

# DEPARTMENT FOR FIRE-SAFE SUSTAINABLE BUILT ENVIRONMENT

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# REPORT 448/25-560-1-EN

About performance comparison of lightweight noncombustible sheet in rooftop PV-related fires

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# Summary:

- The AllShield BarrierSheet was able to prevent spread beyond the area of the ignition source when only a single, enlarged wood crib (as compared to the standard crib used for PV fire tests at ZAG) was used for ignition. This was for roof buildups with a PVC membrane used as the top layer in the tests. Therefore, two enlarged wood cribs that are assessed to have a higher heat release rate (in kW) than nominal burners in similar tests (using 15 kW output as the setting), were used in subsequent tests to ensure fire spread beyond the crib area.
- In all tests with successful ignition (i.e., spread beyond the wood crib area), flames progressed across the area covered by the PV module(s).
- The AllShield BarrierSheet effectively prevented direct flame penetration into lower structural layers in all tests.
- In one test (AS-2), early frame deformation may have reduced thermal stress and delayed glass failure.
- White steam (from moisture evaporation) observed in two tests (AS-1 and AS-3)
- Yellow smoke (from PIR decomposition) appeared in two tests (AS-2 and AS-4), indicating material involvement in deeper layers of the roof.
- Localised gaps or burn-through areas allowed some heat transfer to materials in deeper layers of the roof.
- The PIR insulation experienced delamination, yellow deposits, and deformation, especially near joints.
- In one test (AS-2), the thinner (60 mm) PIR boards deformed more than the 120 mm ones used in test AS-4.
- The EPS melted completely under the ignition points in two tests (AS-1 and AS-3), and in one test (AS-3), bitumen and EPS fused and adhered to the plasterboard layer.
- The integrity of the AllShield BarrierSheet and the PIR properties significantly influenced the vertical flame spread and the subsurface damage.
- The temperature measurements confirmed a peak heating beneath the AllShield BarrierSheet, with peak values ranging from ~430 °C (AS-3) to over 800 °C (AS-2)
- The peak temperatures were higher at locations directly below the AllShield BarrierSheet in specimens containing PIR, but the heat transfer throughout the sample was lower in those specimens as the bottom layers did not show much rise in temperature.
- Anchorage points can intensify thermal deformation in insulation layers.
- Visual cues such as smoke colour proved useful for identifying material involvement and combustion behaviour in real time.



## 1. Introduction

The right combination of PV system and roofing products and materials, their thickness, arrangement and the consideration of their properties under different conditions are crucial for minimising the consequences in the event of a fire.

ZAG carried out a series of tests to evaluate and compare the effectiveness of the AllShield BarrierSheets in the event when the fire starts on a roof with a PV system installed.

Various methods were utilised to assess the extent of impact/damage in the tests:

- Visual inspection of the test by observing the behaviour of the fire and various parts of the system
- Video recordings from different angles
- Measurement of the temperature (measured with thermocouples (TCs) placed on different layers of the roof structure during and after the test)
- Visual inspection of the damage to the PV system and the underlying materials (depth and extent) assessed after the end of the test

The results of the tests are analysed to better understand the influence and effectiveness of the individual components of the roof.



# 2. Text matrix and design

## 2.1 Test matrix

Table 1 Test matrix for 4 specimens

Mid-scale (r	o inclination)	Large-scale (no inclination)				
AS-1	AS-2	AS-3	AS-4			
Jinko Solar Tiger Neo JKM440N-54HL4R-V						
S-Dor	ne 6.15	D-D	ome 6.15			
Sarnafil TS 77- 18 (1.8 mm)		Sikaplan G-18 (1.8 r	mm)			
AllShield BarrierSheet						
Izoelast Reflex F P5 and Izoself P3 bitumen	Fragmat Innoplan Alu/Therm 60 mm thick PIR board Izoelast Reflex F P5 and Izoself P3 bitumen	Izoelast Reflex F P5 and Izoself P3 bitumen	Fragmat Innoplan Alu/Therm 120 mm thick PIR boards			
Fragmat EPS 150 kPa, 100 mm thick						

As agreed with the company representative, the overlap of 1 cm of the AllShield BarrierSheets was made only in the test AS-3.

In all tests, AllShield BarrierSheets were secured with anchors.

# 2.2 Specimen design and assembly process

Schematics of the mid- and large-scale specimens are shown in Figure 1.



Figure 1 Illustrations of the mid-scale 2.5 m x 2.5 m (left) and large-scale 3.5 m x 4 m (right) test rigs

The specimens were built according to the installation instructions of the product manufacturer and with the support of the company representative. This ensured that the samples represented a realistic design of a roof buildup. The cross-section of the structure is shown in Figure 2.



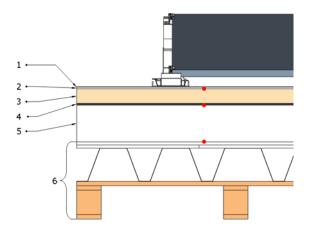


Figure 2 Side view of AS-2 specimen (red dots depict locations of TCs between layers)

- 1. Sikaplan G-18 (PVC) membrane
- 2. AllShield BarrierSheet
- 3. Innoplan Alu/Therm 60 mm PIR boards
- 4. Izoelast Reflex F P5 and Izoself P3 bitumen
- 5. Fragmat EPS 150 (W30) 100 mm thick
- 6. Roof substrate made from plasterboards, metal corrugated roof and wood pallet

# 2.3 Event logging, temperature measurements, ignition source and test procedure

A timeline of all observed events and phenomena during the flaming phase of the experiment was compiled to provide a comprehensive overview of the process. Cameras from two different angles recorded videos, while technicians monitored and documented key observations.

To assess the extent of the damage, photo and video footage were used throughout the flaming phase and during dismantling to document the condition of the PV modules, mounting system and roofing materials.

K-type shielded thermocouples (TCs) were used to measure the temperature development inside the roof segments. TCs were placed at various depths to assess the penetration of heat by the fire and the effects on the roof materials during and after combustion.

Precise locations of TCs can be found in Figure 3 and Figure 5 for mid-scale and large-scale tests, respectively. The numbering of TCs is depicted in Figure 4 and Figure 6 for mid-scale and large-scale tests, respectively.

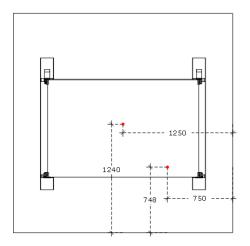


Figure 3 Locations of TCs inside the roof for mid-scale tests

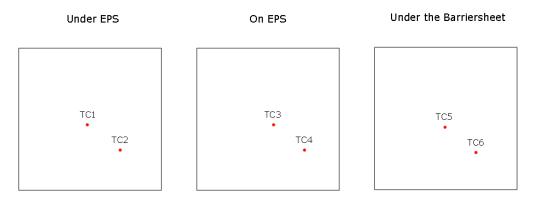


Figure 4 Numeration of TCs for mid-scale tests

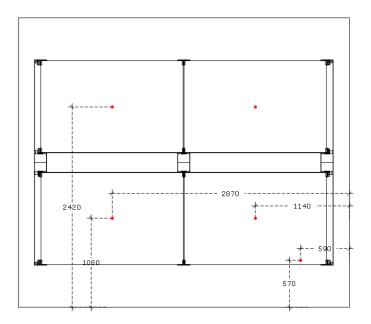
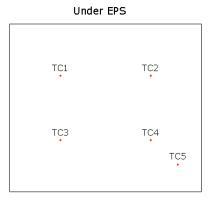
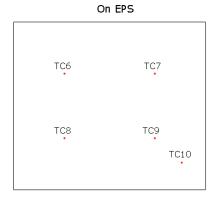


Figure 5 Locations of TCs inside the roof for large-scale tests







#### Under the Barriersheet

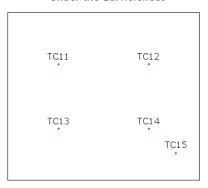


Figure 6 Numeration of TCs for large-scale tests

# 2.4 Ignition source

Figure 7 shows schematic representations of the ignition sources, which were wood cribs made of spruce. Based on prior understanding of fire behaviour in rooftop PV systems, it was determined that the standard crib size from the ZAG test method was insufficient for ensuring flame spread beyond the ignition area. An enlarged crib configuration was therefore adopted.

The common crib used in the ZAG test method consists of 26 sticks, each 10 cm long. The enlarged crib uses 30 sticks, 14 of which are 15 cm long (shown in Figure 7). This modification increased the total wood mass by approximately 40%. When one enlarged crib did not ensure sufficient flame spread, two were used.



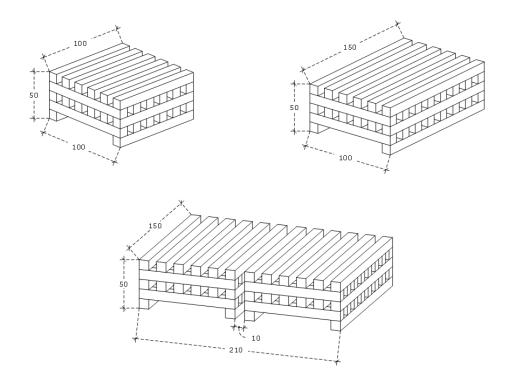


Figure 7 Variants of the wood crib with dimensions: ZAG test method size (top left), enlarged size (top right), and two enlarged cribs (bottom)

#### 2.4.1 Calculating the HRR of the wood crib

The crib used in the ZAG test method is designed to produce an HRR of around 15 kW, equivalent to the HRR of the gas burner in the standard CLC/TR 50670:2016.

A basic HRR estimate follows the SFPE Handbook (5th ed., p. 799) formula:

$$HRR = \Delta h_c \times MLR = 12000 \times 0.00138 = 16.5 \text{ [kW]}.$$

where  $\Delta hc$  is the heat of combustion number (taken from the SFPE Handbook), and MLR is the mass loss rate; the used number was determined through internal test runs.

More refined methods to calculate the heat release rate of the wood crib also account for crib geometry, and two regimes are proposed in the literature<sup>1</sup> - the fuel-controlled and the porosity-controlled. The HRR estimates for a wood crib described in the ZAG test method are as follows (considering the initial mass, the thickness of the sticks, the spacing between the bars and the height of the crib accordingly):

- HRR (fuel surface control) ≈ 15 [kW]
- HRR (crib porosity control) ≈ 13 [kW]

Combining all three abovementioned estimates yields a working HRR value of  $\sim$ 15 kW for the standard wood crib. As the current tests used a 40 percent larger wood crib, and some even two cribs that each were 40 percent larger than the standard wood crib, it is a very fair assessment that the HRR in the current tests is larger than 15 kW. As mentioned, simple algebra cannot be applied, but a 40 percent larger crib might yield around 20 kW and the two enlarged cribs around 40 kW.

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<sup>&</sup>lt;sup>1</sup> McAllister, S.; Finney, M. Burning Rates of Wood Cribs with Implications for Wildland Fires. Fire Technol 2016, 52 (6), 1755–1777. https://doi.org/10.1007/s10694-015-0543-5.



In addition to all this, the quality of the wood, the drying process, stacking consistency, and the addition of alcohol for ignition all contribute to uncertainties, affecting the realistic HRR that the wood cribs used for the tests produce.

# 2.5 Test procedure

The following steps outline the general experimental procedure.

- ~8 mL of isopropyl alcohol is applied with a plastic pipette onto the wood crib, which is then placed under the PV module in the defined position (over TC6 in the mid-scale test and TC-15 in the large-scale test).
- The crib is ignited with a lighter.
- The test was continued until there were no more significant flames under the PV installation area.

In the tests, when two cribs were used, they were placed adjacent to each other on the longer edge. Figure 7 shows all the abovementioned crib variations – nominal crib from ZAG test method, enlarged version with extended sticks and a stack of two enlarged wood cribs.



# 3. Results

# 3.1 Observations during the test

#### 3.1.1 AS-1

The documented observations and events of the AS-1 test are summarised in Table 1. The test was performed on 29. 05. 2025 with the ambient temperature of 21 °C and humidity of 46%. The most important events are illustrated by photos and video screenshots taken at certain times during the test. The test was performed with the ignition of two wood cribs.

Table 2 Observations for test AS-1

Time (min)	Events
2	Flames went out from the right edge
3	Flames went out from the bottom edge
3-4	Delamination of solar cells from the PV module (over ignition source)
4.5-5	Flames went out from the upper edge
7	Flames went out from the left edge
7.5	The membrane is burning outside the PV module area (from the right side)
8	The membrane is burning outside of the PV mounting system (after wind shield)
12	The glass of the PV module shattered
21-22	A few flames left under the PV module only
30	The test finished by extinguishing tiny flames

Flames emerged from the right edge of the PV module at 2 minutes and from the bottom edge by minute 3. Between minutes 3 and 4, delamination of solar cells was observed above the position of the ignition source (Figure 8). By 4.5 minutes, flames reached the upper edge, while at 7 minutes, they extended to the left edge of the module (Figure 9). At 7.5 minutes, the membrane ignited outside the PV module area, starting from the right side. White smoke, considered to be water steam, began emerging from beneath the AllShield BarrierSheet shortly thereafter (Figure 10). At 12 minutes, the PV glass shattered, with the fire largely contained under the module area (Figure 11). By minutes 21–22, only a few small flames remained beneath the PV module. The test finished at 30 minutes with the extinguishment of the final residual flames, while the progression of the fire throughout the test can be seen in the video snapshots shown in Figure 12 and Figure 13.





Figure 8 Sample AS-1 Initial fire spread - flames coming out from the short edge of the panel, delamination of solar cells, burning of membrane (4 min after ignition) (FotoPortal 050524d-002)

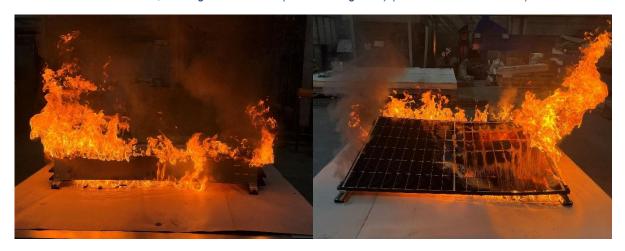


Figure 9 Sample AS-1 The extent of fire after 7 min - back (left) and front (right) view (FotoPortal (left 050524d-004, right 050524d-006))

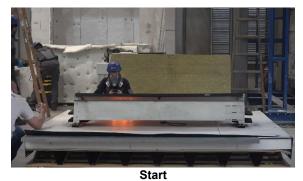




Figure 10 Sample AS-1 White smoke emerging from below the AllShield BarrierSheet (FotoPortal 050524d-007)

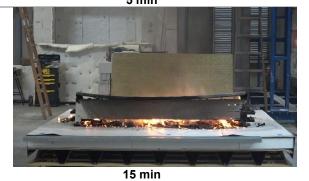


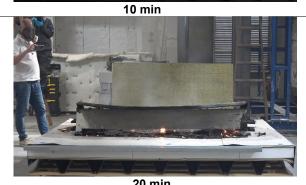
Figure 11 Sample AS-1 PV glass shattered after 12 min - fire was contained under the PV area, except on the side of the ignition source (FotoPortal 050524d-010)











**20 min**Figure 12 Sample AS-1 Snapshots from the camera pointed toward the long edge of the specimen (FotoPortal 050524d-012, 050524d-014, 050524d-016, 050524d-018 and 050524d-020)





**20 min**Figure 13 Sample AS-1 Snapshots from the camera pointed toward the short edge of the specimen (FotoPortal 050524d-021, 050524d-023, 050524d-025, 050524d-027, 050524d-029 and 050524d-031)



#### 3.1.2 AS-2

The documented observations and events of the AS-2 test are summarised in Table 3. The test was performed on 29. 05. 2025 with the ambient temperature of 20 °C and humidity of 46%. The most important events are illustrated by photos and video screenshots taken at certain times during the test. The test was performed with the ignition of two wood cribs.

Table 3 Observations for test AS-2

Time (min)	Events
1	Sagging of the PV module observed
3,5	Flames from the bottom and the right edge of the PV module
5	Flames went out from of upper edge
6	2 cells of PV module fell down
7-6,5	Fire propagated to the half of the specimen
10	Yellow smoke goes out from the gap between PIR boards
11,5	Flames reached the left edge of the specimen
26	No flames under the PV module
30	Test finished

Deformation of the PV module frame was observed 1 minute into the test, resulting in a visible gap between the panel and the top of the frame. By 3.5 minutes, flames emerged from both the bottom and right edges of the PV module. At 5 minutes, flames reached the upper edge, and two solar cells detached and fell from the module (Figure 14). Between 6.5 and 7 minutes, the fire propagated across approximately half of the specimen. At minute 10, yellow smoke was seen emerging from the gap between the PIR boards and the AllShield BarrierSheet - a major difference compared to the first test, where only white steam was observed (Figure 15). By minute 16, we observe that the damage remained largely confined beneath the PV module area, with minimal spread beyond it (Figure 16). At minute 26, no visible flames remained under the PV module. The test finished at 30 minutes, with the residue flames captured in the video snapshots from the long and short edge perspectives (Figure 17 and Figure 18).

Overall, the fire development and extent of visible damage were similar to the test AS-1. However, the appearance of yellow smoke from the PIR boards indicated different combustion behaviour. Unlike in the first test, the PV glass did not shatter, influencing airflow and energy dynamics beneath the panel.





Figure 14 Sample AS-2 Initial fire spread - flames spread under the right edge of the panel, delamination of solar cells, burning of the membrane (5 min after ignition) (FotoPortal 050524d-033)



Figure 15 Sample AS-2 Yellow smoke from under the AllShield BarrierSheet at 10 min - side view (left), close-up (right) (FotoPortal (left 050524d-035, right 050524d-037))



Figure 16 Sample AS-2 Minimal damage outside of PV module area (16 min) (FotoPortal 050524d-039)



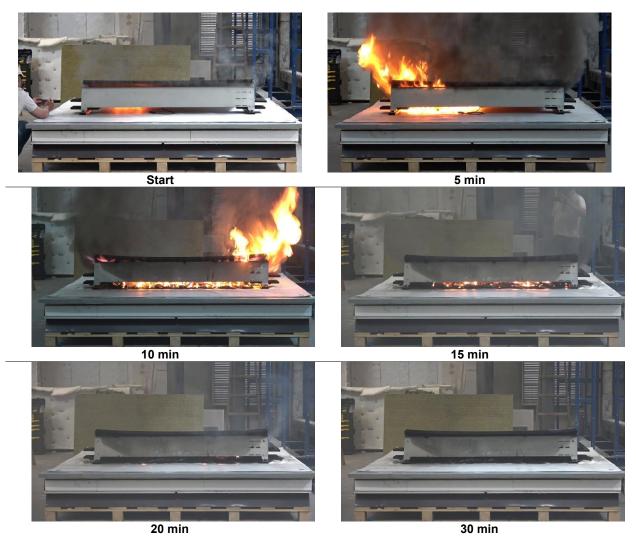


Figure 17 Sample AS-2 Snapshots from the camera pointed toward the long edge of the specimen (FotoPortal 050524d-041, 050524d-043, 050524d-045, 050524d-047, 050524d-049 and 050524d-051)





**20 min**Figure 18 Sample AS-2 Snapshots from the camera pointed toward the short edge of the specimen (FotoPortal 050524d-053, 050524d-055, 050524d-057, 050524d-059, 050524d-061 and 050524d-062)



#### 3.1.3 AS-3

The documented observations and events of the AS-3 test are summarised in Table 4. The test was performed on 28. 05. 2025 with the ambient temperature of 20 °C and humidity of 45%. The most important events are illustrated by photos and video screenshots taken at certain times during the test.

For the first test run, one wood crib (see subsection 2.4) was used as the ignition source. The fire did not propagate and self-extinguished once the crib burned out. The test was repeated using two wood cribs after the replacement of materials in the specimen influenced by the ignition.

Table 4 Observations for the test AS-3

Time (min)	Events		
1 <sup>st</sup> Test			
8	No flame spread		
2 <sup>nd</sup> Test	2 <sup>nd</sup> Test		
6	Flame reached the upper gap between the panels (1st and 2nd PV panels)		
9	Flames are touching (preheating) 2 <sup>nd</sup> PV module		
10,5-11	Flames under 3 <sup>rd</sup> and 4 <sup>th</sup> PV modules		
15-16	Flames reached the left edge of the specimen		
17	The glass of the 3 <sup>rd</sup> PV module shattered.		
18	No flames under the 1 <sup>st</sup> PV module		
20,5	The glass of the 4 <sup>th</sup> PV module shattered		
22,5-23	No flames under the 4 <sup>th</sup> and 3 <sup>rd</sup> PV modules		
24	The glass of the 2 <sup>nd</sup> PV module shattered. No flames under the PV area		

In the initial test, no flame spread was observed, and sample self-extinguished after 8 minutes (Figure 19). Damaged parts were exchanged with new materials, and test was repeated with two wood cribs.

In the second run, flames reached the upper gap between the first and second PV modules by minute 6. Between minutes 10.5 and 11, flames extended beneath the third and fourth PV modules (Figure 22). By 15-16 minutes, the fire had reached the left edge of the specimen. The glass of the third PV module shattered at minute 17, followed by the disappearance of flames under the first module at minute 18. At 20.5 minutes, the glass of the fourth PV module shattered. By 23 minutes, no flames remained under the third and fourth modules. Finally, at minute 24, the glass of the second PV module shattered, with no active flames observed under the PV area. White steam was observed venting through the AllShield BarrierSheet, likely due to moisture evaporation (Figure 21).

The test finished after 30 minutes, with the remainder of the fire development captured in the video snapshots from the long and short edge perspectives (Figure 23 and Figure 24).





Figure 19 Sample AS-3 First try with one wood crib – no flame spread beyond the area of the crib (FotoPortal 050524d-065)



Figure 20 Sample AS-3 Larger wood crib at the ignition (left) and the deformation of the PV module 4 minutes after the ignition (right) (FotoPortal (left 050524d-067, right 050524d-070))



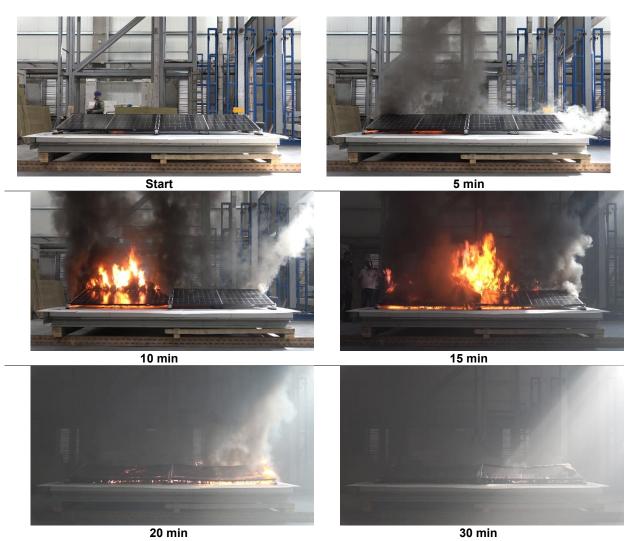


Figure 21 Sample AS-3 Water steam coming from under the membrane (FotoPortal 050524d-071)



Figure 22 Sample AS-3 State of flame spread 10 minutes after the ignition - front view (left) and rear view (right) (FotoPortal (left 050524d-073, right 050524d-076))





**20 min**Figure 23 Sample AS-3 Snapshots from the camera pointed toward the long edge of the specimen (FotoPortal 050524d-077, 050524d-079, 050524d-081, 050524d-083, 050524d-085 and 050524d-087)



Figure 24 Sample AS-3 Snapshots from the camera pointed toward the short edge of the specimen (FotoPortal 050524d-089, 050524d-091, 050524d-093, 050524d-095, 050524d-097 and 050524d-099)

## 3.1.4 AS-4

The documented observations and events of the AS-4 test are summarized in Table 5. The test was performed on 02. 06. 2025 with the ambient temperature of 22 °C and humidity of 46%. The most important events are illustrated by photos and video screenshots taken at certain times during the test.



Table 5 Observations for the test AS-4

Time (min) Events				
1st Test				
8	No flame spread			
2nd Test				
4	Flames went out from the right and the bottom side of the 1st PV module			
5	Flames went out from the upper edge			
5-6	5 cells fell down of the 1 <sup>st</sup> PV module.			
6-7	Notice a dense yellow smoke that was released due to PIR decomposition			
8	The flame front reached 2 <sup>nd</sup> PV module			
11	2 <sup>nd</sup> PV module was fully involved in fire. Flame spread under PV module.			
12	Flame front reached the surface under 3 <sup>rd</sup> and 4 <sup>th</sup> module (PV modules are involved)			
17	Flame front over the membrane reached the end of the mounting system			
	4 <sup>th</sup> PV module shattered			
23	3 <sup>rd</sup> PV module shattered			
26	1 <sup>st</sup> PV module shattered			
30.5	2 <sup>nd</sup> PV module shattered			
40	Test finished			

The first test was performed with one wood crib. The test resulted in no fire spread and self-extinguished within 8 minutes (Figure 25).



Figure 25 Sample AS-4 First test with one wood crib - fire self-extinguished without propagation (FotoPortal 050524d-102)

The damaged materials were replaced, and the test was repeated using two wood cribs (Figure 26).



In the second test, flames emerged from the right and bottom edges of the first PV module by minute 4 and reached the upper edge by minute 5. Between minutes 5 and 6, solar cells started to delaminate from the first module (Figure 27). Around minutes 6-7, dense yellow smoke was observed, resulting from the thermal decomposition of PIR insulation at the front side of the specimen (Figure 28). At minute 8, the flame front reached the second PV module, which became fully involved in fire by minute 11, including flame spread beneath the module. By minute 12, fire had reached the area beneath the third and fourth modules. At 17 minutes, the flame front spread over the membrane and reached the end of the mounting system (Figure 30). During this period, the fourth PV module shattered, followed by the shattering of the 3<sup>rd</sup> PV module at minute 23, likely due to thermal shock during cooling (Figure 31). The first and second modules shattered at 26 and 30.5 minutes, respectively. A combination of yellow smoke and water steam was also observed on the rear side of the specimen, with noticeable yellow staining on the AllShield BarrierSheet (Figure 29). The test finished after 40 minutes, with the fire largely contained within the PV array footprint. Additional flame development is documented in video snapshots from both long and short edge perspectives (Figure 32 and Figure 33).

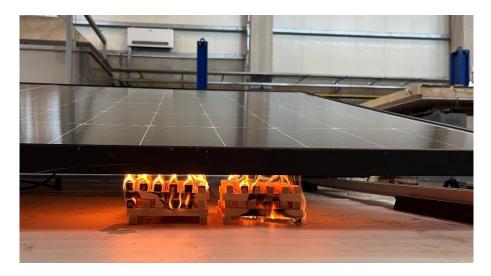


Figure 26 Sample AS-4 Second test - two larger wood cribs right after the ignition (FotoPortal 050524d-104)



Figure 27 Sample AS-4 Close-up of burned membrane (6 min) (FotoPortal 050524d-106)





Figure 28 Sample AS-4 Yellow smoke from PIR boards (left – 7 min) and discolouration on PIR boards (right – 12 min) at the front side of the specimen (FotoPortal (left 050524d-108, right 050524d-110))



Figure 29 Sample AS-4 Combination of yellow smoke and water steam (left) along with yellow stain on the AllShield BarrierSheet (right - 18 min) at the rear side of the specimen (FotoPortal (left 050524d-112, right 050524d-114))



Figure 30 Sample AS-4 Fire spread 16 min after the ignition (FotoPortal 050524d-116)





Figure 31 Sample AS-4 Fire subdued and 3rd PV module shattered due to cooling down (23 min) (FotoPortal 050524d-118)

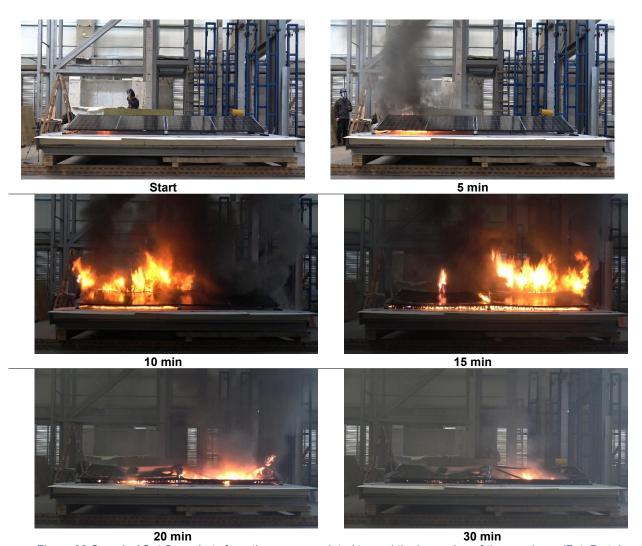


Figure 32 Sample AS-4 Snapshots from the camera pointed toward the long edge of the specimen (FotoPortal 050524d-119, 050524d-121, 050524d-123, 050524d-125, 050524d-127 and 050524d-129)

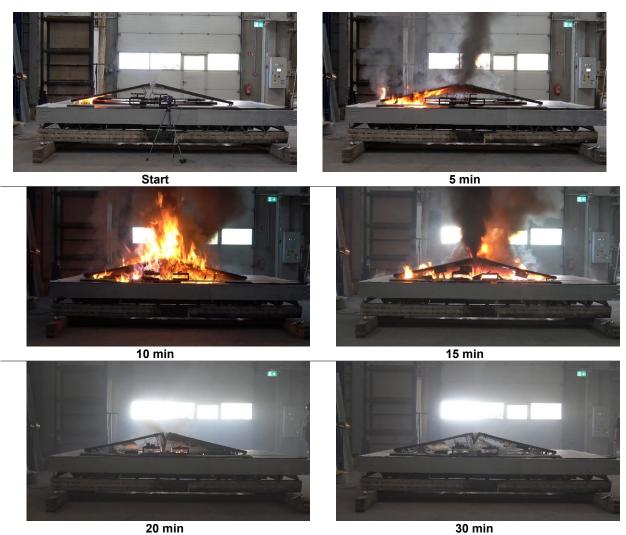


Figure 33 Sample AS-4 Snapshots from the camera pointed toward the short edge of the specimen (FotoPortal 050524d-131, 050524d-133, 050524d-135, 050524d-137, 050524d-139 and 050524d-141)

## 3.2 Temperature data

The temperature diagrams show the temperature distribution measured on specific roof layers. The numeration of TCs in the temperature graphs correlates with the TC numerations on Figure 4 and Figure 6, for mid-scale and large-scale, respectively. The cooling phase was not recorded. Malfunctioned TCs were excluded from the graphs.

#### 3.2.1 AS-1

Figure 34 shows the temperature distribution across all layers during the AS-1 test. Each layer is represented by a single colour, using a solid and dashed line for two distinct TCs. The highest temperature was recorded on TC6, located beneath the AllShield BarrierSheet directly below the ignition source, reaching a peak of approximately 500 °C. TC4, positioned on the EPS surface in the same area, reached around 380 °C, while the remaining thermocouples (TC2, TC3, TC5) measured between 150 °C and 200 °C. Only TC1, placed under the EPS the farthest from the ignition source, remained at room temperature throughout the test. This thermal distribution indicates that the most intense heating was



concentrated in the upper layers directly beneath the ignition source, while deeper components remained relatively less affected due to limited heat transfer.

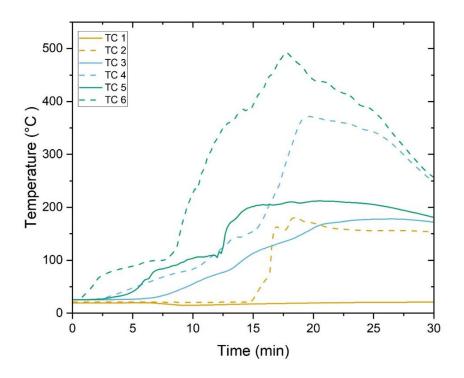


Figure 34 Sample AS-1 Temperature distribution over all roof layers

#### 3.2.2 AS-2

Figure 35 presents the temperature development during the AS-2 test. Like AS-1, thermocouples were positioned below and above the EPS layer, as well as directly under the AllShield BarrierSheet. However, in this case, a PIR insulation layer was installed above the EPS, adding a second thermal barrier between the ignition source and the deeper layers.

The highest temperature was recorded on TC6, located beneath the AllShield BarrierSheet and directly below the ignition source, reaching a peak of approximately 800 °C. TC5, also positioned beneath the AllShield BarrierSheet but slightly offset from the ignition point, recorded a maximum of around 600 °C. These temperatures are significantly higher than those observed in AS-1, indicating more intense heat exposure at the top layer due to the inclusion of PIR, which prevented the heat from penetrating downward the sample at the same rate as observed in AS-1.

In contrast, all other thermocouples remained below 50 °C, suggesting that the PIR layer effectively delayed heat transfer to the EPS and underlying roof components. This thermal profile highlights the important insulating role of the additional PIR layer in limiting downward heat propagation during the fire.

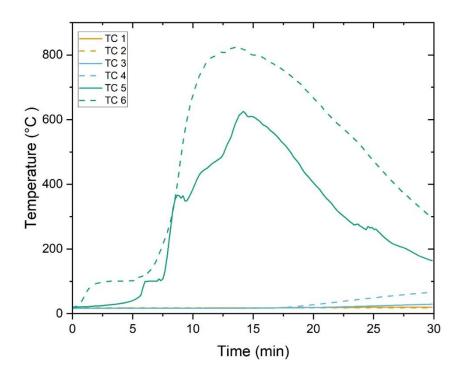


Figure 35 Sample AS-2 Temperature distribution over all roof layers

#### 3.2.3 AS-3

The next figures present the temperature development across the three monitored roof layers during the AS-3 large-scale test: below the EPS layer (Figure 36), on top of the EPS layer (Figure 37), and beneath the AllShield BarrierSheet (Figure 38). Each graph shows five thermocouples per layer (TC1-TC5, TC6-TC10, TC11-TC15, respectively), corresponding to the layout shown in Figure 6.

The highest temperatures were recorded beneath the AllShield BarrierSheet (Figure 38), where TC14 peaked at approximately 430 °C, followed by TC11 at around 200 °C. Other TCs in this layer showed moderate heating, with TC13 and TC12 reaching between 100-150 °C. TC15, however, remained close to room temperature throughout the test, which is likely due to a malfunction or faulty contact during installation.

At the EPS surface level (Figure 37), TC6 and TC7 recorded the highest temperatures, both reaching approximately 150 °C, indicating notable heat transfer near the ignition zone. TC8 measured a lower peak of about 70 °C, while TC10 remained at room temperature. TC9 malfunctioned and was excluded from the analysis.

Due to the failure of TC9, which was positioned directly below the ignition source, the temperature distribution on this layer appears somewhat counterintuitive - temperatures at the EPS surface seem lower than in the layer below, where TC4 (under the EPS) reached around 200 °C. However, it is reasonable to assume that, had TC9 functioned properly, it would have recorded a temperature higher than 200 °C, aligning the thermal profile with expectations and clarifying the heat gradient through the roof structure.



In the lowest layer (Figure 36), beneath the EPS, the temperatures remained generally low, with most thermocouples (TC1 - TC3 and TC5) below 60 °C, and only TC4 reaching around 200 °C. This temperature distribution reflects the localisation of the fire and the effectiveness of the multi-layer roof structure in delaying heat penetration into deeper components.

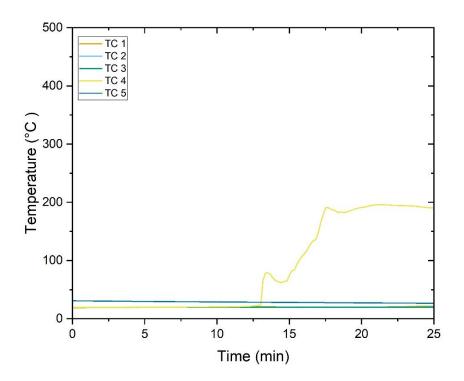


Figure 36 Sample AS-3 Temperature distribution under the EPS

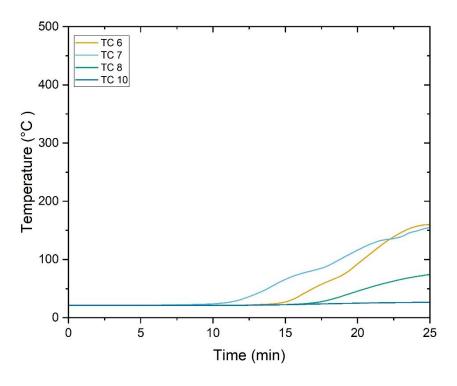


Figure 37 Sample AS-3 Temperature distribution over the EPS

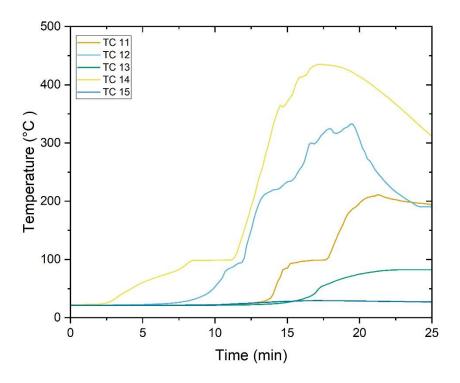


Figure 38 Sample AS-3 Temperature distribution under the AllShield BarrierSheet

#### 3.2.4 AS-4

The next figures show the temperature development during the AS-4 test for two monitored layers: below the EPS insulation (TC1-TC5; Figure 39) and beneath the AllShield BarrierSheet (TC6-TC10; Figure 40). TC9 malfunctioned during the test and was excluded from the analysis.

In the upper layer, beneath the AllShield BarrierSheet, TC10 recorded the highest temperature, peaking at approximately 700 °C, followed by TC8 and TC7, which reached around 630 °C. TC6, located further from the ignition source, measured a lower peak of about 210 °C. These values reflect intense heating in the uppermost part of the system, closest to the radiant heat.

In contrast, all thermocouples placed under the EPS layer remained at room temperature throughout the test, indicating that the EPS and barrier system effectively prevented heat penetration into the deeper roof layers.

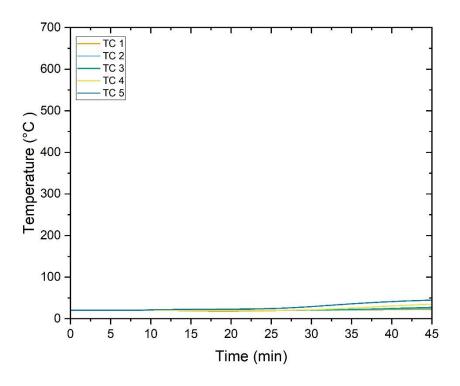


Figure 39 Sample AS-4 Temperature distribution under the EPS

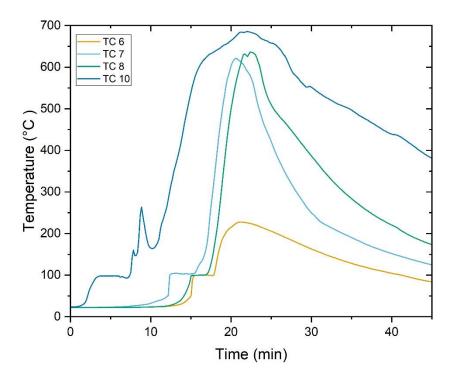


Figure 40 Sample AS-4 Temperature distribution under the AllShield BarrierSheet



# 3.3 Damage assessment

#### 3.3.1 AS-1

Visual inspection after the test revealed that most of the fire damage was concentrated directly beneath the PV modules. As shown in Figure 41, removal of the modules exposed clear burn patterns, with the most severe degradation occurring in the central area of the specimen. The membrane exhibited a distinct edge of fire propagation and showed visible shrinking in areas exposed to elevated temperatures (Figure 42).

Beyond the actively burned zone, the membrane had partially bonded to the AllShield BarrierSheet due to heat exposure, causing peeling of its top layer during removal (Figure 43). In the underlying layers, the bitumen showed localised delamination where the bottom side of the AllShield BarrierSheet had adhered to it during the test (Figure 44).

Although the flame did not breach the AllShield BarrierSheet, thermal transfer still affected deeper components. In several spots, the EPS insulation layer beneath the burned area melted entirely, with the full 10 cm thickness consumed by heat (Figure 45). Overall, the barrier system prevented flame penetration, and most of the damage can be attributed to heat transfer rather than direct flame exposure.



Figure 41 Sample AS-1 after the test with (left) and without (right) the PV module (FotoPortal (left 050524d-158, right 050524d-160))



Figure 42 Sample AS-1 Close-up of membrane showing edge of fire propagation (left) and shrinking due to heat exposure (right) (FotoPortal (left 050524d-161, right 050524d-164))



Figure 43 Sample AS-1 outside of the burned area, the membrane got stuck to the AllShield BarrierSheet (left), peeling off the top layer and the state of the AllShield BarrierSheet below the affected part (right) (FotoPortal (left 050524d-165, right 050524d-168))



Figure 44 Sample AS-1 Bitumen top layer after removal of AllShield BarrierSheet. The bottom side of the AllShield BarrierSheet got stuck to the bitumen layer below the burned area (FotoPortal 050524d-170)

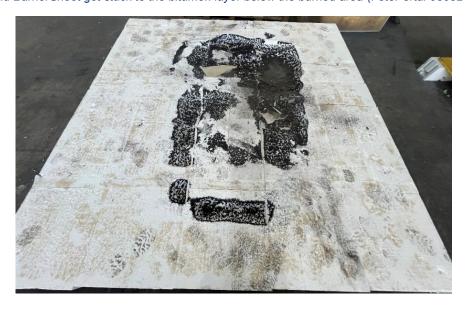


Figure 45 Sample AS-1 The EPS layer melted under the burned area below the PV modules (FotoPortal 050524d-172)



#### 3.3.2 AS-2

Post-test inspection revealed how heat and combustion by-products affected the deeper layers of the specimen, even though flames were contained above the AllShield BarrierSheet.

As shown in Figure 46, removal of the PV modules exposed the burned surface, with visible degradation directly beneath the module area. The AllShield BarrierSheet layer (Figure 47) exhibited localised burn-through and gaps between adjacent boards (Figure 48), which may have facilitated localised heat transfer. Beneath the barrier, the PIR insulation layer showed the most prominent signs of damage (Figure 49). Close-up views revealed destruction of the upper aluminium foil and deformation along board edges under the most intense heat exposure (Figure 50 - left). Outside the main burned area, a yellow-brown, greasy deposit was left on the PIR surface — a residue from some sort of thermal decomposition of PIR (Figure 50 - right), similar in colour to observed yellow smoke during the test.

A side view of the PIR board joints (Figure 51) highlights how these junctions were affected by heat. In particular, the central PIR board experienced severe deformation – buckling - (Figure 52), likely due to a combination of thermal stress and mechanical constraint from anchoring elements. As the heat acted on the anchored points, the board warped considerably. Below this layer, the bitumen membrane showed no significant thermal degradation, although the greasy residue from the PIR layer penetrated through the PIR joints and stained the bitumen locally (Figure 53 - left). The EPS layer also remained mostly intact, aside from slight discolouration and minor deformation directly beneath the ignition source (Figure 53 - right; Figure 54). These signs confirm that while the barrier system prevented flame penetration, heat conduction and the release of volatile compounds from PIR still caused visible, though limited, damage in the deeper layers.



Figure 46 Sample AS-2 after the test with (left) and without (right) the PV module (FotoPortal (left 050524d-174, right 050524d-175))



Figure 47 Sample AS-2 Overview of AllShield BarrierSheet layer (FotoPortal 050524d-178)



Figure 48 Sample AS-2 Closer look at two places (left and right) with burned area and gaps between the boards (FotoPortal (left 050524d-180, right 050524d-182))





Figure 49 Sample AS-2 PIR layer after the test (FotoPortal 050524d-184)



Figure 50 Sample AS-2 Closer look at the PIR - destroyed upper aluminium layer and deformation at the edges of the boards below the burning area (left) and yellow-brown greasy deposit outside the burning area (right) (FotoPortal (left 050524d-186, right 050524d-188))



Figure 51 Sample AS-2 Side view of PIR board joints showing damage by the heat to the PIR boards (left) and also some buckling of PIR (right) (FotoPortal (left 050524d-190, right 050524d-192))





Figure 52 Sample AS-2 Deformation of the middle PIR board (FotoPortal 050524d-194)



Figure 53 Sample AS-2 Overview of bitumen (left) and EPS (right) layers showing some discolouration (FotoPortal (left 050524d-196, right 050524d-198))



Figure 54 Sample AS-2 Damage to the EPS layer directly under the ignition source (black spots indicate melting of bitumen above the EPS) (FotoPortal 050524d-200)



#### 3.3.3 AS-3

The fire in the first test self-extinguished without propagating. Damage was localised under the ignition source. As shown in Figure 55, the membrane and the AllShield BarrierSheet sustained surface damage in the ignition area.

More notably, despite the small, affected area (approximately 20 cm<sup>2</sup>), the damage extended through all layers down to the EPS insulation. As shown in Figure 56, the bitumen and the EPS beneath the ignition point had completely melted. This localised burn-through required the full replacement of the damaged section before the next test could be carried out.



Figure 55 Sample AS-3 First test with a single enlarged wood crib - damage on membrane (left) and AllShield BarrierSheet (right) (FotoPortal (left 050524d-202, right 050524d-204))

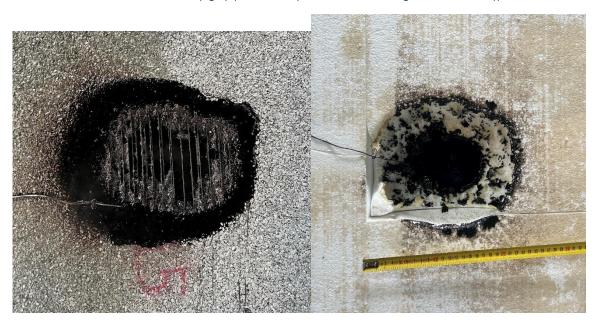


Figure 56 Sample AS-3 First test with a single enlarged wood crib - damage on bitumen (left) and EPS (right) (FotoPortal (left 050524d-206, right 050524d-208))

After the test, removal of the PV modules revealed concentrated fire damage beneath the burned area, as shown in Figure 57. The membrane burned through completely in several places (Figure 58). Beneath this, the bitumen layer showed significant degradation and traces of the AllShield BarrierSheet fused to its surface in areas directly affected by fire (Figure 59).



The EPS layer underneath exhibited extensive melting in parts, particularly beneath the areas of highest thermal exposure. As visible in Figure 60, both EPS and bitumen residues were present, indicating damage to the materials by heat. The most severe damage was localised but notable - in one section, the bitumen had completely liquefied and fused with the melted EPS. This fused mass adhered to the plasterboard below, which serves as the structural base layer beneath the roof system (Figure 61).



Figure 57 Sample AS-3 Specimen after the test with (left) and without (right) the PV modules (FotoPortal (left 050524d-210, right 050524d-212))



Figure 58 Sample AS-3 A closer look at the membrane, showing two close-ups (left and right) of AllShield BarrierSheet under the burnt areas (FotoPortal (left 050524d-214, right 050524d-216))





Figure 59 Sample AS-3 Overview of bitumen layer showing residues of the AllShield BarrierSheet under the burning area (FotoPortal 050524d-218)



Figure 60 Sample AS-3 Overview of EPS layer showing melted areas along with bitumen residues (FotoPortal 050524d-220)



Figure 61 Sample AS-3 A closer look at the EPS area (left) and the fused EPS/bitumen on plasterboard (right) (FotoPortal (left 050524d-222, right 050524d-224))



#### 3.3.4 AS-4

Post-test inspection of the specimen (Figure 62) revealed the condition of the layers beneath the PV modules. The AllShield BarrierSheet showed some gaps between joints (Figure 63 and Figure 64) but largely maintained its shape.

Damage to the PIR insulation layer (Figure 65) was evident beneath the burned area, with a distinctive yellow-brown deposit visible outside the main fire zone, consistent with residues observed in earlier tests.

A side view of the PIR board joints (Figure 66) demonstrates that, unlike the previous test with 60 mm thick PIR boards (AS-2), the thicker 120 mm PIR panels used in this test resisted deformation and heat penetration more effectively. The damage extended approximately halfway through the board's depth, with visible discolouration through most of the thickness, but without actual structural collapse of the boards. The upper aluminium foil layer was damaged similarly to the previous test, showing burn-through in the regions exposed to fire.



Figure 62 Sample AS-4 Specimen after the test with (left) and without (right) the PV modules (FotoPortal (left 050524d-226, right 050524d-228))



Figure 63 Sample AS-4 Overview of the AllShield BarrierSheet after the test (FotoPortal 050524d-230)





Figure 64 Sample AS-4: A closer look at the AllShield BarrierSheet gap between joints after the test (FotoPortal 050524d-232)



Figure 65 Sample AS-4 Overview of PIR layer showing damage under the burnt area and yellow-brown deposit outside of the burned area (FotoPortal 050524d-234)



Figure 66 Sample AS-4 Side view of PIR board joints in two locations, with the most severe burns (left and right) showing that the damage did not manage to penetrate to the underside of PIR at any point (FotoPortal (left 050524d-236, right 050524d-238))



# 4. Conclusion

AllShield BarrierSheet has proven its ability to prevent spread beyond the area of the ignition source on a rooftop with a PVC membrane, even in the event of ignition with an enlarged wood crib, compared to that described in the ZAG test method. The fire tests conducted (AS-1 to AS-4) provided valuable insights into fire behaviour, material performance, and the protective role of the AllShield BarrierSheet in the designed scenarios. Across all tests, flame development generally remained confined to the area below the PV array, and the barrier system consistently prevented direct flame penetration to deeper structural layers. However, the combination of thermal radiation, conduction, and decomposition products caused varying levels of subsurface damage.

In AS-1, flames progressed steadily across the area covered by the PV module, resulting in glass breakage and visible thermal damage down to the EPS layer, although the barrier remained intact. AS-2 showed similar fire development, but the glass did not shatter, likely due to early frame deformation, which may have influenced airflow and cooling. The yellow smoke observed from PIR decomposition indicated differences in combustion behaviour compared to AS-1.

In AS-3, after the initial failure to ignite, the second test confirmed full flame spread across multiple modules. Although all four modules eventually shattered, the damage below the barrier was relatively localised. However, the EPS melted and fused with the bitumen and stuck to the plasterboard, indicating the intensity of the heat transfer despite the effectiveness of the barrier. The AS-4 test lasted 40 minutes. The use of two larger cribs enabled consistent ignition, and all four modules were involved. The thicker PIR boards (120 mm) resisted mechanical deformation, and fire penetration remained limited to the upper half of the insulation. However, yellow deposits and greasy residues again highlighted the role of PIR decomposition in heat and smoke propagation.

Temperature data confirmed the localisation of heat at the uppermost layers, with the highest values consistently recorded beneath the AllShield BarrierSheet near the ignition source. Recorded temperatures below the AllShield BarrierSheet also show a plateau at 100 °C, indicating some cooling effect coming from the materials, potentially evaporation of crystalline-bound water or similar. In AS-1, peak temperatures reached approximately 500 °C, while in AS-2, they exceeded 800 °C, demonstrating more intense combustion and heat release in the presence of PIR. AS-3 and AS-4 showed similar trends, with peak temperatures in the barrier layer reaching 430 °C and 700 °C, respectively. Meanwhile, thermocouples located beneath the EPS layer remained near room temperature in all tests except AS-1, indicating that the barrier and insulation systems effectively limited downward heat transfer. The variations in temperature distribution also highlighted the influence of test geometry, material layering, and ignition configuration on overall fire dynamics.

Overall, the AllShield BarrierSheet proved to be effective at restricting flame spread beneath the PV modules, though thermal damage through conduction and pyrolysis still affected deeper layers. PIR composition, anchoring, and board thickness were key factors influencing subsurface damage and post-test deformation.

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