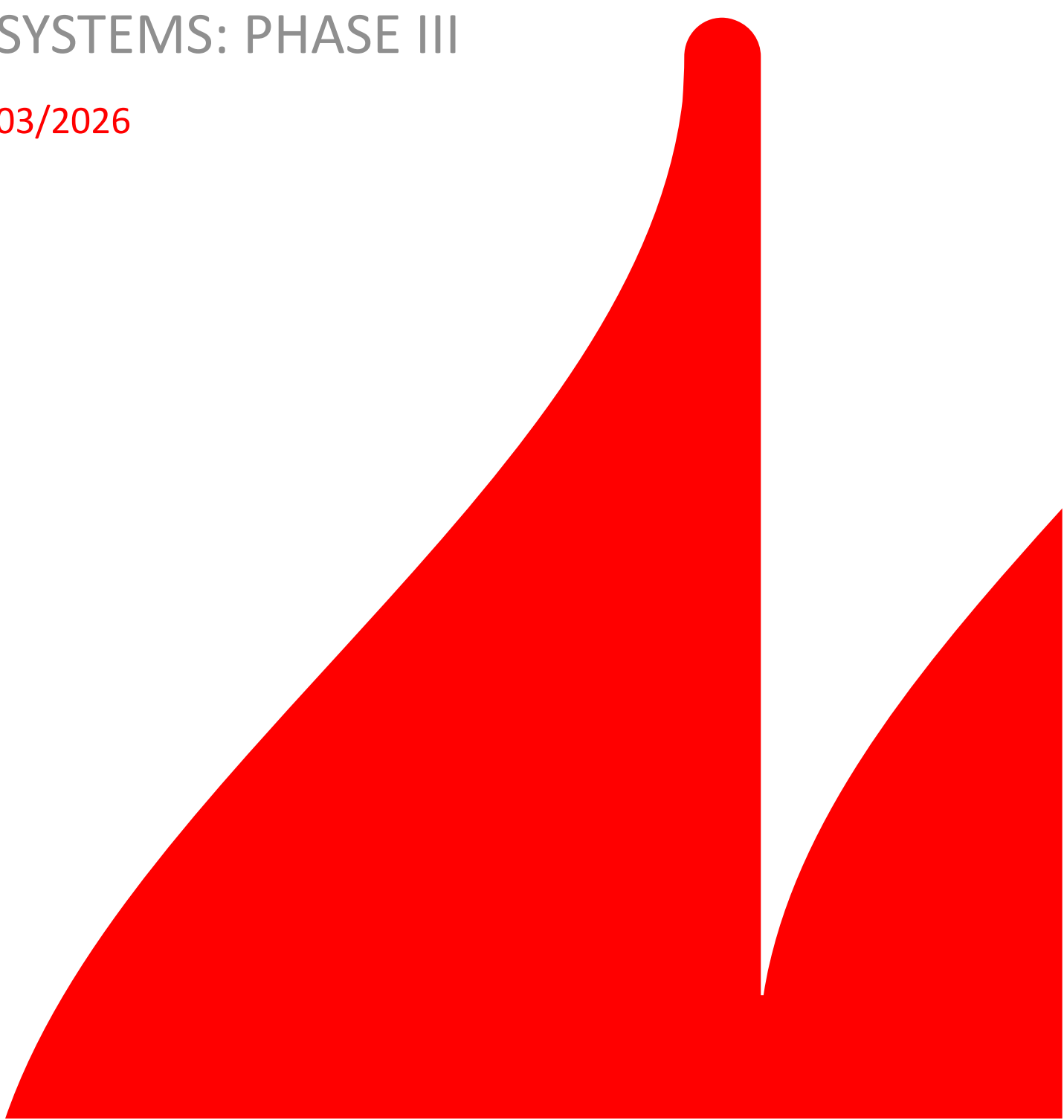




LARGE-SCALE TESTS OF  
FLAME-SPREAD ON ROOF  
BUILD-UPS WITH PV  
SYSTEMS: PHASE III

03/2026



## REPORT INFORMATION

**Client:** EUMEPS – European Manufacturers of Expanded Polystyrene  
**Address:** 71 Avenue Cortenberg B-1000  
 1000 Brussels  
 Belgium  
  
**Case number:** SIEC21006  
**Report number:** 21006-001  
**Prepared by:** J. S. Kristensen, PhD jsk@dbigroup.dk  
**Approved by:** A. Frost-Jensen, Director of afj@dbigroup.dk  
 Infrastructure & Quality

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## 1. INTRODUCTION

In this report the Danish Institute of Fire and Security Technology (DBI) outlines the method and results of two large-scale tests and six medium scale tests conducted by IVH, the German Rigid Foam Industry Association and EUMEPS, the European Manufacturers of Expanded Polystyrene. In these tests, the effect of three different types of mitigation layers between a PVC membrane and the subjacent insulation material were assessed.

As part of the European Union’s Energy Performance of Buildings Directive, photovoltaic (PV) systems are required on an increased amount of the built environment [1]. However, the implementation of the technology introduces an increased fire-related risk as outlined by several stakeholders, including Swiss RE [2] and recently conducted research [3], [4]. The fire-related risk of building applied photovoltaic (BAPV) systems arises from an increased probability of ignition and altered fire dynamics within the cavity between the roof surface and the backside of the BAPV module.

In the previous two reports [5], [6], summarised in the white paper [7], a total of seven large-scale tests have been conducted. The seven tests illustrated that the introduction of a cement-bonded particle board (CBP) between a PVC membrane ( $B_{ROOF}(t1)$ ) and EPS insulation i) reduced the probability of self-sustained flame spread, and ii) prevented ignition of the EPS insulation in the test where self-sustained flame spread occurred below the BAPV system [7].

The effect of CBP was only tested with a thickness of 12 mm which can represent a substantial load on existing roof construction in addition to the BAPV itself. Thus, the effect of an 8 mm thick CFB from the same manufacturer, as well as a 6 mm thick cement board, are examined in two large-scale tests similar to the previously conducted tests as illustrated in Figure 1a.

In addition, six medium scale tests with a single PV module were conducted at the facilities of DBI as seen in Figure 1b. The roof construction build-ups and BAPV system of the medium scale tests were similar to the two large-scale tests presented herein and all tests conducted with the PVC membrane in the phase I and II reports [5], [6]. The objective of the tests was i) to eliminate the influence of ambient parameters and ii), to verify the findings from the large-scale test.

The two large-scale tests were performed at the premises of Twente Safety Campus (Troned, NL). 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, September 4<sup>th</sup>, 2025. DBI observed the four tests. KIWA BDA conducted the testing and provided two test reports [8], [9] to IVH and EUMEPS, who shared the reports, videos, and thermocouple data



a)



b)

Figure 1 – **a)** Aerial view of test 8 and test 9 (closest) in September 2025 at the test area in the Netherlands. **b)** One of the six medium scale tests conducted at DBI’s facilities in Denmark.

with DBI. Based on that, DBI analysed the results which are presented in this report.

The six medium scale tests were all conducted at DBI's facilities in Hvidovre (DK). The client shipped all materials and the simple roof build-ups were assembled by DBI employees who also installed thermocouples between the individual layers. DBI carried out all tests from where half of them was witnessed by a EUMEPS representative. The findings from the six tests are presented in this report.

The report is structured as follows: First, the two large-scale and six medium scale roof configurations are described, which is followed up by the instrumentation set-up and results. In each section, the two large-scale tests are presented first and followed by the six medium scale tests. This order allows continuous discussion of the large-scale tests and facilitates comparison with the medium scale tests. This comparison helps evaluate the performance of the thinner cement boards and the reduced influence of ambient parameters.

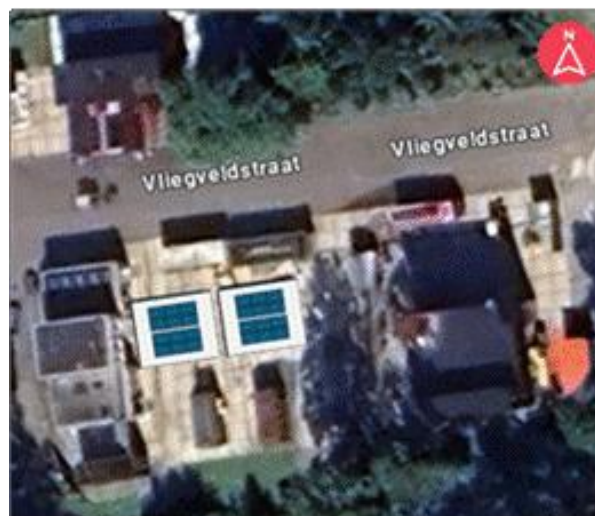


Figure 2 – Test location and construction orientation.

## 2. TEST SET-UPS

The test set-ups consisted of four components: i) the roof build-ups, ii) the PV system, iii) instrumentation and iv) the ignition source. In general, the objective was to keep all key variables, besides the roof build-ups, constant across the large- and medium scale tests. In general, that was achieved, but the potential consequences of the few variables are discussed in the following subsections.

### 2.1. Roof build-ups

The detail of the roof build-ups varied between the large- and medium scale tests. The reason for that was, that the medium scale tests only examined a small area of the large-scale tests, which were constructed as exact roof constructions. As such, the PVC roofing membrane and underlying materials were mechanically fixed to a trapezoidal steel deck representing a loadbearing of a lightweight roof build-up, whereas no mechanical fixation was used in the medium scale tests.

In addition, all tests in this report were solely conducted with an insulation thickness of 100 mm, whereas the maximum thickness of the EPS and mineral wool insulation were respectively 260 mm and 120 mm in the previously conducted tests [5], [6]. It is acknowledged that the thickness of the insulation is relevant from an energy efficiency perspective, but the short time duration of a fire incident solely renders thermal heat transfer through the uppermost insulation layer relevant if the remaining parameters are unchanged. Thus, it is not expected that the reduced thickness of the insulation in the medium scale test affects the outcome of the test, when compared to previously conducted large-scale tests [5], [6].

#### 2.1.1. Large-scale

Following the consecutive numbering of the large-scale tests presented in the phase I (tests 1-4) [5] and phase II (tests 5-7) [6] reports, the two tests are referred to as test 8 and 9.

In both tests, the roof build-ups covered a squared area of 49 m<sup>2</sup>, with side lengths of 7 meters. They were constructed atop a metal support structure and a 0.75 mm thick trapezoidal steel deck, identified as layers 1 and 2 in Table 1. In general, the two test build-ups were constructed similar to the previous tests with the sole difference being the mitigation layer between the 1.5 mm thick PVC membrane and the subjacent EPS insulation, defined as layer #5 in Table 1.

Thus, the objective was to examine whether the two thinner mitigation layers, compared to the previously tested 12 mm thick cement-bonded particle board [5], [6], can perform similar and thus i) reduce the probability of self-sustained flame spread, and ii) reduce heat transfer from a fire between the roof surface and PV module - if self-sustained flame spread occurs.

#### CONSTRUCTION PRODUCTS:

**PVC Roofing membrane:** Bauder THERMOFOL M15, 1.5 mm, light grey, (B<sub>ROOF</sub>(t1))

**Cement-Bonded Particle Board:** CETRIS BASIC, 12 mm, Euroclass A2-s1,d0

**Cement board:** Knauf Aquapanel cement board rooftop, 6 mm, Euroclass A1

**Expanded Polystyrene (EPS) insulation:** Brohlburg EPS DAA, 100 mm, Euroclass E

**Mineral wool insulation:** Rockwool Hardrock 08, 100 mm, Euroclass A1

Table 1 – Roof build-up of the two large-scale tests. Materials from top (layer # 6) to bottom (#1). The numbered red markers indicate location of thermocouples between installed between the layers in accordance with Figure 4.

Layer	Test 8	Test 9
# 6	1.5 mm PVC-based roof membrane	
# 5	8 mm cement-bonded particle board	6 mm Aquapanel
# 4	100 mm Expanded Polystyrene (EPS) insulation	
# 3	Vapour barrier	
# 2	0,75 mm trapezoidal steel deck	
# 1	Metal support structure	

### 2.1.2. Medium scale

All the medium scale tests were conducted on smaller test mock-ups examining only the uppermost section of the roof constructions. As the tests were conducted below an indoor extraction fan, the mock-ups had to be movable and for that reason they were constructed on top of two EUR-pallets. Thus, the side lengths of each roof mock-up were 1.6 m × 2.0 m, which allowed installation of a single PV module.

The two EUR-pallets were assembled by a 12 mm thick medium density fibre board, on which the six medium scale tests, MT 1 to MT 6, were constructed with the 1.5 mm PVC membrane as the upper layer.

Common for all six medium scale tests were the 1.5 mm thick PVC membrane ( $B_{ROOF}(t1)$ ) which were also used in the large-scale tests. Half of the test was conducted with 100 mm EPS insulation protected with the mitigation layers of respectively 12 mm and 8 mm cement-bonded particle board (CPB), or the 6 mm thick cement board (MT 6 in Table 2). The other half of the tests were conducted with 100 mm mineral wool insulation of which one test, MT 3 in Table 2, examined whether the effect of the 8 mm CPB, tested on EPS in MT 2, was linked to the thermal properties of the subjacent insulation material.

Table 2 – Roof build-up of the six medium scale tests (MT). Materials from top (layer # 4) to bottom (#1). The numbered red markers indicate the location of thermocouples between installed between the layers in accordance with Figure 5.

Layer	MT 1	MT 2	MT 3	MT 4	MT 5	MT 6
# 4	1.5 mm PVC-based roof membrane					
# 3	12 mm cement-bonded particle board (CPB)	8 mm cement-bonded particle board (CPB)				6 mm Aquapanel
# 2	100 mm Expanded Polystyrene		100 mm mineral wool			100 mm Expanded Polystyrene
# 1	12 mm medium density fibreboard (MDF)					

The final two tests, MT 4 and 5 in Table 2, with mineral wool insulation examined repeatability of the test method, as well as if the outcome of the similar large-scale test, test 7, in the phase II report [6], could be repeated in a smaller scale test.

### 2.2. PV system

Throughout all tests the same type of PV module, a LYNUS M19N TOPCon TYPE MONO LY430 Wp, were used. The backside of the monofacial PV module was a plastic based foil. Due to availability, two different mounting systems were used in respectively the large- and medium scale tests as seen from the side view in Figure 1b and Figure 3.

The different mounting systems across the large- and medium scale tests rendered two different cavity geometries between roof surface and PV modules. With the gap distances being defined as the distance between roof surface and the upper edge of the PV module’s frame, the gap heights in the large-scale tests were between 125 mm and 390 mm, whereas there was 80 mm and 345 mm between the roof surface and the lowest and highest part of the PV modules. As such, the inclination remained constant across all tests. However, the gap height in the medium-scale tests was 40 mm lower than in the two large-scale tests in this report and the seven tests presented in the phase I and II reports [5], [6].

From previously conducted research, it is known that the gap height between the roof surface and PV module is a parameter that can affect whether self-sustained flame spread occur [10]. In addition, the term critical gap

height determines that gap height at which self-sustained flame spread occur, whereas no self-sustained flame spread occurs outside the domain of the ignition source if the gap height is above the critical height [10]. However, the critical gap height is closely related to the heat release rate of the ignition source as radiative heat transfer from the flame to the roof surface, i.e. pre-heating of the PVC membrane, is closely linked as exemplified in the steady state experiments conducted by both Ju et al. [11] and Tang et al. [12]. As such, ignition sources with higher heat release rates renders higher critical gap heights. If self-sustained flame spread occurs, limited studies of flame spread beneath inclined PV modules do not indicate that a reduction in the local gap height at the ignition location significantly affects the flame spread rate along the roof [10].

Following that, the use of a similar ignition source across the large and medium scale tests would render a higher heart transfer towards the roof surface in the latter and thus increase the likelihood of self-sustained flame spread, whereupon the medium scale tests can be considered more conservative.

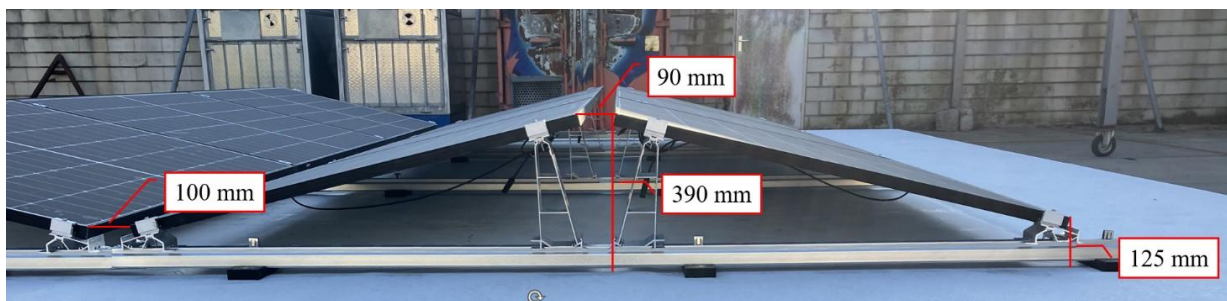


Figure 3 – Partial side view of the East/West-orientated PV array. The distances between the lower edges of the two array sections, the upper edges of the modules, as well as the distances from the PV modules to the roof surface are all measured from the top of the module frames. The same mounting system and PV modules were used across all large-scale tests as well as phase I and II off this project from where the illustration originates [5-7].

### 2.3. Instrumentation

Contrary to the large-scale tests, the medium scale tests, allowed measurement of the heat release rate (HRR) via oxygen calorimetry. The measurements were conducted under the extraction hood of DBI’s room corner test and the HRRs were calculated as per the method described in EN ISO 13823 [13].

As indicated by the red dots in Table 1 and sketches in figure 4, a total of 16 type-k thermocouples (TCs) were installed in each of the large-scale tests. Due to expected limited flame spread in the two tests, compared to the previous seven large-scale tests [5], [6], the number of TCs was

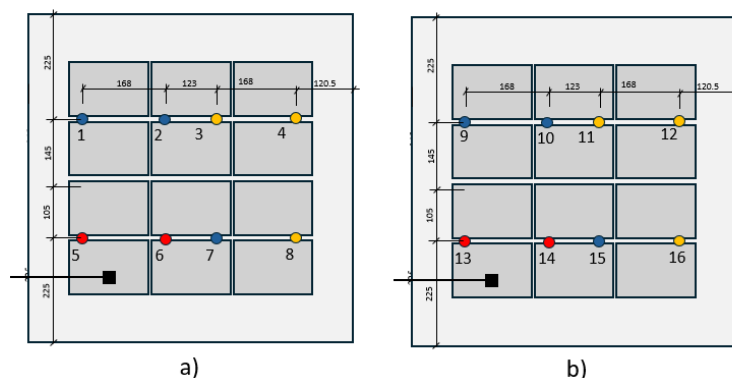


Figure 4 – Sectional top view sketch of large-scale tests 8 and 9. Location of PV modules (dark grey rectangles), gas burner (black square on the lower left) and thermocouples which are numbered and colour coded for later use. **a)** between layers #6 and #5 in accordance with Table 1, **b)** between layers #5 and #4 in accordance with Table 1.

reduced. In each test, half of the TCs were installed between the PVC membrane and mitigation layer, whereas the other half were installed below the mitigation layer and thus on top of the EPS insulation as per Table 1.

With TC5 and TC6 being the thermocouples installed closest to the ignition source (figure 4a), but outside the footprint of the PV module below which the ignition source was located, significant temperature increase would indicate self-sustained flame spread. Thus, the location of the thermocouples in the two large-scale tests provided limited data quantifying heat transfer near the location of the ignition source.

Contrary to the thermocouple density in the large-scale tests, a total of 19 TCs were installed in each of the medium scale tests. As seen from the TC locations in Table 2 and Figure 5, nine TCs were installed between the PVC membrane and subjacent insulation, whereas only five TCs were installed between each of the remaining layers. The objective of the additional TCs in the uppermost layer of thermocouples, TC1, TC4, TC6 and TC9, were to quantify potential heat transfer from a fire below the PV module to the near vicinity outside the footprint of the single PV module, whereas the purpose of the remaining TCs was quantification of heat transfer from the roof surface through the roof construction.

Finally, both the large- and medium scale tests were recorded with a video camera during the whole duration of the tests. All recordings were terminated when there were no visible flames between the PV modules and roof surface.

## 2.4. Ignition source

In both the large- and medium scale tests, a gas burner with a heat release rate (HRR) of 15 kW ( $\pm 1$  kW), following the specifications presented in technical report CLC/TR 50670:2016 [10], was used as ignition source during the initial 10 minutes of each test. The HRR was based on a propane (95%) flow of 324 mg/s ( $\pm 20$  mg/s), monitored by a Bronkhorst flowmeter.

In all tests, the square-shaped gas burner was positioned at the midpoint along the width of the single PV module in the medium scale tests. The horizontal distance from the burner's nearest edge to the lower edge of the PV module was 120 mm, while the vertical clearance between the bottom of the burner and the roof construction measured 80 mm.

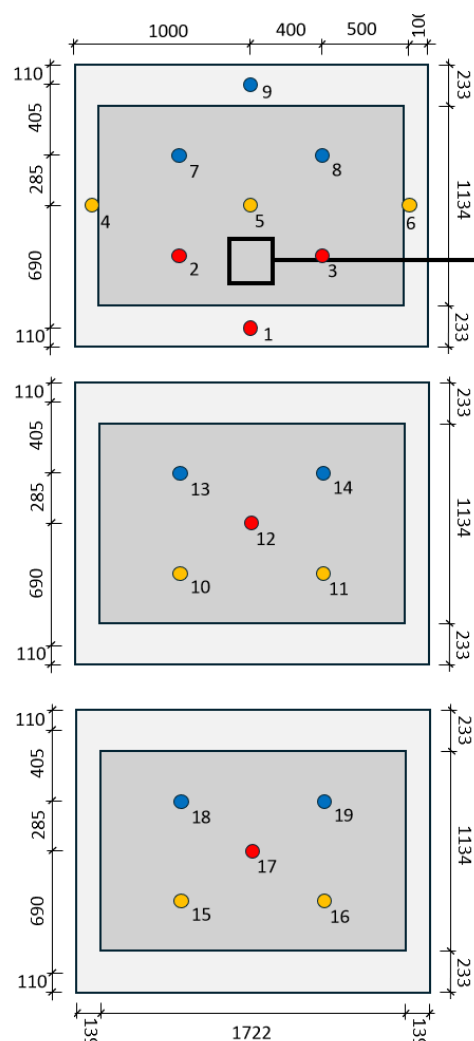


Figure 5 – Location of thermocouples (TCs) in the medium scale tests. The dark grey rectangle and black square indicate the location and dimensions of respectively the PV module and the gas burner. TC1-TC9 were installed between layers #1 and #2, whereas TC10-TC19 were installed in accordance with Table 2.

### 3. TEST RESULTS

The test results are divided into two sections, i) visual observations, and ii) data measurements from the thermocouples and heat release rate based on oxygen calorimetry which are used to quantify the visual findings. Like some of the previous sections of the report, the findings are separated into an initial discussion of the two large-scale tests, followed by the six medium scale tests.

#### 3.1. Visual observations of flame spread and damage

##### 3.1.1. Large-scale

In the two large-scale tests, test 8 and test 9 with mitigations layer of respectively the 8 mm cement-bonded particle board and the 6 mm cement board, no self-sustained flame spread occurred outside the domain of the ignition source after the gas burner was turned off after 10 minutes. As such, the fire only affected a single PV module in each test and damaged the areas of the roof sections seen in figure 6a & c.

Similar to previously conducted tests with the 12 mm cement-bonded particle board, the heat transfer from the ignition source melted the EPS insulation directly below the gas burner as seen in figure 6b & d. From inspection of the EPS cavity, there was no indication of a combustion process. It was assumed that the darker spots of the EPS occurred due to concentration of the graphite in the dark EPS beads. In both large-scale tests, the EPS cavities reached temperatures that caused melting and localised holes in the subjacent moisture barrier as visually prominent in Figure 6d.

##### 3.1.2. Medium scale

Two outcomes were observed in the medium scale test. Either no self-sustained flame spread occurred outside the domain of the ignition source and the fire self-extinguished when the gas burner was turned off, or the fire propagated below all the PV module. The former outcome, illustrated in the videoframes from medium scale test 1 in Figure 7, was observed in all tests with a cement-bonded particle board (CPB) or the cement board, including medium scale test 3 with 8 mm CPB on top of mineral wool insulation. Without the CPB between the PVC membrane and mineral wool insulation, self-sustained flame spread occurred in the two tests as seen in the videoframes from medium scale test 4 (MT4) in Figure 8. Similar figures of all six medium scale tests are found in appendix A on page 19.

In MT4, the extraction in the laboratory could not follow the smoke production and the laboratory became full of smoke as seen in Figure 8b-c. 10 minutes after ignition, the laboratory gate was opened to allow additional ventilation of the fire which self-extinguished 14 minutes after ignition. As observed in large-scale tests [8], [9], the fire only propagated below the PV module in the tests with self-sustained flame spread, as the fire did not propagate to the area of PVC membrane in front of the lower PV module edge in Figure 8c. In the repeated test of MT4, MT5, the fire was extinguished with water 5 minutes after ignition to prevent significant smoke spread outside the extraction hood. Consequently, the repeatability of the test method is solely based on the initial 5 minutes after ignition.

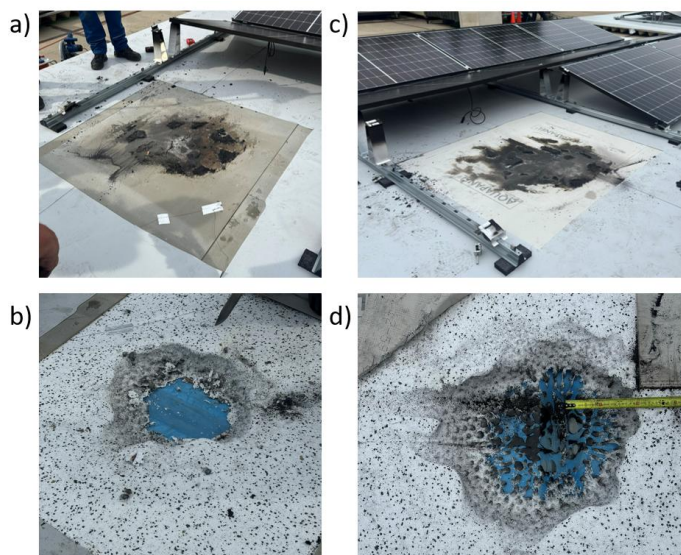


Figure 6 – Visual damage of the mitigation layers, EPS insulation and vapour barrier in large-scale tests 8 (a-b) and 9 (c-d).

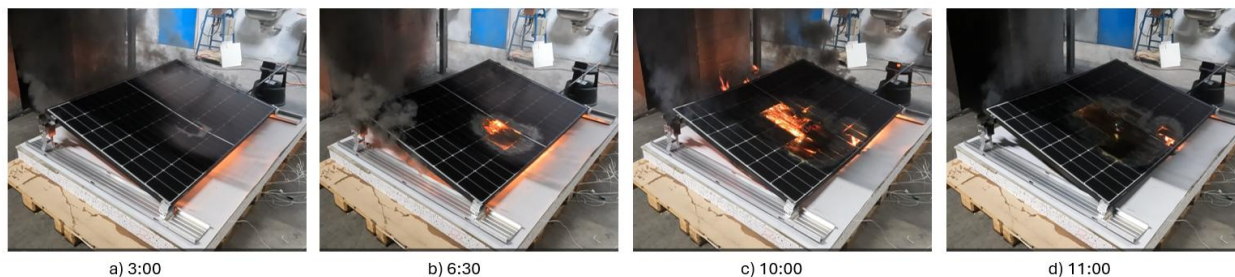


Figure 7 – MT1 with 1.5 mm PVC membrane, 12 mm CBP and 100 mm EPS insulation. Time from ignition in min:sec.



Figure 8 – MT4 with 1.5 mm PVC membrane on top of 100 mm mineral wool insulation. Time from ignition in min:sec.

Considering the width and length of the damaged PVC membrane area in the two large-scale tests and six medium scale tests, plotted in Figure 9, a distinct effect of the cement based mitigation layers is identified. In MT4 and MT5, the damage reaches the maximum dimensions, corresponding to the width of the PV module and the length between the roof area below the lower edge of the PV module and the edge of the roof mock-up closest to the most elevated part of the module, as shown in Figure 10.

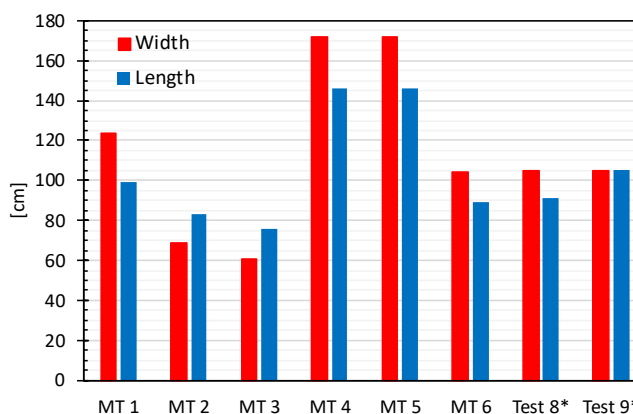


Figure 9 – Damaged area of the PVC roofing membrane in the six medium scale tests, MT1-6, and two large-scale tests, test 8-9.

\*Dimensions based on measurements in reports by KIWA BDA.

Taking the previously conducted seven large-scale tests [5], [6] into consideration, the outcome of the six medium scale tests are almost identical, as the self-sustained flame spread also occurred in the test with mineral wool, test 7 in phase II report [6], whereas no self-sustained flame spread occurred in three of the four tests conducted with the 12 mm thick cement-bonded particle board (CPB) [7]. In addition, the outcome of MT2 and large-scale test 8, as well as MT6 and large-scale test 9 is almost similar, which indicate that the medium scale test can serve as an adequate substitute for the large-scale tests.

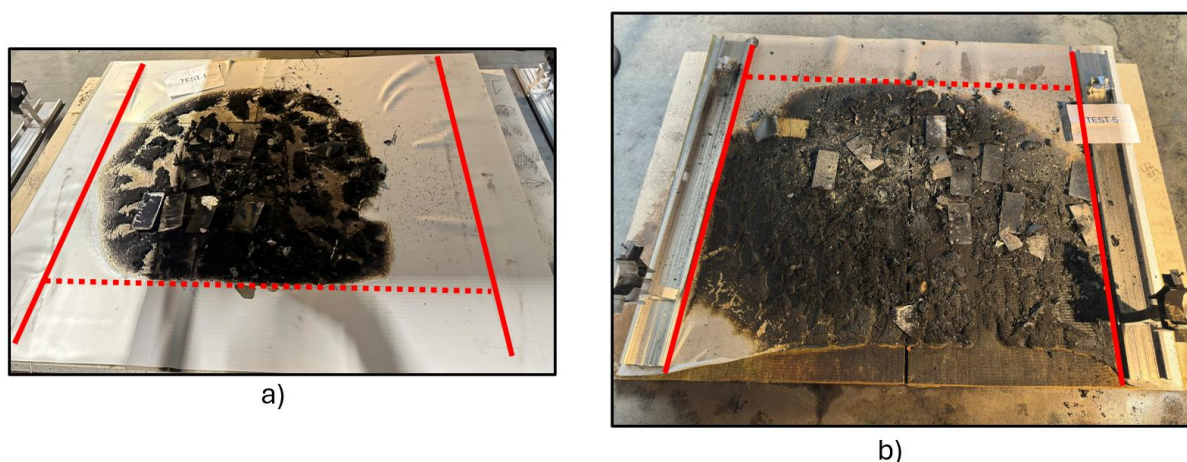


Figure 10 – Damaged area of the PVC roofing membrane in two of the medium scale tests. **a)** MT1 with a mitigation layer of 12 mm cement bonded particle board between the membrane and adjacent EPS insulation. **b)** MT5 with the membrane installed directly on 100 mm mineral wool insulation. MT5 was extinguished 5 minutes after ignition due to smoke production. Note that the two images were taken from different sides of the roof mock-ups. The dotted red line indicates the location of the PV modules lowest edge, whereas the solid red lines indicate the edge of the mounting systems.

Following the gap height discussion in section 2.2, it is acknowledged that the outcome of the medium scale tests should be more severe than in the large scale tests due to the 40 mm lower gap distance between the roof surface and PV module. Thus, the dimensions of the damaged area should, from a theoretical perspective, be larger in the medium scale tests conducted with the 8 mm CPB (MT2) and the 6 mm Cement board (MT6) than in their respective large-scale counterparts, test 8 and test 9. However, the gap height is not the only parameter affecting the outcome of such tests and it is expected that localised flows between the PV module and roof surface, caused by the extraction fan, in the indoor medium scale tests can have affected the outcome of the test as discussed in previous research [4, p. 136].

Based on the damaged area in tests MT2 and MT3, both conducted with the 8 mm thick CPB on top of respectively 100 mm EPS and mineral wool insulation, the similar outcome indicates that the thermal properties of the subjacent insulation materials had no influence on the results. This correlates well with the assumption that the short time duration of a fire incident in a cavity between a PV module and thermally thin PVC membrane renders solely the uppermost part of the subjacent material relevant when determining the likelihood of self-sustained flame spread. As discussed in the previous reports [5], [6], the three cement-based mitigation layers all have a higher density, conductivity and specific heat capacity, than the mineral wool insulation and consequently, the mitigation layers serve as a heat sink that absorbs the energy transferred towards the pre-heating zone of the thermally thin PVC membrane. In the tests conducted with the mitigation layers, the absorbed energy prevents the examined PVC membrane from reaching its ignition temperature near the flame front and since flame spread is essentially a series of ignitions, the fire self-extinguishes due to an insufficient concentration of combustible pyrolysis gases.

Although the fire did not propagate in the tests conducted with any of the mitigation layers installed on top of the EPS insulation, the energy from the ignited area of PVC membrane, as well as heat transfer from the gas burner, did affect an area of EPS directly below the ignition source as seen from figure 11a.

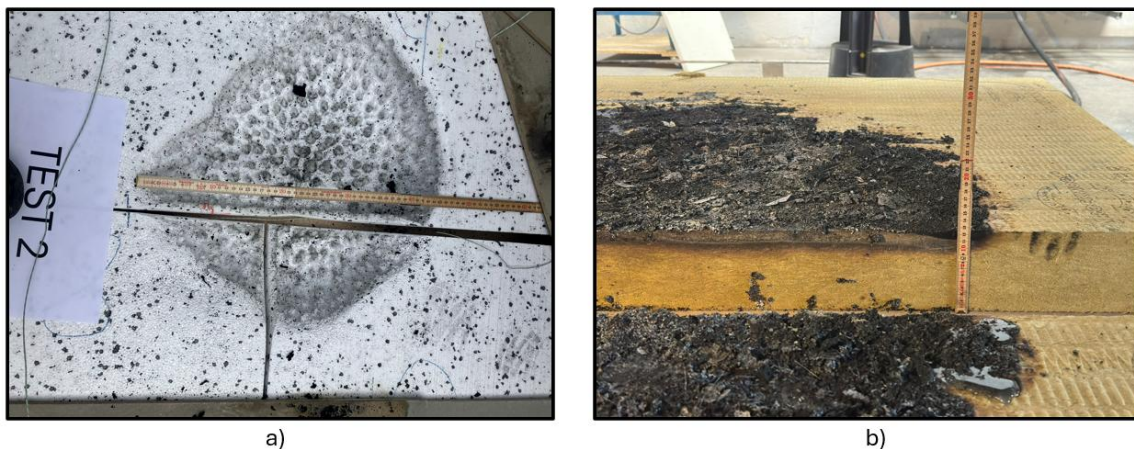


Figure 11 – Damage of the insulation materials. **a)** MT2 with a mitigation layer of 8 mm cement bonded particle board between the membrane and subjacent EPS insulation. **b)** Side view of the mineral wool insulation in MT5 where the membrane was installed directly on 100 mm insulation at the location of the gas burner. MT5 was extinguished 5 minutes after ignition due to smoke production.

Dimensions of the EPS voids below the location of the gas burner in medium and large-scale tests are plotted in Figure 12. In general, the width and length of the damaged EPS insulation were smaller than the corresponding damage of the PVC membrane in Figure 9, with the medium scale test conducted with the 6 mm cement board being the sole exception.

Comparing the medium and large-scale tests with respectively the 8 mm cement-bonded particle board (CPB) (MT2 & Test 8) and 6 mm cement board (MT6 & Test 9), two observations can be made: i) the depth of the EPS void were significantly higher than in the test with the 12 mm CPB and reached the maximum of 10 cm in three of four tests. ii) based on the limited number of tests, no consistent relationship was identified between the medium- and large-scale results.

Similar to the damaged EPS insulation, the mineral wool insulation was also affected by the heat transfer from the fire between the PV module and roof surface as seen from the extinguished MT5 in figure 11b. Unfortunately, no similar side view image was taken of test MT4, but based on previously conducted tests with flame spread below BAPV systems installed on roof built-ups with a PVC membrane and mineral wool insulation, more severe thermal damage would be expected [14], [15].

It is acknowledged that an increased number of tests could have rendered a clearer test outcome in the tests with EPS insulation, but in general the findings from the total nine large-scale tests, including the two tests in this report, were verified in the smaller scale.

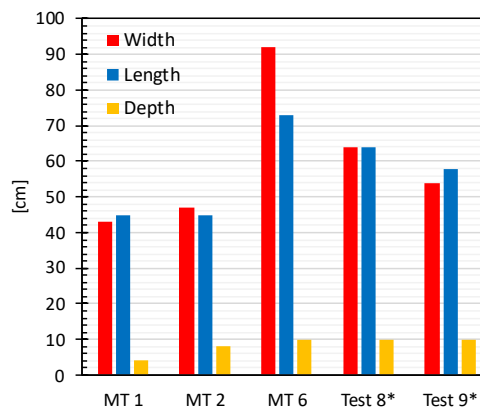


Figure 12 – Dimensions of the EPS void in the three medium and two large-scale tests conducted with mitigation layers between the PVC membrane and 100 mm thick EPS insulation. **MT1:** 12 mm CPB, **MT2 & Test 8:** 8 mm CPB, and **MT6 & Test 9:** 6 mm cement board. \*Based on measurements by KIWA BDA.

## 3.2. Quantitative results

Due to the limited flame spread in the two large-scale tests, the quantitative analysis mainly focuses on the data obtained during the medium-scale tests in the form of heat release rate and temperature measurements.

### 3.2.1. Large-scale

Due to the combination of limited flame spread in the two large-scale tests and the installation of only eight thermocouples below the PVC membrane, limited measurements were obtained. In both tests, the highest temperatures were measured at the location of TC5 in Figure 5a and peaked at respectively 53 °C and 93 °C in tests 8 and 9 according to the test report from KIWA BDA [8], [9]. Similarly, the highest temperatures, 48 °C and 76 °C for respectively tests 8 and 9, were measured between the mitigations layers and EPS insulation at the location of TC13 in Figure 5b [8], [9].

As such, none of the installed thermocouples were near an area of the roof surface that was ignited and the heat transfer towards the EPS insulation was limited. The higher surface temperatures in test 9, conducted with the 6 mm cement board, indicates that the product serves as a less efficient heat sink when compared to the 8 mm thick cement-bonded particle board.

### 3.2.2. Medium scale

Besides the visual observations discussed in section 3.1.2, the outcomes of the tests were quantified by thermocouple and heat release rate measurements.

From the heat release rates (HRR) plotted in Figure 13, the two trends from the visual observations are verified as significantly higher HRR were measured in medium scale tests 4 (MT4) and 5 (MT5), being the two tests with no mitigation layer between the PVC membrane and subjacent mineral wool insulation. In addition, the HRR measurements of the two repeated tests also indicate a decent repeatability of the tests, until MT5 was extinguished.

The repeatability of the test method is also evident when comparing the HRRs measured in the two tests with an 8 mm thick cement-bonded particle board used as a mitigation layer between the PVC membrane and, respectively, the EPS (MT2) and mineral wool (MT3) insulation. Similar to the damaged area of the PVC membrane shown in Figure 9, the outcomes of the two tests are nearly identical. This indicates that the thermal properties of the insulation are less important when the test is conducted with this specific PVC membrane and mitigation layer.

In tests MT1 and MT4, an increase of the HRR is observed near the end of the tests. For MT1, this increase corresponds well with the visual observations in Figure 7c, where the fire has propagated to a larger area of the roof mock-up. The fire self-extinguished 10 minutes after ignition as self-sustained flame spread was not

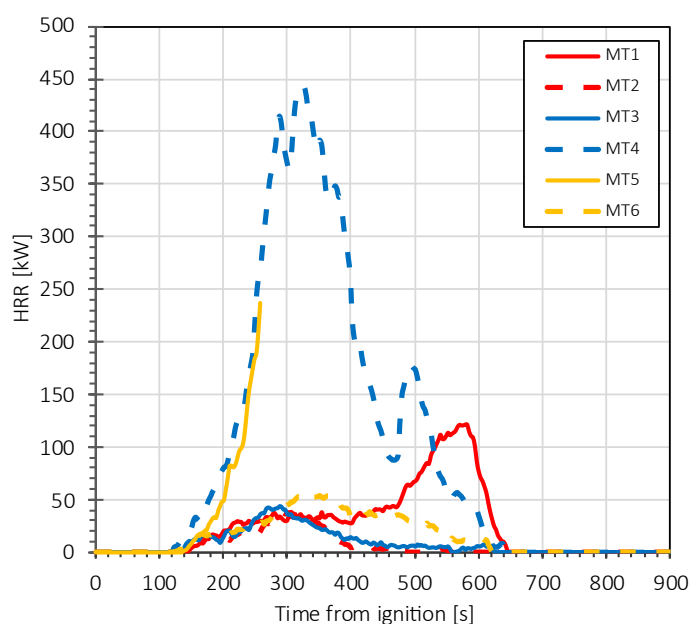


Figure 13 – Heat release rate (HRR) measured during the six medium scale (MT) tests. Note: MT5 was extinguished 5 minutes after ignition due to smoke production.

possible without the additional heat transfer from the gas burner which was switched off. In the MT4, the timing of the second peak corresponds to the breakage of the PV module's glass front, which allowed additional oxygen to enter and exposed additional fuel from the polymeric laminates used in the PV module.

The trends identified in the visual observations and HRR measurements of the medium scale tests repeat themselves when looking at the temperatures measured between the PVC membrane and the subjacent materials. First of all, the initial parts of the two repeated tests with mineral wool and no mitigation layer, MT4 and MT5, are near identical as seen in Figure 14. In addition, the limited temperature increase of TC1 verifies that the fire did not propagate outside the lowest edge of the PV module and thus outside the cavity between the module and roof surface as visually observed in Figure 10.

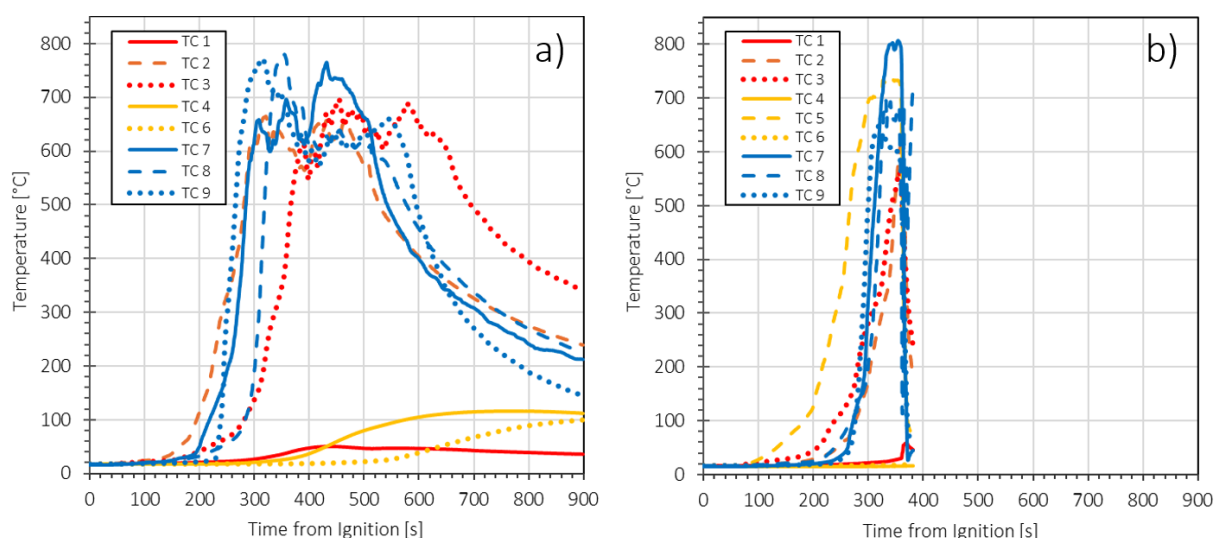


Figure 14 – Temperature measurements of the repeated medium scale tests 4 (a) and 5 (b) with mineral wool insulation. Note: i) that TC 5, located closest to the gas burner, failed in MT3, and ii) MT5 was extinguished 5 minutes after ignition due to smoke production

Compared to the repeated tests without a mitigation layer, the temperatures measured between the PVC membrane and mitigation layers were significantly lower, as seen from the temperature measurements from tests MT2 and MT3 in Figure 15, which were conducted with a mitigation layer of 8 mm cement-bonded particle board on top of respectively EPS insulation and mineral wool insulation.

Between the two tests with the 8 mm CPB, the overall trends are similar although significantly higher temperatures are measured by TC5 in MT2 compared to MT3. With TC5 being the upstream thermocouple closest to the gas burner, slightly different relative positioning of the roof mock-up, PV module and gas burner across the two tests can have resulted in a shorter distance between the thermocouple and gas burner in test MT3.

Finally, the temperatures measured below the PVC membrane in tests MT1 and MT6 with mitigation layers of respectively 12 mm CPB and 6 mm cement board, plotted in Figure 15 are higher than the two tests conducted with the 8 mm CPB, which can be explained by two things: i) the larger damaged area and higher HRR in MT1 leads to a higher heat flux towards the roof surface and thus higher temperatures, and ii) the thinner mitigation layer in MT6 can absorb less energy than the thicker CPB which leads to a higher temperature of the boundary layer between the PVC membrane and cement board.

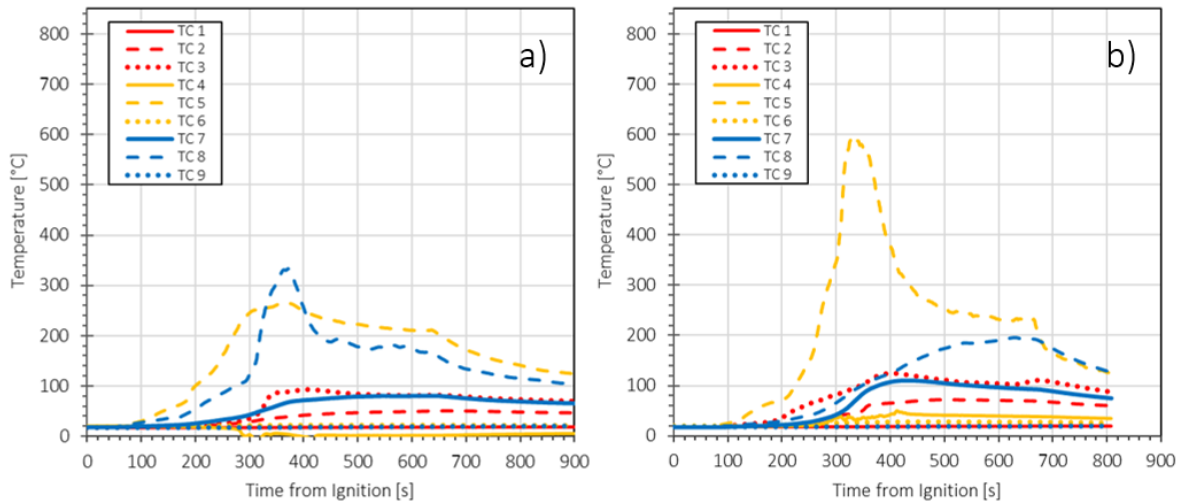


Figure 16 – Temperature measurements from medium-scale tests MT2 (a) and MT3 (b), conducted with an 8 mm cement-bonded particle board used as a mitigation layer between the PVC membrane and either 100 mm EPS insulation (a) or mineral wool insulation (b), respectively.

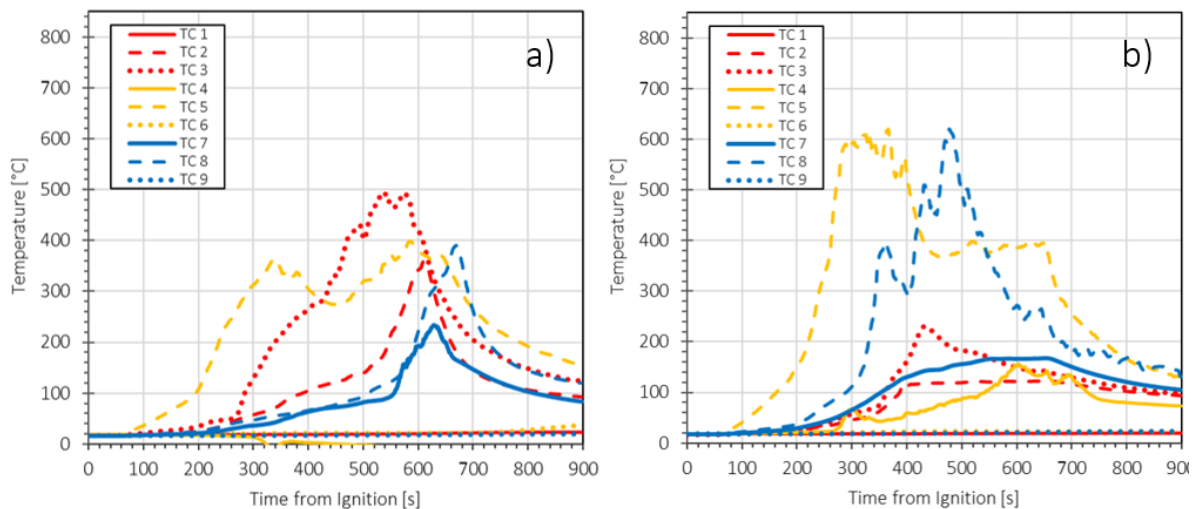


Figure 15 – Temperature measurements of the medium scale tests 1 (a) and 6 (b) with respectively the 12 mm cement-bonded particle board between and 6 mm cement board between the PVC membrane and EPS insulation.

The thickness, mass and thermal parameters of the mitigation layer also influenced the heat transfer from the fire, through the mitigation products and towards the insulation materials. Comparing the highest temperatures measured below the three mitigation solutions between the PVC membrane and EPS insulation, three things are noticed in Figure 17: i) In all three tests, a plateau was reached around 100 °C, ii) the plateau was reached faster for the thinner mitigation layers, and iii) the time duration of the plateau was shorter for the thinner materials.

With all three mitigation layers being based on cementitious composite products, it is expected that the plateau is linked to the chemically bound water within the product. Due to the high specific heat of water, the

bound water served a buffer during the initial phase of the heating, absorbing significant amounts of energy and thus preventing heat transfer to the subject insulation materials. As soon as the water was vaporised, heat transfer through the mitigation layers were based on the conductivity of the thermally altered materials.

Comparing MT1 and MT2 with mitigation layers of respectively the 12 mm and 8 mm cement-bonded particle board (CPB), the temperature of the thinner product increases faster, as seen in Figure 17, due to the lower areal mass. In addition, the thickness affects the secondary temperature increase which was initiated around 750 and 550 seconds after ignition for MT1 and MT2.

Comparison of the temperatures between the mitigation layers and EPS also indicate that other thermal parameters than the thickness might be different between the cement board and the Cement-bonded particle boards (CPB) as the plateau was reached faster and a significantly higher peak temperature was reached. However, it is acknowledged that the high temperature of 250 °C can also be due to a more direct contact between the thermocouple and backside of the mitigation material after the EPS has melted.

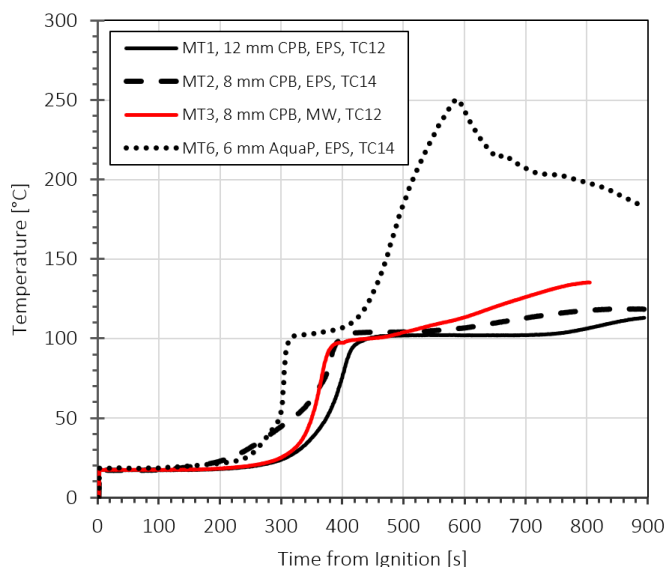


Figure 17 – Temperature measurements between the mitigation layer and subjacent EPS insulation (MT1, MT2 & MT6) or mineral wool insulation (MT3) at the location of either TC12 or TC14 in accordance with figure 5.

Finally, the faster secondary temperature increases below the mitigation layer in MT3 with mineral wool insulation, compared to MT2 with the same mitigation layer on EPS insulation illustrates that the upper part of the mineral wool isolates significantly better than the gradually growing void of melted EPS.

## 4. CONCLUSION

Based on designs by IVH, the German Rigid Foam Industry Association and EUMEPS, the European Manufacturers of Expanded Polystyrene, a total of eight tests, two large-scale tests and six medium scale tests, were conducted to examine the impact of PV-related fires on flat roofs below east/west orientated PV systems. The built-up of six medium scale tests, each with side lengths of 2 m x 1.6 m and a single PV module, were similar to the nine previously conducted large-scale tests, including the two tests presented in this report.

All tests were conducted with a 1.5 mm thick PVC membrane ( $B_{ROOF}(t1)$ ) and in three of the medium scale tests, it was examined if mitigation layers of either a 6 mm cement board, or an 8 mm or 12 mm thick cement-bonded particle board (CPB) could protect the subjacent layer of expanded polystyrene (EPS) insulation. The effect of the 8 mm CPB was also examined when installed between the PVC membrane and non-combustible mineral wool insulation, whereas the remaining two medium scale tests were repeated tests of a roof mock-up where the PVC membrane was installed directly on top of the mineral wool insulation. The medium scale tests were conducted indoor below an extraction hood to reduce the number of external parameters across the tests, contrary to the large-scale tests which were conducted outdoor.

The two large-scale tests were conducted on squared roof build-ups with side lengths of 7 meters to examine flame spread below a 12 module east/west orientated BAPV array. The upper layers of the roof build-ups were constructed similar to the two medium scale tests with mitigation layers of either the 8 mm CPB or 6 mm cement board between the PVC membrane and EPS insulation, whereas large-scale tests with a mitigation layer of the 12 mm CPB between the membrane and EPS insulation, as well as the PVC membrane on top of the mineral wool had previously been conducted and presented in other reports [5], [6], [7].

The main objectives of the tests were to assess the effect of the two thinner mitigation layers in both large- and medium scale tests, as well as to examine if the outcome of the medium scale tests were resembling the findings in the nine large-scale tests. Similar to the previously presented findings, the severity of the consequences was first and foremost based on the thermal properties of the materials below the PVC membrane and the main conclusions were:

- In both the large- and medium scale tests, no self-sustained flame spread occurred in the tests where any of the three mitigation layers with a thickness of 6 mm, 8 mm or 12 mm were installed between the PVC membrane and the subjacent EPS or mineral wool insulation.
- In the two repeated medium scale tests, with the PVC membrane installed on mineral wool, self-sustained flame spread occurred. In both tests, the extraction fan could not keep up with the smoke production and for that reason, one of the tests was terminated and extinguished with water 5 minutes after ignition.
- Despite no self-sustained flame spread in the tests with a mitigation layer between the PVC membrane and EPS insulation, heat transfer from the ignition source caused the formation of a void within the insulation. No significant difference in the dimensions and temperatures of the void was observed between the test with 8 mm and 12 mm CPB, whereas both parameters increased in the test with the 6 mm cement board.
- The tests confirm and extend previous findings. A mitigation layer with suitable thermal properties modifies the energy balance in the fire dynamic system between the PV module and the roof system, thereby reducing the likelihood of self-sustained flame spread.

The results presented herein are limited to the specific roof construction build-ups tested, incorporating a comparable building-applied PV system. The findings indicate a potential reduction in fire-related consequences when a cement-based mitigation layer is installed between thermally thin roofing membrane and the subjacent insulation.

The tests verify previous findings, but similar to previous reports it is still expected that they are only valid for thermally thin single-ply roofing membranes. The tests within this report were solely conducted with a roofing membrane with a thickness of 1.5 mm and based on fundamental flame spread theory, the results are also valid for thinner versions of the same product, but not valid for thicker versions.

Accordingly, these results should be regarded as a basis for further technical discussion on mitigating the consequences of PV-related fires, rather than as definitive solutions. The tests were not conducted in accordance with standardised methods, do not represent an approved system configuration, and have not been subject to formal fire classification.

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## APPENDIX A – VIDEO FRAMES FROM MEDIUM SCALE TESTS.

Flame spread in the six medium scale tests conducted at DBI.

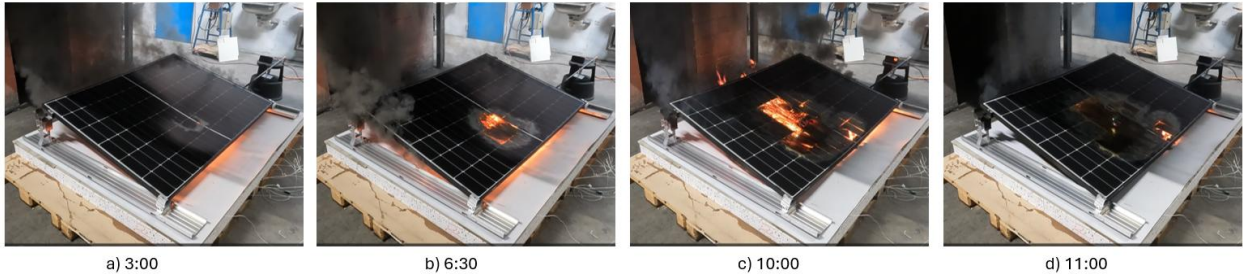


Figure A 1 – MT1 with 1.5 mm PVC membrane, 12 mm CBP and 100 mm EPS insulation. Time from ignition in min:sec.

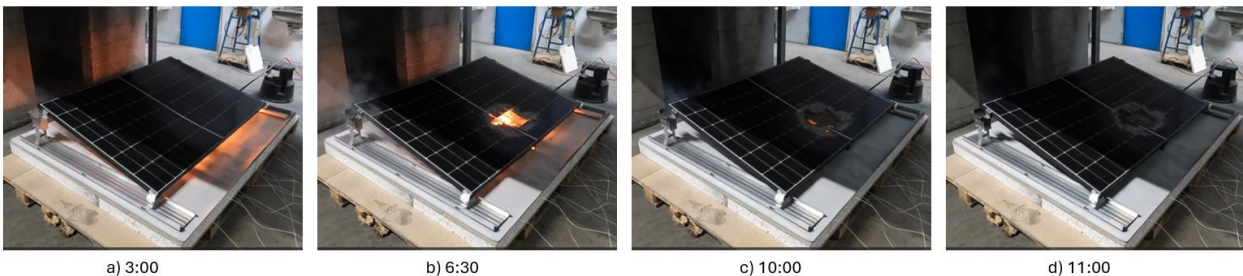


Figure A 2 – MT2 with 1.5 mm PVC membrane, 8 mm CBP and 100 mm EPS insulation. Time from ignition in min:sec.

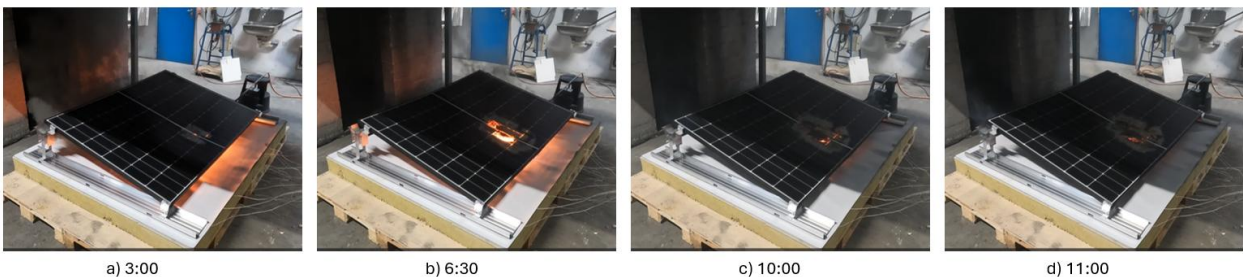


Figure A 3 – MT3 with 1.5 mm PVC membrane, 8 mm CBP and 100 mm mineral wool insulation. Time from ignition in min:sec.



Figure A 4 – MT4 with 1.5 mm PVC membrane on top of 100 mm mineral wool insulation. Time from ignition in min:sec.



Figure A 5 – MT5 with 1.5 mm PVC membrane on top of 100 mm mineral wool insulation. Time from ignition in min:sec.



Figure A 6 – MT6 with 1.5 mm PVC membrane, 6 mm cement board and 100 mm EPS insulation. Time from ignition in min:sec.