# SOLIT Safety of Life in Tunnels

## Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems

## Scientific Final Report of the SOLIT² Research Project prepared by the SOLIT² Research Consortium

## Annex 2:
## Selected Results of Full Scale Fire Tests

Gefördert durch:

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This document was produced with best knowledge and with great care. These documents and its annex documents are for the use of experienced fire protection engineers. A case by case evaluation of the application of this document for a specific case must be done by the reader.

**Classification:**

The scientific research project SOLIT² - Safety of Life in Tunnels was promoted by the German ministry of economics and technology (BMWi; Code No. 19S9008) based on a decision of the German Bundestag. All members of the consortium have set up separate scientific reports related to their aim of study. Most outstanding outcomes have been concluded in the present Guidance. The Guideline has been set up jointly among the consortia members and presents the common final report. The Guideline is part of the work package. All individual reports are available on behalf of the project coordinator.

**Imprint:**

**Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems.**

**Annex 2: Selected Results of Full Scale Fire Tests**

This document is based on the main document „Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems". The following other Annex documents are available:
Annex 1: Status analysis
Annex 3: Engineering Guidance for Fixed Fire Fighting Systems in Tunnels
Annex 4: Application Example for a Risk Analysis
Annex 5: Safety Evaluation of Technical Equipment
Annex 6: Life Cycle Costs of Technical Equipment
Annex 7: Fire Tests and Fire Scenarios for Evaluation of FFFS

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## Table of contents

# 1. Introduction

During the SOLIT² research program, a large scale fire test program with more than 30 full scale fire tests was carried out. The major aim of this test program was to study the effects of FFFS in tunnels particularly regarding the possibilities of compensation.

This document presents selected results of this fire test program.

It should be emphasized that the results, test data and its interpretation is only applicable to the specific fixed firefighting system, which was used in the tests having been part of the SOLIT² test program.

The data can be used as an indication, but similar test data should be available to evaluate the effectiveness of a specific FFFS system for a specific tunnel. For details see also Annex 7 “Fire Tests and Fire Scenarios for Evaluation of FFFS”

# 2. Test Tunnel

The fire tests were performed in the test tunnel of San Pedro des Anes, located in the northern part of Spain.

The tunnel has a length of 600 m with a slope of 1%. The width of the original tunnel is 9,5 m with a height of 8,20 m.

To perform fire tests with semi-transversal ventilation and to protect the tunnel, some modifications were made prior to the test program.

Over a length of 450 m a suspended ceiling with a height of 5,20 m was installed. Furthermore, in the surrounding of the fire area, additional walls were installed to provide a tunnel with of 7,50 m.

*Ventilation System*

The tunnel of San Pedro des Anes is equipped with several ventilation systems. At one end of the tunnel, 6 jet fans are installed, creating a longitudinal air flow of maximum 6,5 m/s.

Furthermore, 8 dumpers with a free area of ~ 1m² in the vicinity of the fire place were used for the tests with semi transversal ventilation.

The semi transversal ventilation of the test tunnel of San Pedro des Anes is designed to deal with free burning fires of approx. 30 MW.

# 3. Fire Scenarios

Two fire scenarios were used for these tests. To represent severe truck fires, a standardized fire load with wooden pallets was used.

To evaluate the effects of a FFFS on liquid (class B) fires and fires with a large smoke production, diesel pool fires were used. This scenario does not well represent a spillage fire, e.g. from a tank rupture, as liquid in a pool does not have a similar burning behavior, as the pool will contain the liquid. Real life spills will have a depths of s few mm only and thus will be very limited in the burning time, further the fuel will quickly be diluted by the water sprayed on it.

A further detailed description can be found in Annex 7.

The following description of the fire load corresponds to the example fire tests for the presentation of a selection of test results.

## 3.1 Class A Fire Load (Truck Fire)

During the SOLIT project a realistic fire load of a truck was developed. This is simulated by wooden Euro pallets. This fire load during a free burning test has a potential HRR of 150 MW. Such fire load is considered as a standard and was also used for other well recognised full scale fire test programs.

### 3.1.1 *Mock Up*

The loading area of a truck is considered as place of the highest fire load of a truck. This part of the truck is simulated by wooden (EURO) pallets with a humidity of less than 20 %. This fire load can be considered as repeatable and due to the open areas of the pallets, well ventilated.

Other parts on the vehicle, such as plastic parts of the drivers cab are covered by this worst case assumption.

To simulate the impact of driver’s cabin and solid rear doors on the ventilation conditions inside the fire load, steel plates were mounted onto the racks on the front and back side of the mock up. The longitudinal sides were stabilized with racks. This is on the one hand representing the supporting structure of a truck and one the other hand preventing pallets from down out during the test.

The complete mock-up was prepared by wooden pallets. A basement of wooden pallets was separated by fire protection boards from the main fire load.

Two different heights of the basement as part of the mock up were used to simulate a truck fire:

- Basement of 1,5 m.
- Basement of 0,2 m.

A different size of basement was used to simulate a greater distance between the top of the mock up and the FFFS, hence to simulate a higher tunnel.

As fire load above the basement the following amount of pallets was used.

Number of pallets: 408

Total weight: ~9600 kg

Total energy content: ~140 GJ

This amount of pallets represents the main fire load of a typical truck with a height of 4,0 m and has a potential HRR of approx. 150 MW.

### 3.1.2 *Fire Load*

#### 3.1.2.1 Wooden pallets

As fire load, wooden pallets (Euro pallet) were used. These standardized pallets have the following dimensions:

Length: 0,80 m

Width: 1,20 m

Height: 0,16 m

Weight: ~ 20 kg

#### 3.1.2.2 PVC Tarpaulin

A non fire retardant PVC tarpaulin was used as an external cover for the pallets in some of the fire tests in order to investigate its influence on the fire

*Figure 2: Mock up with PVC tarpaulin and basement*

spread and to the water mist suppression system. The following dimensions of PVC tarpaulin was used to wrap the mock up: 10,5 m x 7,5 m as shown in Figure 2.

### 3.1.3 *Ignition source*

The ignition source consisted of 3 pools with gasoline. Each pool had the dimensions of 0,15 m² Three pools were positioned together on the side of the truck below the second pile of pallets seen from upstream. Each of the three pools were filled up 2,0 L gasoline. All pools were ignited together at the same time.

With type of ignition source, a fire occurring from a

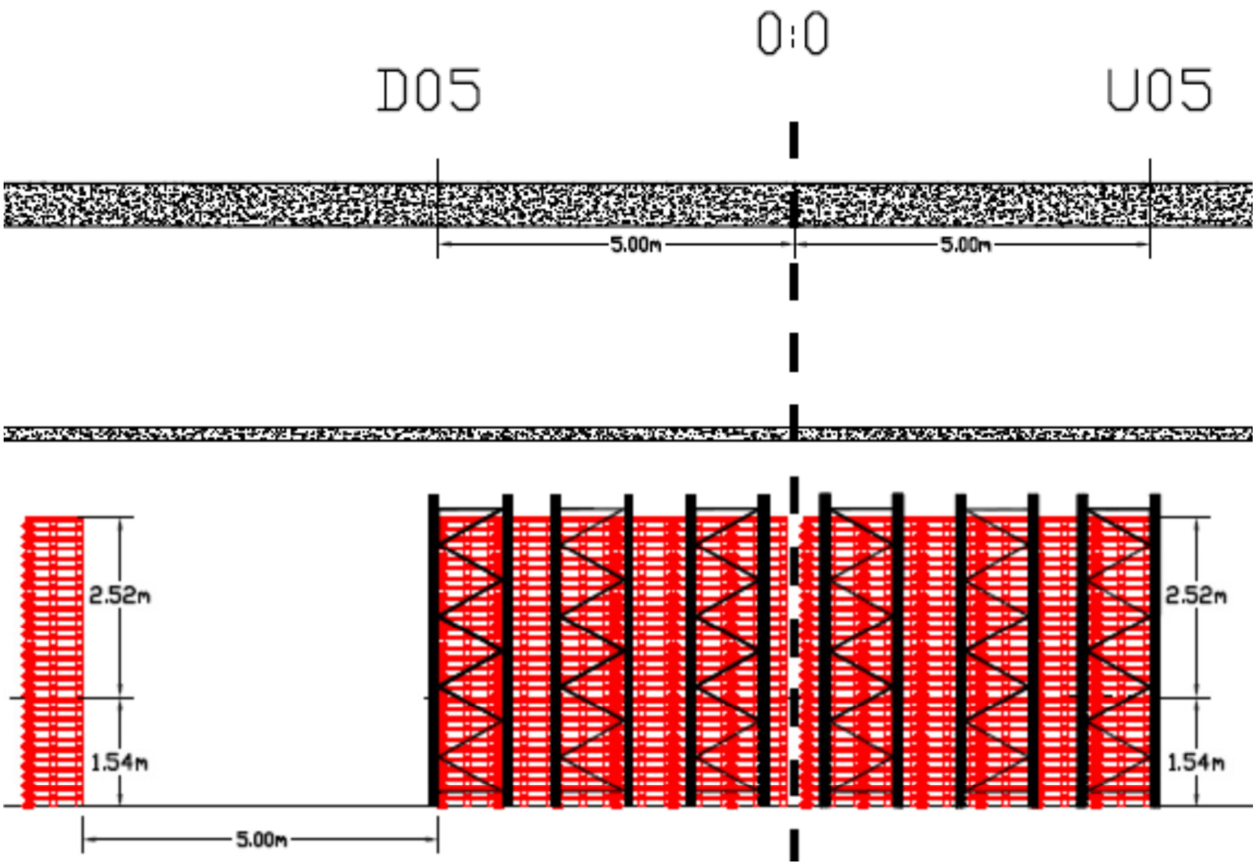


*Figure 1: Class A truck fire load with a high basement structure.*

technical default or other small starting source should be simulated.

3.1.3.1 Target

To evaluate the fire spread to adjacent objects, an additional fire load was placed on the downstream side of the fire load, called the target object. The target object had the same height and width than one stack of the original fire load. The target was positioned at a distance of 5,0 m downstream from the original fire load.

### 3.2 Class B Fire Load (Pool Fire)

Liquid fires, usually called pool fires, are realised in pools with diesel. These scenarios were to a large extend developed during the UPTUN und SOLIT fire tests and simulate a fire with a defined HRR.

It should be clearly emphasized that realistic spillage fires or fires resulting from a rupture of a tank can only be partly simulated with such pool fires that are used for fire tests.

In reality, it is very unlikely that the fuel collects up to a height that is typically used for pool fire scenarios in fire tests (e.g. 10 cm) and that the liquid is contained by a steel pool.

During this research project pool fires with a nominal HRR of the following value were carried out:

- HRR 5 MW
- HRR 60 MW
- HRR 100 MW

Due to the tunnel environment and ventilation conditions, fires with a real HRR of 160 MW were achieved.

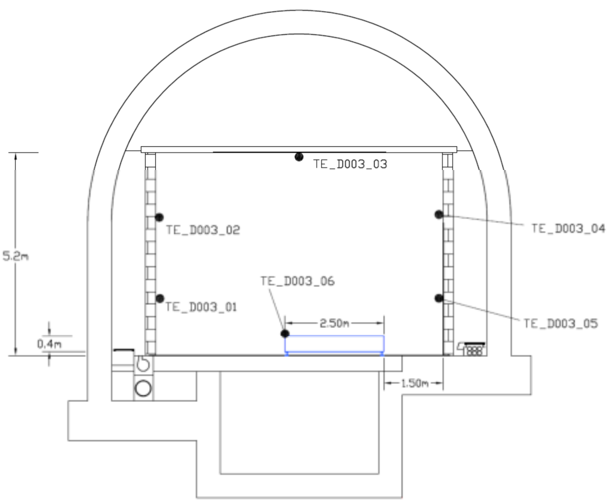


*Figure 3: Cross sectional view: Mock up of a pool fire (view from downstream to upstream)*

#### 3.2.1 *Mock Up*

Exemplarily, the mock-up of a 60 MW fire with the position of the thermocouples is shown in Figure 3. The dimension of the seven pools was 2500 mm x 1600 mm x 400 mm (l x w x h).

#### 3.2.2 *Fire Load*

In order to create a fire of a HRR of 60 MW, each of the pools were filled with 90 l diesel. Approx. 630 l were used with a heating value of 44,8 MJ/kg.

#### 3.2.3 *Ignition source*

The ignition source was 1 l gasoline for each pool.

## 4. Fixed Fire Fighting System

The water mist suppression system in the test tunnel was built as a temporary system. The very same pipe installation in the tests was used for the full series of tests. Further, more severe temperatures during the pre-burn time were expected to occur in the tests due to the longer pre-burn times compared to a real life fire.

However, all major layout parameters of the water mist system were corresponding to the real installation in the tunnel, as e.g.:

- Type of the nozzle (Shape, K-factor, etc.)
- Distance between nozzles
- Angle of the nozzles regarding the vertical axis
- Maximum distance between pipes
- Distance of the nozzle to the fire load/carrier
- Pressure at the most remote nozzle

#### 4.1.1 *Pump*

To generate the pressure for the water mist system, a diesel driven pump was located in a container outside of the test tunnel. The water was supplied from a 500 m³ water tank and fed by a low pressure booster pump to the high pressure pump.

The pressure and the flow rate of the pump are adjustable by controlling the revolutions per minute (rpm) of the engine.

Due to the starting procedure and the adjustment of the rpm´s, the activation to full power needs approx. 30 seconds.

#### 4.1.2 *Pipe network and nozzles*

The water mist system was installed over a length of 60 m. The section pipes were fed from the pump

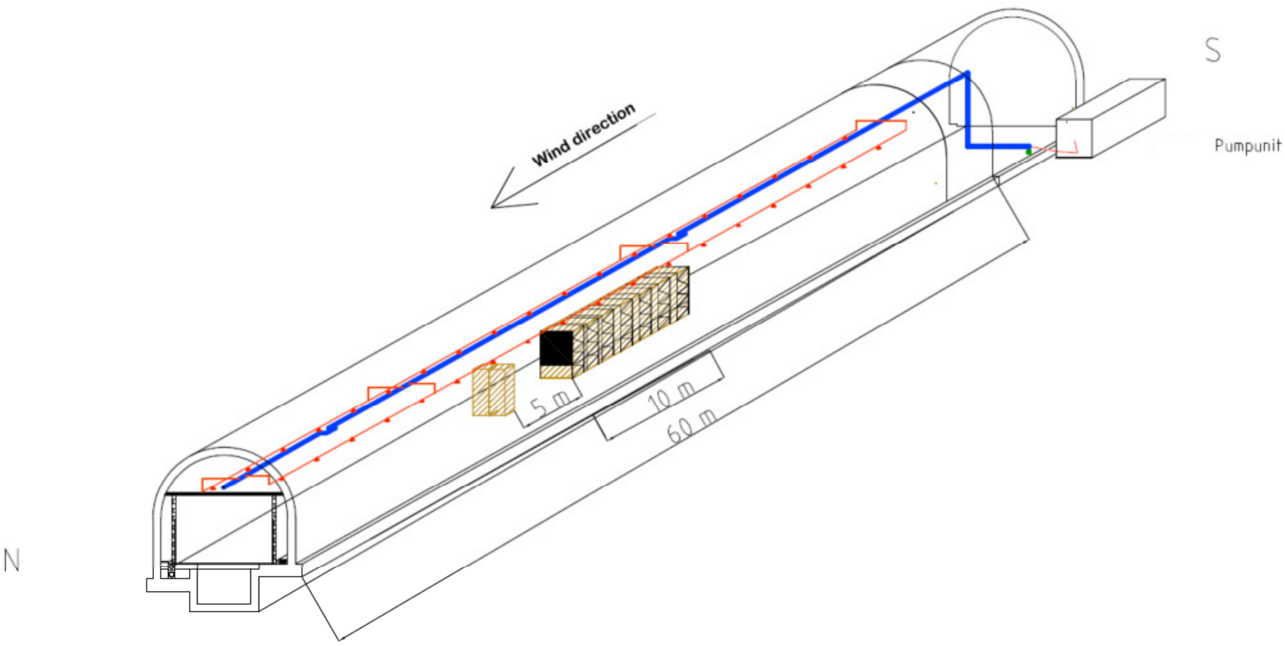


*Figure 4: Schematic view of the water mist system*

unit by a main pipe, which was installed on the top of the test tunnel. During the test program, different nozzle layouts were tested in order to find the best result in suppressing the fire efficiently. The water mist system is shown in Figure 4.

#### 4.1.3 *Layout Parameters*

Due to the special conditions in tunnels, layout parameters are in most cases given with a volumetric figure such as l/m³/min or as area figure, e.g. l/m²/min (mm/min).

It has to be pointed out that results are only applicable to the same type of nozzle that are used in fire tests.

## 5. Measurements

### 5.1 General

The position of the test section as well as the different measurement layers can be seen in Figure 6.

It shows the measurement set up over the test tunnel in general.

As described above, D and U indicate the directions from the fire load and the number indicates the distance from the centre point of the fire load.

The measurements were arranged in accordance with *SOLIT² Engineering Guidance – Annex 7: Fire Scenarios and Fire Tests for the Evaluation of FFFS.*

### 5.2 Basic Measurement variables

The following measurement variables (approx. 160 sensors) were monitored and recorded across the test tunnel during the fire test (see Figure 5):

- Temperatures
- Heat Flux
- Water pressure in the FFFS
- Flow rate in the FFFS
- Air velocity
- Relative air humidity
- Material humidity (wooden pallets)
- Gas concentrations or oxygen, carbon dioxide and carbon monoxide
- Visual recording

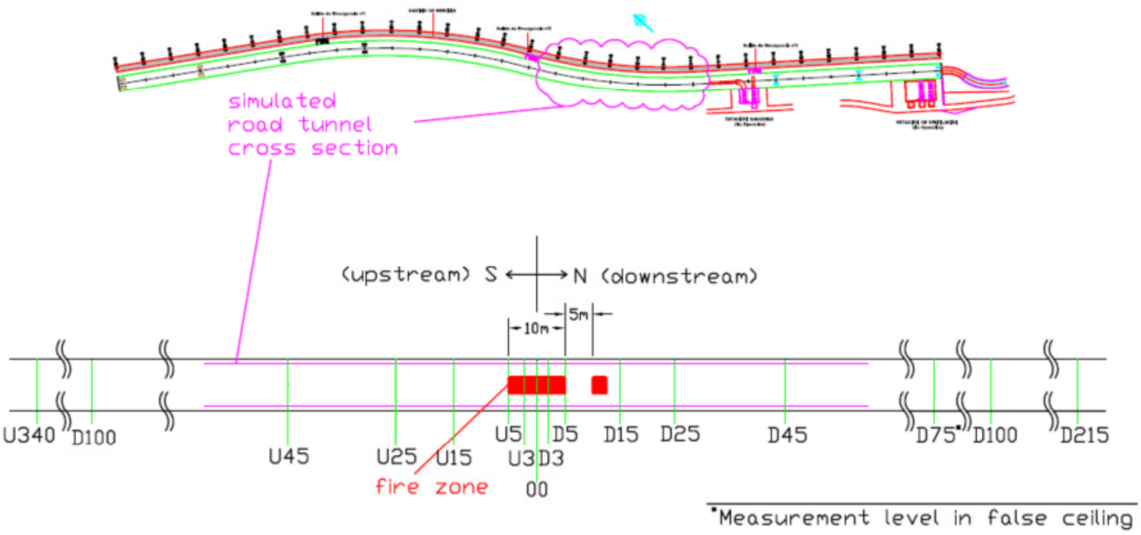


*Figure 6: Overview of the measurement levels*


*Figure 5: Various measurement equipment in the test tunnel*

### 5.3 Heat Release Rate

The heat release rate is estimated by using the oxygen consumption method. Therefore the gas concentrations, temperatures and air velocity are measured in the exhaust gases. In case of tests with semi-transversal ventilation, this must be measured in the main tunnel as well as in the exhaust duct.

As turbulences may occur, a stable smoke layering cannot be assumed. Therefore it is essential to measure all values in several positions of the cross section.

# 6. Results

## 6.1 Class A Fire with Cover and Longitudinal Ventilation

*Figure 7: SOLIT Truck Fire Load with Cover*

*Figure 8: SOLIT Truck Fire Load shortly before activating the FFFS*

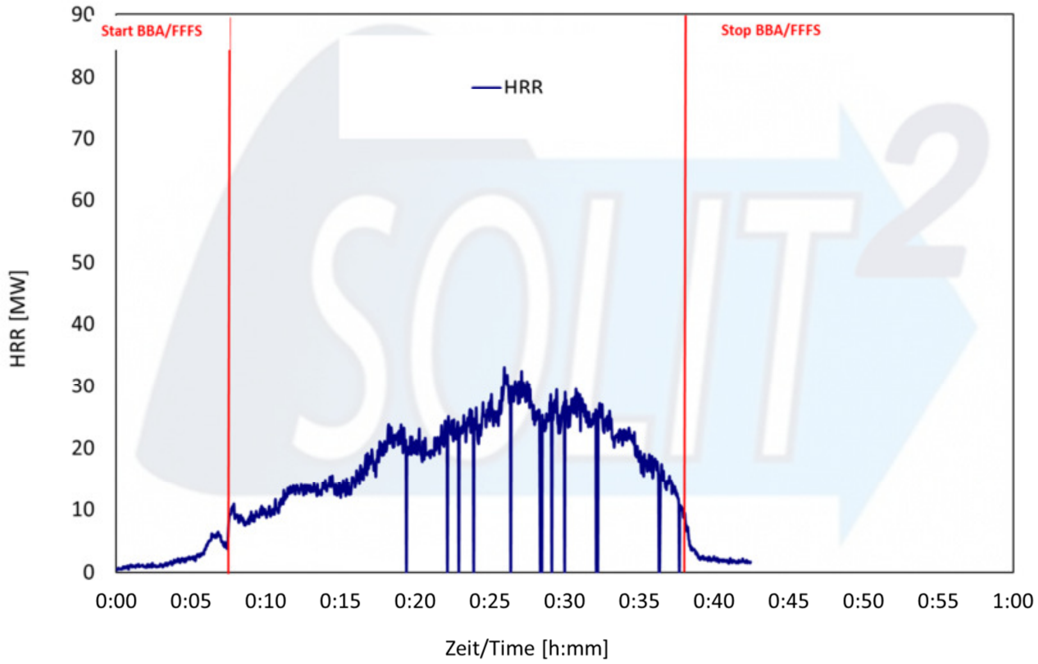


*Figure 9: HRR during the fire test calculated by the oxygen consumption method. The fire growth rate and the maximum height is significantly reduced compared to a free burning fire. Due to the tarpaulin, the suppression effect of the water mist is delayed.*

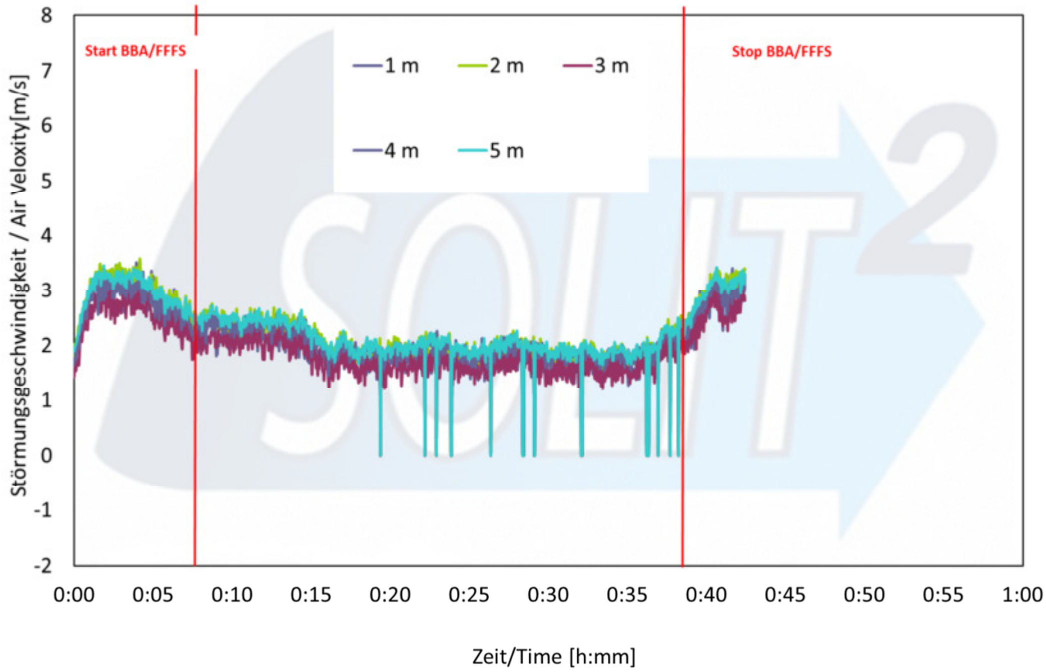


*Figure 10: Air velocity in the center of the tunnel in various heights at U45. A slight reduction due to the fire can be seen.*

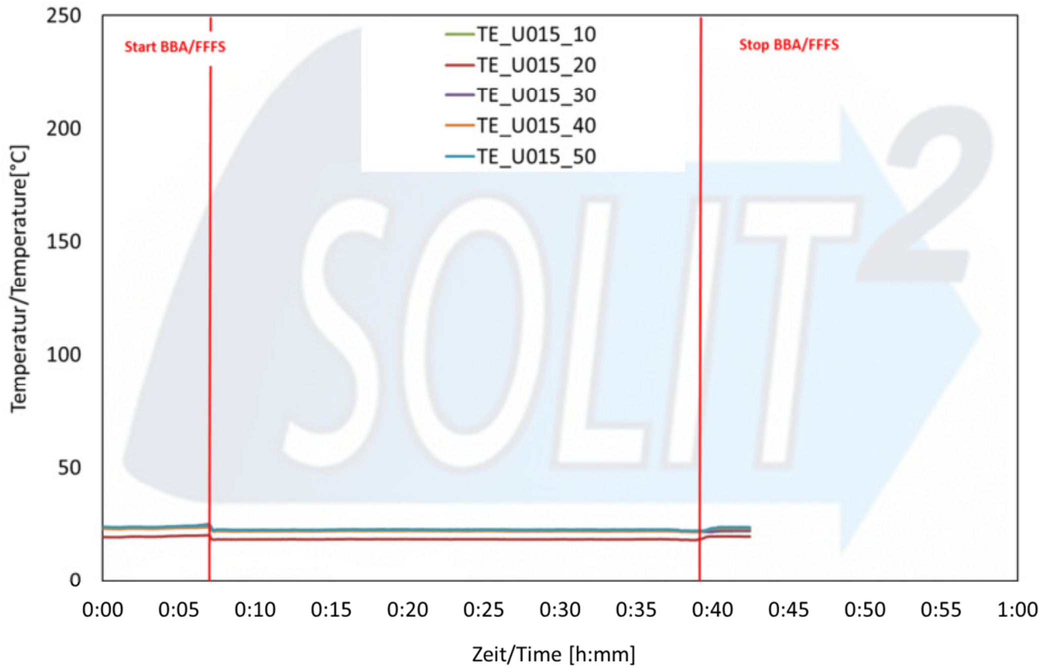


*Figure 11: Temperatures in various heights at U15. No backlayering of smoke is observed.*

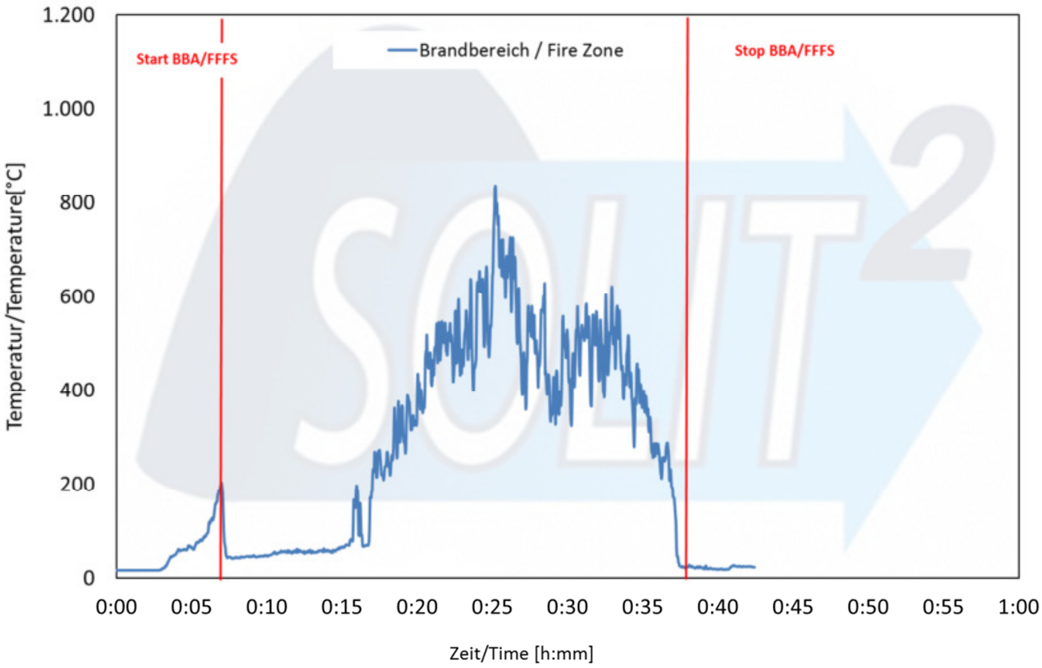


*Figure 12: Ceiling temperature above the fire load in the direct flame zone*

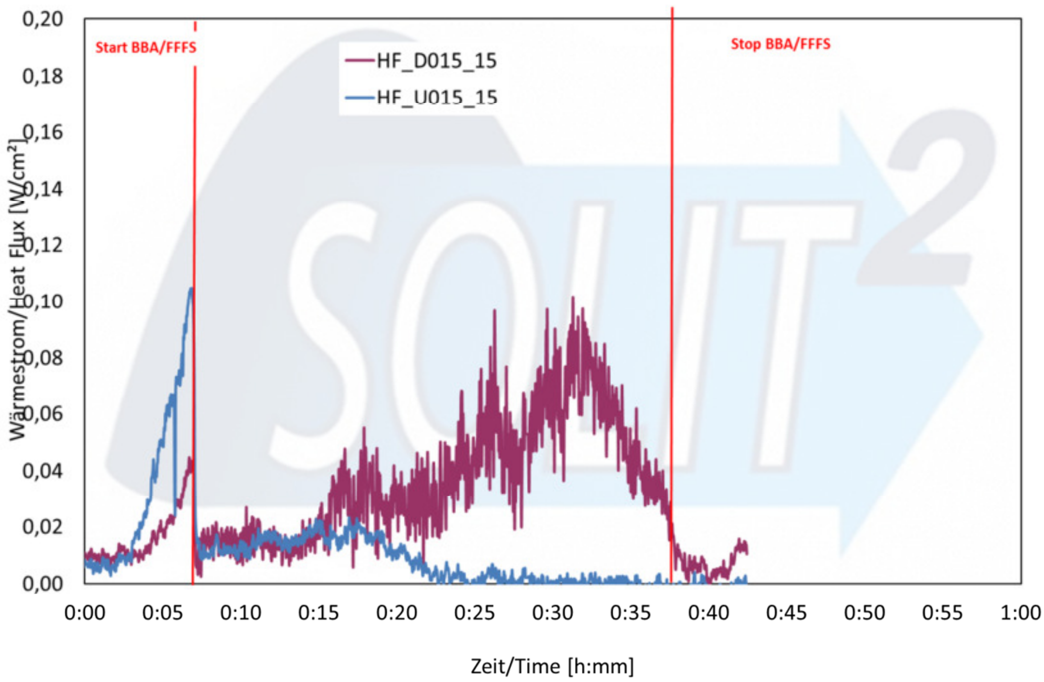


*Figure 13: Heat Flux measured at 1,5 m height at D15 and U15*

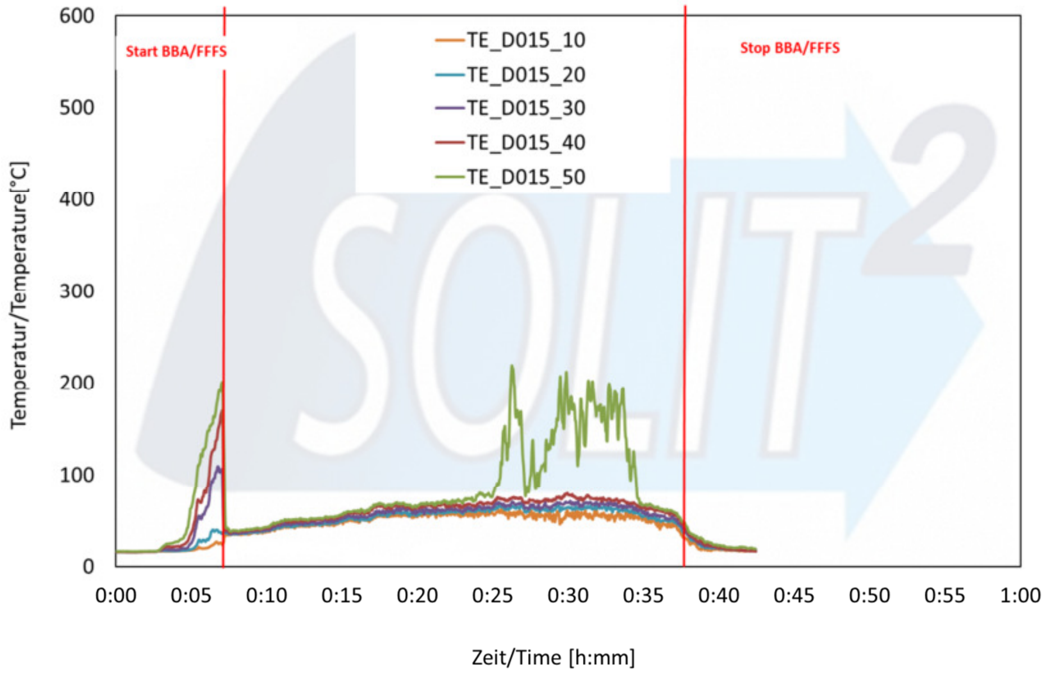


*Figure 14: Temperatures in various heights at D15.*

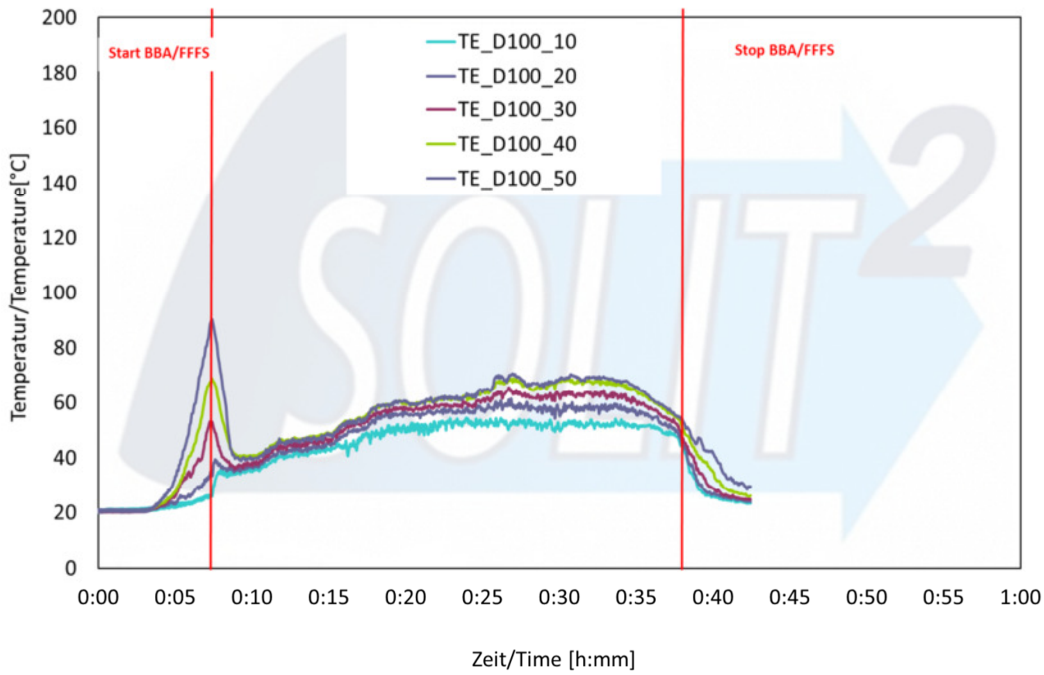


*Figure 15: Temperatures in various heights at D100*

*Summary:*

A typical for class A fires with a small ignition source, the fire developed slowly in the beginning. After 1-2 minutes the fire growth rate raised rapidly. Compared to a free burning fire the fire growth rate was slowed down significantly after activation of the FFFS as well as the maximum HRR was limited to a significantly lower level. Although the fire reached ~ 30 MW with an air velocity of only 2-2,5 m/s, no back layering was observed. Temperatures on the downstream side were also reduced to a level that fire fighters operations can be carried out.

After 30 minutes of activation of the FFFS the fire brigade was able to finally extinguish the remaining fire within few minutes. It should be pointed out that the FFFS was still activated during the fire fighters operation.

## 6.2 Class A Fire without Cover

*Figure 16: Target object after a fire test with a SOLIT truck fire load*

*Figure 17: Upstream side of a SOLIT Class A fire load during the fire test.*

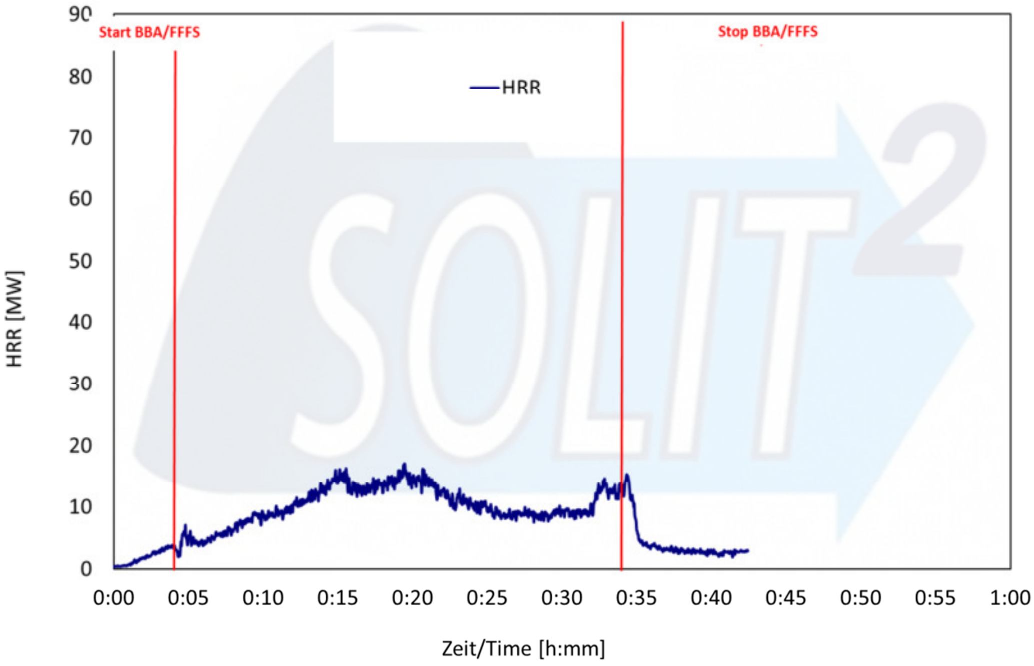


*Figure 18: HRR during the fire test calculated by the oxygen consumption method. The fire growth rate and the maximum height are significantly reduced compared to a free burning fire. As the effect of the FFFS was not delayed due to a tarpaulin, the HRR is smaller compared with a the same fire load with tarpaulin.*

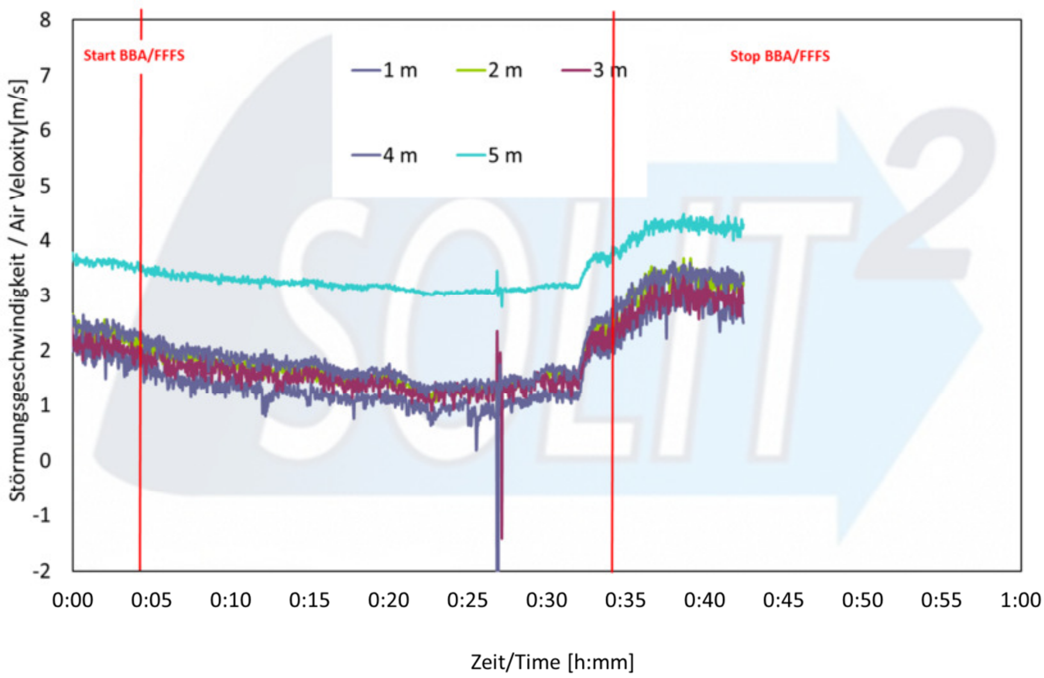


*Figure 19: Air velocity in the center of the tunnel in various heights at U45. A slight reduction due to the fire can be seen.*

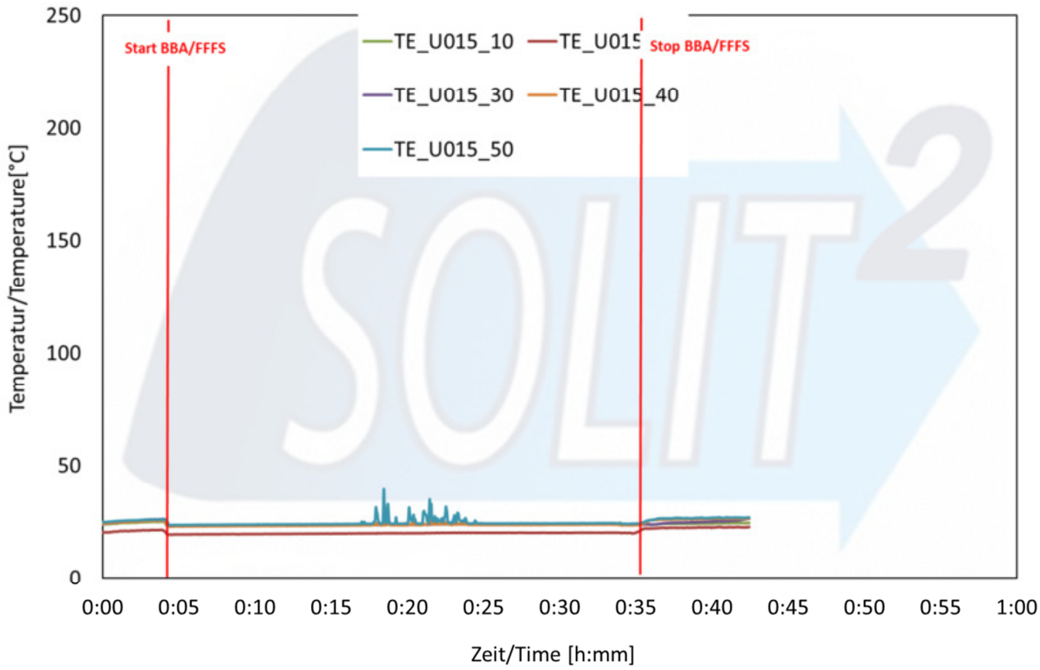


*Figure 20: Temperatures in various heights at U15.*

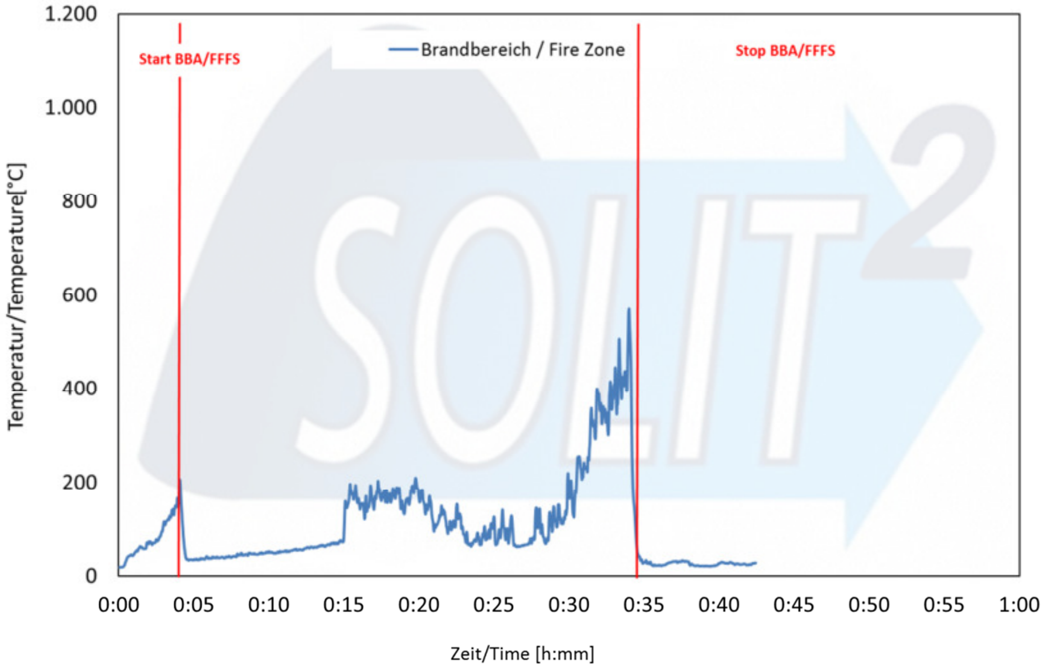


*Figure 21: Ceiling temperature above the fire load in the direct flame zone*

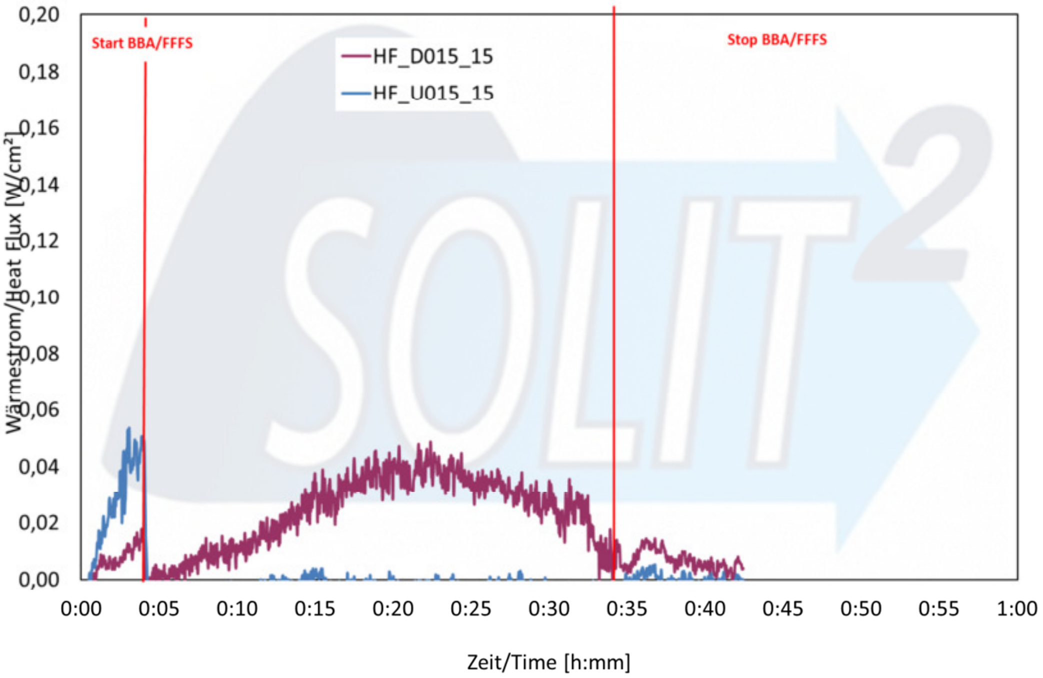


*Figure 22: Heat Flux measured at 1,5 m height at D15 and U15*

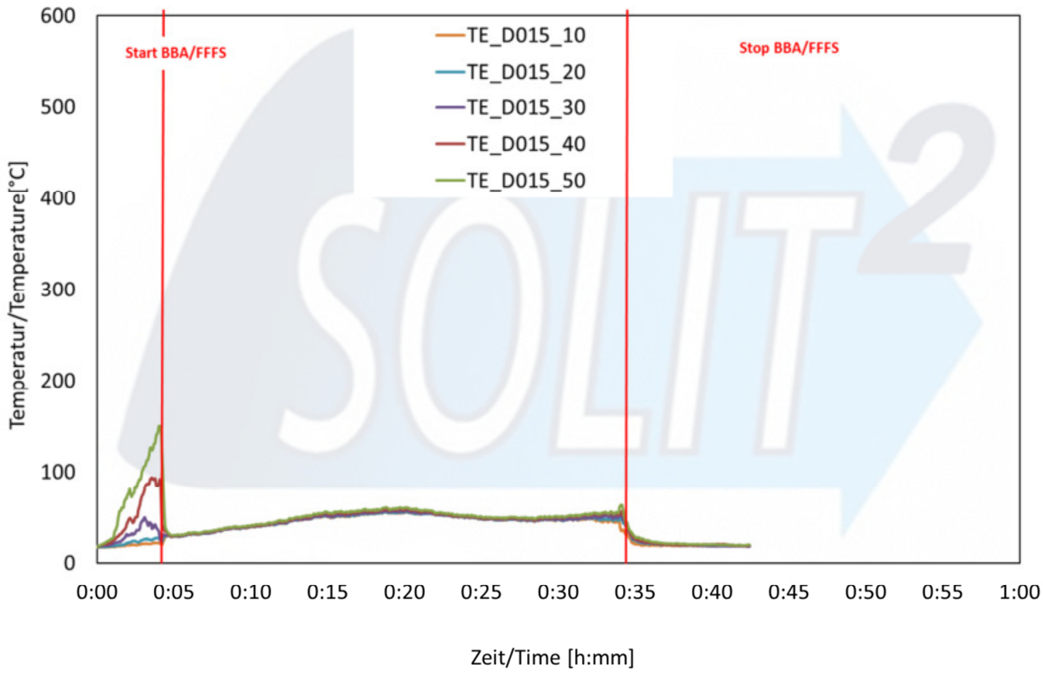


*Figure 23: Temperatures in various heights at D15.*

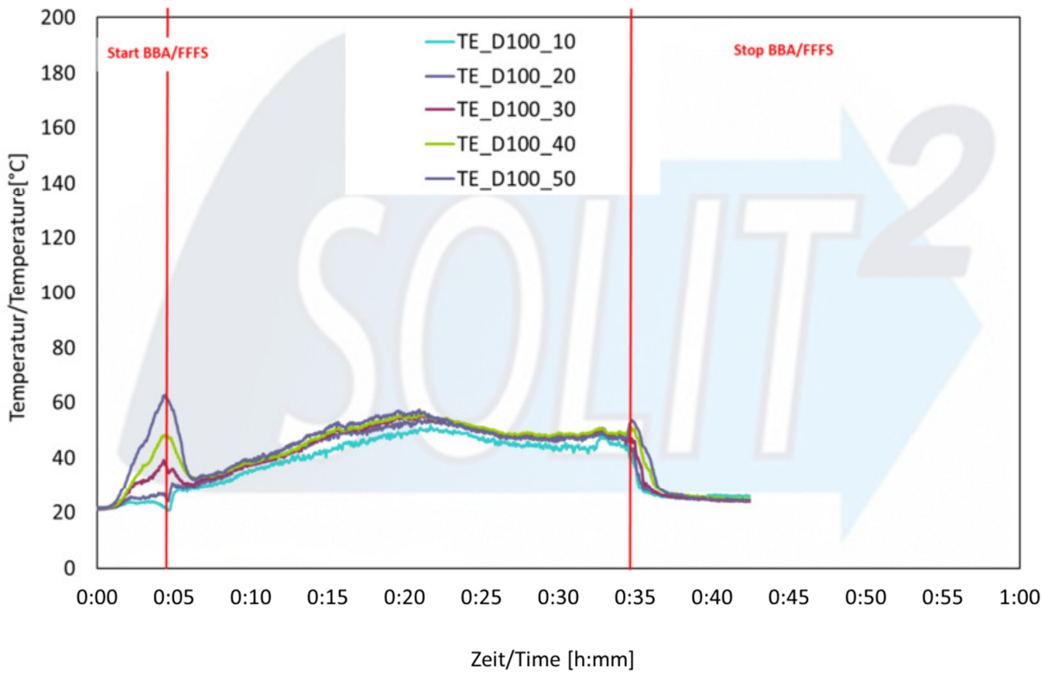


*Figure 24: Temperatures in various heights at D100*

*Summary:*

A typical for class A fires with a small ignition source, the fire developed slowly in the beginning. After 1-2 minutes the fire growth rate started raised rapidly. Compared to a free burning fire the fire growth rate was slowed down significantly after activation of the FFFS as well as the maximum HRR was limited to a significantly lower level. Although the fire reached ~ 20 MW with an air velocity of only 1-1,5 m/s, no back layering was observed. Temperatures on the downstream side were also reduced to a level that fire fighters operations can be carried out. The radiation was blocked by the water mist.

After 30 minutes of activation of the FFFS the fire brigade was able to finally extinguish the remaining fire within few minutes. It should be pointed out that the FFFS was still activated during the fire fighters operation.

## 6.3 Class B Fire with Longitudinal Ventilation

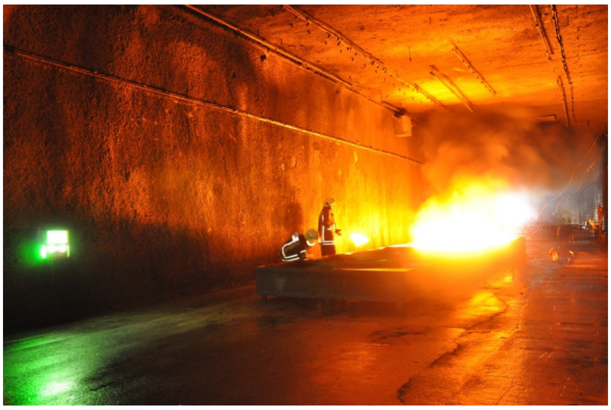

*Figure 25: Ignition of the 60 MW pool*

*Figure 26: Backlayering of a 60 MW pool fire approx. 60 s after ignition*

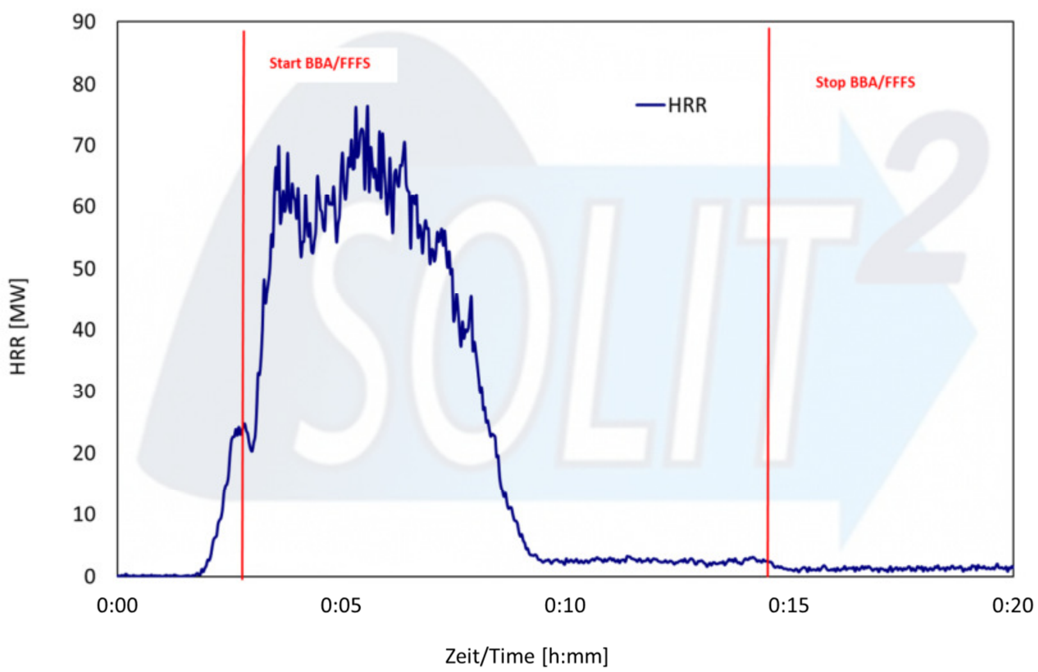


*Figure 27: HRR during the fire test calculated by the oxygen consumption method. The FFFS was activated before the fire reached the maximum HRR.*

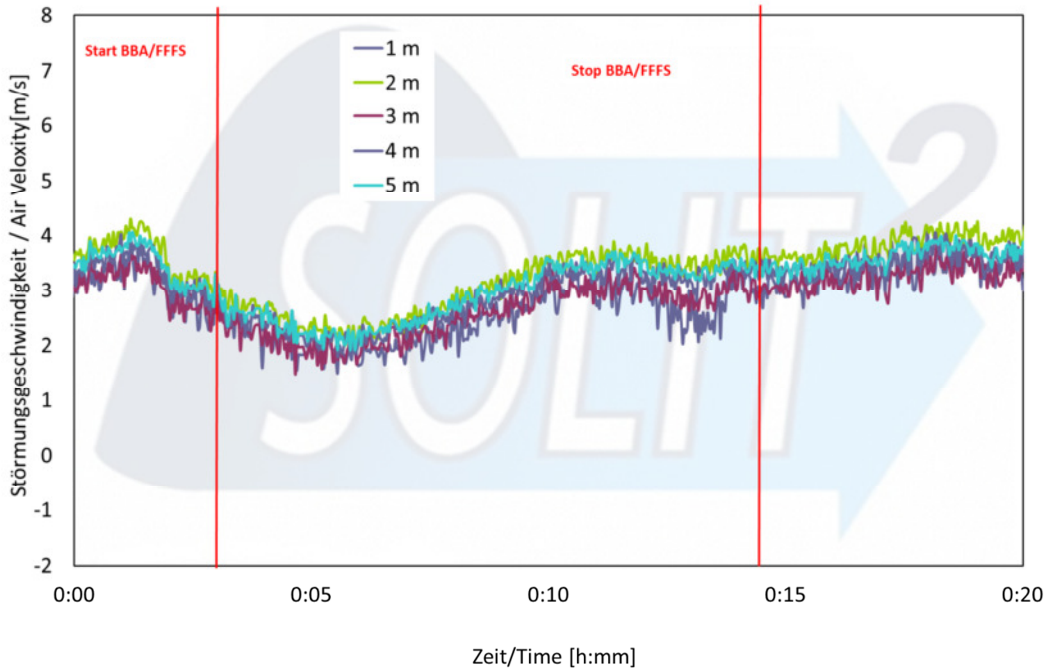


*Figure 28: Air velocity in the center of the tunnel in various heights at U45. A reduction due to the fire can be seen.*

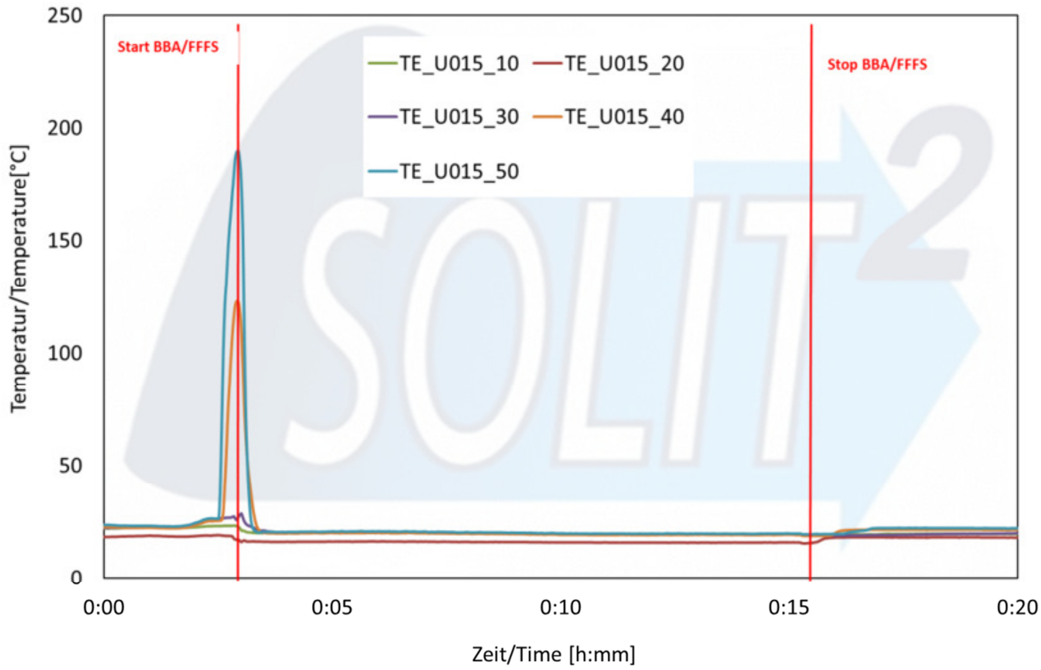


*Figure 29: Temperatures in various heights at U15. A strong backlayering before the activation of the FFFS can be observed.*

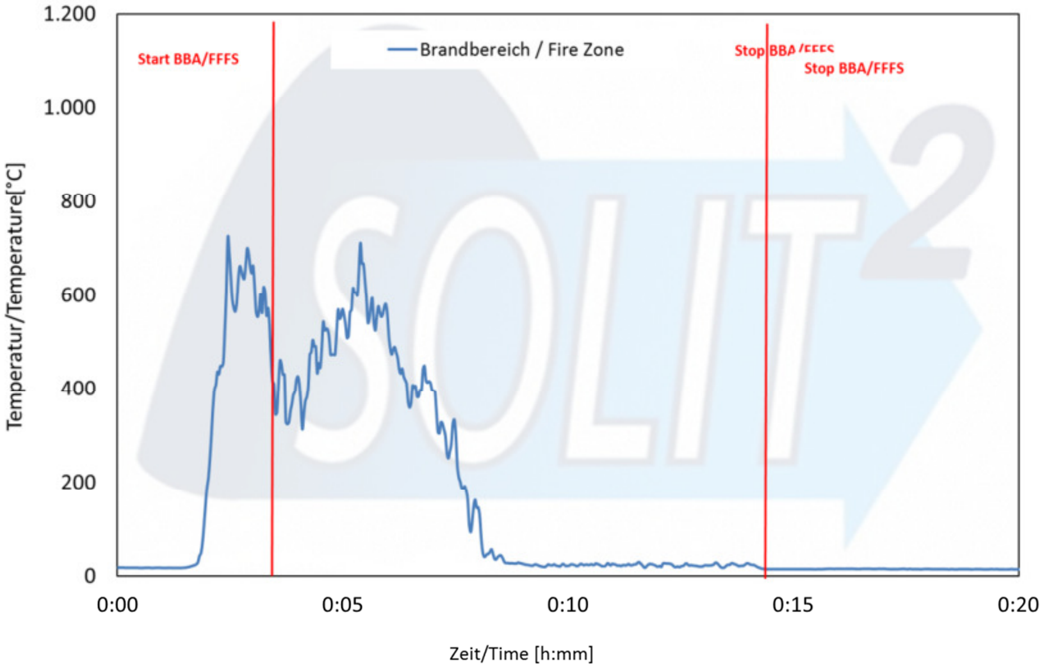


*Figure 30: Ceiling temperature above the fire load in the direct flame zone*

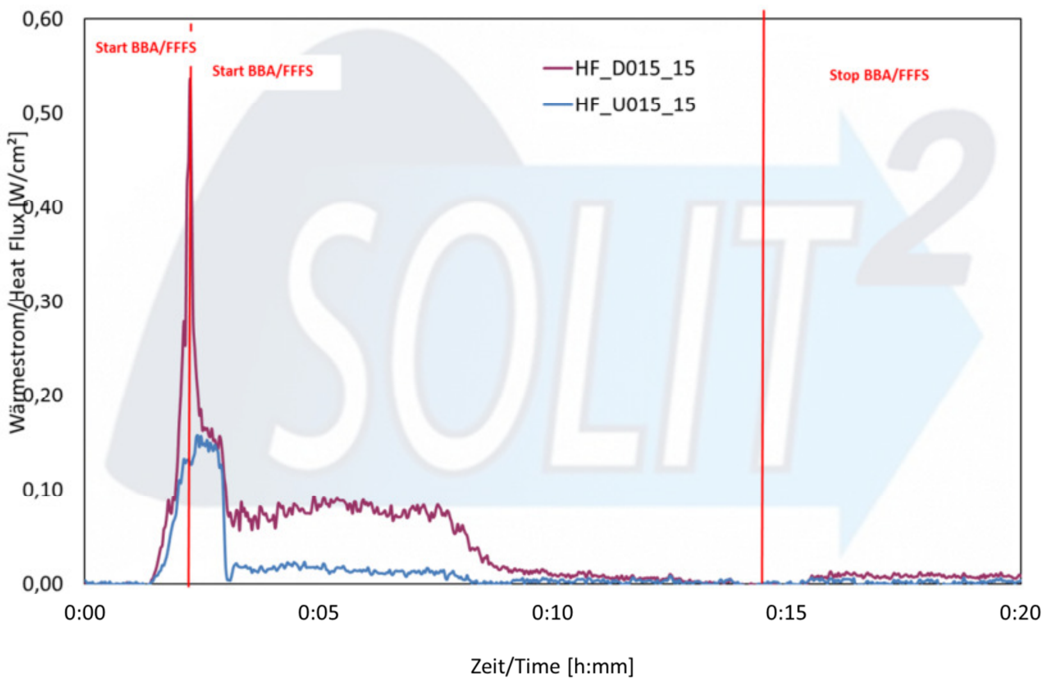


*Figure 31: Heat Flux measured at 1,5 m height at D15 and U15*

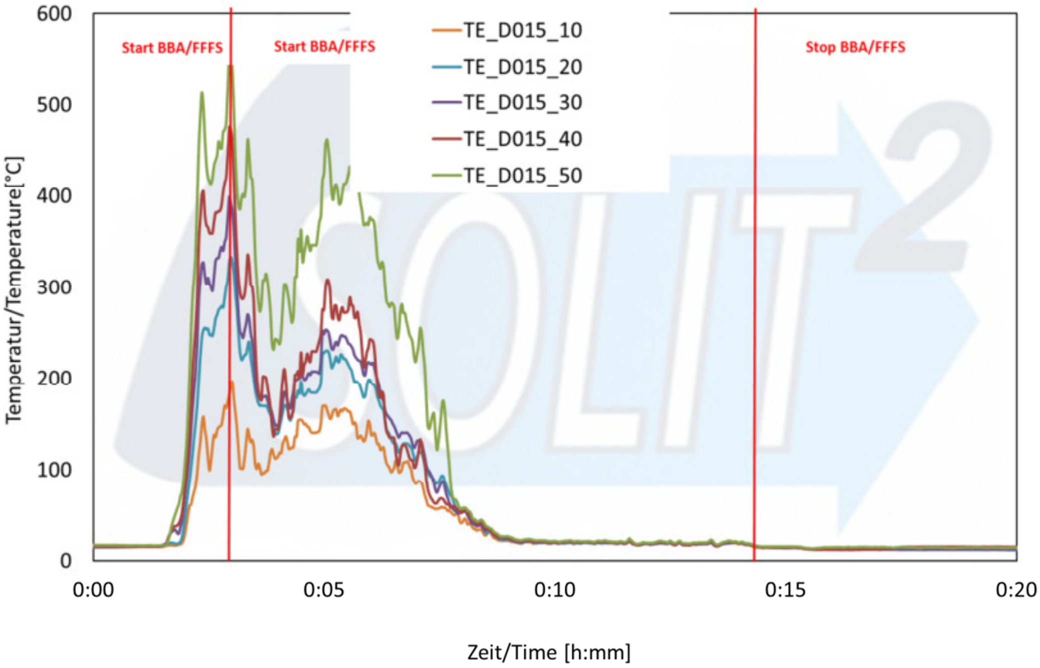


*Figure 32: Temperatures in various heights at D15. Flames are almost spreading until D15.*

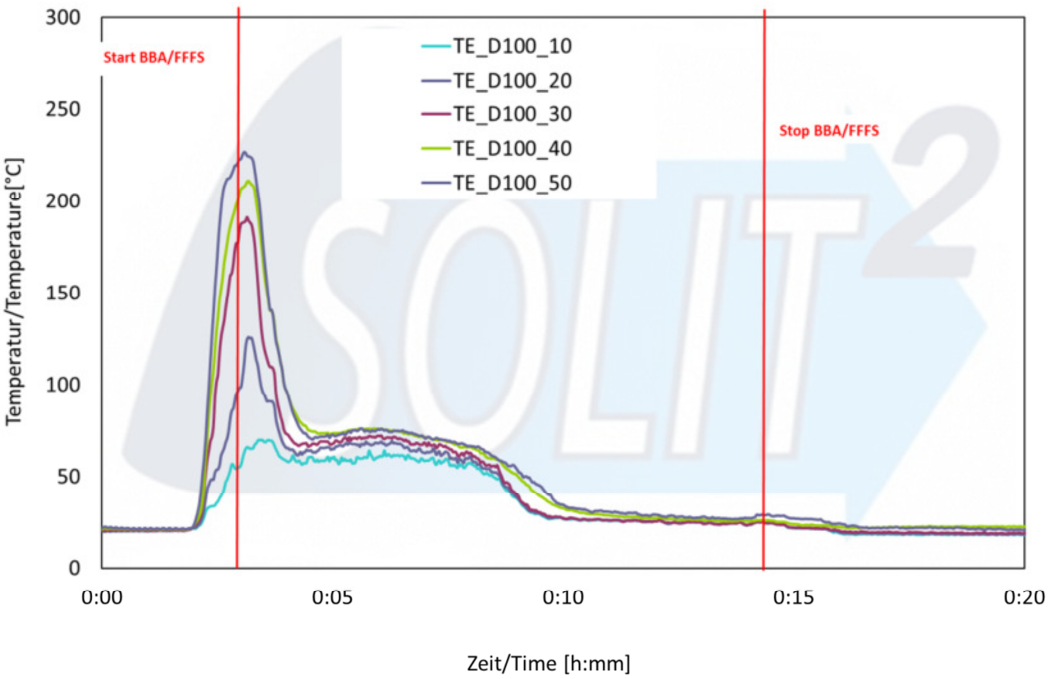


*Figure 33: Temperatures in various heights at D100*

*Summary:*

Class B Diesel pool fires need some time to fully develop after ignition. Typically this will take 2-3 minutes deeding on the ventilation and other conditions. The maximum HRR is reached after activation of the FFFS.

The fire created a large back layering of smoke which completely disappeared shortly after activation of the FFFS. After a few minutes the fire was extinguished pool by pool.

After each fire tests, the pools are re-ignited to burn the remaining Diesel. This is on the one hand necessary to check the HRR calculation and ensures that the fire was extinguished by the FFFS and not by a lack of fuel.

## 6.4 Class B Fire with Semi-Transversal Ventilation at 120 m³/s

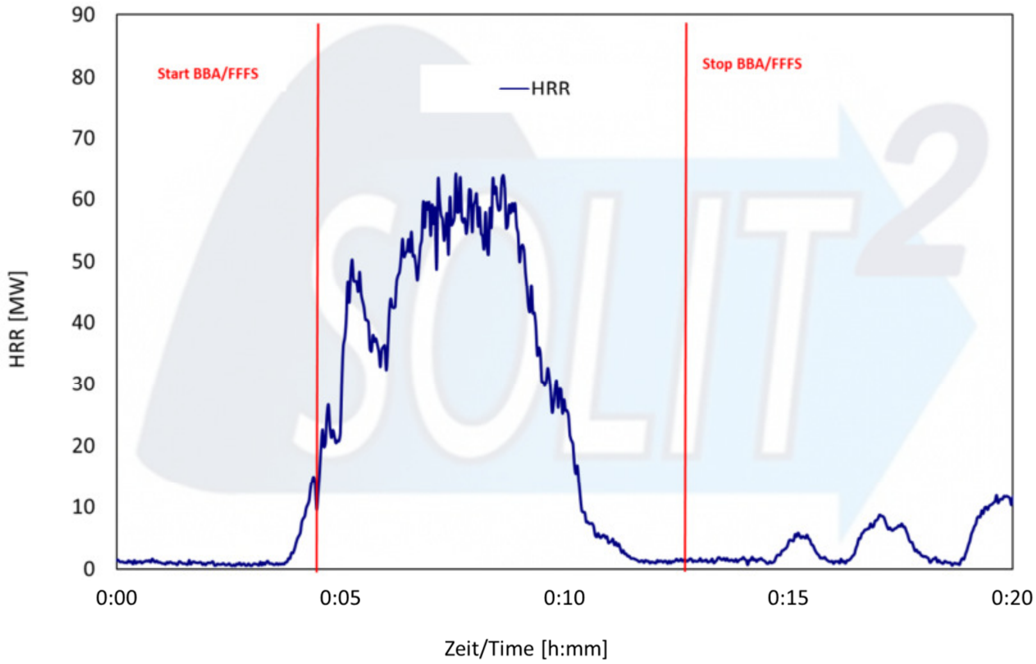


*Figure 34: HRR during the fire test calculated by the oxygen consumption method. The FFFS was activated before the fire reached the maximum HRR. After the stop of the FFFS the re-ignition process can be seen.*

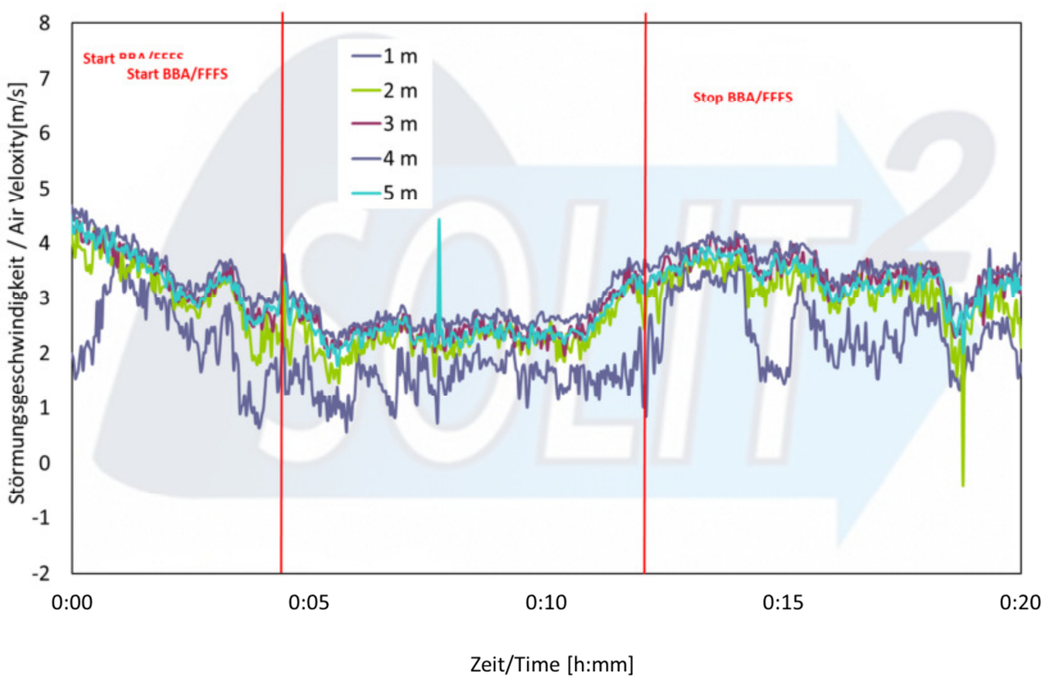


*Figure 35: Air velocity in the center of the tunnel in various heights at U45. A slight reduction due to the fire can be seen.*

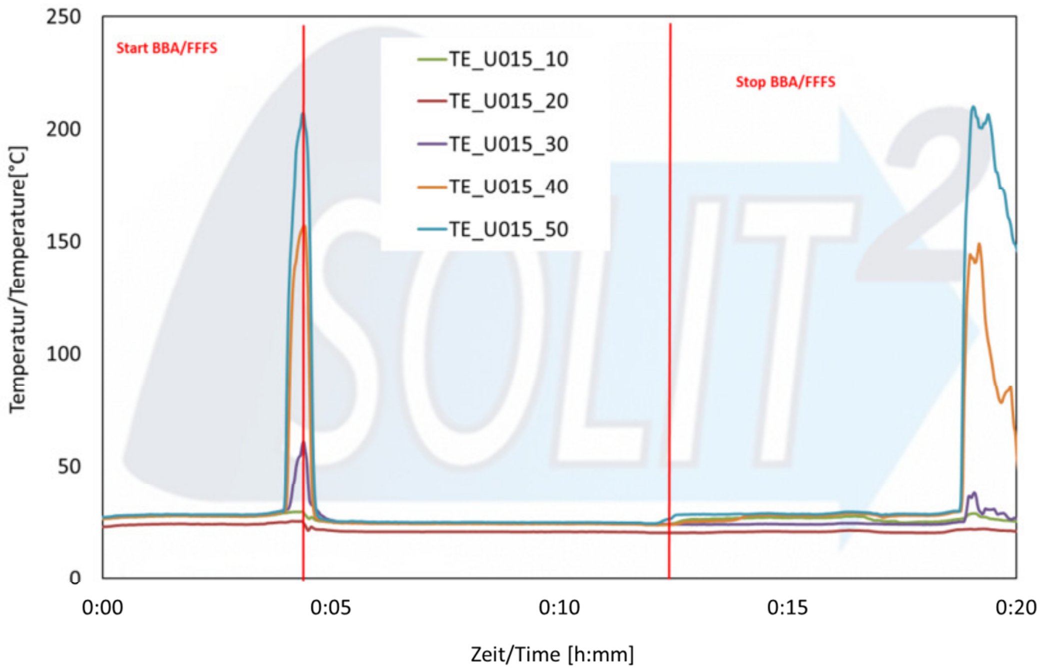


*Figure 36: Temperatures in various heights at U15. No backlayering of smoke is observed. The peak after the stop of the FFFS is the re ignition process.*

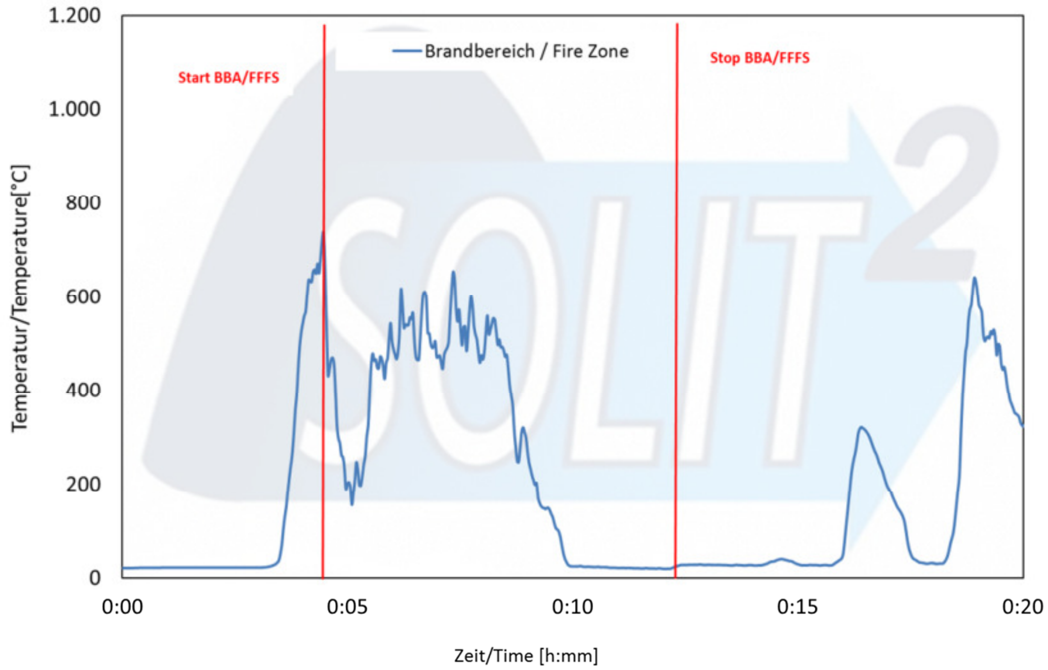


*Figure 37: Ceiling temperature above the fire load in the direct flame zone*

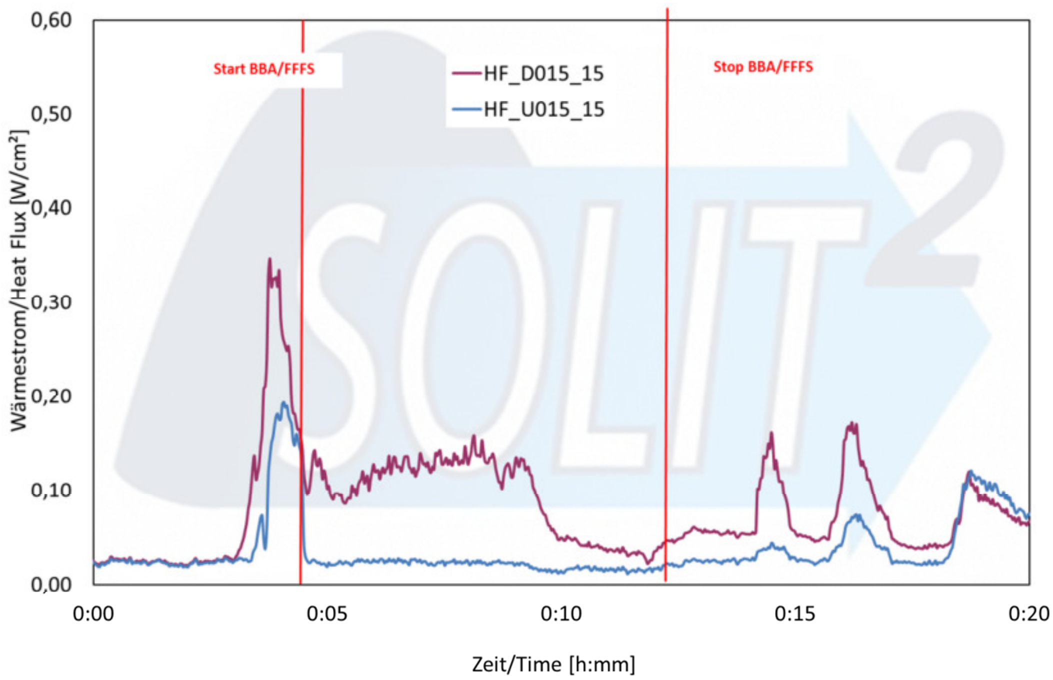


*Figure 38: Heat Flux measured at 1,5 m height at D15 and U15*

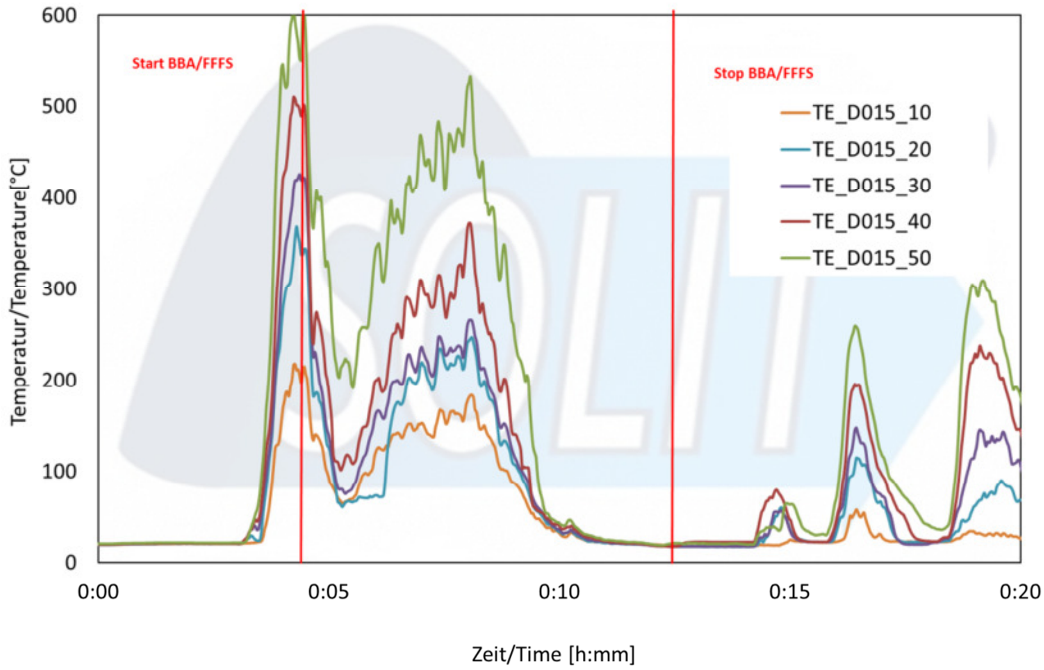


*Figure 39: Temperatures in various heights at D15.*

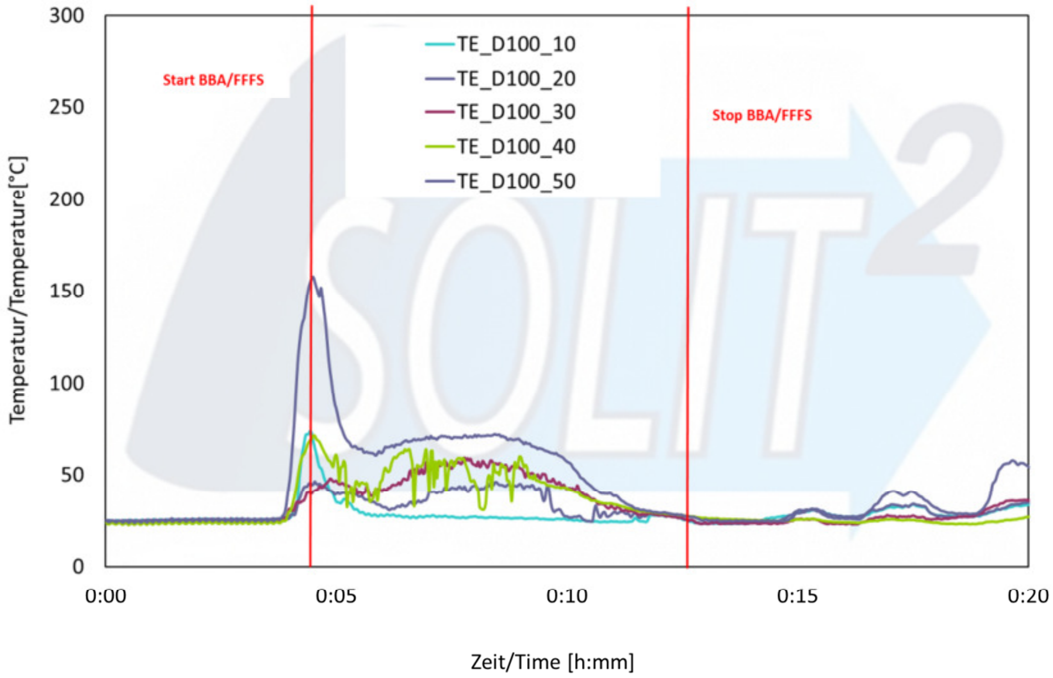


*Figure 40: Temperatures in various heights at D100*

*Summary:*

Class B Diesel pool fires need some time to fully develop after ignition. Typically this will take 2-3 minutes deeding on the ventilation and other conditions. The maximum HRR is reached after activation of the FFFS.

The fire created a large back layering of smoke which completely disappeared shortly after activation of the FFFS. After a few minutes the fire was extinguished pool by pool. A smoke layering was also observed downstream outside the zone of the FFFS.

After each fire tests, the pools are re-ignited to burn the remaining Diesel. This is on the one hand necessary to check the HRR calculation and ensures that the fire was extinguished by the FFFS and not by a lack of fuel.

### 6.5 Class B Fire with Semi Transversal Ventilation at 80 m³/s

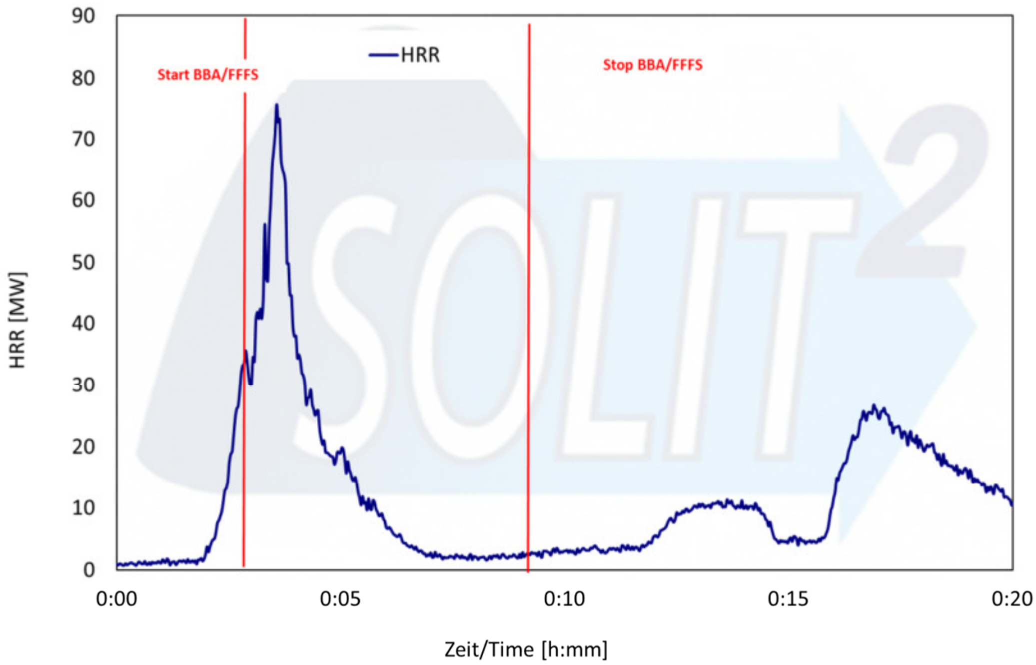


*Figure 41: HRR during the fire test calculated by the oxygen consumption method. The FFFS was activated before the fire reached the maximum HRR. After the stop of the FFFS the re-ignition process can be seen.*

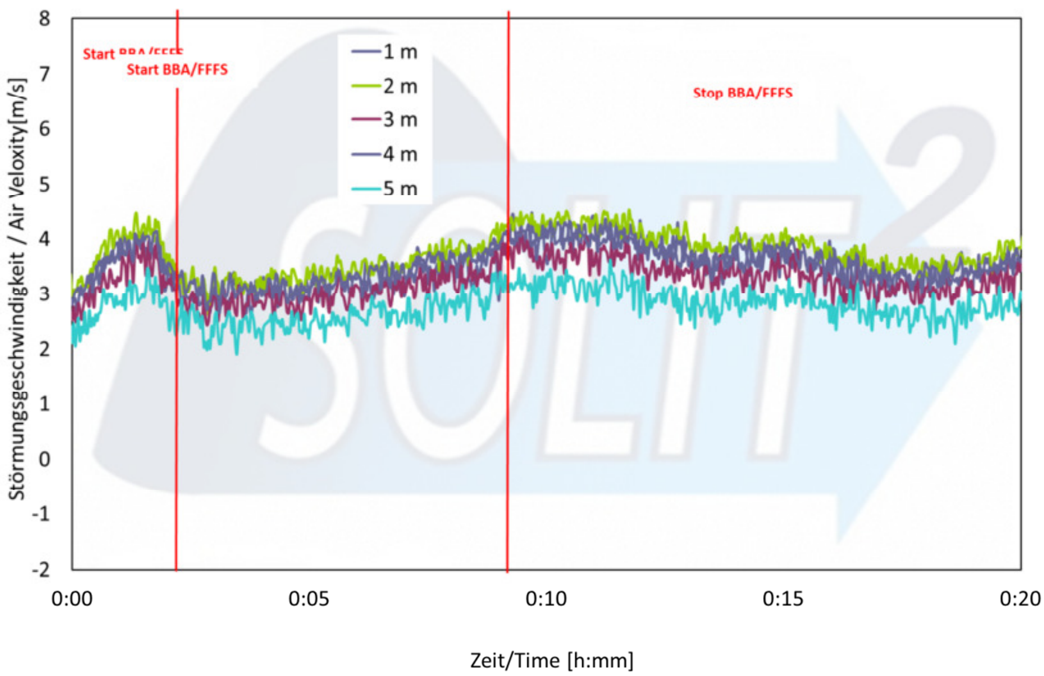


*Figure 42: Air velocity in the center of the tunnel in various heights at U45. A slight reduction due to the fire can be seen.*

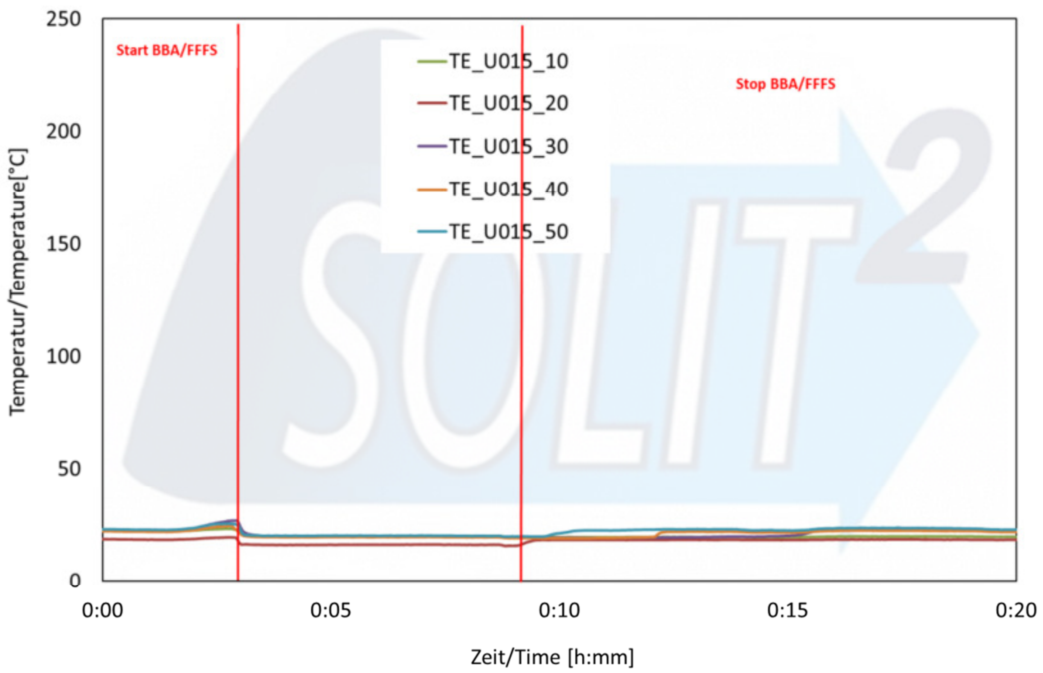


*Figure 43: Temperatures in various heights at U15. No back layering of smoke is observed.*

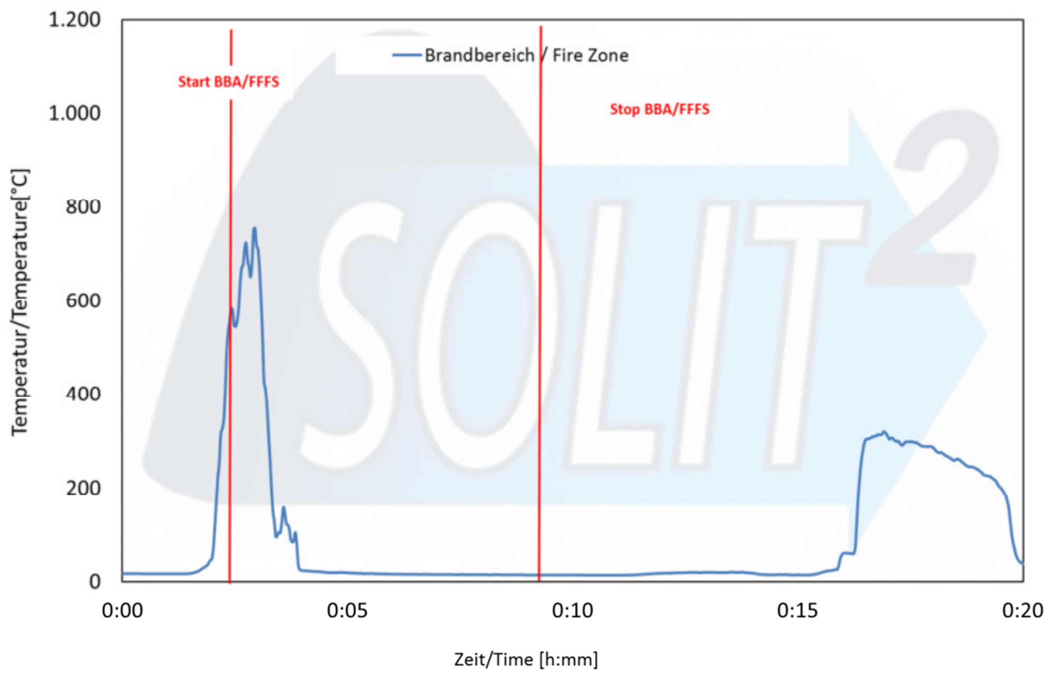


*Figure 44: Ceiling temperature above the fire load in the direct flame zone*

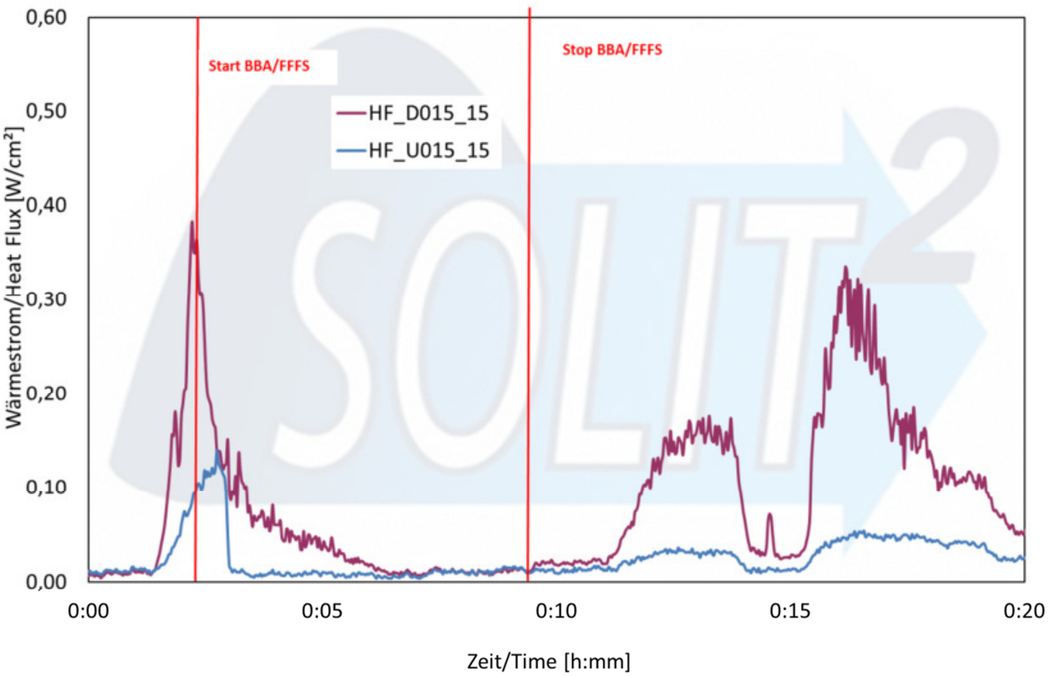


*Figure 45: Heat Flux measured at 1,5 m height at D15 and U15*

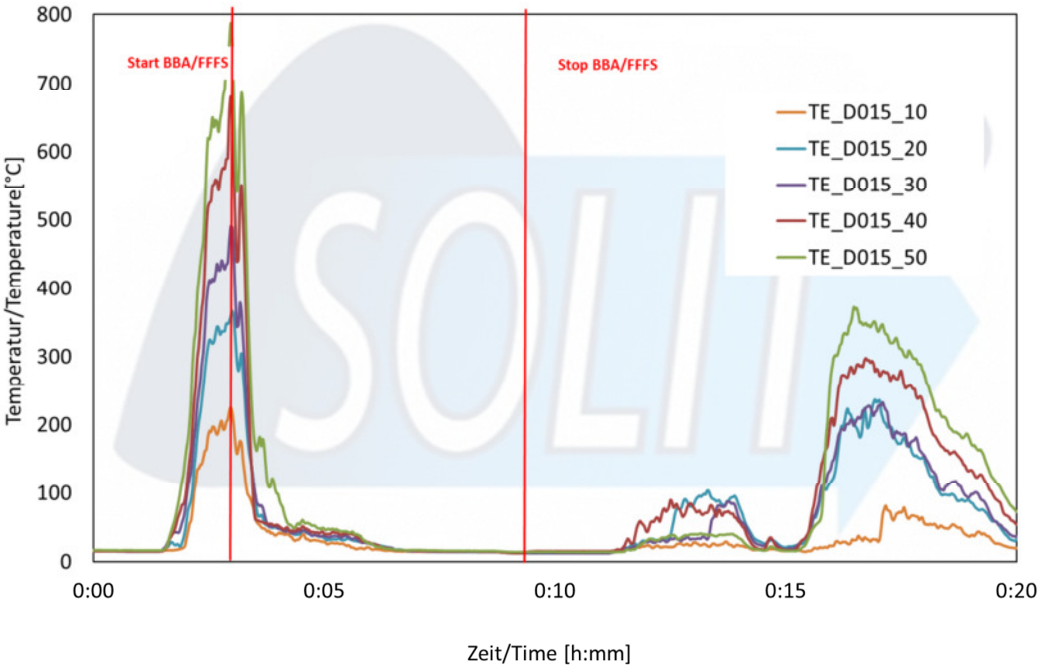


*Figure 46: Temperatures in various heights at D15. The peaks of the temperature after the stop of the FFFS is due to the re ignition process.*

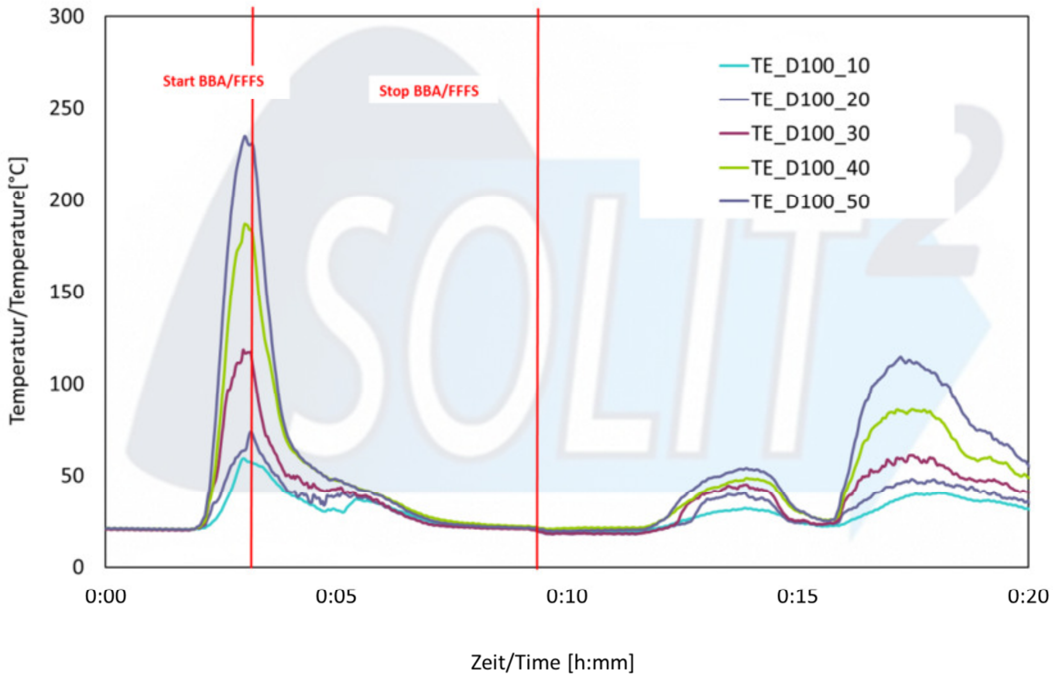


*Figure 47: Temperatures in various heights at D100*

*Summary:*

Class B Diesel pool fires need some time to fully develop after ignition. Typically this will take 2-3 minutes deeding on the ventilation and other conditions. The maximum HRR is reached after activation of the FFFS.

The fire created a large back layering of smoke which completely disappeared shortly after activation of the FFFS. After a few minutes the fire was extinguished pool by pool. A smoke layering was also ob-served downstream outside the zone of the FFFS.

After each fire tests, the pools are re-ignited to burn the remaining Diesel. This is on the one hand necessary to check the HRR calculation and ensures that the fire was extinguished by the FFFS and not by a lack of fuel.

It should be pointed out that the semi-transversal ventilation system in combination with the FFFS, even with a reduced capability of only 80 $m^3/s$ was able to reach the same effect in regard of smoke management than with the higher capability. The smoke extraction system was designed only for 30 MW free burning fire.

# 7. Literature

## 7.1 Figures

Unless otherwise stated, the rights for figures in this document belong to the partners of the SOLIT² consortium. For all other figures a link to the full source is given. The usage is based on the German UrhG §51 Nr.1.

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