LARGE-SCALE TESTS OF FLAME-SPREAD ON ROOF BUILD-UPS WITH PV SYSTEMS: PHASE II

11/2025

REPORT INFORMATION

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2	2025-11-27	All	Final version based on comments from Steffen Kahrmann.

CONTENTS

1 INTRODUCTION

In this report the Danish Institute of Fire and Security Technology (DBI) outlines the method and results of three large-scale tests conducted by IVH, the German Rigid Foam Industry Association and EUMEPS, the European Manufacturers of Expanded Polystyrene.

This report presents follow up tests to the four tests presented in the previous part of the testing programme [1]. In the report at hand, the performance of two different roof construction build-ups is assessed in a total of three tests. The design of the roof build-ups and their construction were determined by IVH and EUMEPS and assembled two days prior to the test day, April 8th 2025. DBI provided feedback related to the test design and instrumentation of the roof build-ups as well as attended and observed the four tests. KIWA conducted the testing and provided two test reports [2], [3] to IVH and EUMEPS, who shared the videos and thermocouple data with DBI. Based on that, DBI analysed the results which are presented in this report.

The roof construction build-up tested twice consisted of a PVC membrane, cement-bonded particle board (CPB) and EPS insulation, whereas the other consisted of a PVC membrane and mineral wool (MW) insulation. According to the test protocol, a fire was initiated in the cavity between the roof surface and an array of twelve building applied photovoltaic (BAPV) modules. The main updates to this testing programme, compared to the previous tests reported in [4], are:

- The PV arrays were increased in size to 12 modules per test (in previous round of test 4 modules were used).
- In each test, the arrays were grouped into two adjacent sections with 6 modules each. This is done to evaluate flame spread between the two adjacent sections.

Due to limited self-sustained flame spread in the cavity between the PV modules and the roof surface in the first test conducted on the roof build-up conducted with the CPB and expanded polystyrene (EPS) an additional test was conducted. Thus, a total of three tests were performed at the premises of Twente Airfield and Safety Campus (Troned, NL) on April 8, 2025.

The objectives of this study were:

- Evaluate the extent of the flame spread along the EPS- and mineral wool insulated roof constructions.
- Assess heat transfer, and potential flame spread into the roof constructions during and after the tests.
- Evaluate the effect of a cement-bonded particle board to protect a subjacent layer of EPS insulation in case of a PV-related fire between the roof surface and PV array.

The report is structured as follows: First, the two roof configurations are presented along with their respective characteristics. This is followed by a description of the instrumentation, a visual analysis of the tests, and a presentation of the relevant temperature measurements. The results are discussed through the report, which concludes with a summary discussing the influence of the various parameters examined.

As the three tests are following the initial four tests analysed in the phase I report of this project [4], a consecutive numbering is used in the report at hand.

<u>Thus, the three tests presented in this report is denominated test 5, test 6 and test 7.</u>

2 TEST SETUPS

The test location, test built-up and instrumentation is presented in the following part of the report.

2.1 Location of the tests

Prior to the test day, two test setups were constructed in a designated test area located between several low buildings, as shown in Figure 1 and Figure 2. The surrounding buildings, primarily situated to the east and west of the test site, provided some shielding from potential wind effects. The tests were conducted sequentially, one at a time.

Figure 1 - Aerial view of the two roof construction build-ups used for tests 5-7.

2.2 Roof build-ups

In all tests, the roof build-ups covered an area of 49 m², with side lengths of 7 meters. They were constructed atop a metal support structure and a 0.75 mm thick trapezoidal steel deck. A 2° roof inclination was ensured between the "eastern" and "western" edge. This inclination aligns with the minimum slope requirements specified in most European building regulations.

Roof build-up 1 was used in both test 5 and 6, since test 5 resulted in limited flame spread and no mechanical damage to the PV mounting system. Therefore test 6 was conducted as a repetition, where the burner was moved to the neighbouring undamaged section of the PV array. A mechanical fan was used to introduce a forced air flow (slightly higher compared to the observed wind velocities on the day of the test). Roof build-up 1 was similar to two of the roof constructions tested in previous test rounds on respectively October 30th 2024 and January 29th 2025, with the only difference being the thickness of the EPS insulation. Those tests are in the phase I report of this project [1].

The roof build-up construction 1 consisted of the following layers (starting from exterior):

- 1.8 mm PVC membrane, Bauder Thermofol M18.
- 12 mm cement-bonded particle board (CPB) - Cetris Basic cement-bonded particle board.
- 100 mm expanded polystyrene (EPS) insulation containing a polymeric fire retardant.
- 250 µm vapour barrier, BGG Foliengesellshaft, Artic.

Figure 2 – Google maps screen shot of test location at Twente Safety Campus. The PV modules and indication of North is added to the screen shot.

Roof build-up 2 was used in test 7. No forced air flow from mechanical fan was introduced in test 7. The construction consisted of the following layers (starting from exterior):

- 1.8 mm PVC membrane, Bauder Thermofol M18.
- 120 mm thick mineral wool (MW) insulation, Rockwool Hardrock 038.
- 250 µm vapour barrier, BGG Foliengesellshaft, Artic.

The material layers, along with instrumentation placement, are presented in Table 1. Thermal properties of the different materials used in roof build-ups 1 and 6 are presented in Table 2 below.

Table 1 - Test matrix of the three conducted tests, presented as layers and applied wind load. The numbered red dots mark the location of the thermocouple groups described in subsection 2.5.

Layer	Build-up 1		Mock-up 2
	Test 5	**Test 6**	**Test 7**
# 6	1.8 mm PVC-based roofing membrane		
# 5	④ 12 mm Cement-bonded Particle Board ④		③ -
# 4	③ 100 mm Expanded Polystyrene (EPS) ③		② 120 mm Mineral Wool
# 3	② Vapour barrier ②		
# 2	0.75 mm trapezoidal steel deck ①		
# 1	Metal support structure		
Wind load	Low (1.2 m/s -1.5 m/s)	Mechnically induced (1.5 m/s - 2.6 m/s)	Low (not quantified)

Table 2 - material properties of the EPS, CPB, PVC membrane and mineral wool. *Obtained from measurements in Netzsch HFM 446. ** Estimated based on similar products. Values without reference were taken from [3]

Material	Parameter	Value
EPS	Density [kg/m^3]	25
	Thermal conductivity [W/(mK)]	0.034 – 0.035
Cement-bonded particle board (CPB)	Density [kg/m^3]	1350 – 1500 [3]
	Area density [kg/m^2]	16.2 – 18 [3]
	Thermal conductivity [W/(mK)]	0.200 – 0.287* [3]
	Specific heat capacity [J/(gK)]	1.292 – 1.445*
PVC membrane	Heat of combustion [MJ/kg]	16.4 [4]
Mineral wool	Density [kg/m^3]	160-180**
	Specific heat capacity [J/(gK)]	0.84 – 1.00[6], [7]
	Thermal conductivity [W/(mK)]	0.037 [5]

2.3 PV Array

A twelve-module large photovoltaic (PV) array, with two sections of six PV modules installed side by side, were installed on each of the two roof build-ups. The PV array consisted of six Lynus monocrystalline PV modules with polymer-based back sheets (glass-foil). The array was placed directly on the roofing membrane using an aluminium mounting system, without the use of ballast or mechanical fastening to the underlying roof construction. A side view of the building-applied photovoltaic (BAPV) mounting system is presented in Figure 3 which illustrates the 13° inclination of the PV modules, typical for East/West-oriented installations, and emphasizes the slim cross-section of the aluminium mounting components.

The gap distance between two modules in the same section of the array was 90 mm, whereas 100 mm was measured between the two sections of the PV arrays. Based on research examining the effect of re-radiation in the cavity between the roof surface and the PV module [5], it is expected that increased distances between modules and sections of an array will reduce the likelihood of self-sustained flame spread across a full array of PV modules.

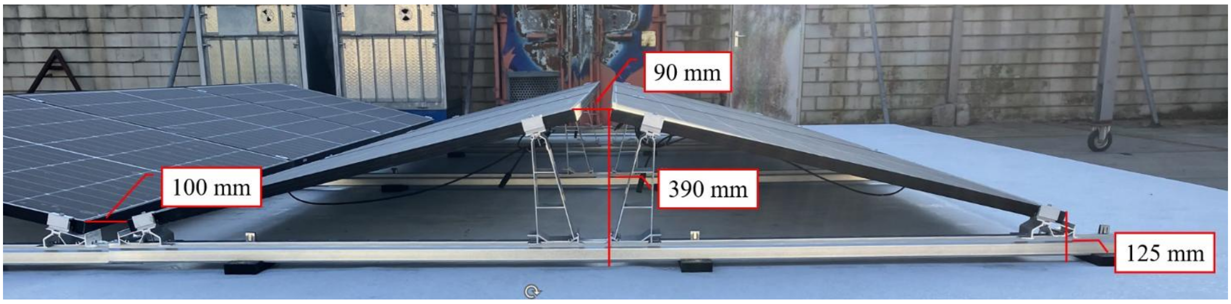

Figure 3 – Partial side view of the East/West-orientated PV array. The distances between the lower edges of the two array sections, the upper edges of the modules, as well as the distances from the PV modules to the roof surface are all measured from the top of the module frames.

2.4 Ignition source

A gas burner with a heat release rate (HRR) of 15 kW (± 1 kW), following the specifications presented in technical report CLC/TR 50670:2016 [6], was used. The HRR was based on a of 324 mg/s (±20 mg/s) propane (95%) flow, monitored by a Bronkhorst flowmeter. In all tests, the square-shaped gas burner was positioned at the midpoint along the long side under the PV module first ignited (PV1 was used in test 5 and 3, whereas PV8 was used in test 6). The horizontal distance from the burner's nearest edge to the lower edge of the PV module was 110 mm, while the vertical clearance between the burner and the roof construction measured 80 mm. A schematic view of the PV array system is illustrated in Figure 4. The burner was on during the initial 10 minutes of test 5 and test 6. In test 7, the burner was removed after 4 min 39 seconds since the flames from the fire within the cavity was deflected by the wind and reached the hose connected to the gas burner. As the intensity of the fire was rendered quite significant, at time where the gas burner was removed, it is not expected that the shorter ignition time affected the outcome of the test.

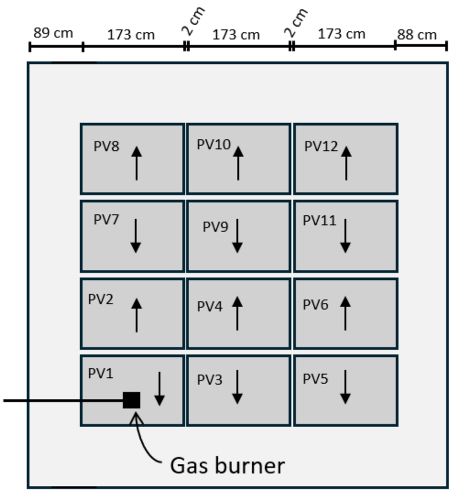

Figure 4 - Schematics of the PV array on the roof construction with corresponding numbering in accordance with their proximity to the gas burner. Arrow points towards the lowest edge of the inclined surface. Not to scale.

2.5 Instrumentation

During the assembly of each roof build-up, a total of 30 thermocouples (TCs) were installed between the different layers of the constructions. The TCs were sorted into four TC groups, where TCs in the same TC group were installed between the same material layers in accordance with Table 1. The TC groups 4 and 3, with six TCs in each layer, were located closest to the steel deck, whereas TC group 1 was located between the PVC membrane and the subjacent insulation material. For simplicity in the result presentation, the thermocouple arrangement within each group has been uniformed and follows the schematic as presented in Figure 5 to Figure 7.

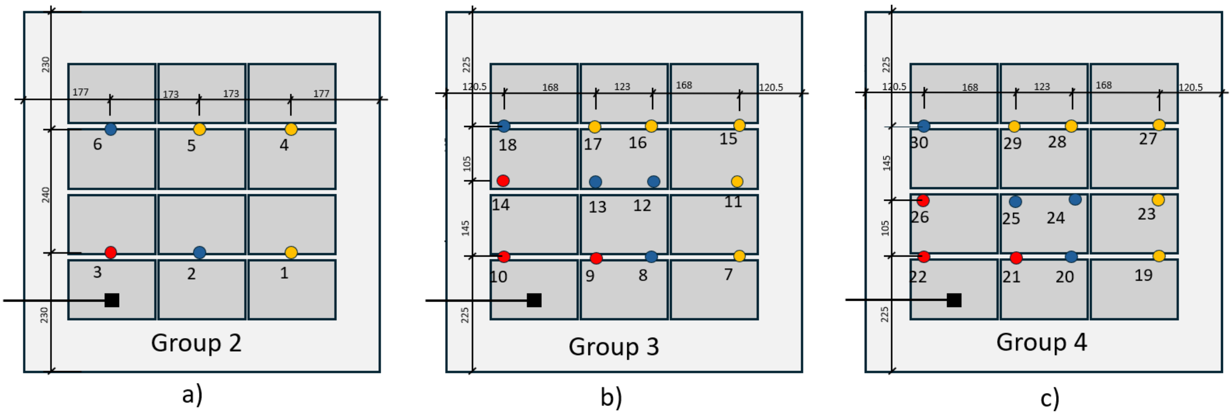

*Figure 5 – Test 5. Thermocouple distribution across the three different measurement layers **a)** below the EPS insulation, **b)** between the EPS insulation and CPB **c)** between CPB and the PVC membrane. Dimensions are given in cm and are approximate.*

The number of thermocouples within each layer varied depending on the proximity of the TC group to the top surface of the roof construction: a larger number of thermocouples were installed closer to the roof surface to quantify the temperatures of the roof surface in case of flame spread. In Figure 5 to Figure 7 the placement of the gas burner is shown in black and the TCs have been colour-coded depending on their horizontal proximity to the gas burner (thermocouples located the closest to the burner are coloured red, and those the further away are coloured yellow). The colour system will be utilized when plotting the temperatures in subsection 3.2.

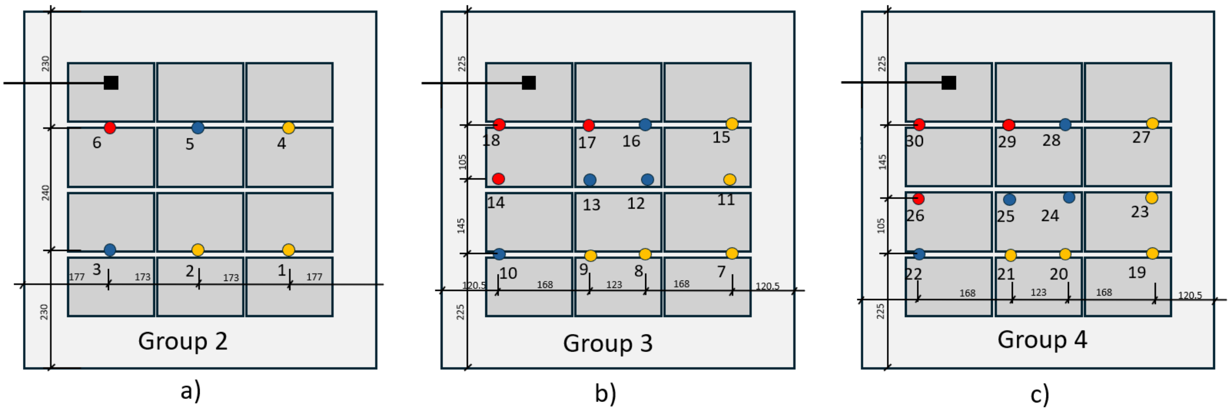

*Figure 6 – Test 6. Thermocouple distribution across the three different measurement layers **a)** below the EPS insulation, **b)** between the EPS insulation and CPB, **c)** between CPB and the PVC membrane. Dimensions are given in cm and are approximate.*

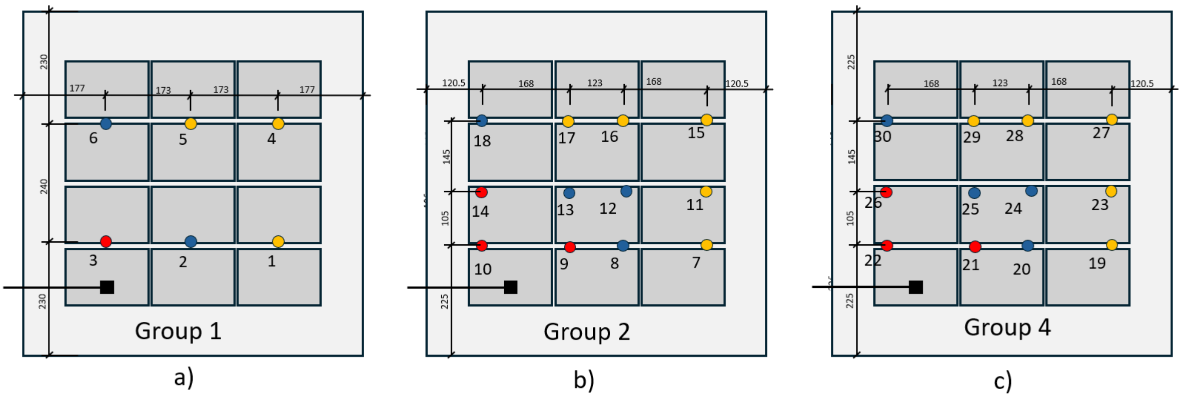

Figure 7 – Test 7. Thermocouple distribution across the three different measurement layers a) below the vapour barrier, ***b)*** *in the middle of mineral wool,* ***c)*** *between mineral wool and the PVC membrane. Dimensions are given in cm and are approximate.*

3 TEST RESULTS

The test results are presented as visual observations in section 3.1 and thermocouple readings in section 3.2. Visual observations focus on the flame spread and the overall damage on the structure at the end of the test. Thermocouple measurements help further quantifying the rate of the flame spread and the heat transfer through the roof build-ups. The ambient conditions were similar during all tests, even though a forced air flow was used in test 6.

3.1 Visual observations of flame spread and damage

Two flame spread trends were observed across the three tests: i) No self-sustained flame spread outside the domain of the gas burner in tests 5 and 6 with EPS and the CPB, and ii) Self-sustained flame spread in the cavity between roof surface and PV array in test 7 with MW insulation. Visual observations of flame spread along and heat transfer into the roof construction build-ups are analysed separately in the following two subsections. The analysis consists of visual observations and discussions of the factors that affected the outcome of the specific tests as well as differentiated the outcome across different tests.

In both test 5 and test 6, no self-sustained flame spread occurred outside the domain of the gas burner, and only a limited area of the PVC membrane was damaged as seen from the videoframes in Figure 9 and Figure 8. The damaged elliptical area in test 6 was slightly larger than the round area in test 5, as illustrated in Figure 10. The elliptical shape corresponds well with the direction of the induced airflow in test 6, as the wind driven flame spread deflected a larger section of the flame in the wind direction, rather than beneath the inclined PV module as seen in test 5.

Melting of the EPS insulation was observed on a limited area directly below the burner and comparable melted areas were seen in both tests (see Figure 10). The areas of melted EPS were limited to a diameter of approximately 25 cm in both tests and the melting indicates that the temperature of the boundary layer between the cement-bonded particle board and EPS insulation exceeded 100˚C [7]. Comparing the outcome of tests 5 and 6 with test 2 and 3 from the previous phase of the project [1], the extent of flame spread was lower in test 5 and 6.

Similar to tests 5 and 6, tests 2 and 3 were also conducted with the 12 mm thick cement-bonded particle board as a mitigation layer between a 1.8 mm thick PVC membrane and subjacent layers of 180 mm to 220 mm thick

EPS insulation [1]. With EPS being a homogeneous insulation material, the thermal parameters of all three products, roofing membrane, CPB and EPS, were similar across all four tests. Thus, similar thermal boundary layers were expected between the PVC membrane and the cement-bonded particle board, as well as between the cement-bonded particle board and the EPS insulation despite the various insulation thickness.

Considering the flame spread trends in tests 5 and 6 in this report and tests 2 and 3 in the previous phase of the project [1], two outcomes are observed with various frequency. In three of the four tests, no self-sustained flame spread were observed outside the ignition source, whereas the fire propagated below all four PV modules in test 3 in phase I [1].

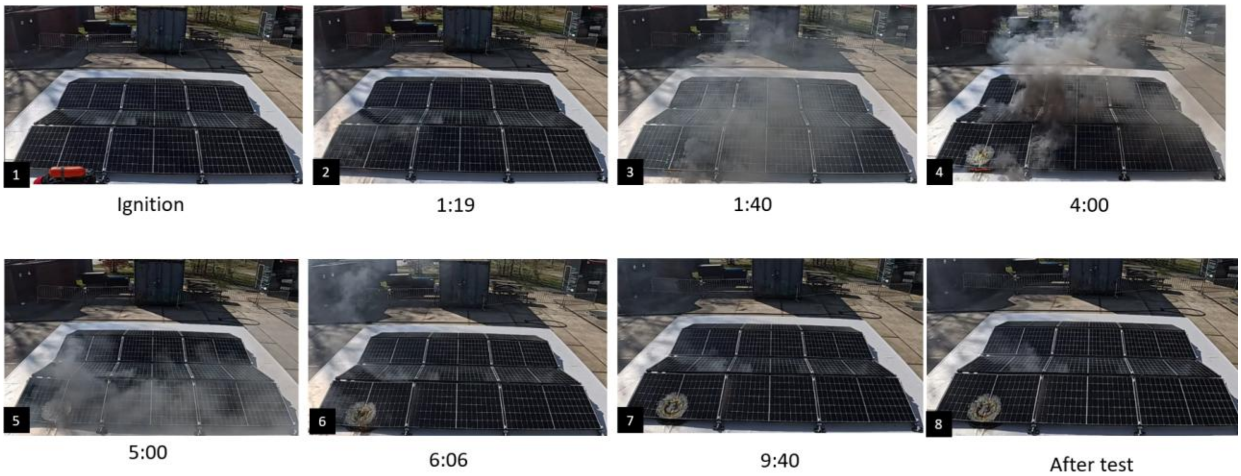

*Figure 9 – Visual observations of flame spread and fire behaviour during test 5. Time defined in minutes and seconds (min:sec) after ignition. **1)** Ignition below PV1 on lower left side of video frame, **2)** first black smoke appearing, **3)** first flames visible in video recording, and **8)** final damage visual damage before examination of roof construction below PV system. No flame spread outside the roof construction below PV 1.*

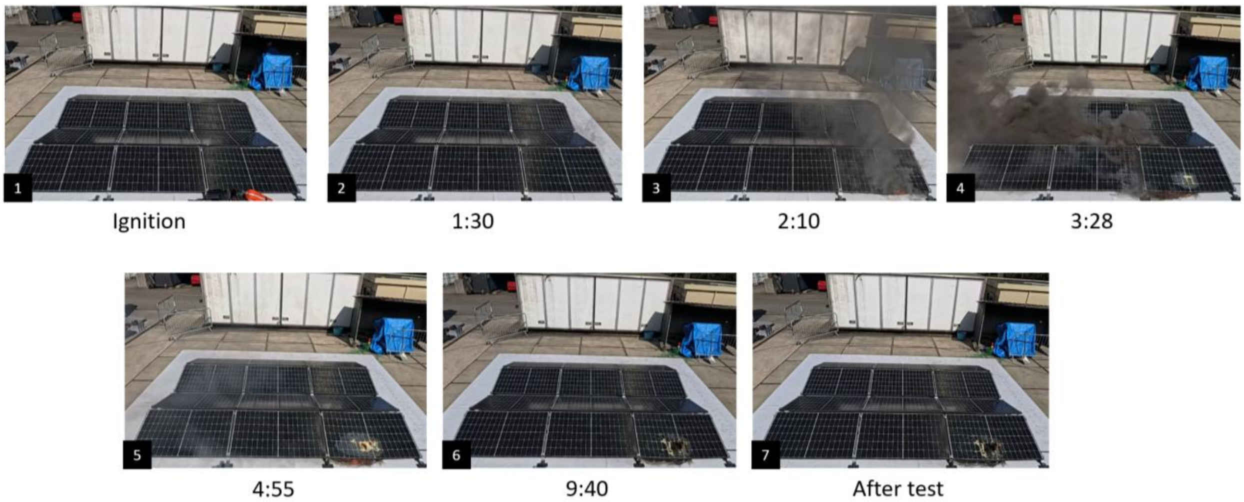

*Figure 8 – Visual observations of flame spread and fire behaviour during test 6. Time defined in minutes and seconds (min:sec) after ignition. **1)** Ignition below PV1 on lower right side of video frame, **2)** first black smoke appearing, **3)** first flames visible in video recording, **8)** final damage visual damage before examination of roof construction below PV system. Limited flame spread outside the roof construction below PV 1.*

a) b)

Figure 11 – Burned area of PVC roofing membrane. ***a)*** *test 5* ***b)*** *test 6*

a) b)

Figure 10 – Melted area of EPS under the cement-bonded particle board. ***a)*** *test 5* ***b)*** *test 6*

No matter the occurrence of self-sustained flame spread in the four tests, the area of melted EPS insulation in all tests were limited to a similar size area below the gas burner. Consequently, it can be concluded that the melting of EPS was caused by heat transfer from the gas burner flame, rather than the combustion of the PVC membrane in the cavity between the roof surface and PV modules.

The reason for that is, that the density and specific heat capacity of the cement-bonded particle board (CPB), specified in Table 2, make it sufficiently efficient to prevent significant temperature increases in the EPS outside the domain of the ignition source. In addition, the thermal properties of the CPB have the potential to prevent self-sustained flame spread over the thermally thin 1.8 mm thick single-ply PVC membrane, as the energy transferred from the flame front to the PVC membrane is absorbed by the CPB. The thermal conductivity of the CPB is sufficiently high to remove the heat from the membrane and due the high density and specific heat capacity, the CPB functions as a heat sink. In three of the four tests, the heat sink effect prevented the PVC membrane from exceeding its ignition temperature outside the domain of the ignition source [1]. In the single test with self-sustained flame spread, the material absorbed the energy from the burning roofing membrane preventing thermal degradation of the EPS insulation even if the ambient conditions are favourable for self-sustained flame spread as observed in test 3 described in the phase I report [1].

Self-sustained flame spread also occurred in third of the three tests conducted during the test campaign on April 8th 2025, as illustrated in the eight subfigures of Figure 12.

Significant flame spread was observed along the roof surface in test 7, with the PVC membrane installed on top of 120 mm MW insulation. From the video recording back smoke was observed 2 minutes into the test (Figure 12, subfigure 2) which is consistent with observations in test 5 and 6.

Due to the fast fire growth, and because the wind deflected the flames from the fire in the cavity between the PV modules and roof surface towards the gas burners' supply hose (Figure 12, subfigures 3 and 4) the testing institute, KIWA, decided to remove the gas burner after less than 5 minutes due to safety concerns [3]. The fire growth over the PVC membrane resulted in collapse of the mounting system below PV 1 and PV 2 (in accordance with the module layout in Figure 4) after around 6 minutes of the test. The fire propagated to the neighbouring section (PV7-PV12) of the array around 8 minutes into the test as seen from Figure 12, subfigure 5.

For safety and environmental reasons the test institute, KIWA, terminated the test 11 minutes after it was initiated, and the fire was extinguished with water [3]. By the end of the test, the flames had propagated along both sections of the PV array and it is expected that the fire would have propagated below all 12 PV modules if the test had not been terminated. Due to the wind direction, the PVC membrane was burnt outside the PV array in the downwind direction, but only limited damage was seen on the other sides, as illustrated in Figure 12, which corresponds with findings in previously conducted large-scale tests by Kristensen & Jomaas [5], PU Europe [6] and Kingspan [7].

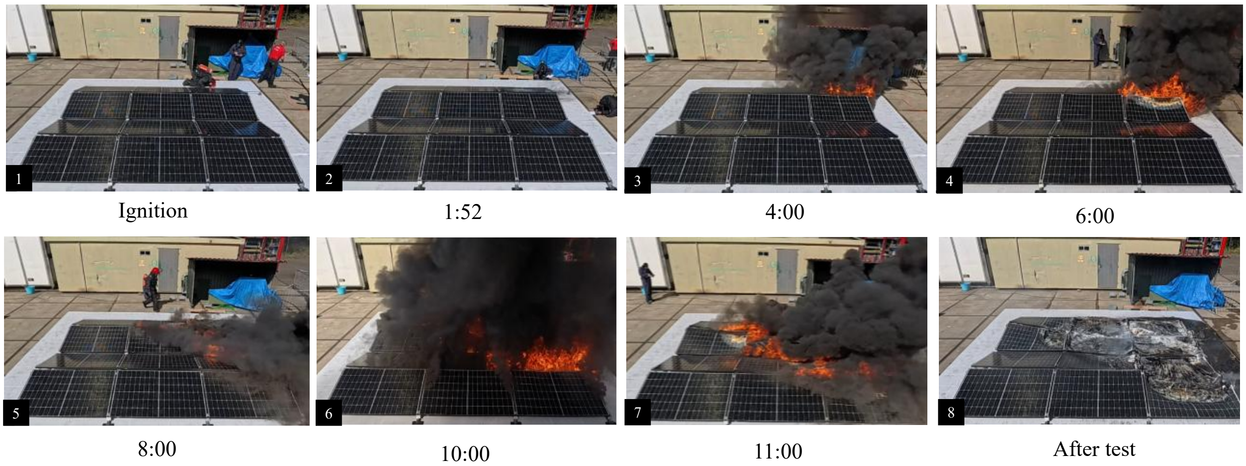

*Figure 12 – Visual observations of flame spread and fire behaviour during test 7. Time defined in minutes and seconds (min:sec) after ignition. **1)** Ignition below PV1 on upper left side of video frame, **2)** first observable smoke, **4)** The collapse of the first PV module, **6)** flame spread from the section with PV1-PV6 to the section with PV7-PV12, **7)** shortly before extinguishment of the roof build-up 11 minutes after ignition, and **8)** visual damage after extinguishment.*

In all three tests, the roofing membrane near the gas burner ignited within two minutes after initiation of the test. Subsequently, radiative feedback, caused by flame deflection beneath PV1 (PV8 in test 6), heated the surrounding roof surface, leading to the release of combustible pyrolysis gases near the flame front [5], [11]. When the concentration of these gases exceeded their lower flammability limit, an additional area of the roof surface beneath PV1 ignited.

The critical heat flux for ignition of flexible PVC is 10 – 21 kW/m^2 [12] and in case of self-sustained flame spread, the flame spread rate depends on thermal balance of the system (materials, the surrounding structure and ambient conditions). In the presented tests 5 and 6, no self-sustained flame spread was observed, indicating that the incident heat flux to the PVC was insufficient to overcome the heat losses to the CPB and thus prevent self-sustained flame spread outside the domain of the ignition source. With the ambient conditions across all three tests being similar, the material subjacent to the roofing membrane represents the only difference between tests 5-6 and test 7.

As the fire dynamic system of the modified roof construction, depends on the materials thermal properties and the geometry of the cavity, the importance of the mineral wool insulation or cement-bonded particle board's thermal parameters can be explained from fundamental heat transfer perspective. If the 1.8 mm thick membrane is assumed thermally thin, the substrate below the roofing membrane will have a significant influence on the heat transfer through the system, i.e. CPB in test 5 and test 6, and MW in test 7.

Based on the thermal properties defined in the thermal diffusivity ($\alpha = \frac{k}{\rho c_p}$) of mineral wool insulation is around 1.1 × 10^{-7} m^2/s and around 2.8 × 10^{-7} m^2/s for the cement-bonded particle board (CPB), which corresponds with the outcome of the tests as a lower thermal diffusivity means that the heat is distributed slower inside a material and that the thermal gradients through the material are larger for similar thicknesses. However, the thermal diffusivity of the materials cannot stand alone, as a significant increase of the CPB density could yield thermal diffusivity lower than the thermal diffusivity of the MW, although a density increase would enhance the effect of the specific heat capacity, c_p, and thus render the CPB a better heat sink. Assuming similar ambient conditions and initial heat transfer from the gas burner to the nearby surface of the PVC membrane across the three tests, the mineral wool led to a faster development of thermal equilibrium between the lower side of the PVC membrane and the uppermost surface of the MW. This enabled self-sustained flame spread. In contrast, thermal equilibrium was not reached between the PVC membrane and the cement-bonded particle board, as the pre-heating of the thermally thin membrane was transferred to the CPB before the membrane's ignition temperature was achieved in three of the four tests presented in this and the previous report.

3.2 Thermocouple measurements during the tests

Thermocouples (TCs) were installed between the different layers of the roof build-up constructions to evaluate the effect of the heat transfer from the fire during each test and to validate the visual observations presented in Section 3.1. The installation of the TC groups within the different layers of the constructions follows the positioning as presented in Table 1 and Figure 5 to Figure 7.

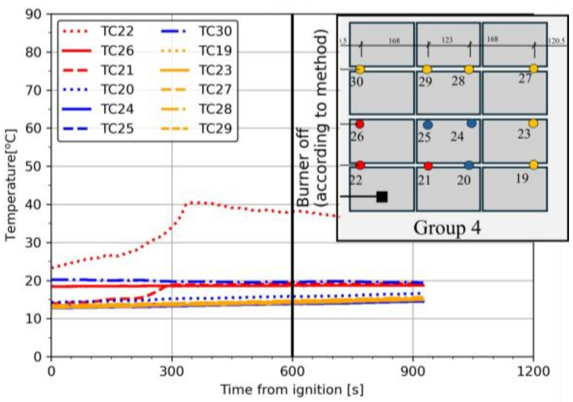

Figure 13 – Thermocouple measurements directly below the PVC membrane in test 5

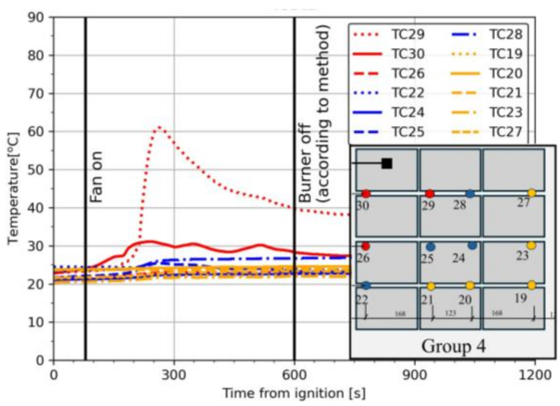

Figure 14 – Thermocouple measurements directly below the PVC membrane in test 6

Temperature measurements between the cement-bonded particle board (CPB) and PVC membrane in test 5 and test 6 are plotted in Figure 13 and Figure 14. Only a minor temperature rise can be observed below the roofing membrane in test 5 and test 6, as the thermocouples were not placed directly below the gas burner and there was no significant flame spread to the area of the roof construction near the thermocouples TC21 and TC22 in test 5, as well as TC29 and TC30 in test 6.

In test 5 the highest temperature is measured with TC22, located towards the opening of the cavity space between the PV panels. In test 6, on the other hand, the highest temperature was observed on TC 29, located deeper inside the PV array construction and in the downwind direction relative to the location of the burner. This corresponds with the increased damage of the PVC membrane observed in the downwind direction of test 6 (see Figure 11 b). The temperatures are lower, however comparable with those measured during the previous round of tests where no self-sustained flame spread occurred (i.e. test 6 in [4]).

The temperature measurements for test 7 are plotted in Figure 16 to Figure 17. To some extent, the temperature readings allow the estimation of a flame spread rate in the cavity between the roof surface and the PV array. The flame spread rates, along with the distances between thermocouples and the burner, are summarized in Table 3.

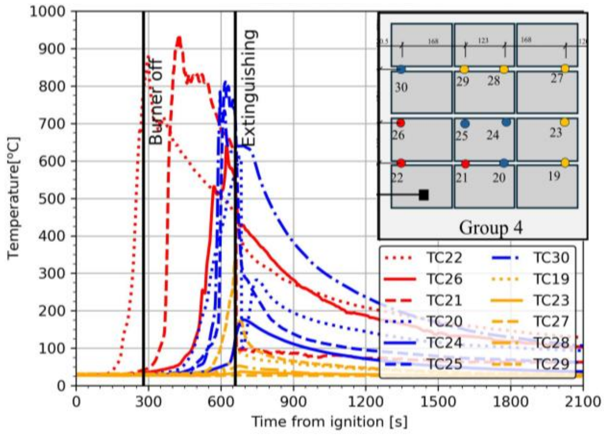

Figure 16 – Thermocouple measurements in test 7 below the PVC roof layer (TC group 4).

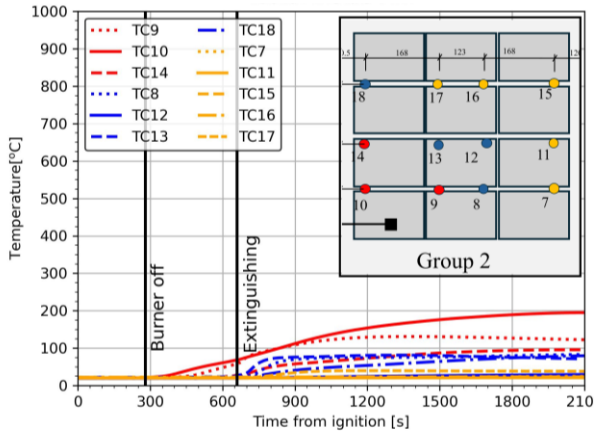

Figure 15 – Thermocouple measurements in test 7 inside mineral wool (TC Group 2).

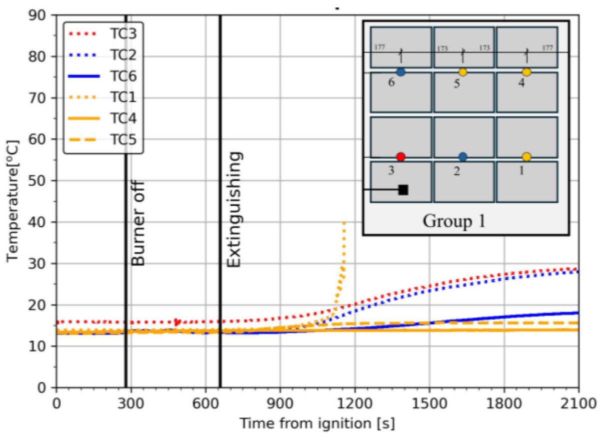

Figure 17 - Thermocouple measurements in test 7 below the vapour barrier (TC group 1).

For the purpose of this report the flame front reaching the thermocouple is defined as time when thermocouple measurement reaches 300˚C during a relatively steep temperature rise. The critical temperature of 300˚C is based on engineering judgement. It is difficult to determine an objective critical temperature, because the unburned PVC layer protects the thermocouples even after the pyrolysis zone has passed the above material. Considering the defined criteria the flame spread to PV3 at around 6th minute (the burner is already removed at this point) and to edge between the adjacent array (TC 26 and TC 30) at around 9th – 10th minute.

Table 3– distances from thermocouples to the burner, time for flame to reach the thermocouple and flame spread rate in test 7.

TC number	20	21	22	25	26	29	30
Distance from burner (m)	2.5	1.4	1.0	2.3	2.1	3.6	3.5
Time to flame reaching TC (min)*	9	6	4	10	9	11	10
Flame spread rate (m/min)	0.28	0.24	0.26	0.23	0.23	0.33	0.35

** time defined roughly based on the temperature criteria of 300˚C and a relatively steep temperature rise*

The results indicate that the flame spread in direction along the section of the PV array first ignited is slightly slower compared to flame spread to the adjacent section of the PV array (see in Table 3, that the flame spread rate to TC 29 and 30 are faster compared to other thermocouples). Nevertheless, it must be considered, that the flame spread rate increases as the fire grows larger, and therefore the average flame spread rate is higher for further located thermocouples. In the present test, the flame spread rates can be considered roughly uniform in all directions of the PV array system, ranging from 0.23 – 0.35 m/min. However, the wind direction should be considered when evaluating the estimated flame spread rate, as most of the fire propagated against the dominant wind direction as illustrated in Figure 12. In case the ignition source had been located in the centre or diagonal opposite corner of the PV array, it is assumed that the flame spread rate would be higher in the downwind direction.

The increase of temperatures inside the 120 mm of mineral wool starts rising at around 5th minute of the test where the gas burner is already turned off and removed. These temperatures keep rising long after the fire is extinguished to a maximum of almost 200˚C. The thermocouples reaching temperatures higher than 75˚C were TC 10, TC 9, TC 14, TC 8, TC 13 and TC 18 – again indicating roughly uniform heat transfer in all directions of the PV array with adjacent sections. Only a small temperature increase was observed in the thermocouples beneath the vapour barrier during test 7 as plotted in Figure 17.

The temperature measurements below the roofing membrane and inside the mineral wool for the same coordinates in test 7 are plotted in Figure 18, whereas the temperature measurements inside MW insulation in test 7 for the entire duration of the observations (including cooling) is presented in Figure 19. The figure shows that the cooling back to the initial temperature of mineral wool took for about 6 hours – even though the fire was extinguished with water 11 minutes after the test was initiated.

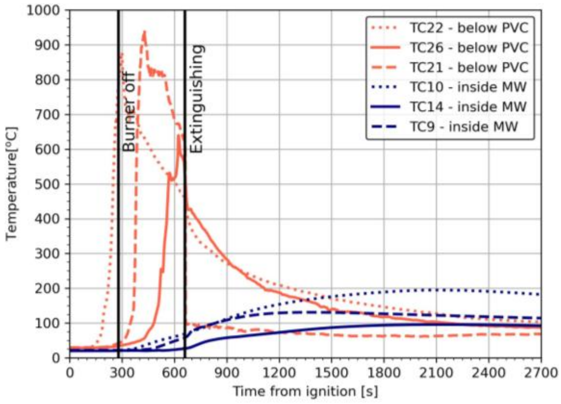

Figure 18 – Thermocouple measurements in test 5 and test 6 directly below the PVC membrane and the representative locations

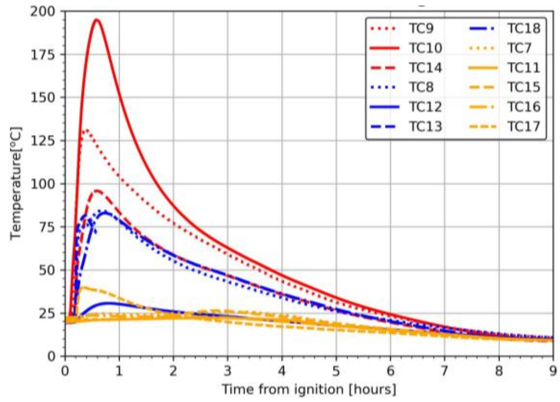

Figure 19 – Thermocouple measurements in test 5 and test 6 directly below the PVC roof layer and the representative locations

4 CONCLUSION

A series of three large-scale fire tests designed by IVH, the German Rigid Foam Industry Association and EUMEPS, the European Manufacturers of Expanded Polystyrene were conducted to examine the impact of PV-related fires on flat roofs below a 12 module east/west orientated BAPV array and two different roof built-ups. One the roof construction consisted of a 1.8 mm thick PVC-based Bauder Thermofol M18 (B_{ROOF}(t1)) roofing membrane installed on a 12 mm thick cement-bonded particle board (CPB) which served as a mitigation layer to protect the subjacent layer of EPS insulation. The other bulit-up consisted of the same PVC membrane product installed directly on non-combustible mineral wool insulation.

The main objective of the tests was to evaluate the ability of the CPB to protect the expanded polystyrene (EPS) insulation with polymeric fire retardant and potentially reduce horizontal flame spread in the cavity between the roof surface and the PV array as seen in one of tests conducted during previous phase of the project [1]. The severity of the consequence was first and foremost affected by the material layer below the PVC membrane and the main conclusions were:

- In the two tests conducted with the cement-bonded particle board between the PVC membrane and the EPS, no self-sustained flame spread was observed in the cavity between the roof surface and PV array.
- The tests demonstrated that the 12 mm thick cement-bonded particle board can mitigate the consequences in case of a PV-related fire significantly, as only a limited area of EPS was melted directly below the burner.
- Self-sustained flame spread was observed below the PV array in the test with mineral wool insulation not protected by a cement-bonded particle board. The test was terminated by the test institute, KIWA, due to safety and environmental concerns.
- The tests indicate that the implementation of a mitigation layer with appropriate thermal properties, like the cement-bonded particle board, modify the energy balance of the fire dynamic system below PV array and reduce heat transfer to the subjacent insulation material. This modification evaluated in this report

effectively decrease the likelihood of self-sustained flame spread along thermally thin roof coverings.

- It is expected that the effect of such mitigation layer is only valid for thermally thin single-ply roofing membranes. The tests are solely conducted with a product with a thickness of 1.8 mm. Based on fundamental flame spread theory, the results are also valid for thinner versions of the same membrane, but not valid for the same product if it is thicker than 1.8 mm.

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