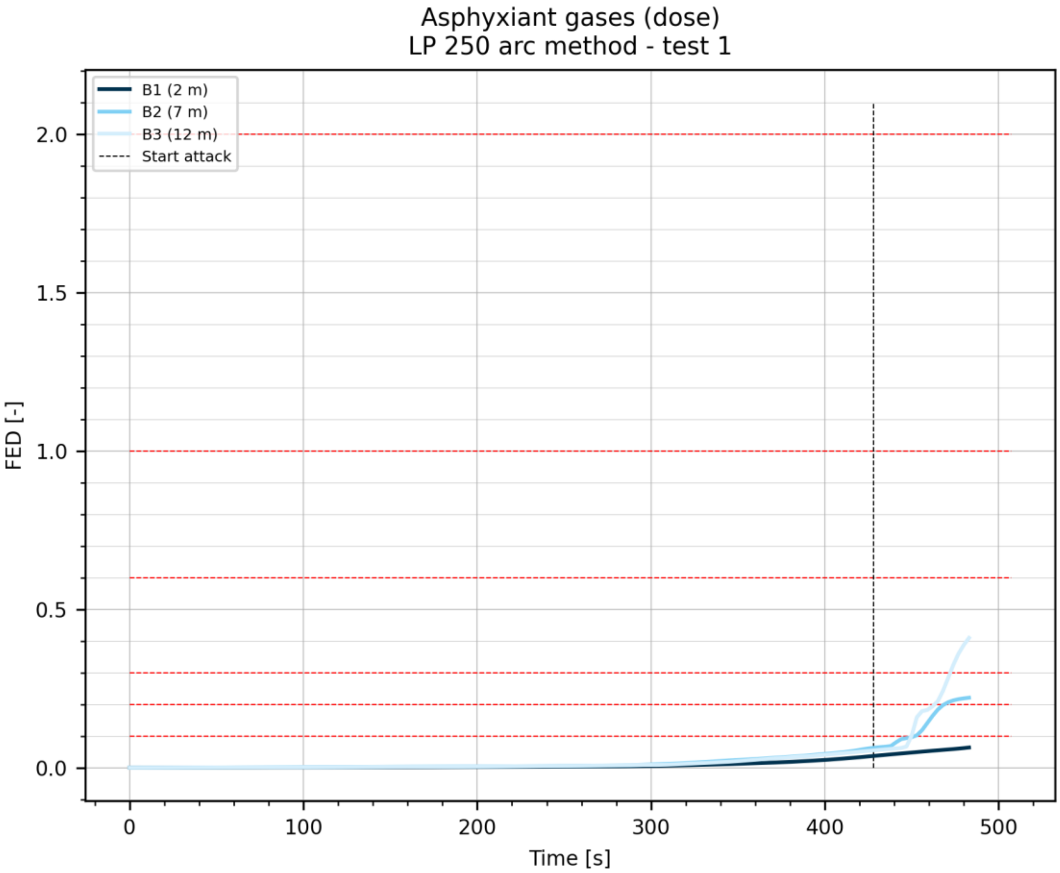

Irritant gases (dose)
LP 250 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

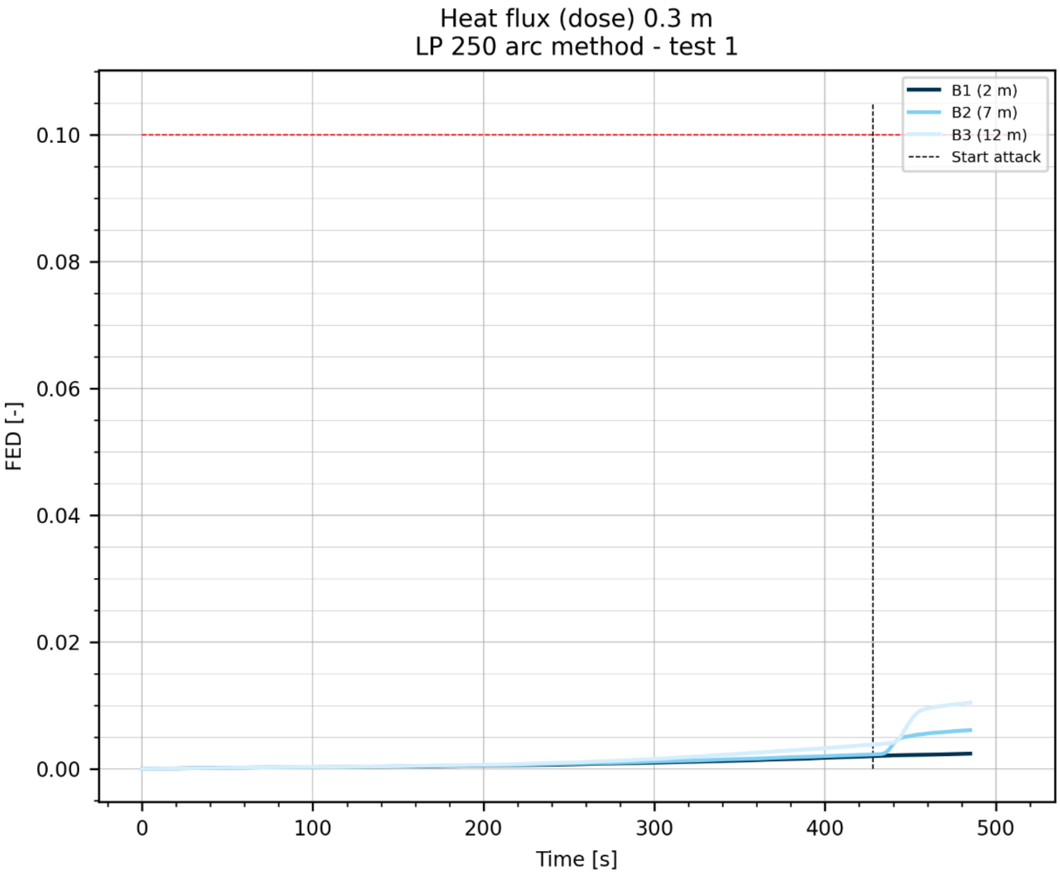

Asphyxiant gases (dose)
LP 250 3D pulse method - test 2
FED [-]
Time [s]
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500

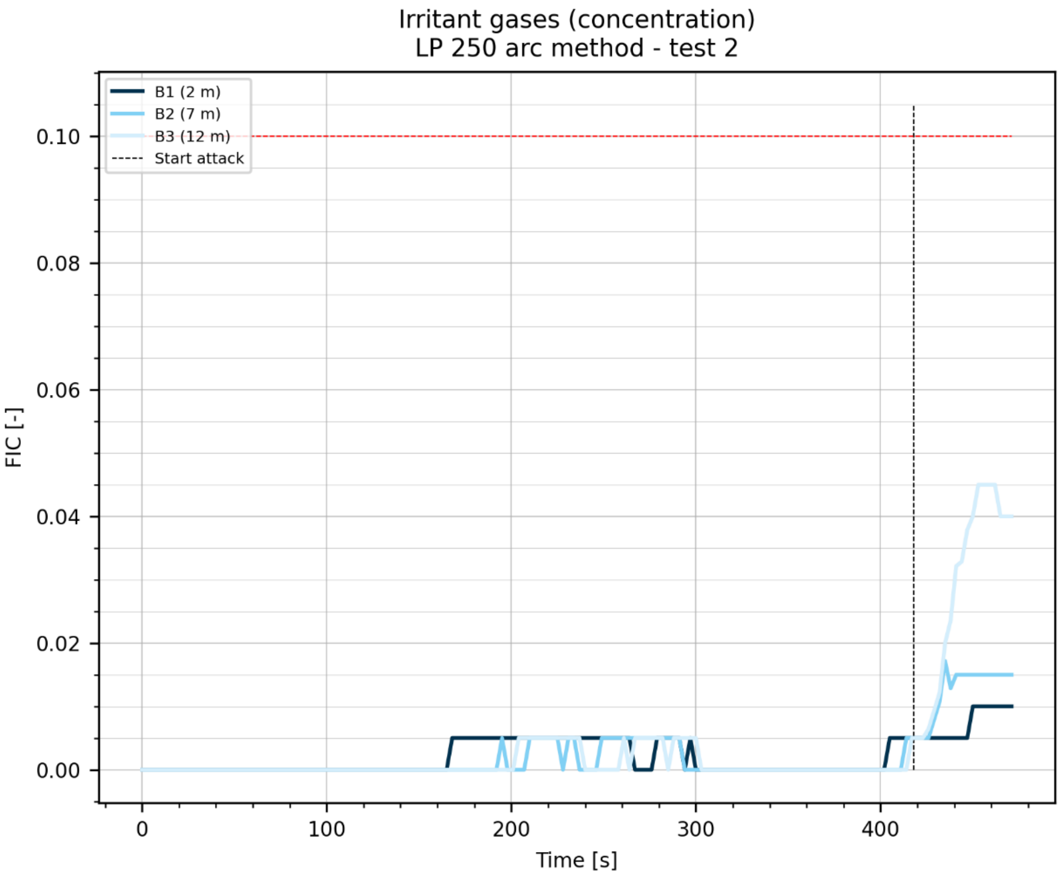

Heat flux (dose) 0.3 m
LP 250 3D pulse method - test 2
FED [-]
Time [s]
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500

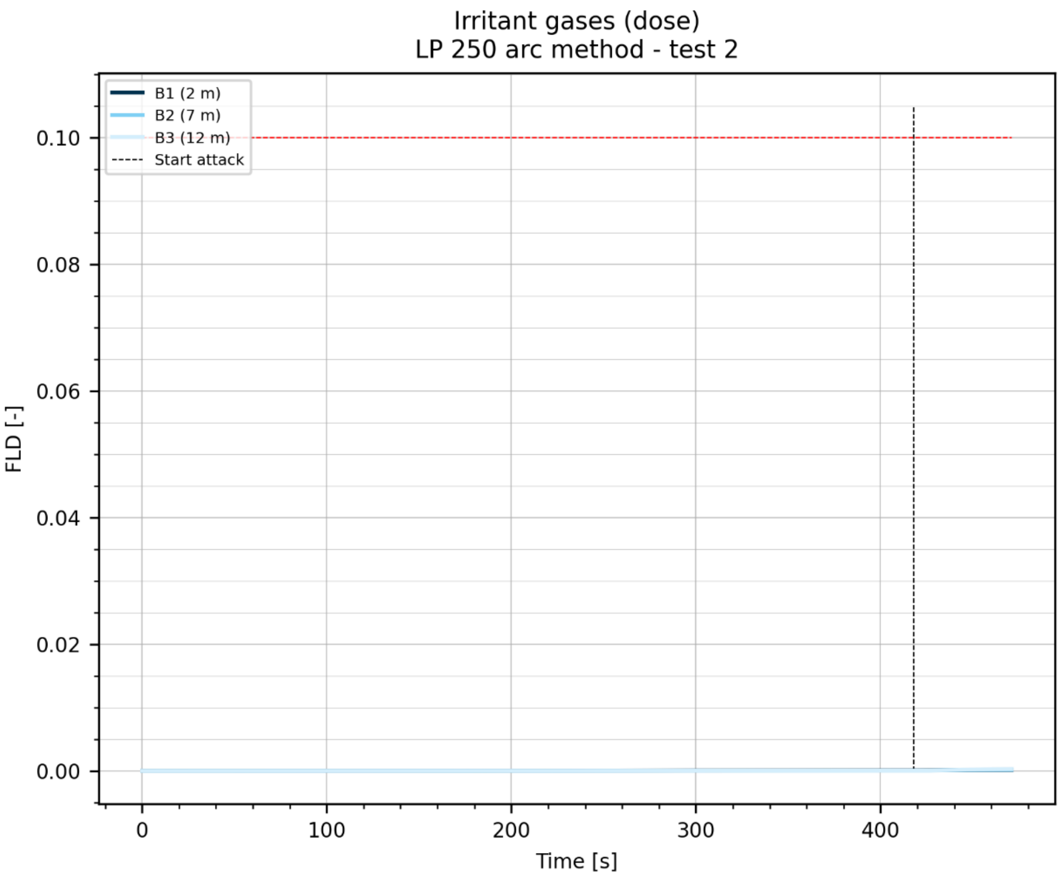

Irritant gases (concentration)
LP 250 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
0.10
0.08
0.06
0.04
0.02
0.00
FIC [-]
0
100
200
300
400
500
Time [s]

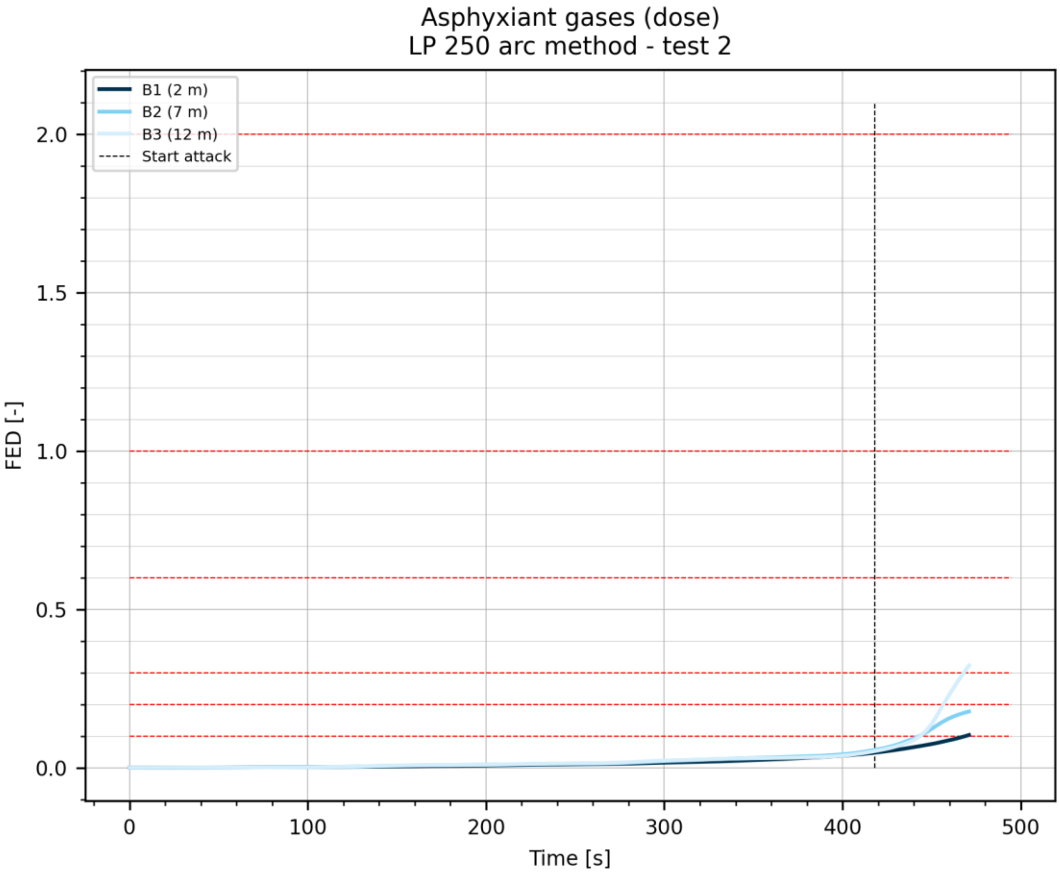

Irritant gases (dose)
LP 250 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
0.10
0.08
0.06
0.04
0.02
0.00
FLD [-]
0
100
200
300
400
500
Time [s]

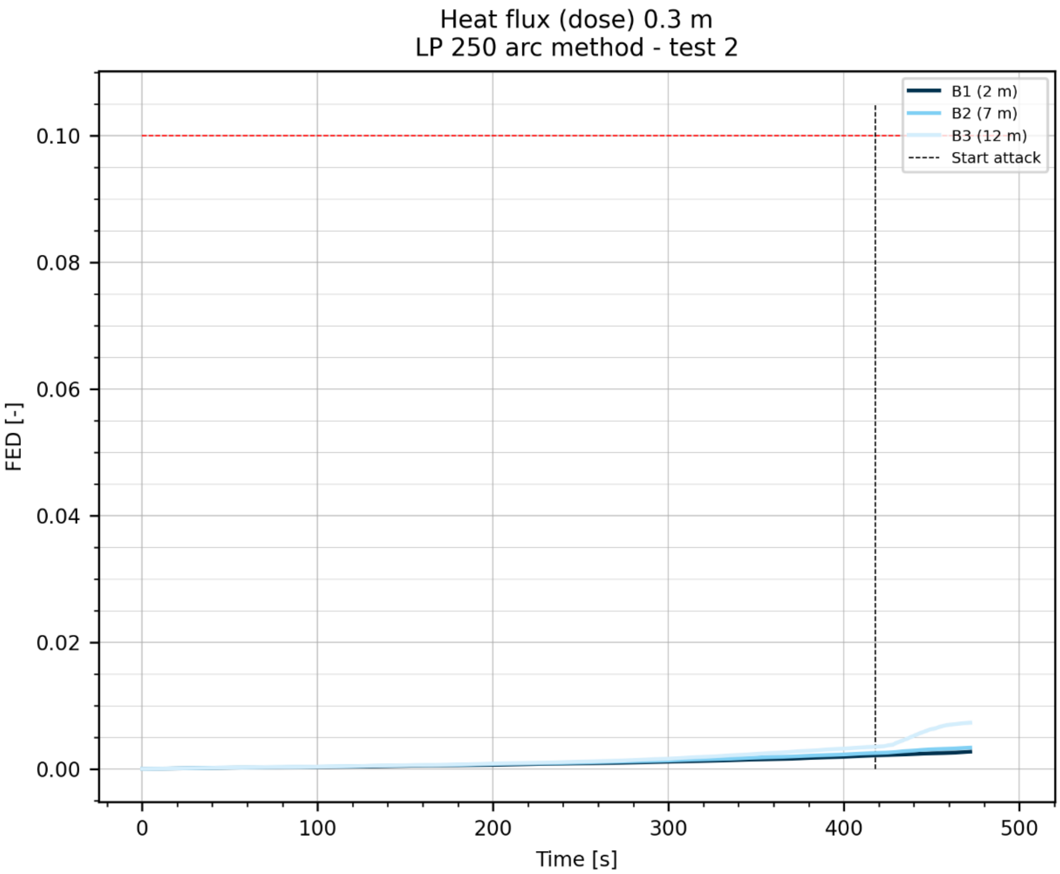

Asphyxiant gases (dose)
LP 250 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
500
Time [s]


Heat flux (dose) 0.3 m
LP 250 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
500
Time [s]


Irritant gases (concentration)
LP 250 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]


Irritant gases (dose)
LP 250 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]


Asphyxiant gases (dose)
LP 250 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500


Heat flux (dose) 0.3 m
LP 250 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.00
0.02
0.04
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0.10
0
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200
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400
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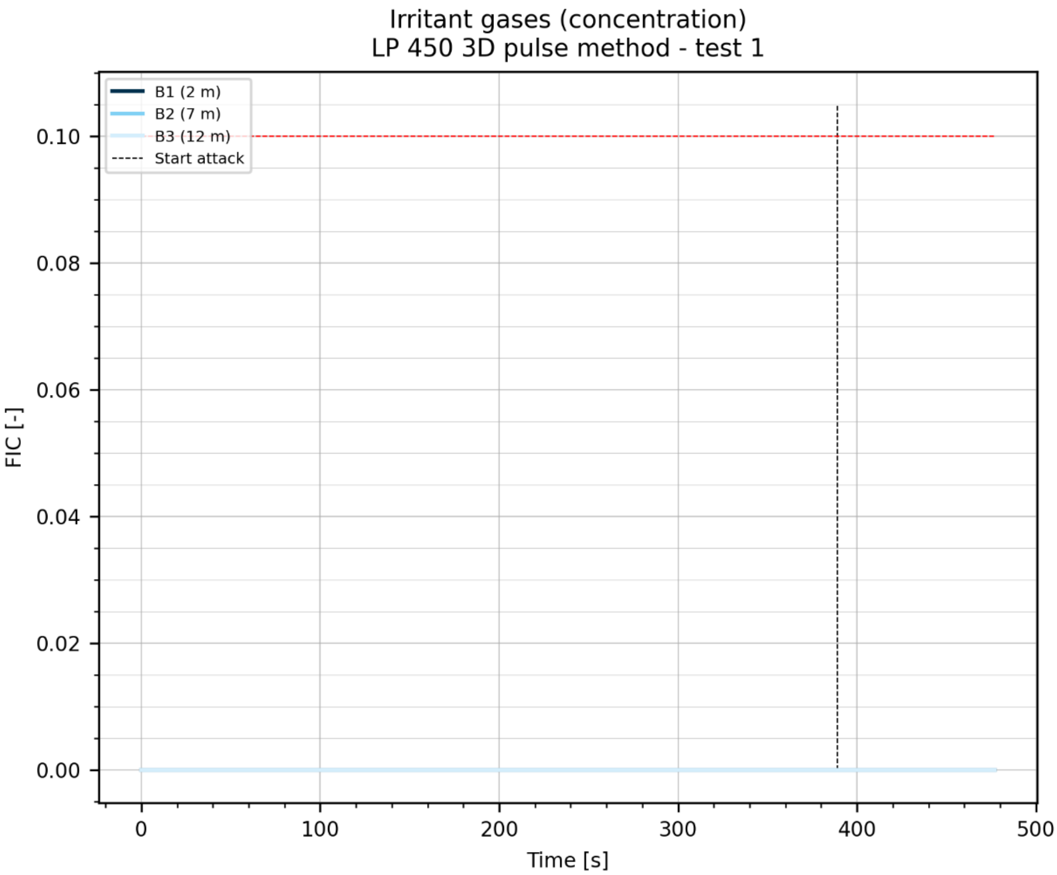
Irritant gases (concentration)
LP 450 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
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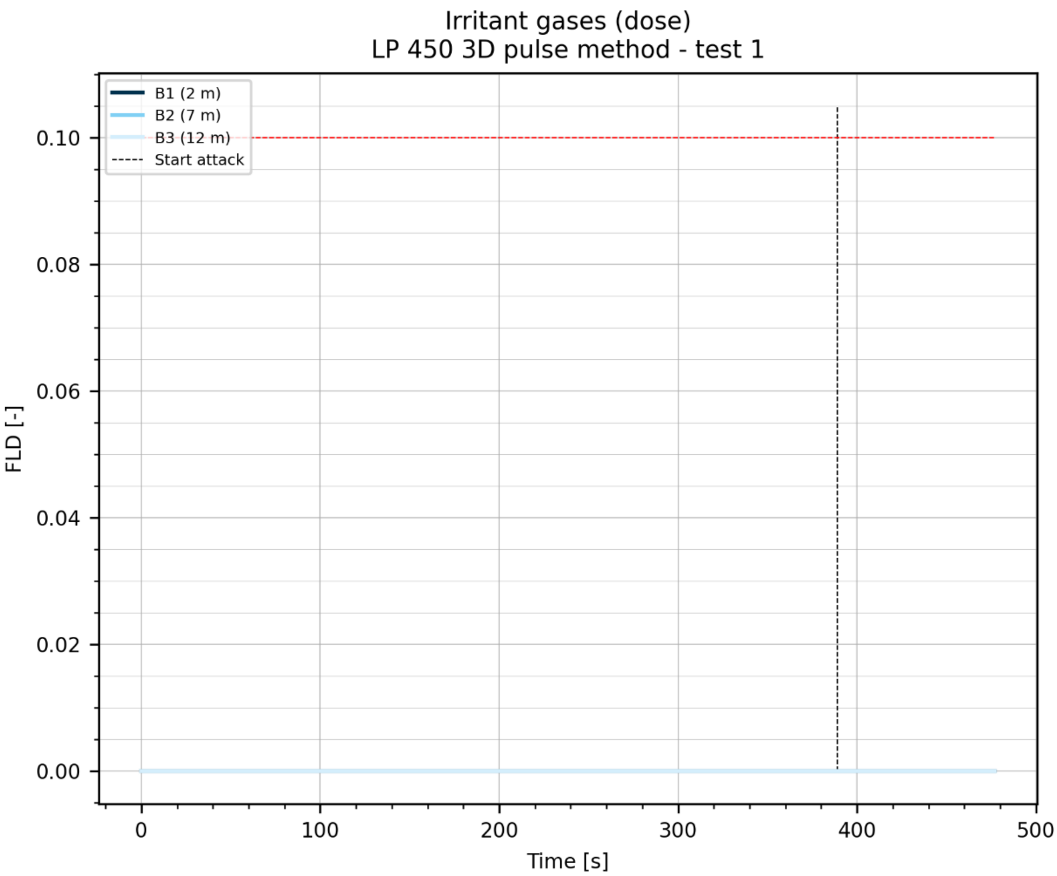
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500
Time [s]


Irritant gases (dose)
LP 450 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
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0.02
0.04
0.06
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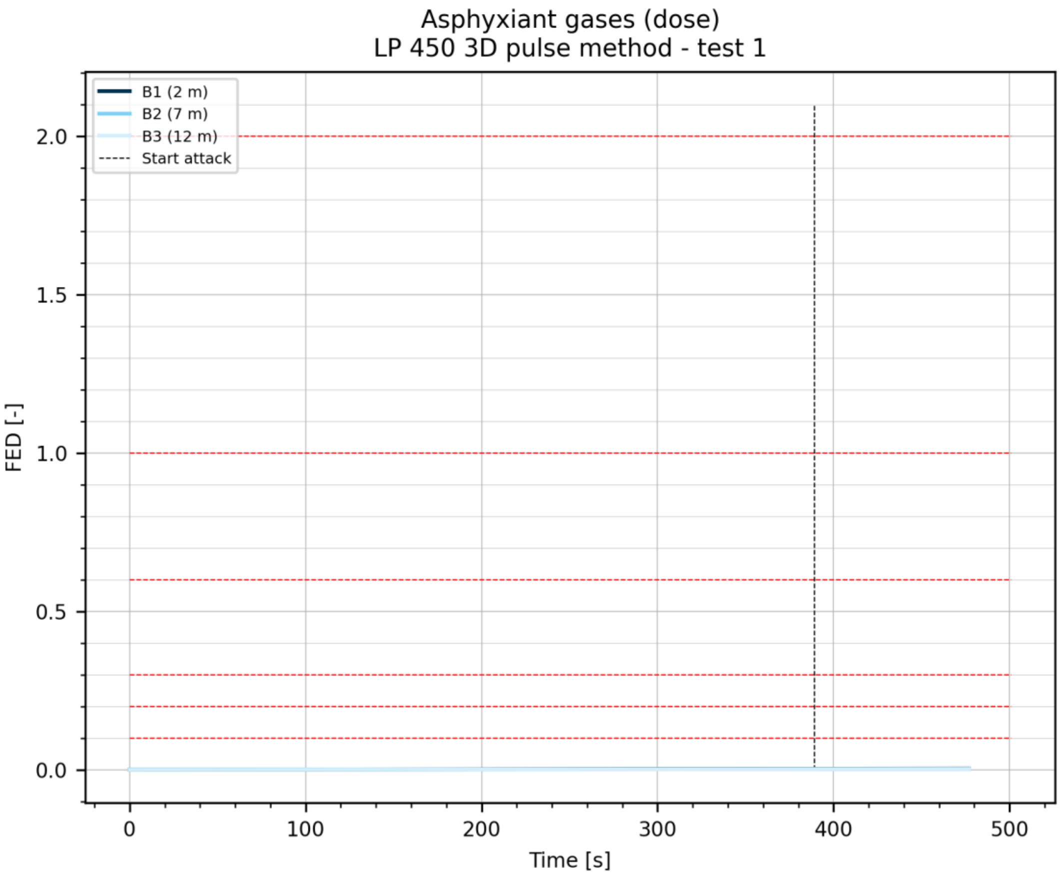
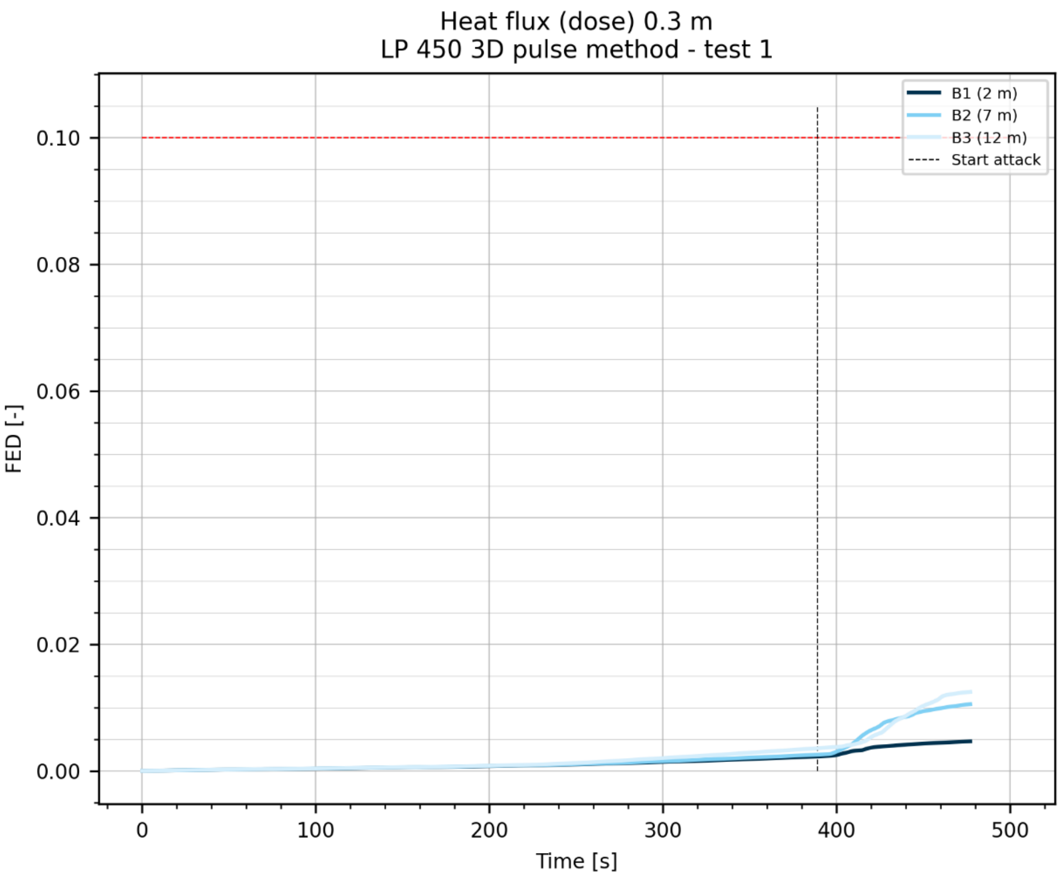
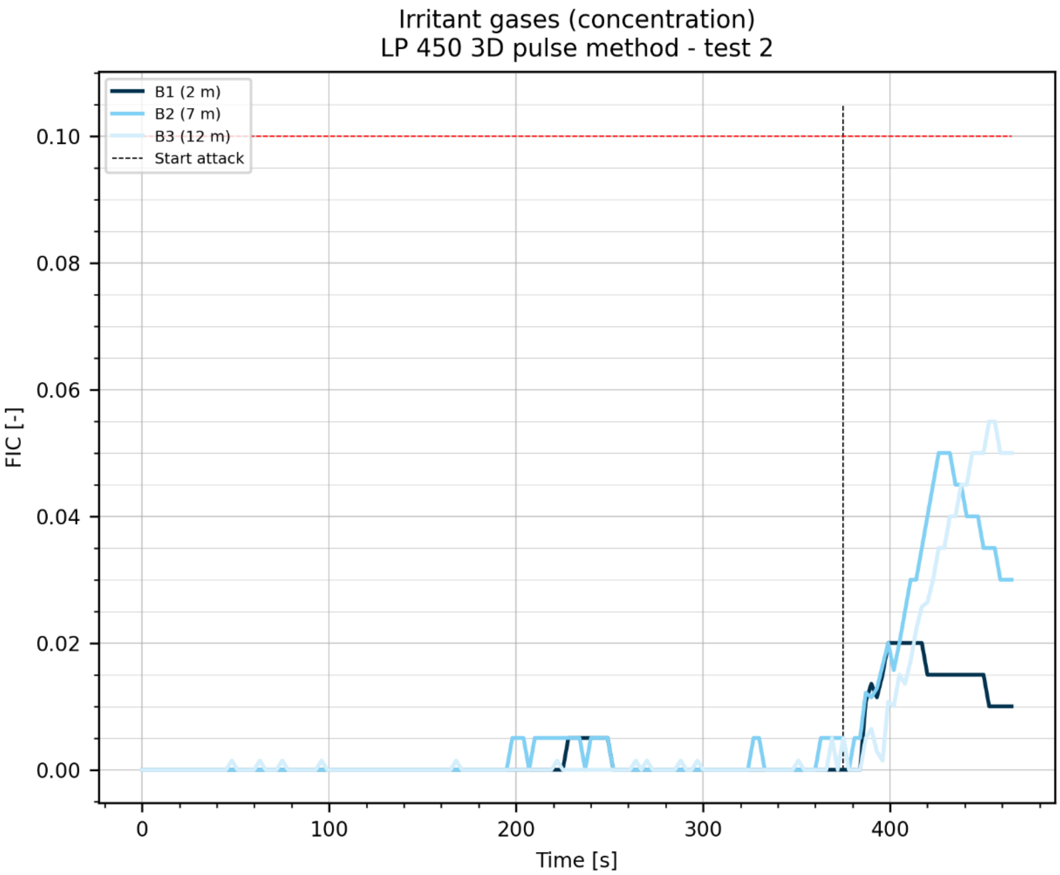
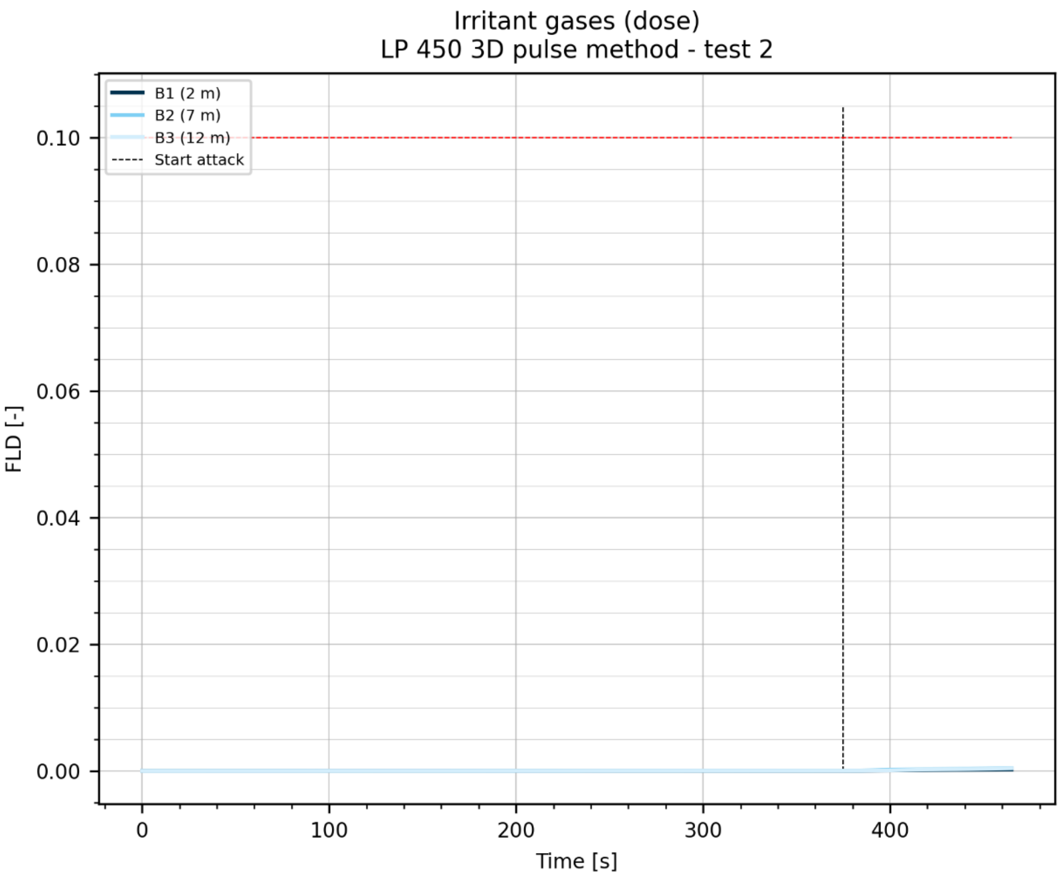
0.10
0
100
200
300
400
500
Time [s]


Asphyxiant gases (dose)
LP 450 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500


Heat flux (dose) 0.3 m
LP 450 3D pulse method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500



Irritant gases (concentration)
LP 450 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]



Irritant gases (dose)
LP 450 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
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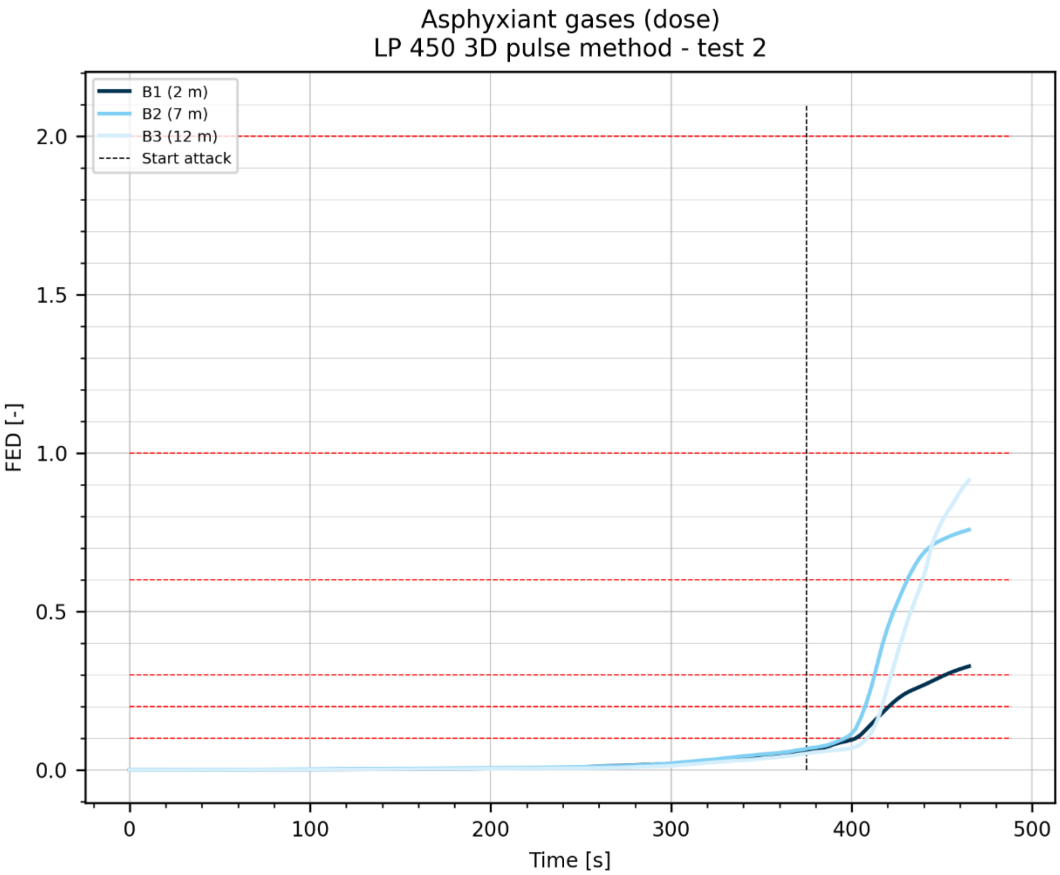
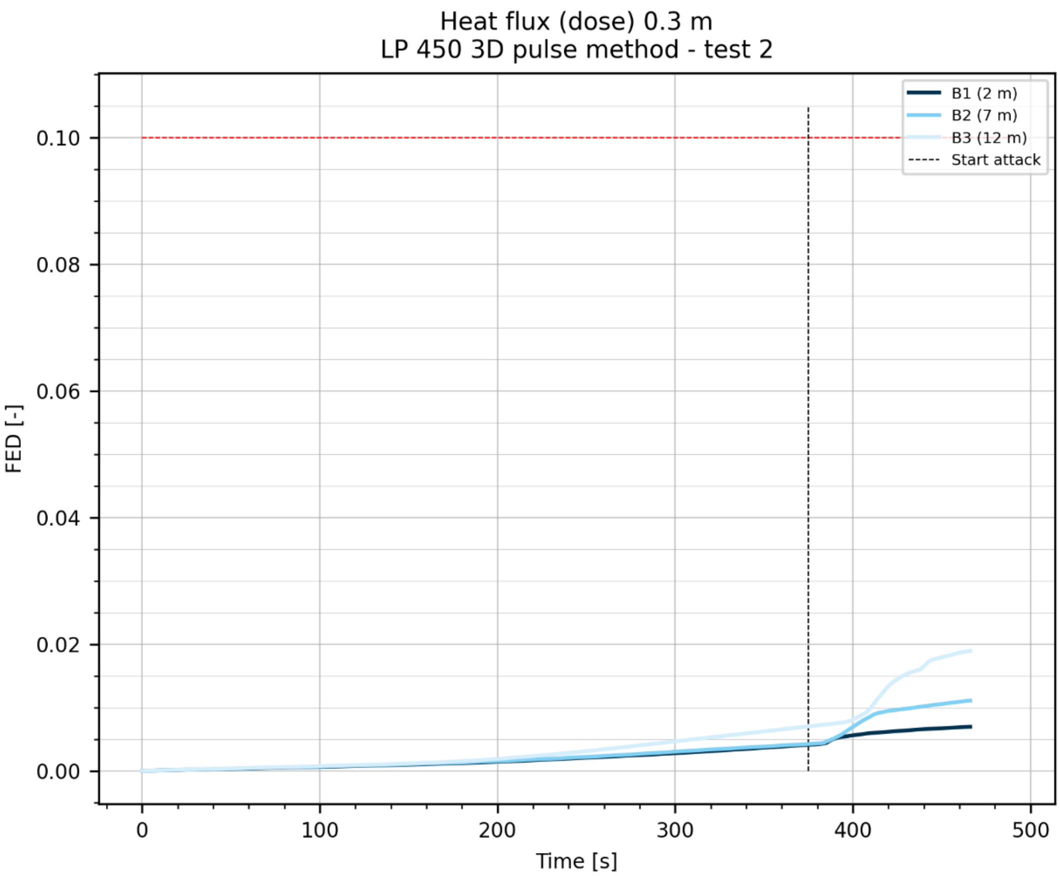
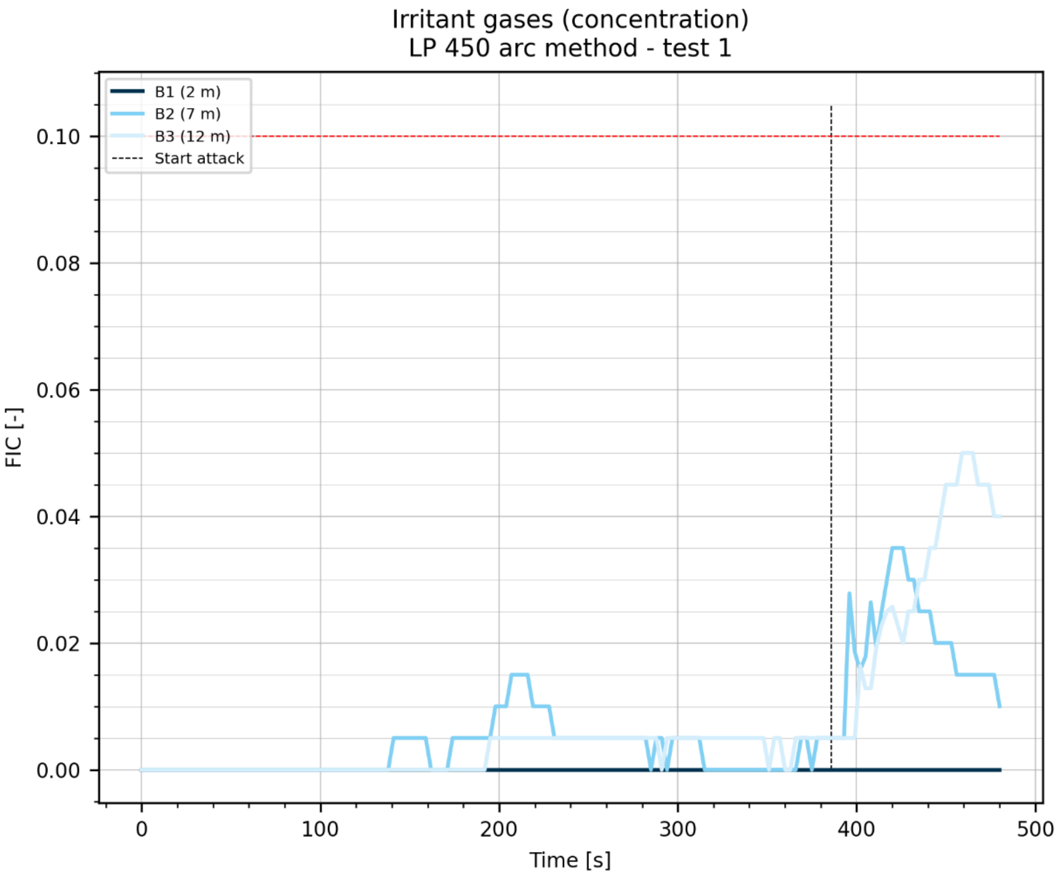
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]


Asphyxiant gases (dose)
LP 450 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
500
Time [s]


Heat flux (dose) 0.3 m
LP 450 3D pulse method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
500
Time [s]


Irritant gases (concentration)
LP 450 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
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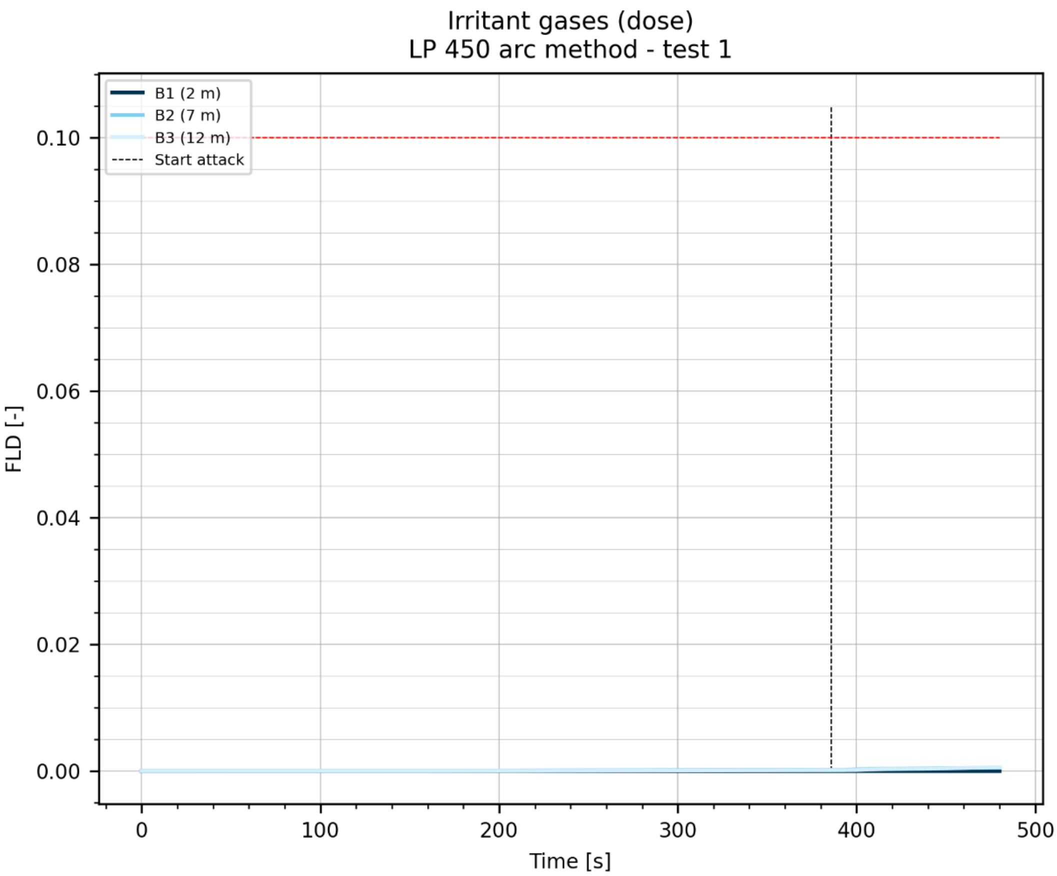
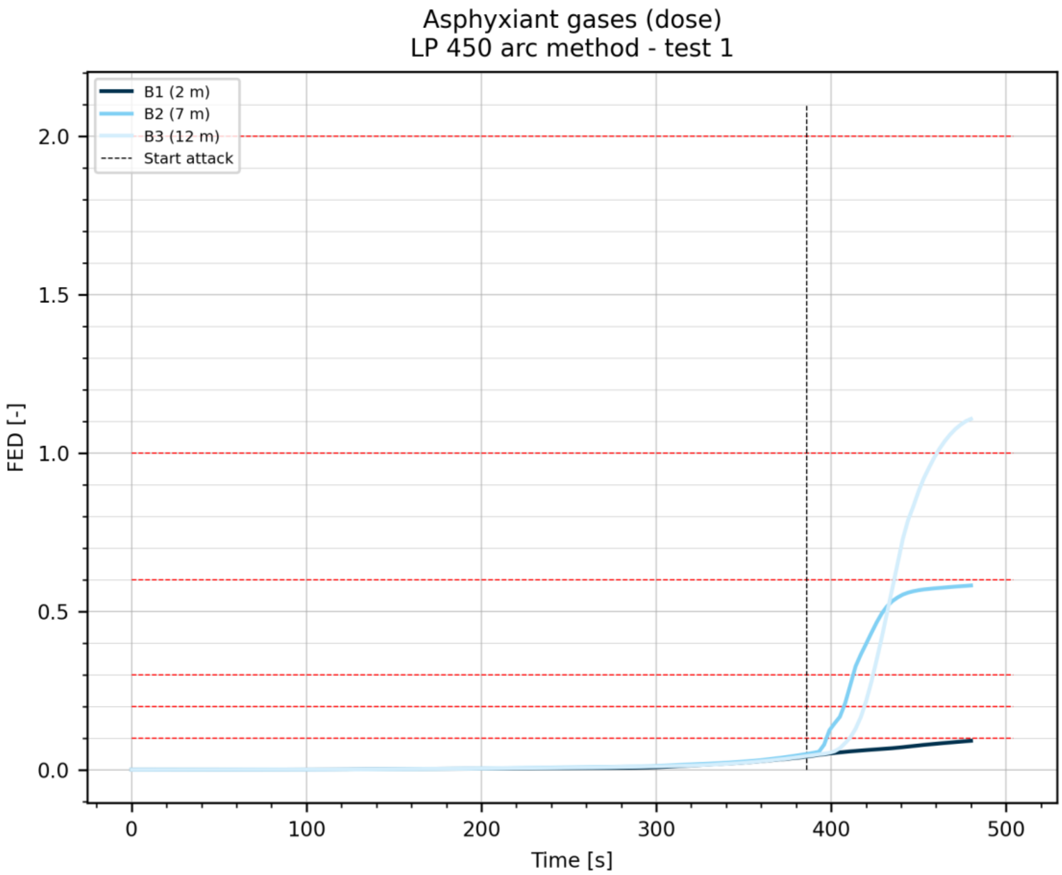
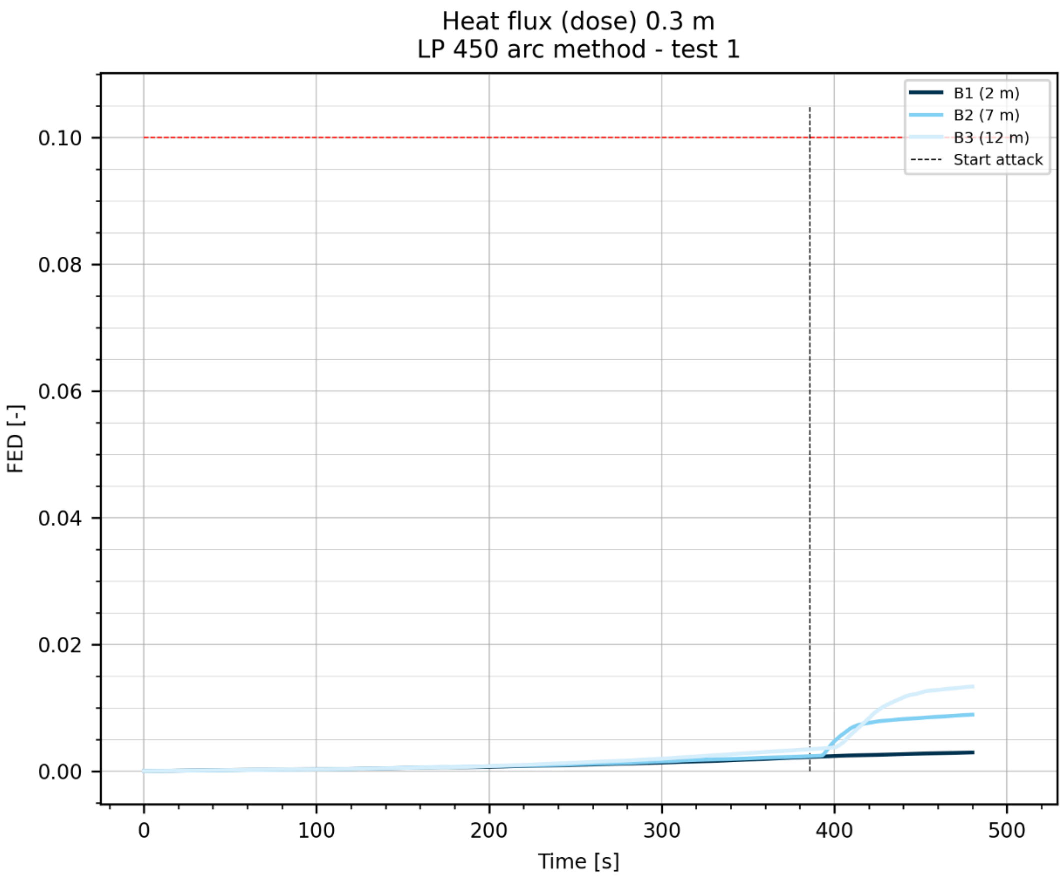
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500
Time [s]

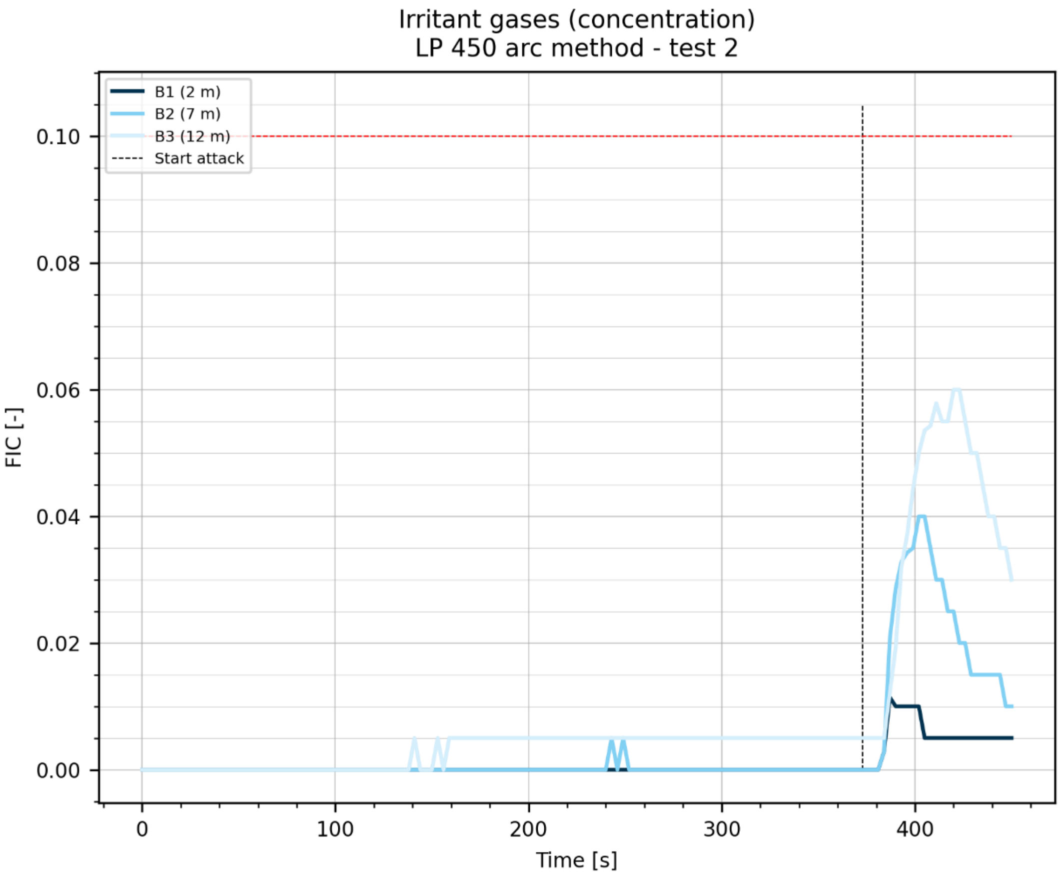

Irritant gases (dose)
LP 450 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500
Time [s]



Asphyxiant gases (dose)
LP 450 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400
500



Heat flux (dose) 0.3 m
LP 450 arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
500


Irritant gases (concentration)
LP 450 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
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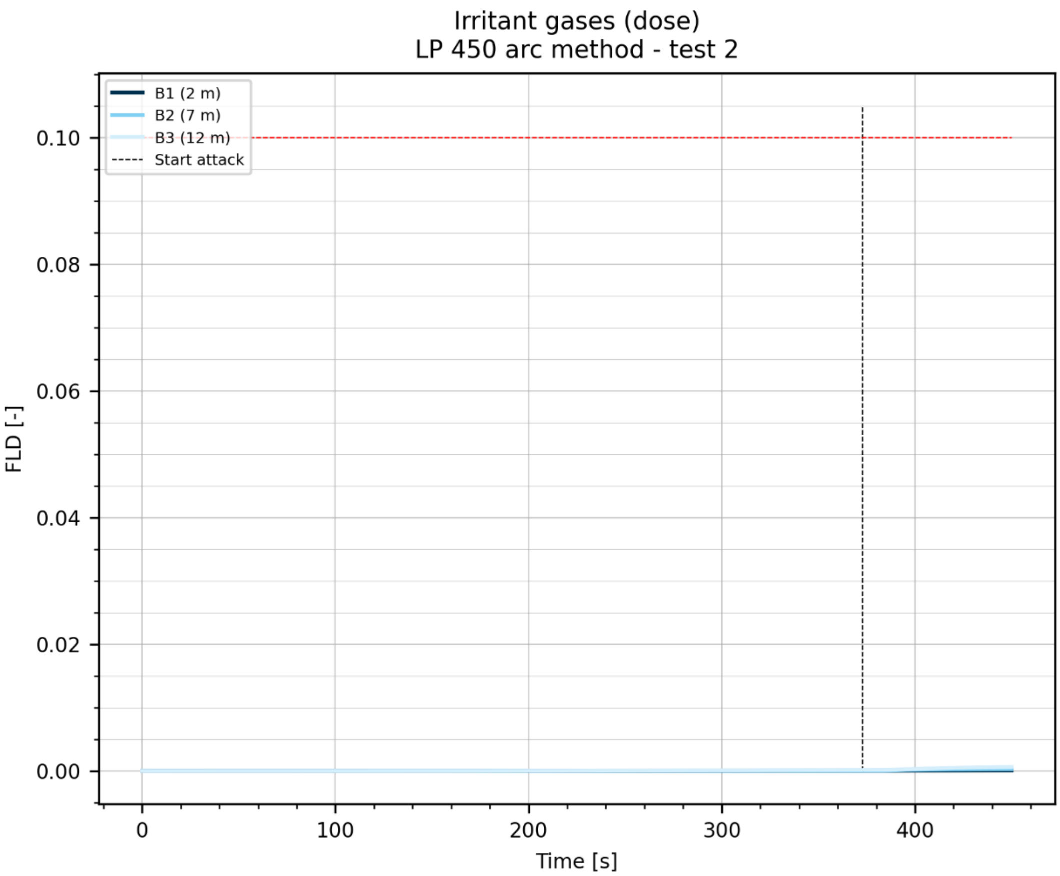
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]


Irritant gases (dose)
LP 450 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
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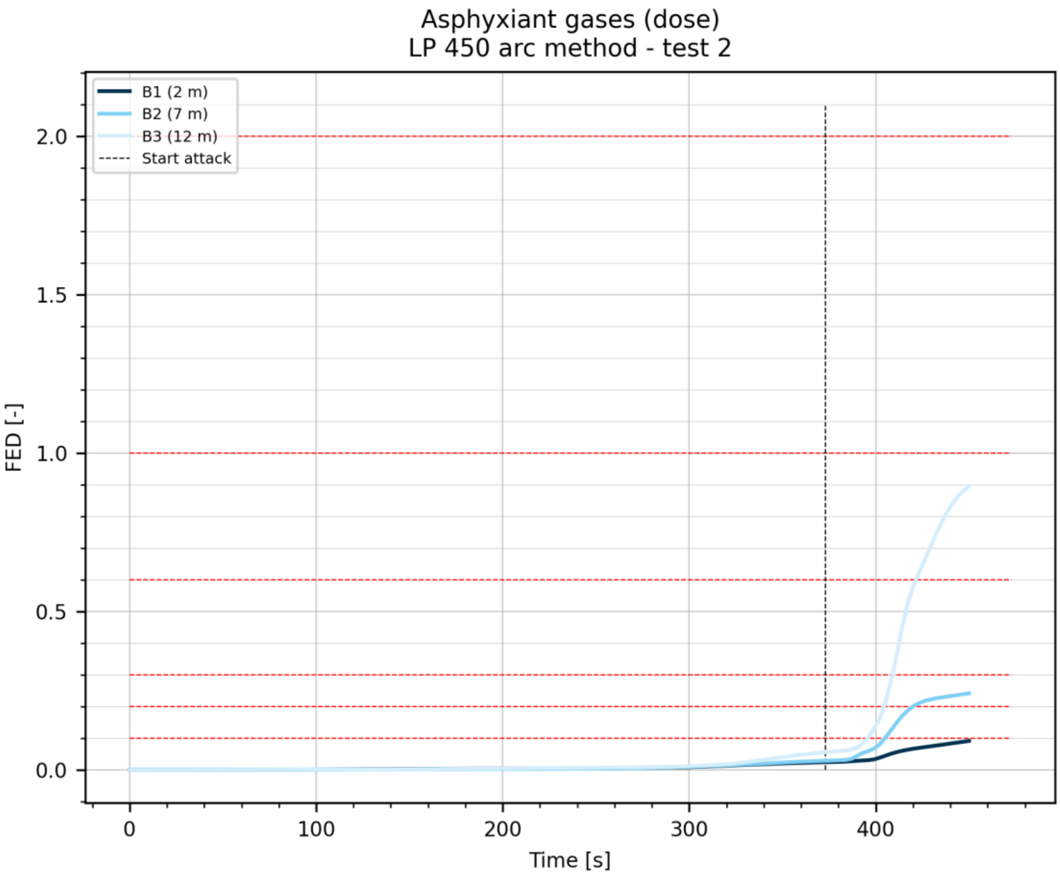
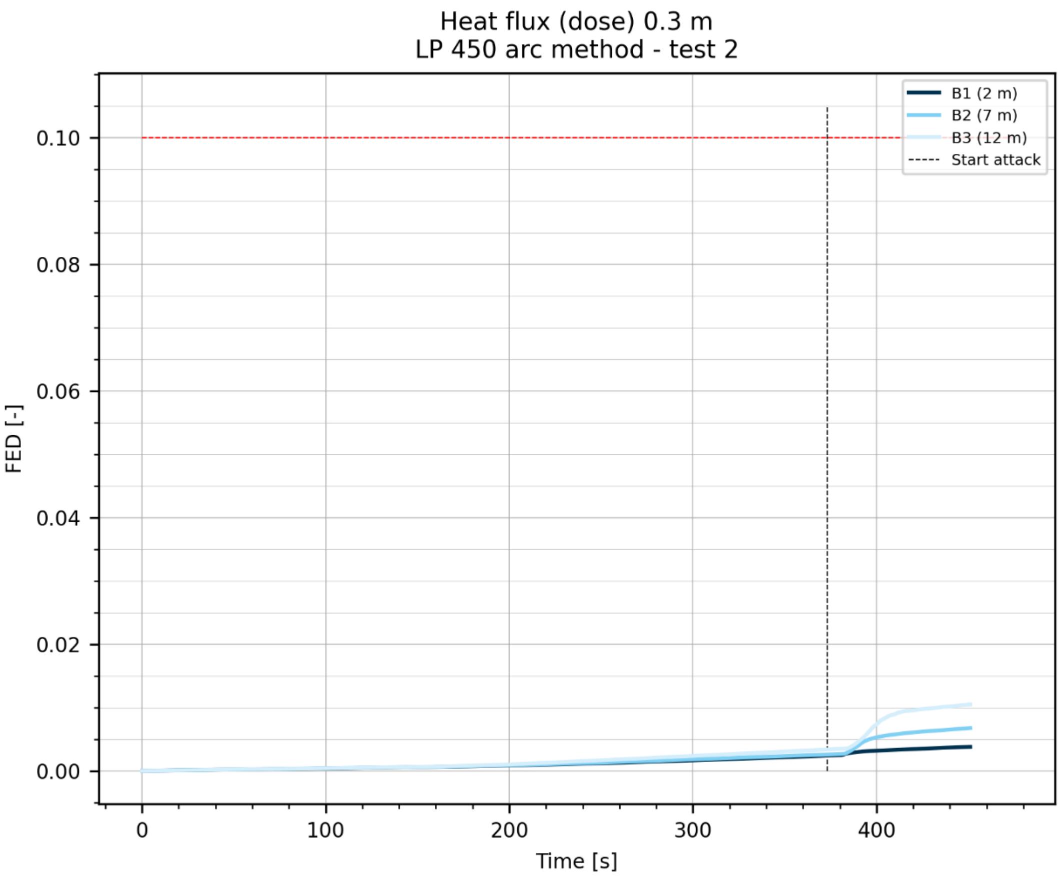
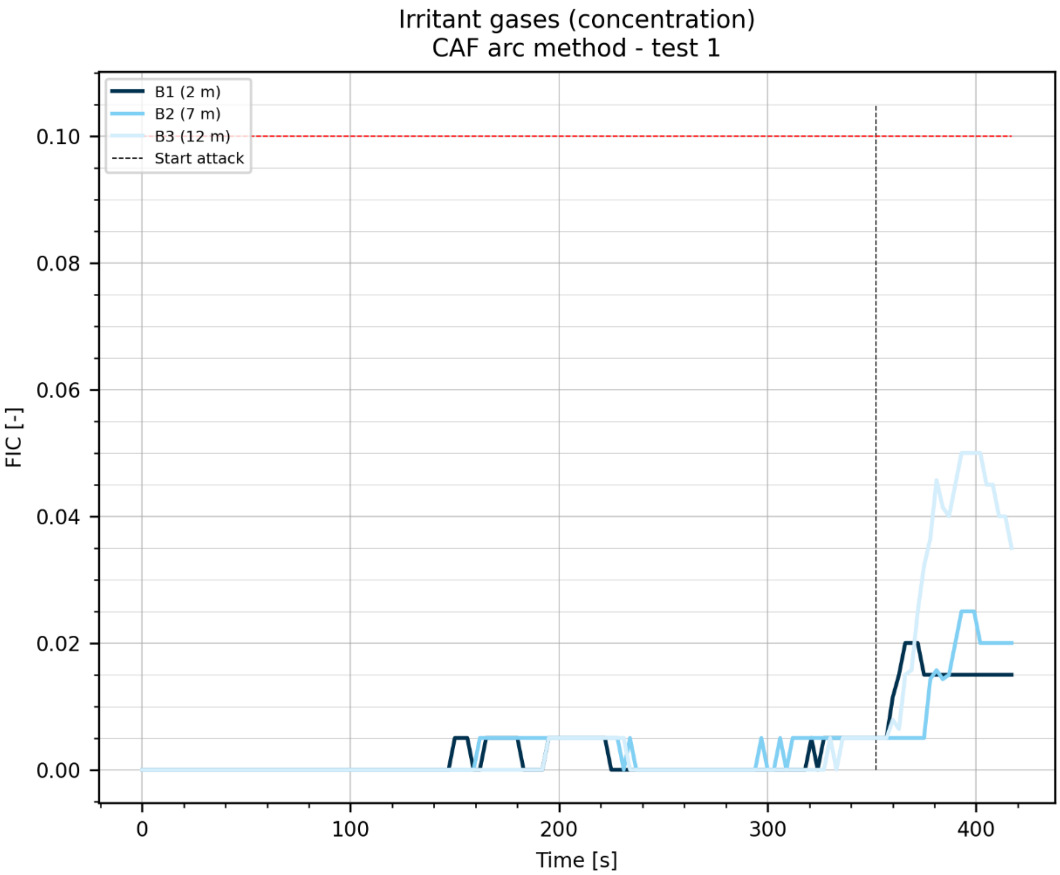
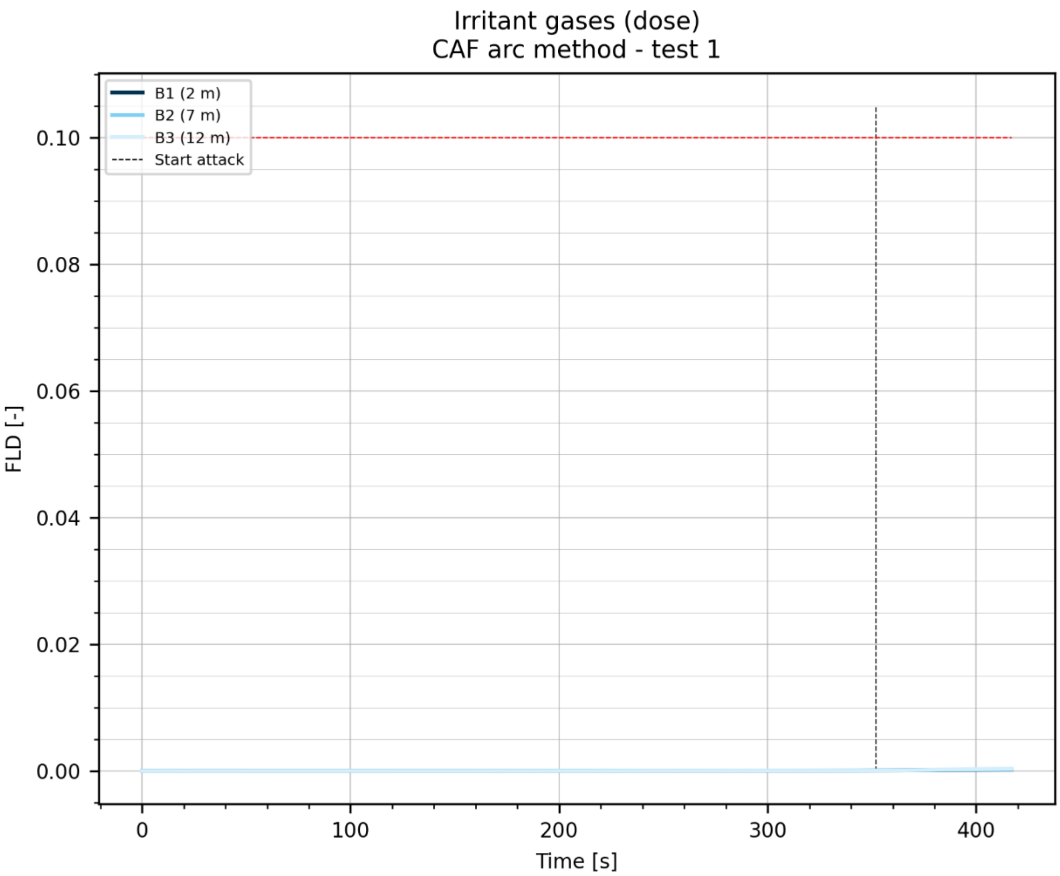
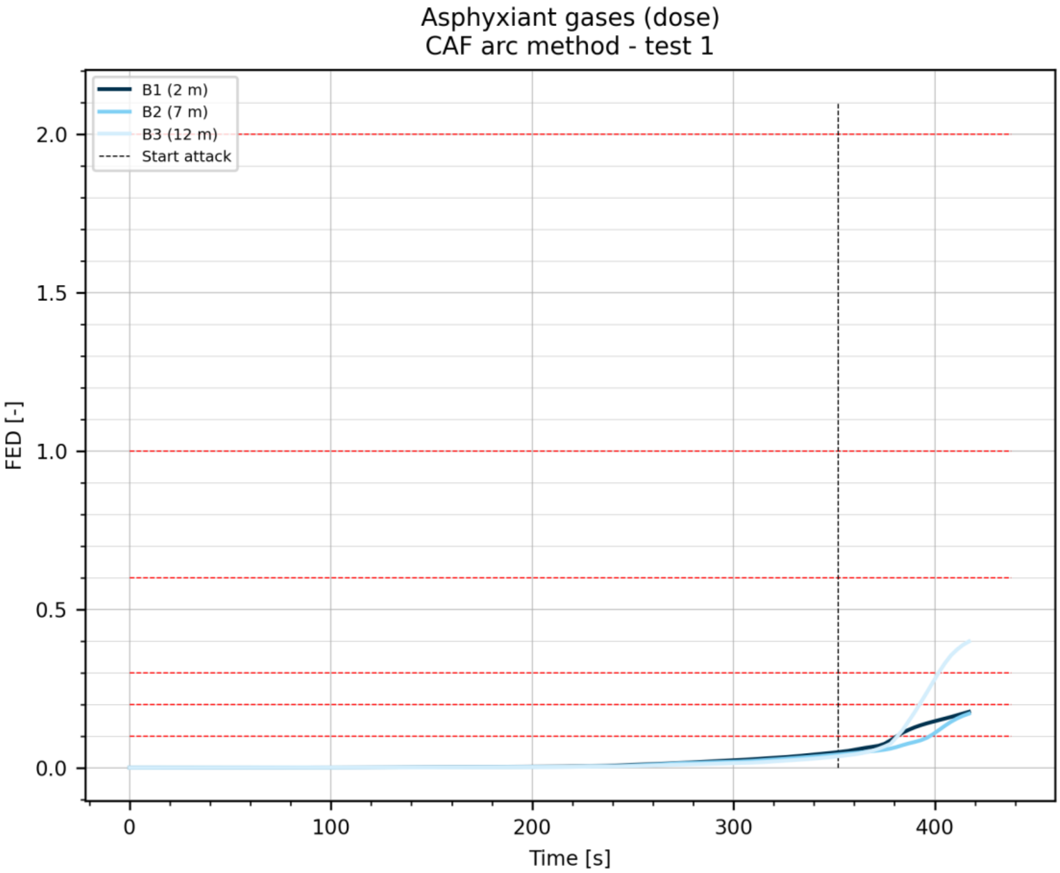
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]


Asphyxiant gases (dose)
LP 450 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400

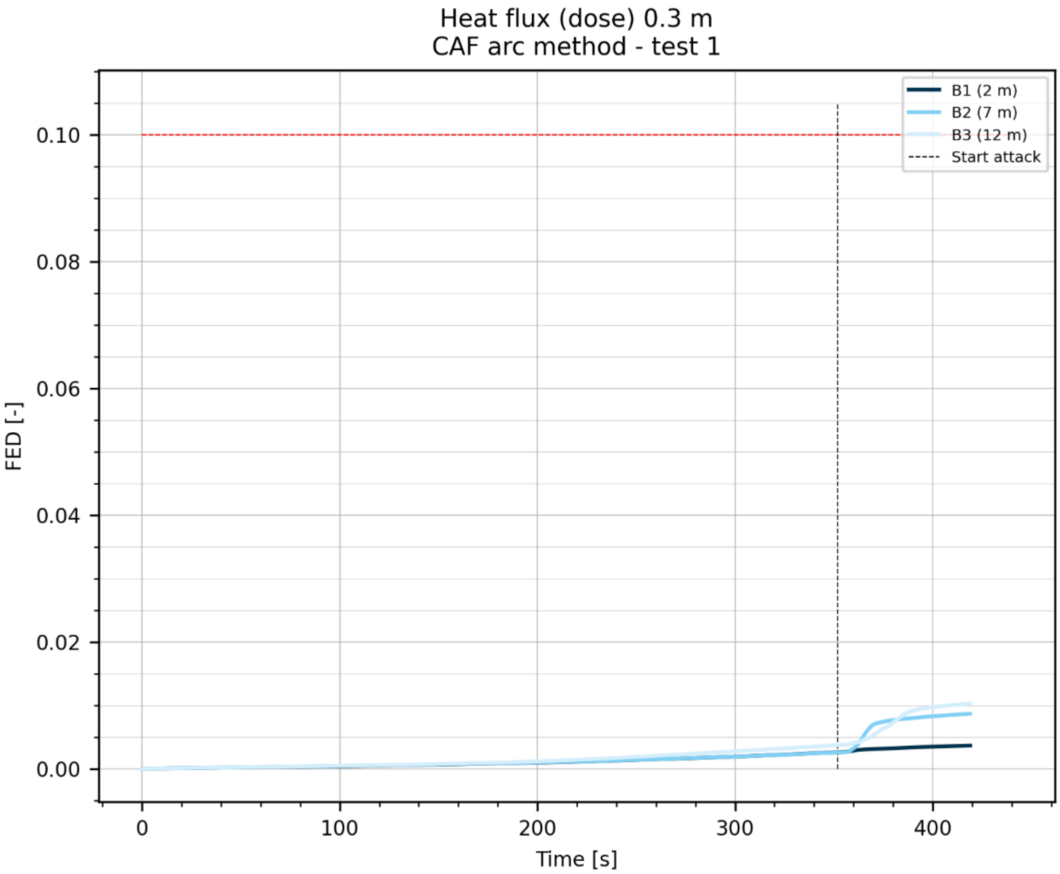

Heat flux (dose) 0.3 m
LP 450 arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400


Irritant gases (concentration)
CAF arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

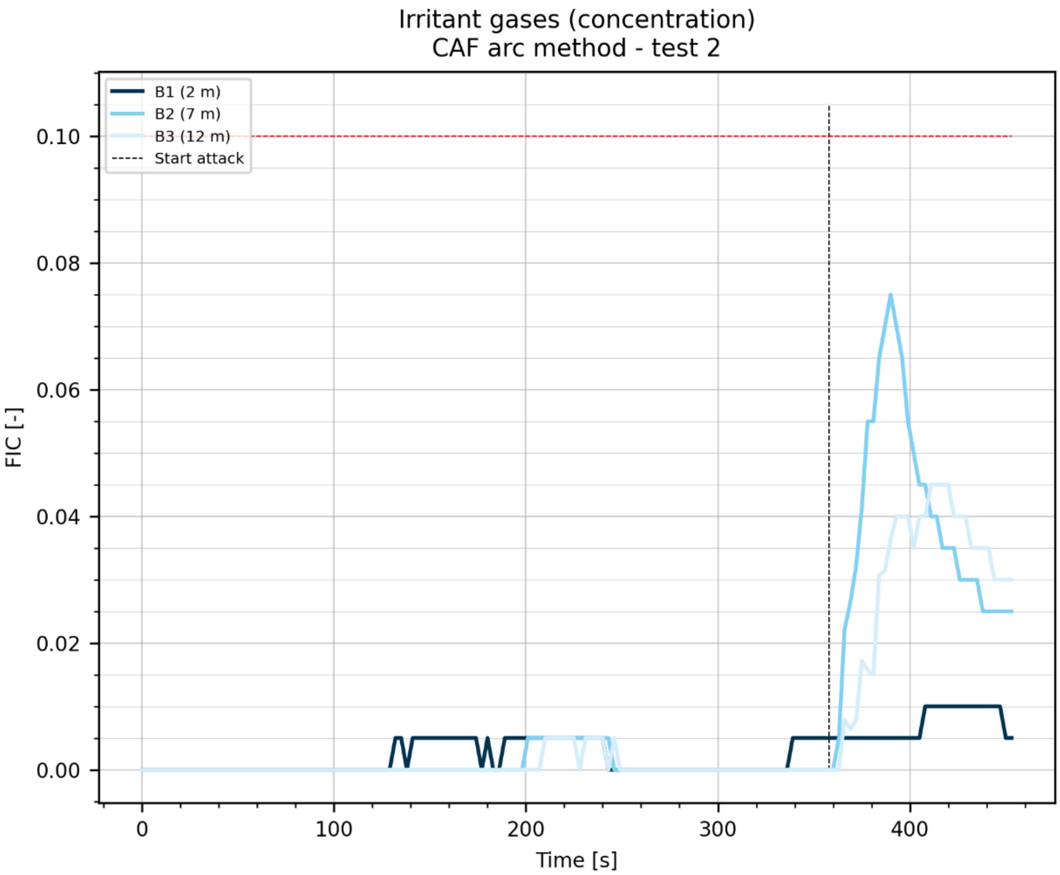

Irritant gases (dose)
CAF arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400
Time [s]

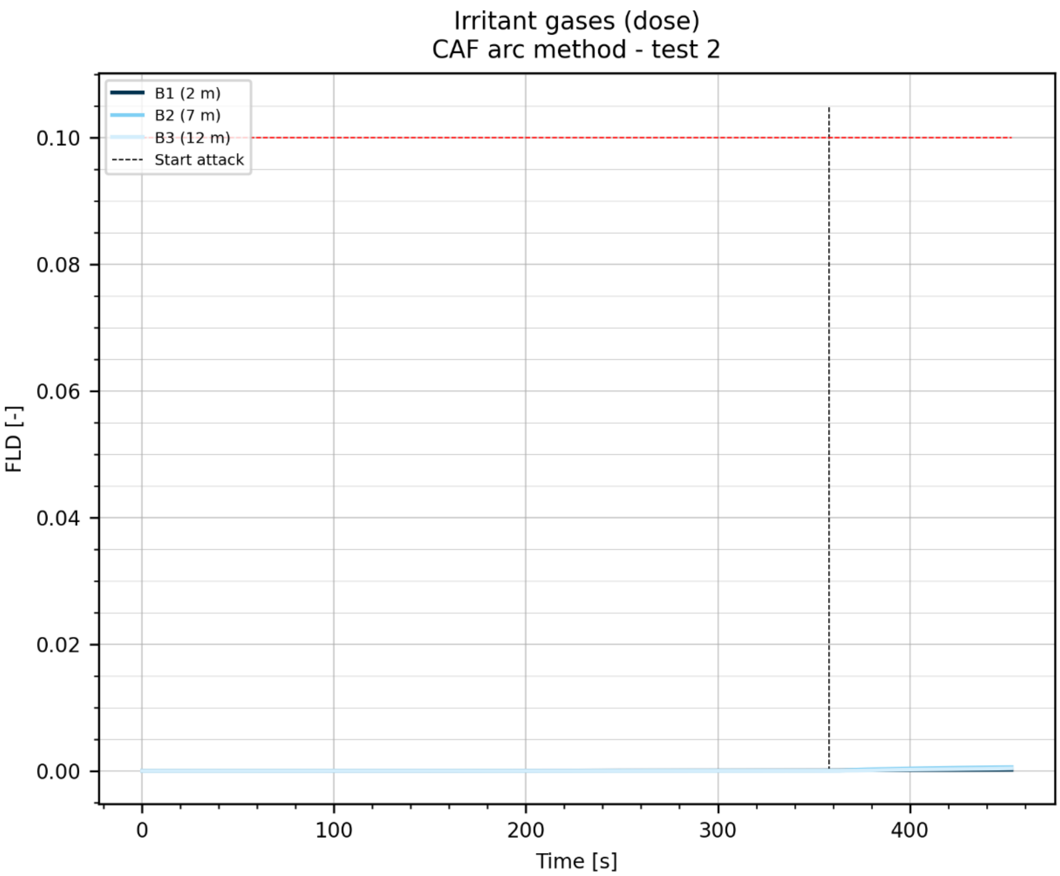


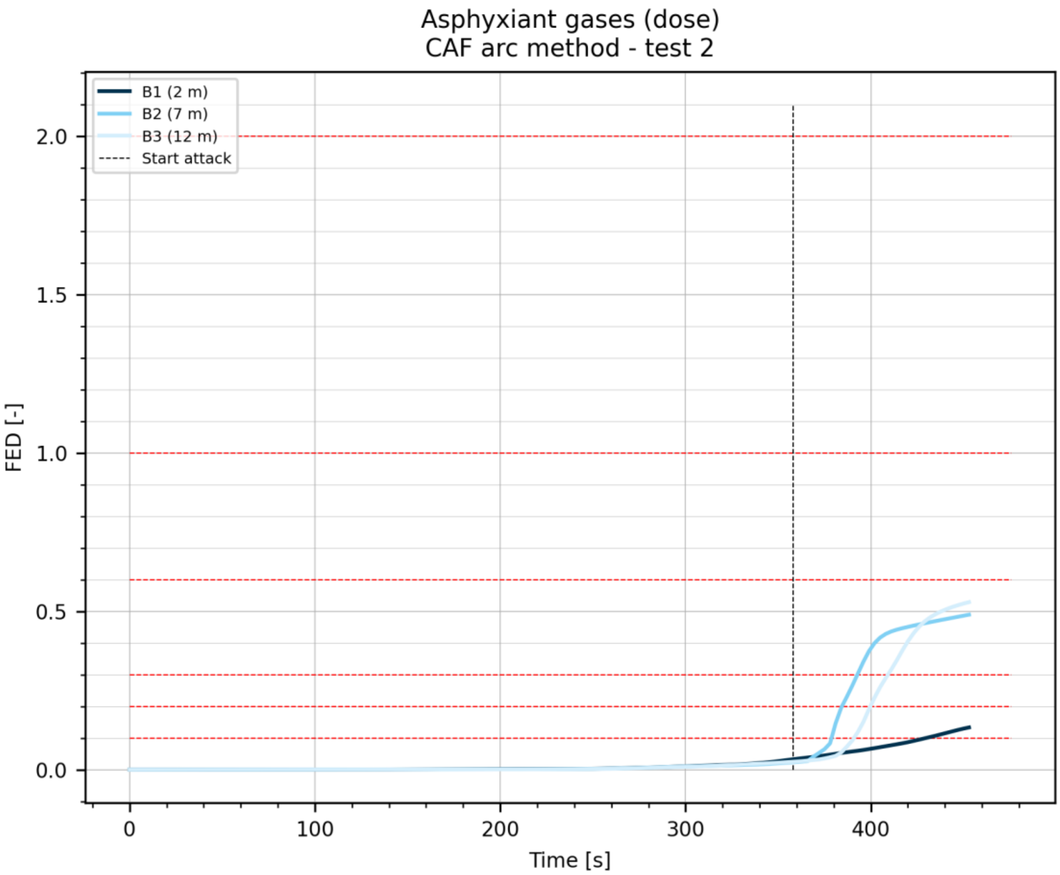
Asphyxiant gases (dose)
CAF arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.0
0.5
1.0
1.5
2.0
0
100
200
300
400

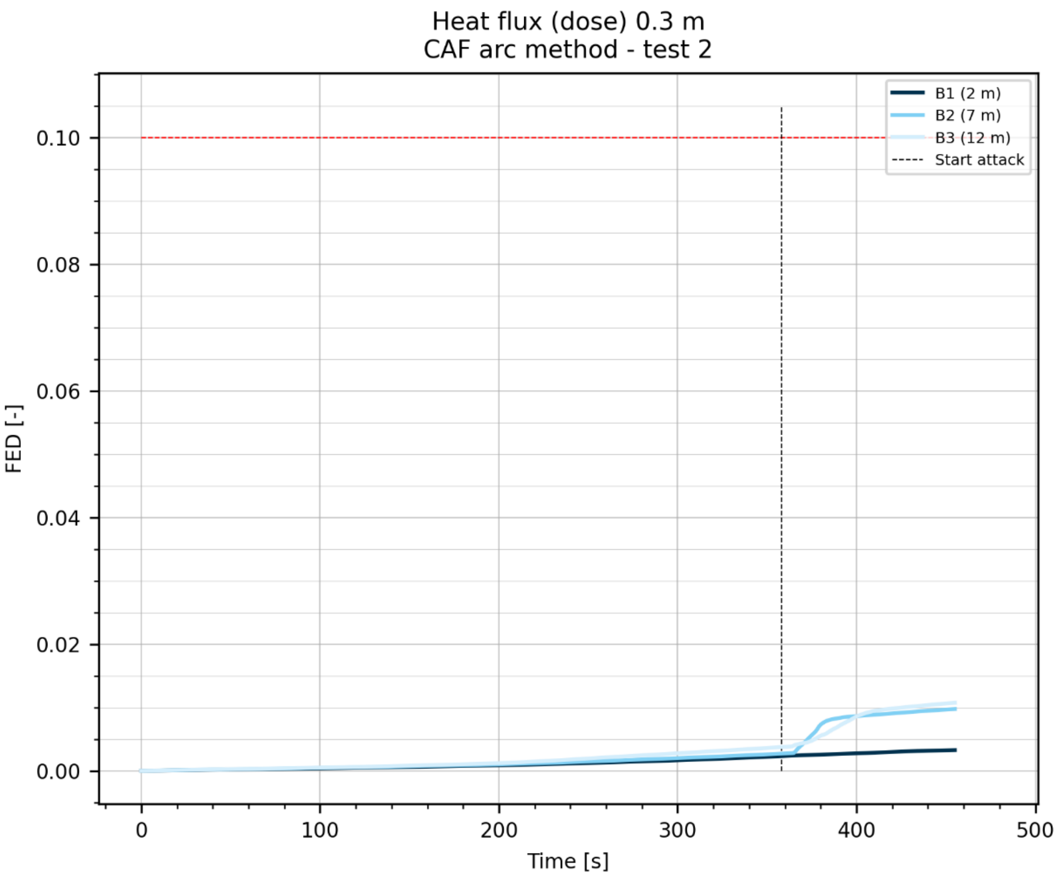


Heat flux (dose) 0.3 m
CAF arc method - test 1
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.00
0.02
0.04
0.06
0.08
0.10
0
100
200
300
400


Irritant gases (concentration)
CAF arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FIC [-]
Time [s]


Irritant gases (dose)
CAF arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FLD [-]
Time [s]


Asphyxiant gases (dose)
CAF arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400


Heat flux (dose) 0.3 m
CAF arc method - test 2
B1 (2 m)
B2 (7 m)
B3 (12 m)
Start attack
FED [-]
Time [s]
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
500