

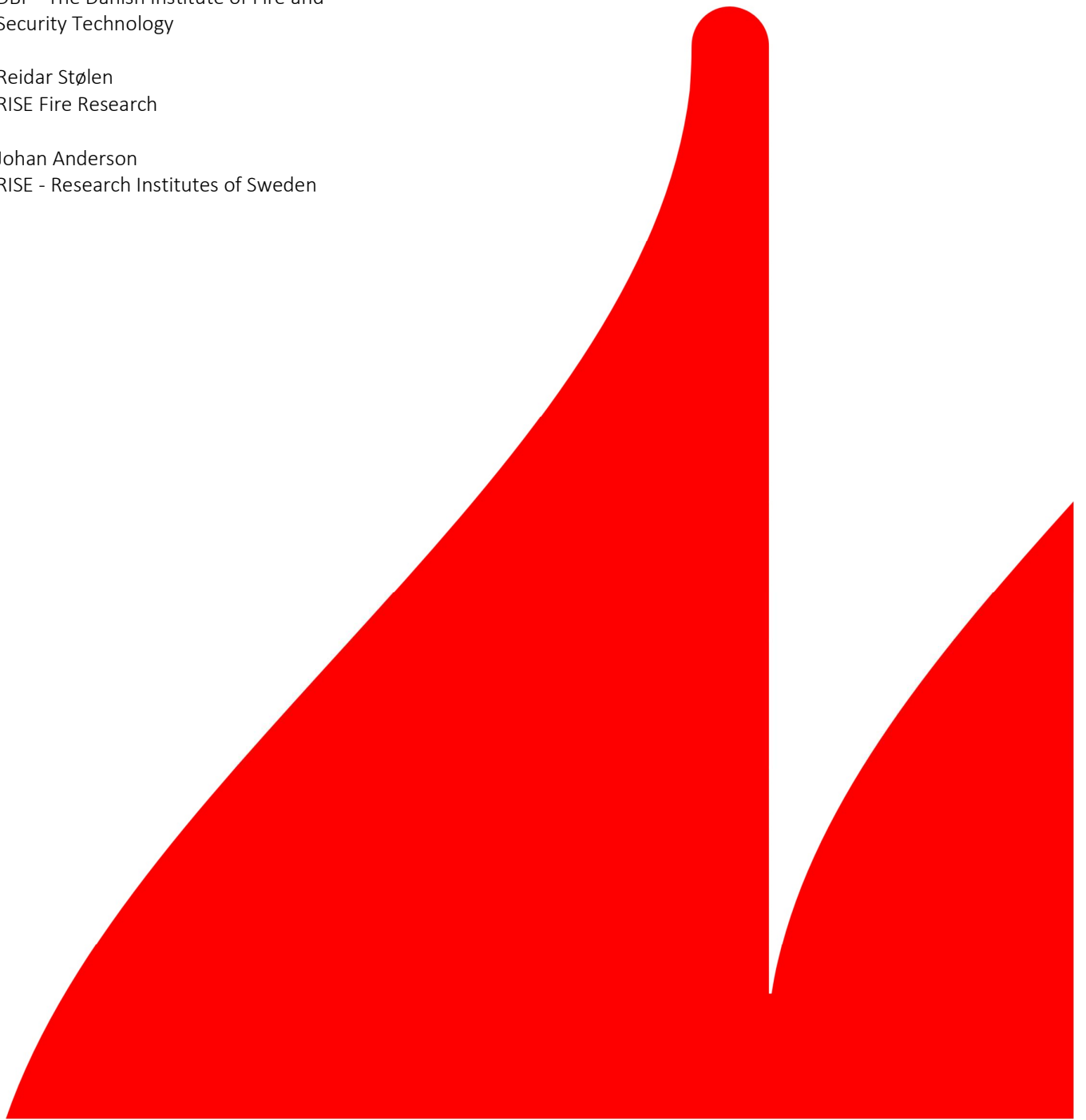
SOL-IGNIS

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Fire Testing of Roof- Mounted Solar Panels

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1. INTRODUCTION

The implementation of photovoltaic (PV) systems in the built environment is a central component of Europe's strategy for achieving a green energy transition and reducing reliance on fossil fuels[1]. However, several recent fire incidents involving rooftop PV systems, such as those at IKEA facilities [2], [3],[4] the Miramar shopping centre in Spain [5], a school in Belgium [6], and two separate events in Germany [7], have highlighted emerging fire safety challenges associated with these installations. A recent study of different national statistics by Rus et al. [8] shows that the risk of fire in PV installations are not negligible and that the consequences of such fires vary from localized damage of components to complete building loss.

Existing European fire classification methods for roof constructions, including EN 13501-5 [9], were developed without specifically considering the altered fire dynamics introduced by building applied photovoltaic (BAPV) systems. When PV modules are installed, they form a cavity between the module and the roof surface. This configuration can promote deflected flames and increase radiative heat transfer. Recent international studies indicate that fire spread beneath PV modules is governed by the combined influence of thermal exposure, material properties, module geometry and airflow conditions [10], [11]. Furthermore, other experiments have shown that the cavity formed beneath PV modules can modify the flame configuration and thermal exposure of the roof surface and, under certain conditions, promote sustained flame spread beneath the PV array [12], [13], [14], [15], [16], [17].

The fire behaviour beneath BAPV systems depends on the interaction between several parameters. These include the geometry of the PV installation, such as cavity height and module inclination; the properties of the PV module and roof construction; the characteristics of the ignition source; and ambient conditions such as airflow and temperature. The present state of knowledge concerning these parameters and their influence on fire development is reviewed in Section 2. Particular attention is given to the mechanisms influencing flame spread beneath PV modules and heat transfer into the underlying roof construction, as these mechanisms form the basis for the experimental investigation presented in this report.

The SOL-IGNIS project investigates the feasibility of adapting CEN/TS 1187 Test 2 to account for fire behaviour associated with BAPV installations on predominantly flat roof constructions. The study evaluates whether a modified CEN/TS 1187 Test 2 configuration can reproduce important fire phenomena observed in large scale roof experiments, in particular the occurrence and spatial progression of sustained flame spread beneath a PV array and the associated thermal exposure of the roof construction. The study further examines the sensitivity of the modified configuration to changes in cavity height and imposed airflow.

The experimental programme was conducted at two scales. Three large scale experiments were performed on 6m × 6m roof mock ups fitted with an East/West-oriented array consisting of four PV modules. Two experiments used a two layer bituminous roofing system, providing a repeated reference configuration, while the third experiment used a single ply PVC roofing membrane to investigate the influence of a roof covering with substantially different thermal characteristics. The large scale experiments were conducted indoors without external wind and provided the reference fire behaviour against which the modified test configuration was assessed. A second experimental campaign was conducted using a modified medium scale CEN/TS 1187 Test 2 apparatus. In this configuration, a calcium silicate board positioned above the roof specimen was used as an inert representation of the geometric confinement created by a PV module. The medium scale programme was performed using the same two layer bituminous roofing system as the first two large scale experiments. Two cavity heights, 60 mm and 90 mm, were investigated at imposed airflow velocities of 0 m/s, 2 m/s and 4 m/s. Each configuration was tested twice, resulting in twelve medium scale experiments. The programme therefore allowed the influence of cavity height and airflow on flame propagation, damaged length and temperature development within the roof construction to be examined under controlled conditions.

The large and medium scale configurations differ in several important respects, including specimen dimensions, PV module representation, inclination, ignition source and airflow boundary conditions. The comparison between the two scales is therefore not intended to establish direct scale equivalence, validate a classification procedure or demonstrate identical quantitative responses. Instead, the comparison is used to assess whether the modified medium scale configuration reproduces the principal qualitative fire spread mechanisms observed in the large scale experiments and whether it responds systematically to changes in relevant experimental parameters.

The experimental methodology and complete test programme are presented in Section 4, including the roof constructions, PV and simulated PV configurations, ignition sources, instrumentation and test procedures. The results of the large and medium scale experiments are presented in Section 5. Section 6 discusses the correspondence between the two experimental scales, the influence of cavity height and imposed airflow, the effect of the investigated roof covering materials, and the limitations of the present experimental programme. The main conclusions and recommendations for further development of the modified test concept are presented in Section 7.

2. CURRENT STATE OF KNOWLEDGE

2.1. Fire Behaviour of roof constructions with BAPV systems

The fire behaviour of roof constructions incorporating BAPV systems has been investigated experimentally at a range of scales. Following the large scale experiments conducted by Kristensen and Jomaas [12], additional large scale roof experiments have been reported by commercial organisations and industry associations [19], [20], [21], [22], while research studies have investigated individual parameters influencing fire development beneath PV modules. Together, these studies provide evidence that the installation of PV modules can alter the fire behaviour of an otherwise conventional roof construction [23].

Previous experimental investigations have shown that introducing a PV module above a roof surface modifies the local fire dynamics by forming a confined cavity in which flames can be deflected along the roof surface [14]. Under certain experimental conditions, this altered geometry has enabled sustained flame spread beneath PV modules even for roof coverings that fulfil the $B_{\text{ROOF}}(t_2)$ classification requirements of EN 13501-5 when tested in accordance with CEN/TS 1187 Test 2 [9].

Figure 1 illustrates the ignition process on a conventional flat roof construction without a PV module above the roof surface [13]. After ignition of the wood crib, heat transfer from the flame, predominantly through radiation, increases the temperature of the roof surface within the vicinity of the ignition source. As the temperature of the roofing membrane, often consisting of a bituminous roofing felt or single ply plastic based membrane, increases, the material releases combustible pyrolysis gases. Ignition of the roof surface can occur when the concentration of these gases exceeds their lower flammability limit (LFL) [25], after which heat feedback from the ignited membrane and the wood crib increases the temperature near the newly formed flame front (Figure 1d).

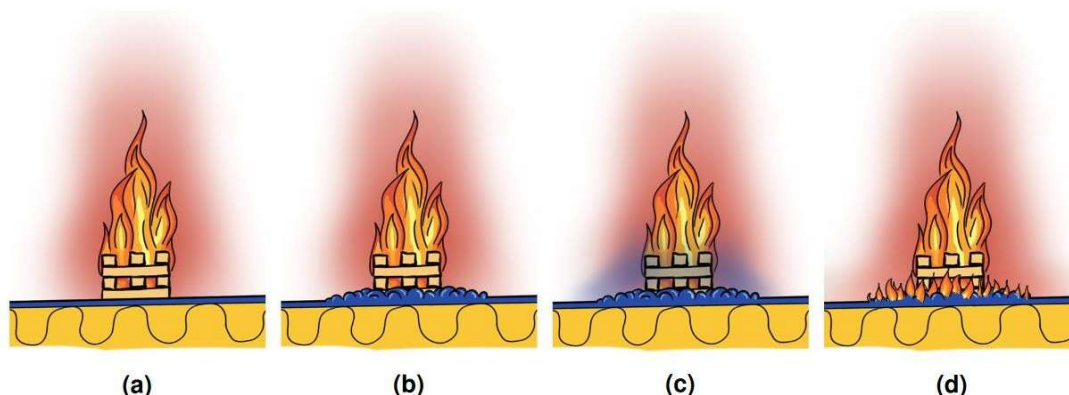


Figure 1 – Sketched ignition process of roof construction (blue roofing membrane, yellow insulation) with wood crib. a) Radiative heat transfer from ignited wood crib (fading red cloud), b) Heat of nearby roofing membrane, c) Release of combustible pyrolysis gases (fading blue cloud), d) Ignition of pyrolysis gases, addition radiative heat transfer, but no self sustained flame spread. From: J.S. Kristensen (2022) [13].

If the combined heat feedback from the wood crib and the ignited roof surface is sufficient to elevate the temperature of the unignited material ahead of the flame front, sufficient combustible pyrolysis gases may be generated to exceed the lower flammability limit (LFL). As a result, the flame front may propagate further away from the domain of the initial ignition source. Due to the relatively low view factor¹ between two perpendicular surfaces [17], the radiative heat transfer from the vertical flame towards a given point on the horizontal roof surface, reduces significantly as the distance between ignition source and point increase [17]. According to established flame spread theory, continued propagation therefore requires that the heat transfer from the existing pyrolysis zone, and flame front, exceeds the energy required to elevate the temperature of the virgin material ahead of the flame front sufficiently [26, p. 200].

The BROOF(t2) classification is intended to characterize the external fire performance of a roof construction under the exposure conditions prescribed by CEN/TS 1187 Test 2. However, the standard test configuration does not include the cavity formed by a BAPV installation.

Still, the installation of a BAPV system introduces a cavity between the roof surface and the backside of the PV modules which can deflect the flame from the initial ignition source as illustrated in Figure 2. The deflection of the flame alters the view factor and can promote a significant increase in the radiative heat transfer towards the surface below the most elevated part of the inclined PV module [14].

¹ View factor is also known as *configuration factor*.

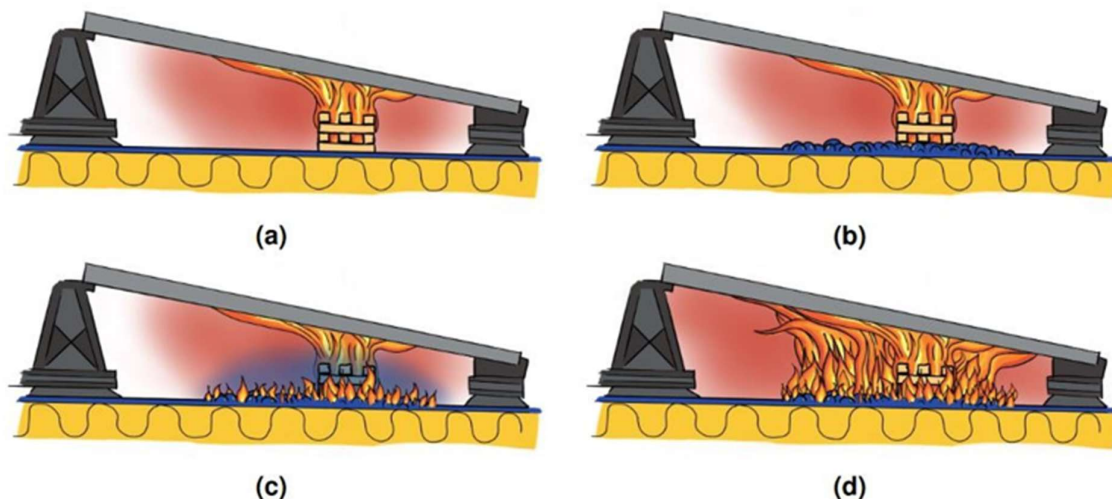


Figure 2 – Sketched ignition process of roof construction (blue roofing membrane, yellow insulation) with wood crib below BAPV module. a) Radiative heat transfer from deflected flame (fading red cloud), b) Heat of nearby roofing membrane, c) Release of combustible pyrolysis gases and initial ignition (fading blue cloud), d) High heat release rate due to higher concentration of pyrolysis gases, heating nearby materials and self sustained flame spread. From: J.S. Kristensen (2022) [13].

Large scale tests have demonstrated that the increased view factor between the roof surface and the flame deflected below the PV module does enable self sustained flame spread [19], [20], [21], [22]. In case of self sustained flame spread, it is essential from a fire safety strategy perspective that the fire does not spread further and propagate into the subadjacent construction. As such, the introduction of a BAPV system on the roof construction increases the potential consequences from i) *flame spread along the building*, to also include ii) *flame spread into the building*. Consequently, it is necessary to examine how the consequences can be mitigated in case of a PV related fire.

Material, geometric and ambient parameters have been studied to understand why the self sustained flame spread occur and thus, how the severity of PV related fires can be reduced to an acceptable level by introducing mitigation measures. For BAPV systems on industrial or commercial flat roof constructions, the parameters affecting the consequences can be divided into three design parameters and two ambient variables, with design parameters being parameters that can be modified or engineered consciously, contrary the ambient variables, wind and temperature. In the following section, the influence of the design parameters is discussed in brief, followed by a discussion of the ambient variables in subsection 2.3.

2.2. Design Parameters

2.2.1. Mounting system – cavity height and inclination

BAPV modules are installed on roofs using mounting systems which are either ballasted, glued, or mechanically fixed to the roof. This results in a geometry where the module creates a cavity between the module and roof surface as described in section 2.1. From a fire dynamics perspective, an important function of the mounting system is that it defines the geometry of the cavity between the roof surface and the backside of the PV module. The cavity is defined by the clearance between the module and roof surface, together with the inclination and arrangement of the modules.

Experimental work of investigating flame spread along the reference material² polymethyl methacrylate (PMMA) identified a critical cavity height between the roof surface and a parallel horizontal inert barrier of

stainless steel, or a PV module [15]. Slow steady state flame spread was observed along the PMMA for cavity heights above the critical gap height, whereas more rapidly accelerating flame spread was observed for gap heights below this value [15]. Similar observations were found, when the PMMA was replaced by small roof construction mock ups with a PV based single ply roof covering compliant with British building regulations ($B_{ROOF}(t_4)$) [16]. However, a binary flame spread scenario was seen in the tests on the roof mock ups. Thus, no flame spread outside the domain of the ignition source was observed in the baseline tests with no cavity and in tests with gap heights above the critical gap height, whereas flame spread along the full roof mock up was seen in tests with a gap height below the critical gap height [16].

The findings are consistent with steady state experiments examining re-radiation from a gas burner below horizontal and inclined surfaces [17], [18]. For inclined surfaces, the highest radiative heat flux is measured below the most elevated part of module the near the gas burner due to a buoyancy driven increased upward gas flow and flame extension, as illustrated in Figure 2. However, increased inclination leads to a reduced view factor between the most elevated part of the PV module and roof surface. Consequently, the effect of inclinations above 10° is not expected to increase the heat flux significantly more.

To conclude, the cavity geometry, and especially the gap height between the back of the PV module and the surface of the roof construction, can serve as a decisive factor that differentiates flame spread from no flame spread. The conclusion is based on tests conducted with a reproducible ignition source which will be discussed further in section 3. In the North European countries, most BAPV modules are installed in East/West orientated configuration or parallel with the roof surface with inclinations between 0° and 15° [27], but systems with higher inclinations are used in areas with significant snowfall during winter.

2.2.2. PV modules

The majority of photovoltaic (PV) modules are composed of a technology where the cells are made of the inert material crystalline silicon (c-Si), which represented an unquantified majority of the production in 2007 [28] and 98% of the added capacity in 2024 [29]. A transparent front sheet, often tempered glass, are used in all c-Si PV modules and behind the front sheet, the PV cells are encapsulated between two layers of a transparent polymer, such as ethyl vinyl acetate (EVA) [30], and a backing material in the form of glass or, more commonly, a plastic foil backsheets. Depending on the type of backsheets, the module types are referred to as glass/glass or glass/foil. The total heat release from the combustible materials in a PV module has been found to be in the range from 25 to 45 MJ/m² when tested in the cone calorimeter which is within the range of total heat release from roofing membranes of bitumen, polyvinyl chloride (PVC) and flexible polyolefin (FPO)[31].

Despite the increased fuel load ascribed to the PV modules, experiments on horizontal roof surfaces by Kristensen et al. did not show any significant increase in horizontal fire spread over PMMA in experiments with glass/foil modules compared with an inert stainless steel board[15], whereas a small difference in flame spread length were observed when stainless steel board and PV modules was tested above a PVC based single ply membrane on the roof mock ups [16]. In experiments on vertical noncombustible facades, the contribution from the combustible materials in the PV modules became more apparent and the protection of the combustible encapsulant by the glass/glass modules limited the fire spread compared to glass/foil modules[31], [32], [33]. This indicates that the additional fuel load from the PV modules may or may not contribute significantly to the fire development and that in flat roof configurations, the geometric parameters influencing the flame deflection are dominating the increasing fire spread caused by the PV modules.

² PMMA is often used as reference material for fundamental flame spread studies [15], [26].

2.2.3. Roof construction

Severity of the consequences associated with flame spread in the cavity between the roof surface and a PV module can depend on the roof construction build up hosting the BAPV system. Essentially, the roof build up can be separated in up to three main components: the roof surface, insulation, and loadbearing components. It is acknowledged that other components, such as fasteners, a moisture/vapour barrier and ventilated cavities, are present in most roof constructions, but no known research have systematically studied the influence of these during PV related fires.

Several previous large scale studies have examined the extent to which different insulation or protective layers limit heat penetration and secondary fire development beneath the roofing membrane. Kristensen and Jomaas examined if mitigation layers of mineral wool or PIR insulation could protect a subjacent EPS insulated roof construction [12], whereas PU Europe and Kingspan compared the performance of PIR insulation with mineral wool [19], [20]. Finally, the European Manufactures of Expanded Polystyrene, EUMEPS, examined if either two layers of glass fibre fleece or 12 mm cement fibre board could protect the subjacent layer of EPS [21], [22]. In Kristensen and Jomaas, tests with a mitigation layer of 50 mm thick PIR insulation, the wood crib used for ignition penetrated the mitigation layer after 60 minutes, whereupon self sustained flame spread occurred within the EPS [12]. Ignition of the EPS also occurred in EUMEPS tests conducted with a mitigation layer of glass fleece [22]. Otherwise, the fire solely propagated below the PV array in all tests, besides the test conducted with a cement fibre board where the flames only propagated below one of the four PV modules. All large scale tests were conducted with PVC based single ply membranes.

As such, the large scale tests illustrate that the roof constructions insulation material, or a mitigation layer between the roofing membrane and subjacent insulation material, can serve as barrier which potentially can prevent flame spread along the roof and into the building and in some cases also prevent horizontal fire propagation below the PV modules.

When examining scaled down roof construction mock ups, it was found that the heat transfer towards the subjacent roof construction increased with a reduction of the gap height between the backside of the PV module and the roof surface. The temperature increase occurred for two reasons: i) Increased heat transfer during the pre-heating phase, and ii) slower flame spread in the tests conducted with the lowest gap height due poor combustion efficiency, thus increased heat transfer from the pyrolysis zone toward the subjacent insulation [16]. The available studies therefore indicate that the response of a BAPV roof cannot be attributed solely to the PV module geometry. The thermal and combustion properties of the roofing membrane and the materials immediately beneath it also influence flame propagation and heat penetration into the roof build up. This provides the basis for investigating different roof coverings in the large scale SOL-IGNIS experiments.

2.3. Ambient variables

2.3.1. Airflow and wind

Airflow can influence flame spread by changing the relationship between the flame, the unburned fuel and the combustible gases released from the roof surface. For an unobstructed surface, airflow directed towards the unburned material may produce a more concurrent flame spread configuration by deflecting the flame towards the preheating region, whereas airflow in the opposite direction can produce an opposed configuration [26], [34]. However, the behaviour becomes more complex when the flame is confined within the cavity beneath a PV module.

The influence of wind on fire spread beneath PV modules cannot therefore be characterised as inherently enhancing or suppressing. Instead, it depends on the interaction between the imposed airflow, cavity geometry and buoyancy driven flow generated by the fire. Relevant parameters include wind direction,

module inclination, cavity height and the relative magnitude of the imposed airflow compared with the fire induced flow. Previous studies indicate that airflow may promote combustion by increasing oxygen supply or by deflecting flames towards unburned roofing material. Conversely, sufficiently strong airflow may dilute or remove combustible pyrolysis gases from the ignition region or displace the flame away from the unburned surface, thereby reducing the likelihood of continued propagation [13]. The presence of the PV cavity therefore does not necessarily result in a semi concurrent flame spread condition independently of airflow direction. The resulting flame configuration reflects the combined effects of imposed airflow, buoyancy, cavity geometry, fuel properties and ignition source characteristics.

The literature indicates that airflow can influence both ignition and subsequent flame propagation beneath PV modules, but that the magnitude and direction of this influence depend on the specific configuration [10], [11]. Airflow was therefore treated as an experimental variable in the medium scale SOL-IGNIS programme rather than being assumed to have either a uniformly accelerating or suppressing effect.

2.3.2. Ambient temperature

Higher ambient temperatures reduce the energy required to bring combustible materials up to their ignition point. When the surrounding air is already warm, the preheating phase before ignition is shorter, allowing flames to develop and spread more quickly [25], [26]. This effect is particularly relevant for materials with relatively high ignition temperatures, as the thermal gap between ambient conditions and ignition is smaller. As a result, elevated ambient temperatures contribute to faster flame spread once an ignition source is present.

3. IGNITION SOURCE

For PV related fires in the built environment, the initial fire in the form a competent ignition source can be the outcome of various events which have occurred individually or combined with each other. The term competent ignition source is used within fire safety investigation and is defined as “An ignition source that has sufficient energy and is capable of transferring that energy to the fuel long enough to raise the fuel to its ignition temperature” by the National Institute of Standards and Technology (NIST) [35].

Research has illustrated that events leading to the formation of a competent ignition source can originate from both components of the PV system itself as well external ignition sources not related to the PV system [36]. A study by Mohd Nizam Ong et al. [36], based on data from Australia, Germany, and the UK, indicates that around 2/3 of the examined PV related fires are caused by failure of a PV component. In the Netherlands, 152 PV related fires have been identified between November 2022 and October 2023, from where detailed information was available for 70 of the incidents and the fire occurred in a component of the PV system in 30 cases. In 29 incidents, the fire was not caused by the PV system and the cause of the fire could not be identified in the remaining 11 cases, which leads to the conclusion that there is an equal likelihood of the fire originating within and outside the PV system [37]. In both studies, it is acknowledged that, that the conclusions are based on limited data and that more research is needed to draw final conclusions.

Despite the uncertainty associated with both studies, they do indicate that the introduction of the PV technology into the built environment does introduce additional ignition sources in addition to the limited types of ignition sources already present. Consequently, the definition of the competent ignition should be reconsidered when developing tests for roof constructions in combination with building applied PV systems. When it comes to fires caused by the PV system, the fires are often the result of direct current arcing which can reach temperatures from 6000 K [38]. However, the use of a DC arc as an ignition source for fire tests are not suggested as the repeatability and reproducibility relies on many external factors and plastic components of the DC arc is often ignited as the first nearby fuel as studied by Hastings et al. [39]. As such, ignition of a PV component, caused by DC arcing, serves as an additional type of ignition source on roof constructions, in addition to burning brands, radiation from a nearby building fire, or the fire plume from a subjacent

compartment fire.

From a testing perspective, the introduction of an additional source of ignition does not necessarily require the introduction of a new ignition source when developing a test method for testing roof constructions in combination with BAPV systems. Depending on the ignition source in the existing test method for roof constructions without a BAPV system, such as test 1-4 in CEN/TS 1187, an ignited component of a PV system might not serve as a more severe ignition source. The following sections present the ignition sources used in the different tests.

4. EXPERIMENTAL CAMPAIGN

As described in the introduction, the experimental campaign consists of two different scales, three large scale tests and a series of tests where it is examined whether the existing Nordic test method, CEN/TS 1187 Test 2, can be modified so it quantifies the potential consequences of PV related fires. In the following sections, the evaluation criteria for the pre-normative tests development will be introduced, followed by the introduction of the key variables and overall roof build up.

Based on that, the design of the large scale tests is presented, followed by a presentation of a modified CEN/TS 1187 test method 2 and discussion of input variables. Finally, the test plan is introduced. Table 1 shows a summary of all the tests performed in the SOL-IGNIS test campaign.

Test Series	Scale	Roof Construction	Number of Tests
Large Scale Tests 1-2	Large Scale	Mineral Wool Insulation Two layer bitumen roof membrane	2
Large Scale Test 3	Large Scale	Mineral Wool Insulation Single layer PVC roof membrane	1
Modified CEN/TS 1187 Test 2	Medium Scale	Mineral Wool Insulation Two layer bitumen roof membrane	6
Modified CEN/TS 1187 Test 2	Medium Scale	Mineral Wool Insulation Two layer bitumen roof membrane	6

Table 1 – Summary of test SOL-IGNIS test campaign.

4.1. Evaluation criteria

The standard CEN/TS 1187 Test 2 primarily evaluates the external fire performance of a roof specimen based on the extent of fire spread and damage along the specimen. The modified configuration investigated in the present study was additionally intended to examine the thermal exposure produced within the roof construction when sustained flame spread occurs beneath a simulated PV module. Stølen et al. have previously modified CEN/TS 1187 Test2 [40], investigating the influence of cavity height and imposed airflow on fire spread beneath a plate positioned above the roof specimen. The present study builds on this approach by comparing the fire behaviour produced in the modified configuration with observations from large scale BAPV roof experiments and by evaluating both flame propagation and temperature development within the roof construction.

The modified configuration was therefore evaluated primarily according to its ability to adequately indicate:

- a) self sustained flame spread along the roof surface.

- b) heat transfer from potential flame spread in the cavity to the subjacent insulation material.

As discussed in Section 2, the thermal and combustion properties of the roof covering can influence both flame propagation and the transfer of heat into the roof build up. The large scale experimental programme therefore included two roof covering systems with different thermal characteristics: a two layer bituminous roofing system and a single ply PVC membrane. Where sustained flame spread develops beneath a PV array, the resulting thermal exposure of the underlying roof construction represents an additional parameter of interest. Temperature measurements were therefore included at several depths within the roof build up to characterise the progression of heat through the construction and to supplement the assessment of surface flame spread. The roof covering was retained as an important comparison parameter in the large scale experiments because it represents the uppermost combustible component directly exposed to the cavity fire. Furthermore, the roof covering material is the component which obtains the classification within the classification system defined in EN 13501-5 [9]. The medium scale programme was conducted only with the bituminous roofing system and was therefore used primarily to investigate the sensitivity of the modified configuration to cavity height and imposed airflow.

4.2. Overall roof build-up

With the roof covering representing the key variable in the roof construction build up, the objective of the pre normative work is to evaluate whether a modified CEN/TS 1187 Test 2 can distinguish between the outcomes of tests conducted on similar roof build ups incorporating two different roof coverings. Due to the limited existing data from large scale tests conducted under controlled indoor conditions, the large scale experiments were used to establish reference fire behaviour for comparison with the modified CEN/TS 1187 Test 2 configuration. The comparison was intended to assess whether the modified configuration reproduced the principal fire spread and thermal response characteristics observed at large scale rather than to achieve direct quantitative replication between the two scales.

In both the large scale and modified medium scale configurations, flame spread was assessed and heat transfer into the underlying roof construction was monitored using Type-K thermocouples. The roof build ups were therefore kept as comparable as reasonably possible within the dimensional constraints of the CEN/TS 1187 Test 2 apparatus.

For the purposes of this study, the roof covering and insulation are considered the primary components defining the roof build up. While it is acknowledged that a complete roof assembly includes additional layers, the maximum allowable sample thickness of 150 mm in the CEN/TS 1187 Test 2 [41] limits the investigation to the upper layers of the construction.

4.2.1. Roof coverings

The large scale experimental programme comprised three tests using two different roof covering systems. Tests 1 and 2 were conducted with a two layer bituminous roofing system, providing one repeated configuration, while Test 3 was conducted with a single ply PVC membrane.

These two product types were selected due to their distinct thermal characteristics, where the thickness of the roof coverings is particularly significant. The single ply membrane is considered thermally thin, while the multilayer roofing felt renders the membrane thermally thick [38]. As a result, a uniform temperature distribution is assumed across the single ply membrane, whereas a temperature gradient is expected between the surface and underside of the roofing felt.

The difference in thermal thickness between the two roof coverings affects both evaluation criteria defined in section 4.1. In the case of the thermally thin single ply membrane, the thermal properties of the underlying material can significantly influence flame spread. If the subjacent material possesses high specific heat capacity, thermal conductivity, and density, it can act as a heat sink, thereby inhibiting or delaying ignition of the roof covering ahead of the flame front. Conversely, a material with low density, specific heat, and thermal conductivity would limit heat transfer between the roof covering and insulation, leading to faster heating of the roof covering, which may increase the likelihood of ignition and subsequent flame propagation [38].

4.2.2. Insulation material

With the roof covering representing the key variable, all remaining parameters in the large scale tests were kept constant. The roof constructions were insulated with mineral wool, as this material is commonly used in the built environment in Denmark. Mineral wool was selected over other insulation materials such as PIR, PUR, or EPS, as the introduction of plastic based insulation could increase the overall complexity of the experimental campaign. This is primarily due to the potential for deformation of the roof build up, which would introduce an additional variable that could influence the fire behaviour and overall test outcomes as reported in previous medium and large scale tests [13].

4.3. Large scale tests

With the large scale tests representing the reference tests for the modified CEN/TS 1187 test 2 (medium scale), it is decided that they should be conducted similar to previously conducted large scale tests by other organisations and test institutes. By doing so, it is ensured that the modified medium scale tests are compared to tests which are generally accepted to evaluate the consequences of BAPV related fires on flat roof constructions [19], [20], [21], [22]. As such, all large scale tests will be conducted on squared roof mock ups with side lengths of 6 meters and a small building applied (BAPV) array of four PV modules in an East/West configuration. In the following sections, the roof build up, PV system, instrumentation and ignition source will be discussed.

4.3.1. Roof mock up

As described in section 4.2, the large scale roof constructions were kept identical apart from the roof covering system. Tests 1 and 2 used the two layer bituminous roofing system, whereas Test 3 used the single ply PVC membrane. The sectional build up of the roof mock ups is shown in Figure 3, with the uppermost roof covering layer varying between the bituminous and PVC configurations as indicated in Table 2. To limit variability associated with the material properties of the bituminous roofing system, the upper bitumen layer and flame barrier layer used in Tests 1 and 2 were taken from the same respective material batches.

Table 2 – Overview of the layers in accordance with the sectional view in Figure 3.

Layer	Component	Product	Thickness	Mass
1	Upper bitumen layer	Katepal PF 5500 SBS	4.3 mm	5.5 kg/m ²
	Flame barrier	Katepal K-MS 170/4000 SBS	3.1 mm	4.0 kg/m ²
	OR			
	PVC membrane	-	-	-
	Glass fleece	-	-	-
2	High density MW	Rockwool TF Plade	20 mm	3.5 kg/m ²
3	Lower density MW	Rockwool Dura Underlay	100 mm	13.5 kg/m ²
4	Moisture barrier	Katepal PF 3200 SBS	2.2 mm	3.2 kg/m ²
5	High density MW	Rockwool Dura Underlay	50 mm	6.5 kg/m ²
6	Trapezoidal steel deck	-	-	-

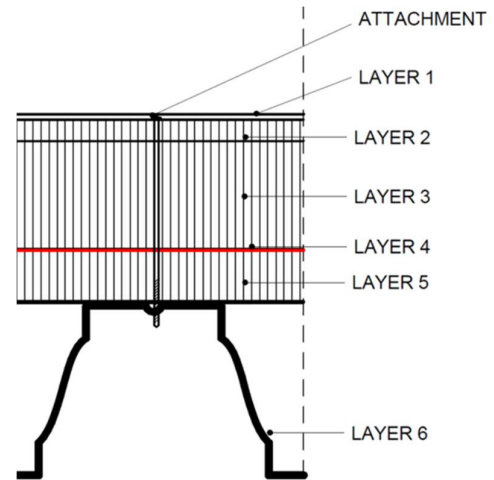
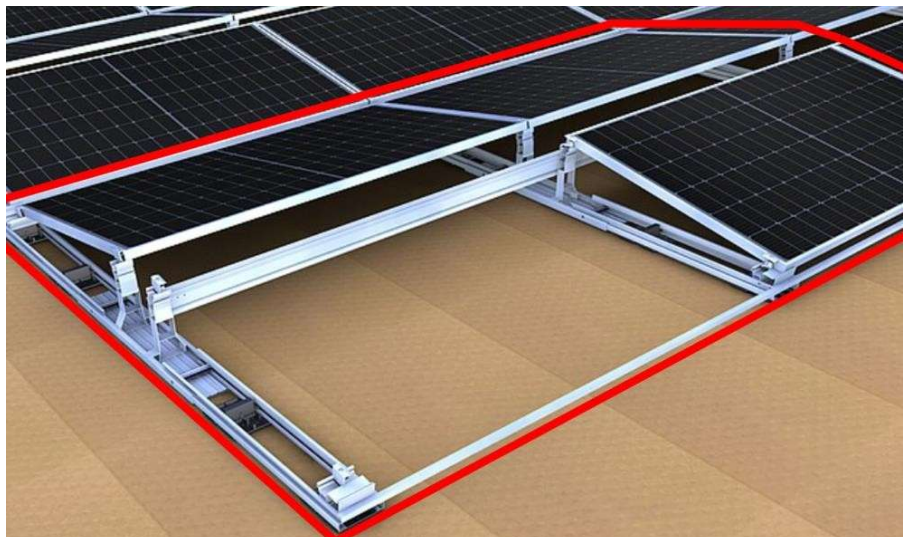


Figure 3 – Sectional view of the roof mock ups used for the large scale tests. Layers from top to bottom in accordance with Table 2.

4.3.2. PV array

The mounting system and PV modules used in the three large scale tests were supplied and installed by BayWa R.E. The small East/West orientated PV array was not ballasted. The PV modules were installed with the modular mounting system “Flat roof system III «the shortcut»” manufactured by the BayWa R.E. owned company Novotegra [42]. The principal geometric parameters of the installation, including the module inclination, clearance between the roof surface and the lower and upper edges of the modules, and the spacing between adjacent modules, are presented below and are illustrated in Figure 4.

- Module inclination: 10°
- Height above roof at high end: 314 mm
- Height above roof at low end: 117 mm
- Distance between opposing modules at the high point: 180 mm



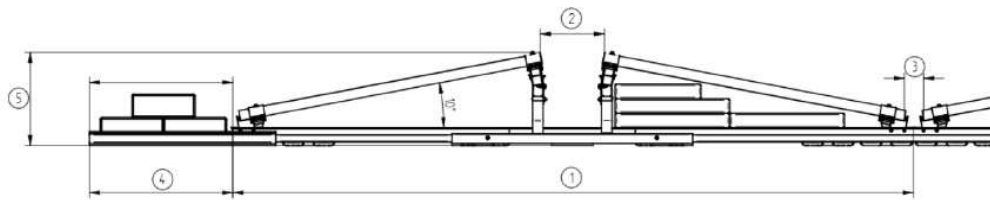


Figure 4 – Upper: Commercial sketch of the mounting system used in the large scale tests. The area highlighted in red corresponds to the array used in the three large scale tests from: REFERENCE. Lower: Sectional side view of the PV mounting system, PV modules and ballast.

4.3.3. Ignition source

Similar to most previously conducted large scale tests, the gas burner specified in CLC/TR 50670 was used as the ignition source [43]. This gas burner was developed through a test series conducted by TÜV Rheinland, Currenta GmbH, and Bergische Universität Wuppertal [44]. The objective of the series was to design a gas burner capable of replacing the wood wool basket used as the ignition source in CEN/TS 1187 Test 1 when evaluating roof constructions in combination with PV modules.

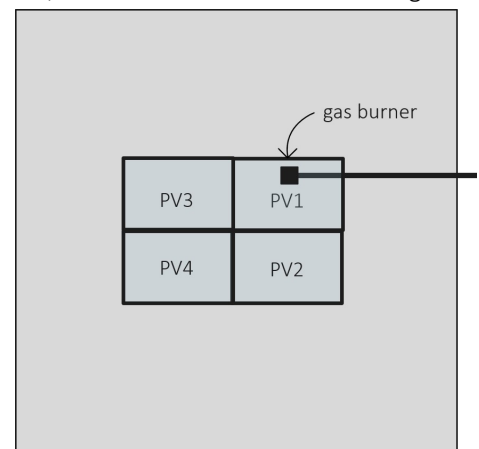


Figure 5 – Top view of the roof surface, PV array and location of gas burner.

It is unclear how the gas burner developed in the German studies came to be included in the CENELEC test report CLC/TR 50670, which, despite its title *External fire exposure to roofs in combination with photovoltaic (PV) arrays – Test method(s)*, does not incorporate any roof construction components and therefore solely evaluates the reaction to fire of the tested PV module.

It is acknowledged that 10 minutes of exposure to a 15 kW gas burner constitutes a significantly more severe ignition source than the wood crib used in CEN/TS 1187 Test 2. However, previous large scale tests have demonstrated that the gas burner is capable of igniting the roofing membrane beneath a single PV module, corresponding to the burner position beneath PV1 shown in Figure 5 [20], [21], [22]. Yet, self sustained flame spread beyond the ignition source, propagating below all four modules, does not always occur, as observed when EUMEPS introduced a 12 mm thick cement fibre board between a single ply PVC based roofing membrane and the subjacent layer of EPS insulation [21]. The varying outcomes reported in previous large scale experiments therefore indicate that ignition by the 15 kW gas burner does not necessarily result in sustained flame propagation beyond the region directly exposed to the burner. The subsequent propagation is also dependent on the fire behaviour of the roof construction and the conditions created beneath the PV array. The 15 kW gas burner was therefore retained as the ignition source for all three large scale experiments

to provide a consistent and sufficiently severe initial exposure while allowing subsequent fire propagation beyond the burner region to be evaluated.

In all tests, the square shaped gas burner was placed at the midpoint of the width of the PV module width, referred to as PV1, as depicted in Figure 5. The horizontal distance from the burner's closest edge to the lower edge of the PV module was 120 mm.

4.3.4. Instrumentation

A total of 31 Type-K thermocouples were installed at three depths within the roof construction. Group 1 (TC1–TC13) was positioned immediately beneath the roof covering, Group 2 (TC14–TC26) between insulation layers 2 and 3, and Group 3 (TC27–TC31) between layers 3 and 4. The thermocouple locations are illustrated in Figure 6. Thermocouples TC1–TC9 were installed below the PV array to quantify heat transfer from the cavity toward the subjacent roof construction. The temperature development could therefore be also measured at a greater depth within the roof construction and compared with the thermal exposure measured immediately beneath the roof covering. Five additional thermocouples (Group 3, TC27–TC31) were installed vertically below TC2, TC4–TC6 and TC8 between layers 3 and 4.

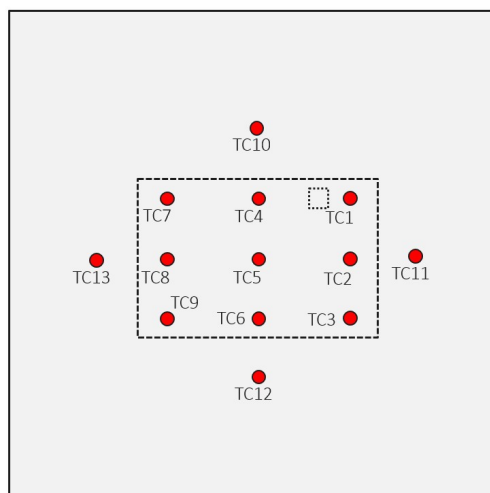


Figure 6 – Location of thermocouples TC1–TC13 immediately beneath the roof covering. Thermocouples TC14–TC22 were positioned directly below TC1–TC9 between layers 2 and 3. The dotted square indicates the location of the gas burner.

Based on the limited flame spread observed outside the PV array in previous large scale experiments [19], [20], [21], [22], four additional thermocouples (TC10–TC13) were positioned immediately beneath the roof covering outside the PV array to identify whether significant thermal exposure extended beyond the array.

All tests were recorded using multiple video cameras. The recordings served as a visual reference for the analysis of the tests and were not used for quantitative data processing. No external wind was applied during the large scale experiments. The tests were conducted indoors, and only the mechanical ventilation of the test hall was operated to extract smoke generated during the experiments. Consequently, the airflow conditions were not controlled as an experimental parameter, although limited air movement associated with the smoke extraction system may have been present.

4.4. Medium scale test: modified CEN/TS 1187 test 2

Building upon the work of Stølen et al. [40], a series of medium scale experiments were conducted using a modified CEN/TS 1187 Test 2 apparatus. As discussed in Section 4.1, the primary objective of the medium scale experimental campaign was to evaluate whether the modified configuration could reproduce the principal fire spread and thermal response characteristics observed during the large scale bituminous roof experiments, while retaining the simplicity and practicality of the standardised test procedure. To enable this comparison, the medium scale configuration incorporated the same two layer bituminous roof covering and upper mineral wool insulation used in the large scale bitumen experiments, while the presence of a PV module was represented by an inert calcium silicate board positioned above the roof specimen. The medium scale configuration remained a simplified representation of the large scale BAPV installation, particularly with respect to the upper boundary geometry, inclination and ignition source. Figure 7 highlights the modified test configuration.

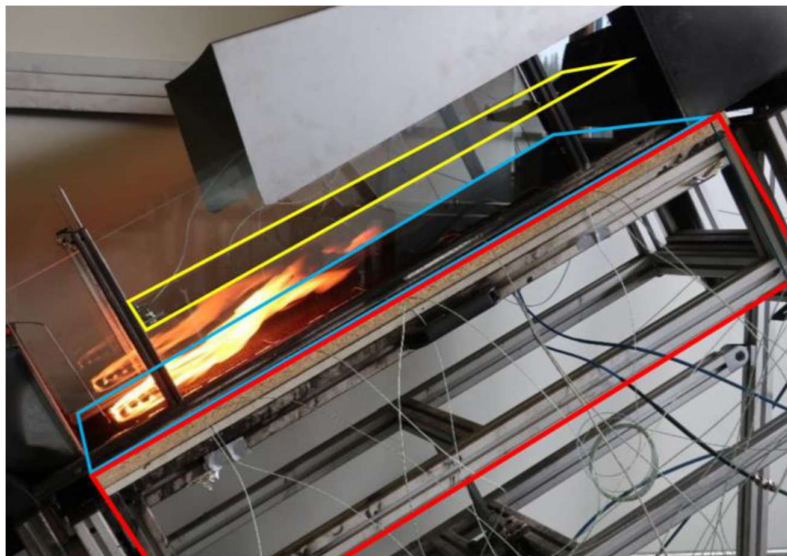


Figure 7 – Edited image from Stølen et al. [40]. Experimental set up of their modified CEN/TS 1187 Test 2. Yellow: A stainless-steel board used as a substitute for a PV module. Blue: Bitumen based roofing felt installed on 22 mm chipboard. Red: Volume below the sample surface which can accommodate insulation materials at a maximum depth of 150 mm.

The medium scale campaign focused on investigating the influence of cavity height and imposed airflow on flame spread beneath a simulated photovoltaic module and the resulting heat transfer into the roof construction.

4.4.1. Test specimen and apparatus

The medium scale test specimen was designed to represent the roof construction used in the large scale experiments while remaining compatible with the modified CEN/TS 1187 Test 2 apparatus [40]. A schematic illustration of the final experimental configuration is shown in Figure 8 and Table 3.

Table 3 – Overview of the layers in accordance with the sectional view in Figure 8.

Layer	Component	Product	Thickness	Mass
1	Calcium Silicate plate		9mm	
2	Adjustable steel frame	-	-	-
3	Upper bitumen layer	Katepal PF 5500 SBS	4.3 mm	5.5 kg/m ²
	Flame barrier	Katepal K-MS 170/4000 SBS	3.1 mm	4.0 kg/m ²
4	High density MW	Rockwool TF Plade	20 mm	3.5 kg/m ²
5	Lower density MW	Rockwool Dura Underlay	30 mm	13.5 kg/m ²

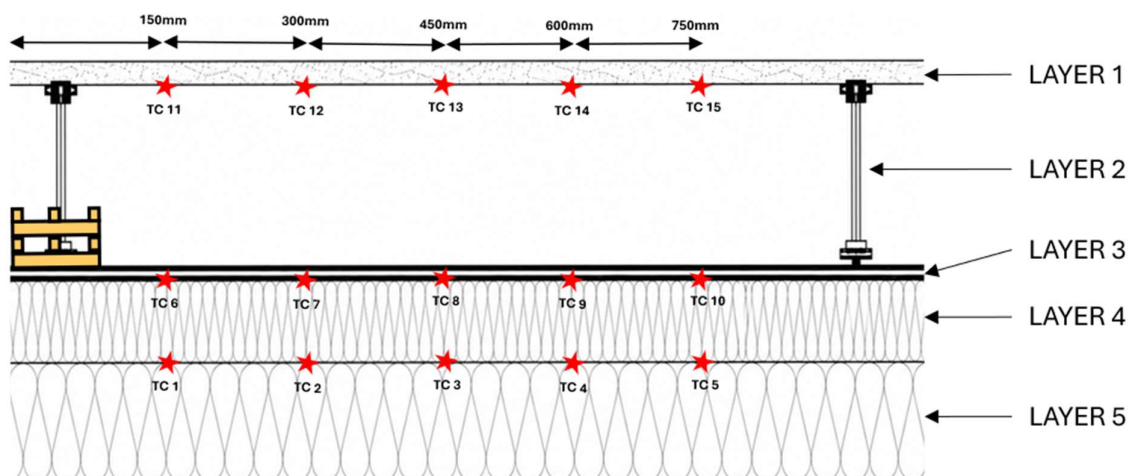


Figure 8 – Sectional view of the roof mock ups used for the medium scale tests. Layers from top to bottom in accordance with Table 3.

The roof build up consisted of a two layer bituminous roofing membrane installed above mineral wool insulation, corresponding to the roof assembly used in the first two large scale experiments. Maintaining an identical roof construction allowed direct comparison between the medium and large scale experiments without introducing additional variables associated with changes in material composition. Due to project limitations, the investigation of the PVC membrane system was not possible and is left to future investigations.

To simulate the presence of a roof mounted photovoltaic (PV) module, a rigid steel support frame was constructed to support a 9 mm calcium silicate board above the roof specimen. The calcium silicate board was selected as an inert substitute for a PV module, providing a non combustible surface while reproducing the geometric confinement created by an installed PV module. The support frame further allowed the cavity height between the roof surface and the underside of the calcium silicate board to be adjusted while maintaining a consistent geometry throughout the experimental campaign. In this setup, the simulated PV module was not subject to inclination and was installed parallel to the roof construction. The ignition source consisted of the standard wood crib specified in CEN/TS 1187 Test 2 [41] and was used without modification in all experiments.

Temperature measurements were obtained using fifteen Type-K thermocouples positioned throughout the test specimen, as illustrated with the red stars in Figure 8. Five thermocouples were drilled through the calcium silicate board to characterise the thermal environment within the cavity beneath the simulated PV module (Group 1). Five additional thermocouples were positioned beneath the bituminous roofing membrane to monitor the thermal exposure at the roof surface (Group 2), while the remaining five thermocouples were installed beneath the upper 20 mm insulation layer to quantify the heat transfer into the roof construction (Group 3).

4.4.2. Experimental programme

The experimental programme comprised twelve medium scale tests investigating the influence of cavity height and wind speed on the fire behaviour beneath the simulated PV module.

Two cavity heights, 60 mm and 90 mm, were selected. The chosen heights were based on previous experimental investigations performed by Stølen et al. [40], in which both cavity heights had been evaluated. Furthermore, the 90 mm cavity height corresponds to the ventilation clearance of approximately 80–100 mm recommended in the Danish guidance for photovoltaic installations [27] to ensure adequate ventilation beneath roof mounted PV modules. The 90 mm cavity height was therefore selected as a practically relevant configuration within the range specified in the Danish guidance [27], while the 60 mm cavity provided a smaller separation for investigating the sensitivity of the fire behaviour to cavity height.

For each cavity height, tests were performed at wind speeds of 0 m/s, 2 m/s and 4 m/s. These conditions were selected to investigate the sensitivity of the modified configuration to increasing airflow within the operational range of the test apparatus. The 0 m/s condition represented the absence of intentionally imposed airflow, whereas the 2 m/s and 4 m/s conditions provided progressively greater forced airflow exposure. Each test condition was repeated twice to provide an initial indication of the repeatability of the experimental configuration, resulting in six unique test configurations and a total of twelve experiments.

4.4.3 Test procedure

Prior to each experiment, a new roof specimen was prepared and installed in the test apparatus together with the calcium silicate board and supporting steel frame. The cavity height was adjusted to the desired test configuration before the instrumentation was connected and verified.

The wind speed was adjusted to the prescribed test condition. Once the desired wind conditions had stabilised, the wood crib was ignited and was positioned in accordance with the modified CEN/TS 1187 Test 2 configuration, after which the experiment commenced. Throughout each test, temperatures were continuously recorded from all thermocouples and visual observations were performed as the wood crib burned. Each experiment was conducted in accordance with the predefined test procedure, ensuring that only the cavity height and wind speed varied between individual tests.

5. RESULTS

5.1. Large scale tests

Three large scale experiments were conducted using the roof constructions described in Section 4.3. Tests 1 and 2 were performed with the bituminous roofing system, whereas Test 3 was conducted using the PVC roofing membrane. The measured temperature developments for the three experiments are presented in the following sections.

5.1.1. Test 1

The temperature development recorded during Test 1 is presented in Figure 9.

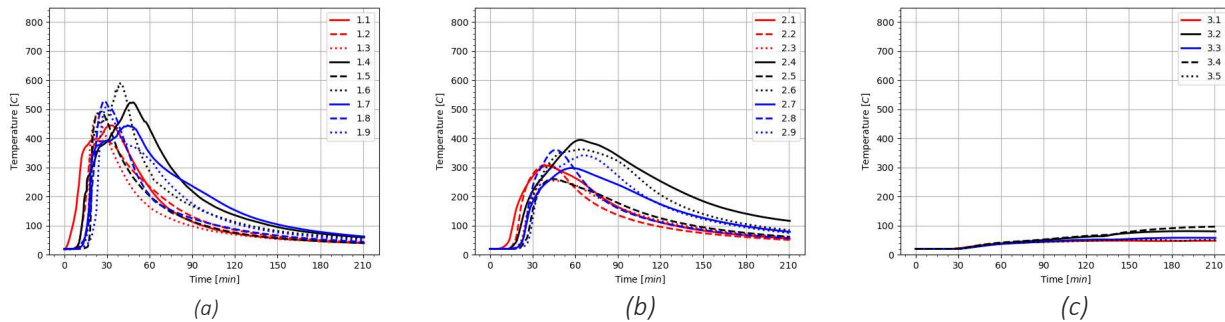


Figure 9 – Temperature measurements Test 1 (a) Group 1 (b) Group 2 (c) Group 3.

Immediately following ignition, a rapid increase in temperature was observed beneath the bitumen roof covering. Depending on the measurement location, peak temperatures of approximately 600 °C were reached after 40 minutes, after which the temperatures gradually decreased for the remainder of the experiment. Although differences in the peak temperatures were observed between the individual thermocouples, the overall temperature development was similar throughout measurement Group 1. The time delay between the peaking of each thermocouple corresponds with the flame front propagation seen during the tests, whereby initially the hottest areas correspond to the burner location subsequently moving to the other parts of the roof beneath the PV array.

A corresponding temperature development was measured in Group 2 beneath the upper mineral wool insulation layer, peaking around 400 °C between 30 to 60 minutes after ignition. Compared with the measurements beneath the roof covering, both the peak temperatures and the rate of temperature increase were lower and occurred later than the corresponding temperature increases in Group 1. At the deepest measurement level, beneath the 100 mm mineral wool insulation layer, considerably lower temperatures were recorded. Following an initial period close to ambient temperature, the temperatures increased gradually throughout the experiment. The highest recorded temperature was approximately 97 °C, while the remaining measurement locations remained below approximately 81 °C.

5.1.2. Test 2

The measured temperature development during Test 2 is presented in Figure 10. Overall, the temperature development followed the same general pattern observed during Test 1, with the highest temperatures recorded immediately beneath the roof covering and progressively lower temperatures measured with increasing depth within the roof construction.

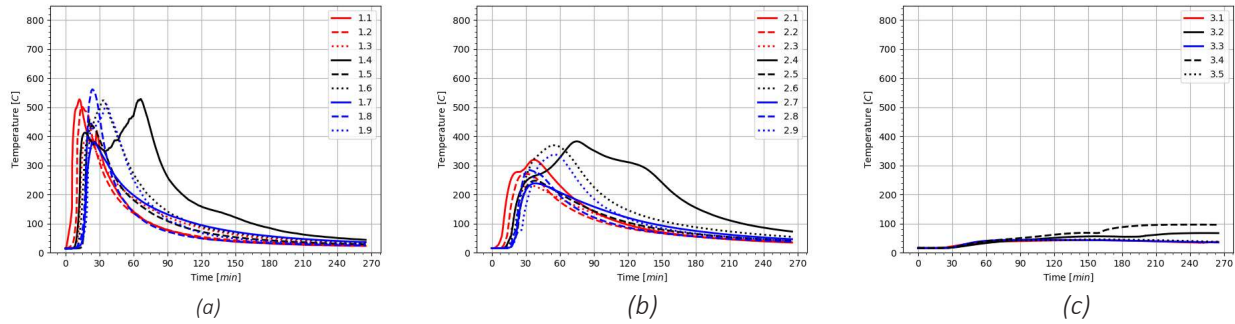


Figure 10 – Temperature measurements Test 2 (a) Group 1 (b) Group 2 (c) Group 3.

Following ignition, a rapid increase in temperature was first recorded by the thermocouples located closest to the ignition source beneath the roof covering. As the experiment progressed, elevated temperatures were successively recorded by the remaining thermocouples, illustrating the movement of the flame front across the roof specimen. This progression is reflected in the increasing delay between the individual temperature peaks, with maximum temperatures ranging from approximately 520 °C to 560 °C and occurring between 10 and 60 minutes after ignition.

A similar sequential temperature development was observed beneath the upper mineral wool insulation layer. Compared with the measurements immediately beneath the roof covering, the temperature increase occurred later and the peak temperatures were lower, ranging from approximately 320 °C to 380 °C. Beneath the 100 mm mineral wool insulation layer, the temperature response remained considerably lower than that recorded at the upper levels of the roof construction. Most thermocouples exhibited only a gradual increase throughout the experiment and remained below 60 °C. However, TCs 3.2 and 3.4 continued to increase during the latter stages of the test and reached temperatures of approximately 67 °C and 96 °C, respectively. As in Test 1, no distinct temperature peak was observed at this depth within the duration of the experiment.

5.1.3. Test 3

The temperature development recorded during Test 3 is shown in Figure 11.

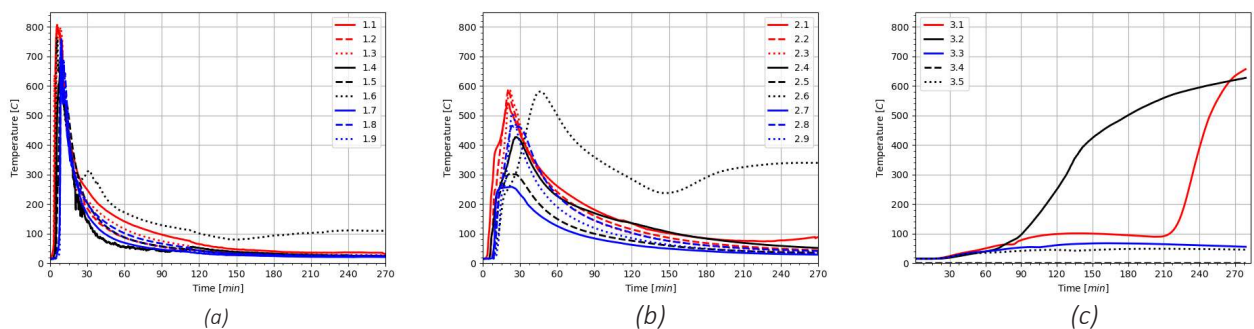


Figure 11 – Temperature measurements Test 3 (a) Group 1 (b) Group 2 (c) Group 3.

Compared with the two bituminous roof tests, a considerably more rapid temperature development and higher initial peak temperatures were measured immediately beneath the PVC roof covering. Following ignition, the temperatures beneath the PVC membrane increased rapidly and reached peak values between approximately 760 °C and 810 °C within the first 5–10 minutes. After the initial peak, the temperatures decreased rapidly before continuing to decline more gradually. Beneath the upper mineral wool insulation layer, peak temperatures between approximately 400 °C and 590 °C were recorded within the first hour of

testing. Most thermocouples subsequently exhibited a gradual reduction in temperature. However, TC 2.6 remained at elevated temperatures throughout the experiment and reached approximately 340 °C towards the end of the test. Compared with Tests 1 and 2, the temperature increase within this layer occurred more rapidly and reached higher temperatures, consistent with the more rapid transfer of thermal exposure through the PVC roof covering.

A different temperature development was observed beneath the 100 mm mineral wool insulation layer. During the initial stage of the experiment, all thermocouples remained close to ambient temperature. Subsequently, TCs 3.1 and 3.2 exhibited pronounced temperature increases, reaching approximately 630–660 °C near the end of the experiment, while the remaining measurement positions remained considerably lower. The pronounced late temperature increase was localised to these two measurement positions, which were located in the region corresponding to the ignition source.

The considerably greater temperatures measured at this depth distinguish Test 3 from the two bituminous roof tests, where only limited temperature increases were recorded beneath the 100 mm mineral wool layer. However, the high temperatures recorded towards the end of the experiment cannot necessarily be attributed solely to heat conduction through an intact PVC membrane. Local deformation, degradation or displacement of the roof covering during prolonged fire exposure may also have influenced the thermal exposure of the underlying layers.

Evaluation of the fire spread outside the PV array footprint can be evaluated through the TCs 10-13 of Group 1 in each construction. The temperature development recorded by the Group 1 thermocouples positioned outside the PV array is presented in Figure 12 for all three large scale tests. A pronounced difference was observed between the PVC and bituminous roof constructions. During Test 3, TCs 10 and 11 in Figure 12(c), located outside the PV array on the side corresponding to the burner location, reached peak temperatures of approximately 690 °C. In comparison, the corresponding thermocouples in Tests 1 and 2 showed considerably smaller temperature increases, with peak values generally remaining below approximately 140 °C. The measurements therefore indicate that significant thermal exposure during the PVC test was not restricted to the area directly beneath the PV array but also extended to parts of the surrounding construction, particularly on the sides adjacent to the ignition source beneath PV1. This observation was consistent with the video recordings [45], in which flaming was observed outside the array in the same region.

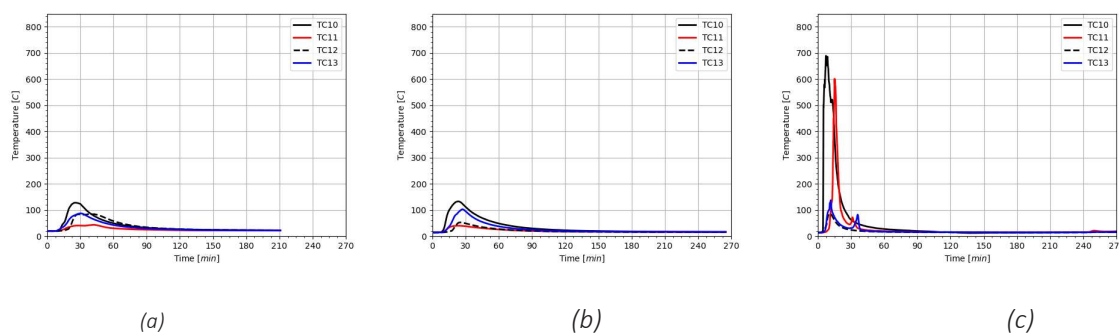


Figure 12 – Temperature measurements outside the PV array in TC Group 1 (a) Test 1 (b) Test 2 (c) Test 3.

5.1.4. Summary of the large scale tests

The temperature measurements obtained during the first two large scale experiments demonstrate a progressive reduction in measured temperatures with increasing depth within the roof construction for the two bituminous roof tests. In both experiments, the highest temperatures were recorded immediately

beneath the roof covering, followed by a delayed and reduced temperature response beneath the upper mineral wool insulation layer. Beneath the 100 mm mineral wool layer, only limited temperature increases were recorded. The sequential response between the individual thermocouple groups corresponded with the visually observed progression of the flame front beneath the PV array and showed a delayed thermal response with increasing depth within the roof construction.

The temperature development recorded during the PVC roof test differed considerably from that observed in the bituminous roof tests. The temperatures immediately beneath the roof covering increased more rapidly and reached higher values during the initial stage of the experiment. A correspondingly stronger temperature response was subsequently measured beneath the upper insulation layer, while pronounced late temperature increases were recorded at two locations beneath the 100 mm mineral wool insulation layer.

A further difference was observed at the measurement locations positioned outside the PV array. During Test 3, temperatures of approximately 690 °C were recorded beneath the PVC membrane on the side adjacent to the ignition source, whereas the corresponding locations during Tests 1 and 2 exhibited only limited temperature increases, generally remaining below approximately 140 °C. Flaming outside the PV array was also observed in the video recordings in the same region. The combined temperature measurements and visual observations therefore show that the fire exposure during the PVC test was not restricted to the area directly beneath the PV array.

Overall, Tests 1 and 2 showed similar temperature development for the repeated bituminous roof configuration, with progressive thermal exposure beneath the PV array and limited temperature increases at the deepest measurement level. Test 3 exhibited a different response, characterised by a more rapid initial temperature increase, higher temperatures within the roof construction, and local fire exposure extending beyond the PV array on the side adjacent to the ignition source.

5.2. Medium scale tests

The large scale experiments presented in Section 5.1 provided the reference fire behaviour for the investigated roof constructions. Based on these observations, a series of medium scale experiments were conducted using the modified $B_{\text{ROOF}}(t_2)$ test setup described in Section 4.4. The objective was to investigate whether the modified configuration reproduced the principal fire spread and thermal response characteristics observed during the large scale bituminous roof experiments, while evaluating the influence of cavity height and wind speed. Temperature measurements were obtained for each test configuration, and the resulting flame spread across the roof surface was recorded. The measured temperature development and flame spread are presented in the following sections.

5.2.1. Temperature Development

60 mm cavity

The average temperature development measured during the medium scale experiments with a cavity height of 60 mm is presented in Figures 13–15. Each curve represents the average of the two repeated tests performed at the corresponding wind speed. In accordance with the test configuration described in Section 4.4, the measurements are presented from left to right for the thermocouples positioned beneath the calcium silicate board, beneath the bituminous roofing membrane, and beneath the upper 20 mm mineral wool insulation layer respectively.

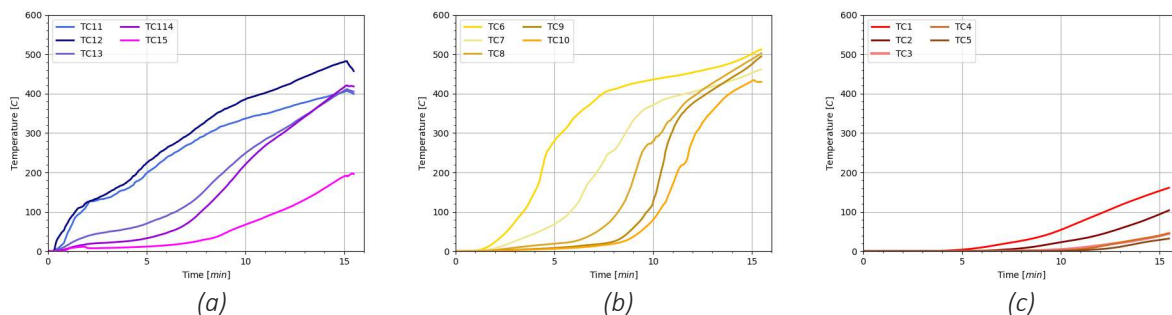


Figure 13 – Temperature measurements 60mm tests at 0m/s (a) Group 1 (b) Group 2 (c) Group 3.

For the tests conducted without applied wind, temperatures above 500 °C were recorded both beneath the calcium silicate board and beneath the roofing membrane. The temperature increase occurred successively across the individual measurement locations, corresponding to the progression of the flame front along the specimen. Beneath the 20 mm mineral wool layer, the temperature response was delayed and considerably lower, with a maximum temperature of approximately 180 °C.

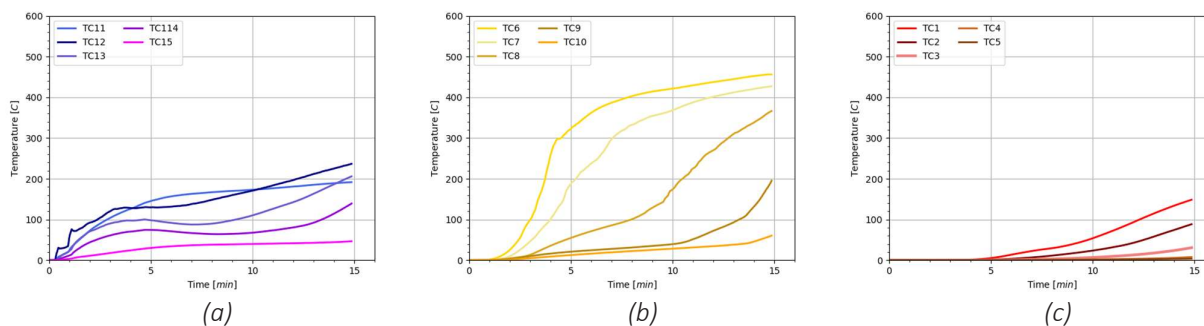


Figure 14 – Temperature measurements 60mm tests at 2m/s (a) Group 1 (b) Group 2 (c) Group 3.

At a wind speed of 2 m/s, the highest temperatures were measured beneath the bituminous roofing membrane, where several thermocouples reached approximately 400–460 °C. The temperatures recorded beneath the calcium silicate board were lower and generally remained below approximately 250 °C. Only limited temperature increases were measured beneath the 20 mm mineral wool layer, with the highest value reaching approximately 150 °C near the end of the test.

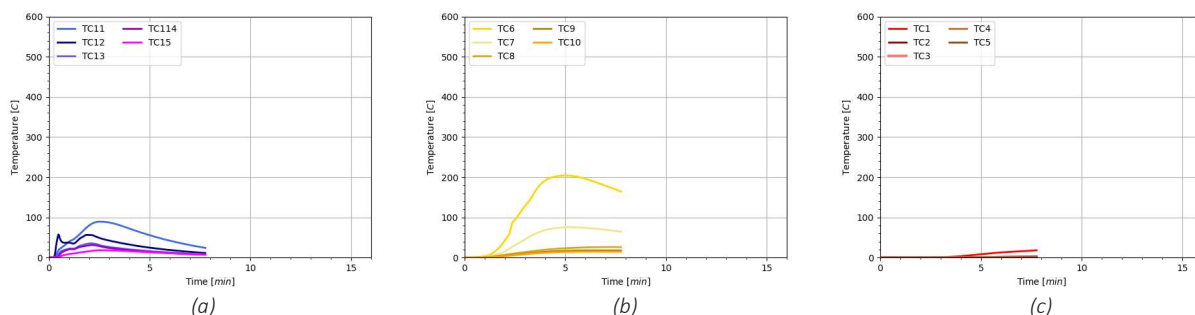


Figure 15 – Temperature measurements 60mm tests at 4m/s (a) Group 1 (b) Group 2 (c) Group 3.

The temperature development at 4 m/s was considerably lower than for the two other wind conditions. Beneath the calcium silicate board, the highest measured temperature was below 100 °C, while the maximum

temperature beneath the roofing membrane was approximately 200 °C. The thermocouples below the 20 mm mineral wool layer remained close to ambient temperature throughout most of the test, increasing marginally only before termination.

The results therefore show that the relationship between the temperatures measured beneath the calcium silicate board and beneath the roofing membrane changed with wind speed. At 0 m/s, comparable maximum temperatures were recorded at the two upper measurement levels, whereas the temperatures beneath the roofing membrane exceeded those measured beneath the calcium silicate board at 2 m/s and 4 m/s. Similar to the large scale tests, successive temperature increases were recorded along the thermocouple positions, while the temperature response beneath the mineral wool remained delayed and lower.

90 mm cavity

The average temperature development measured during the medium scale experiments with a cavity height of 90 mm is presented in Figures 16–18. Overall, the temperature development followed the same general pattern as observed for the 60 mm cavity, with the highest temperatures recorded beneath the bituminous roofing membrane and progressively lower temperatures measured beneath the calcium silicate board and the upper 20 mm mineral wool insulation layer. However, lower temperatures were recorded at several measurement locations for the 90 mm cavity compared with the corresponding 60 mm configuration, particularly beneath the calcium silicate board.

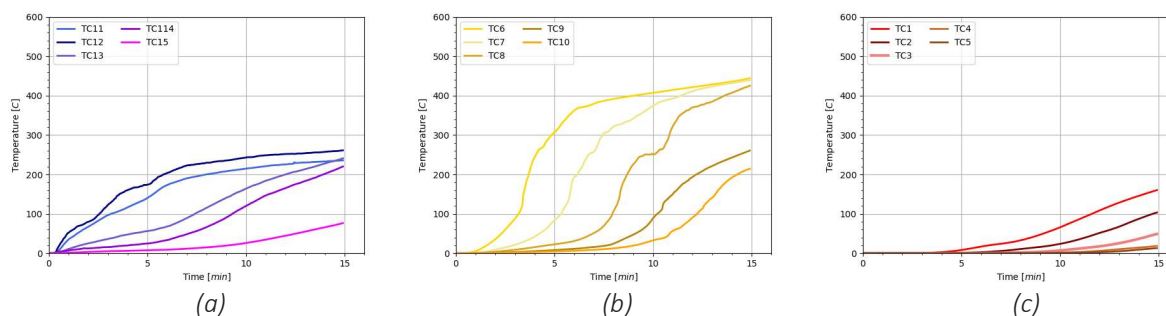


Figure 16 – Temperature measurements 90mm tests at 0m/s (a) Group 1 (b) Group 2 (c) Group 3.

For the tests conducted at 0 m/s, the temperatures beneath the roofing membrane reached approximately 430–450 °C, comparable to those measured for the 60 mm cavity. In contrast, the temperatures beneath the calcium silicate board were considerably lower, with maximum values below approximately 260 °C, while the temperatures beneath the upper insulation layer remained below approximately 160 °C. As for the 60 mm configuration, successive temperature increases were recorded along the thermocouple positions in the same direction as the visually observed flame front progression.

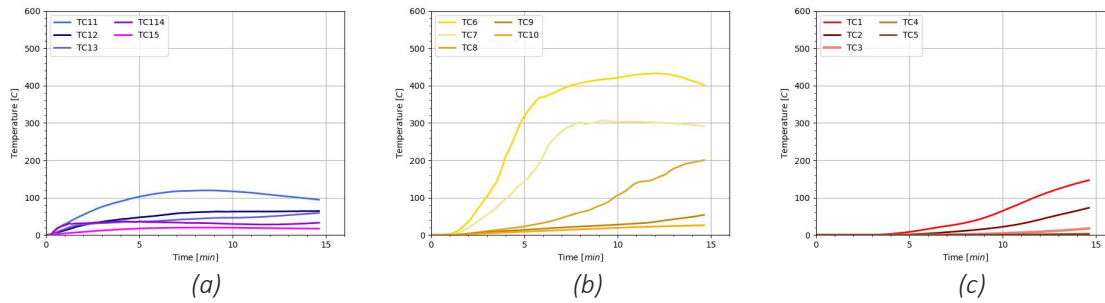


Figure 17 – Temperature measurements 90mm tests at 2m/s (a) Group 1 (b) Group 2 (c) Group 3.

Compared with the 60 mm cavity, lower temperatures were recorded beneath the calcium silicate board for the 90 mm cavity, particularly at the higher imposed airflow velocities. At 2 m/s, the temperature increase beneath the calcium silicate board was lower for the 90 mm cavity than for the corresponding 60 mm configuration.

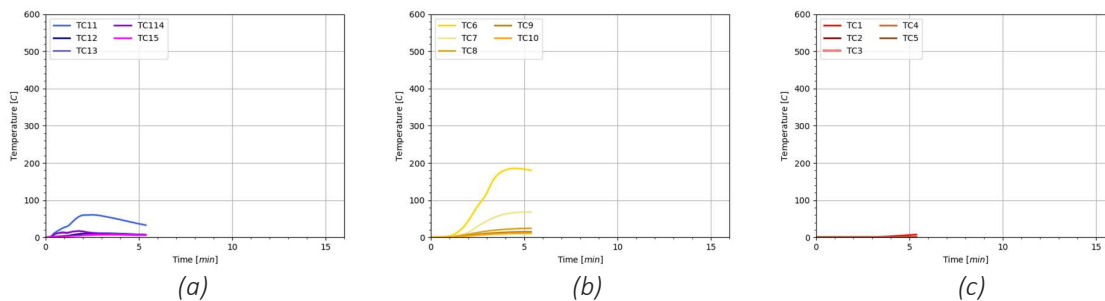


Figure 18 – Temperature measurements 90mm tests at 4m/s (a) Group 1 (b) Group 2 (c) Group 3.

Elevated temperatures were still recorded beneath the bituminous roofing membrane at both 2 m/s and 4 m/s, with peak temperatures remaining comparable to those measured for the corresponding 60 mm cavity configurations.

5.2.2. Flame spread

Following each medium scale experiment, the burnout length of the roofing membrane was measured in accordance with the modified $B_{ROOF}(t_2)$ procedure described in Section 4.4. The reported burnout lengths represent the average of the two repeated experiments performed for each test configuration. According to the acceptance criterion adopted for the modified test method, a burnout length of 550 mm or less

constitutes a passing result [41]. Representative specimens following the tests with cavity heights of 60 mm and 90 mm are presented in Figure 19.

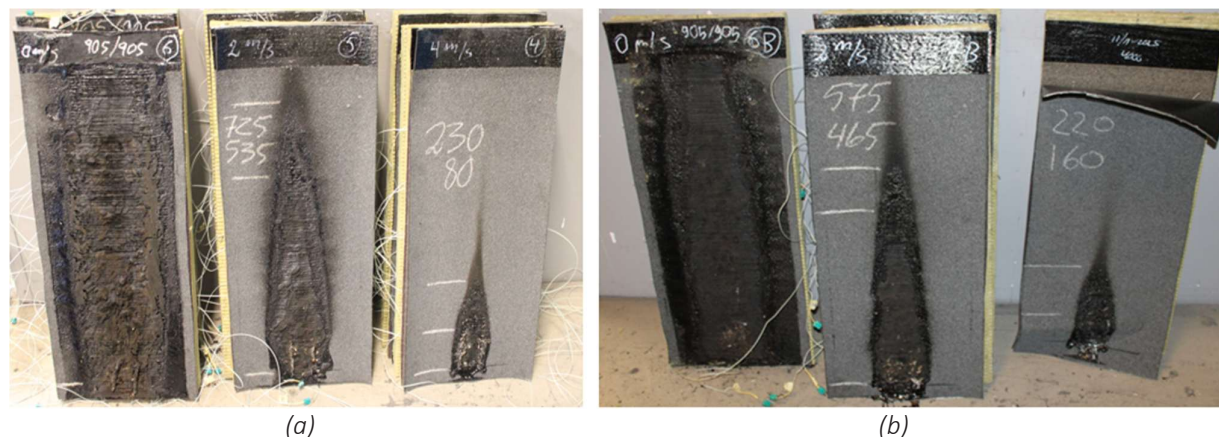


Figure 19 – Flame extensions from tests with 60mm cavity (a) and 90mm cavity (b).

For both cavity heights, the extent of the damaged area decreased with increasing wind speed. At 0 m/s, the burnout extended along a large proportion of the specimen, whereas the damaged area became progressively smaller at 2 m/s and 4 m/s.

The average burnout lengths are summarised in Table 4.

Cavity Height [mm]	Wind Speed [m/s]		
	0	2	4
	Avg. Flame Extension [mm]		
60	905	757,5	257,5
90	730	460	160

Table 4 – Medium scale test results relating to flame extension and pass/fail criteria at different wind speeds.

5.2.3. Summary of the medium scale tests

For both cavity heights, the temperature measurements showed a successive increase in temperature along the thermocouple locations as the flame front propagated beneath the simulated PV module. The highest temperatures were generally recorded beneath the bituminous roofing membrane, whereas lower temperatures were measured beneath the calcium silicate board and within the upper mineral wool insulation layer. The measured burnout lengths decreased with increasing wind speed for both cavity heights. The 60 mm cavity satisfied the acceptance criterion only at 4 m/s, whereas the 90 mm cavity satisfied the criterion at both 2 m/s and 4 m/s: these are shown in green in Table 4. Across the investigated conditions, the 90 mm cavity also produced shorter average burnout lengths than the corresponding 60 mm cavity configurations.

6. DISCUSSION

The SOL-IGNIS project investigated whether a modified CEN/TS 1187 Test 2 configuration could reproduce the principal fire spread and thermal response characteristics observed in large scale BAPV roof experiments. The comparison between the two scales is qualitative, since the configurations differ in specimen dimensions, upper boundary geometry, inclination, ignition source and airflow conditions.

6.1. Large and medium scale experiment correspondence

Progressive flame spread beneath the upper boundary was observed in both the large scale bituminous roof experiments and the medium scale experiments. In the large scale tests, the fire propagated beneath the PV array, while in the medium scale configuration it propagated beneath the calcium silicate board. In both cases, successive temperature increases were recorded along the roof surface as the flame front progressed, followed by a delayed thermal response deeper within the roof construction.

The 0 m/s medium scale configuration provides the closest nominal comparison with the large scale experiments, where no external wind was intentionally applied. Sustained flame spread occurred in the bituminous roof construction at both scales. In the medium scale experiments, average burnout lengths of 905 mm and 730 mm were measured for the 60 mm and 90 mm cavities, respectively. The significance of this comparison is not the absolute burnout distance, but that progressive flame spread developed under the condition most closely corresponding to the large scale experiments. The experiments at 2 m/s and 4 m/s should therefore primarily be considered as a controlled parameter study rather than as direct reproductions of the large scale exposure.

The principal observations and limitations of the cross scale comparison are summarised in Table 4.

Parameter	Large Scale Tests	Modified B _{ROOF} (t ₂) Tests	Comparison
Flame spread	Progressive flame spread beneath the PV array in the bituminous tests. Local fire exposure also extended outside the array during the PVC test.	Progressive flame spread beneath the calcium silicate board for several configurations.	Qualitatively similar progression beneath the upper boundary for the bituminous system.
Temperature progression	Successive temperature increases beneath the roof covering followed by delayed response at greater depth.	Successive temperature increases beneath the roofing system followed by delayed response beneath the upper mineral wool layer.	Similar correspondence in thermal response.
Airflow	No controlled external wind applied.	0, 2 and 4 m/s imposed wind speeds.	Only the 0 m/s configuration provides a nominal cross scale comparison.
Bituminous roof system	Investigated in two repeated large scale experiments.	Investigated in all medium scale experiments.	Direct qualitative comparison possible.
PVC roof system	Investigated in one large scale experiment.	Not investigated.	No cross scale comparison possible.
PV representation	Four inclined commercial PV modules in an East/West arrangement.	Horizontal calcium silicate board.	Different upper boundary geometry and material properties.

Table 4 – Principal observations and limitations in the comparison between the large and medium scale experimental configurations.

6.2. Influence of cavity height and imposed airflow

The medium scale experiments showed that both cavity height and imposed airflow affected the burnout length and temperature development. For the 60 mm cavity, the average burnout length decreased from 905 mm at 0 m/s to 757.5 mm at 2 m/s and 257.5 mm at 4 m/s. For the 90 mm cavity, the corresponding values were 730 mm, 460 mm and 160 mm. At each airflow condition, the 90 mm cavity produced a shorter burnout length than the corresponding 60 mm configuration.

The temperature measurements were consistent with the visual observations of the flame geometry. With increasing imposed airflow, the flame front became more inclined, reducing the radiative feedback provided by the calcium silicate board towards the roof surface. This resulted in reduced heating of the roofing membrane, reduced flame propagation and lower temperatures along the length and through the depth of the construction. The results therefore indicate that cavity height and imposed airflow should not be considered independently when developing a modified test configuration. Their combined influence can substantially change the outcome for the same roof construction.

6.3. Effect of the roof membrane materials

The large scale PVC experiment produced a substantially different thermal response from the two bituminous experiments. The PVC membrane showed a more rapid initial temperature increase, higher temperatures deeper within the construction and local fire exposure outside the PV array on the side adjacent to the ignition source.

This response is consistent with the lower thermal mass of the PVC membrane [38], [46]. The two layer bituminous roofing system had a combined thickness of approximately 7.4 mm and a higher specific heat capacity than the PVC membrane. The thicker bituminous system therefore has a greater capacity to absorb thermal energy before a corresponding temperature increase develops beneath the roof covering. The difference was also observed outside the PV array, where temperatures of approximately 690 °C were measured during the PVC experiment compared with values generally below approximately 140 °C in the two bituminous experiments. Flaming was also observed outside the array in the same region.

At the deepest measurement level, the bituminous tests remained below approximately 100 °C, whereas temperatures of approximately 630–660 °C were recorded at two locations during the PVC experiment. These high local temperatures cannot necessarily be attributed solely to conductive heat transfer through an intact PVC membrane, as local deformation, degradation or displacement of the roof covering may also have influenced the exposure. Only one large scale PVC experiment was performed, and PVC was not investigated in the medium scale programme. Further large scale testing is therefore required to verify the repeatability of the PVC response before corresponding medium scale comparisons are made.

6.4. Limitations and further work

The two repeated large scale bituminous experiments showed similar overall fire development and temperature progression, while each medium scale configuration was tested twice. These repetitions provide an initial indication of repeatability, but are not sufficient to establish statistical repeatability or reproducibility of the method.

The medium scale configuration also differs from the large scale setup in several important respects. The calcium silicate board is horizontal and inert, whereas the large scale configuration used inclined commercial PV modules. The ignition sources and airflow boundary conditions also differ. The calcium silicate board should therefore be regarded as a simplified representation of the upper boundary created by a PV module rather than as a direct thermal representation of the module itself. The present results support continued development of the modified CEN/TS 1187 Test 2 concept as a screening approach. However, they do not establish a validated test configuration or classification procedure. Further work should include additional large scale PVC tests, corresponding medium scale tests with other roof coverings, additional repetitions, and subsequent investigation of roof constructions incorporating combustible insulation materials.

7. CONCLUSION

The results of the SOL-IGNIS project confirm that the presence and geometry of a BAPV installation can substantially influence fire development on flat roof constructions. The cavity formed beneath the PV modules can support sustained flame propagation and increase the thermal exposure of the underlying roof construction. Large scale experiments further showed that the response depends on the roof build up, with the PVC configuration exhibiting a considerably faster and more severe thermal response than the bituminous configuration.

The modified CEN/TS 1187 Test 2 experiments reproduced the principal qualitative fire behaviour observed in the large scale bituminous experiments, including progressive flame spread beneath the upper boundary and a delayed thermal response through the roof construction. The results also demonstrated that cavity height and imposed airflow significantly affected flame propagation and burnout length, highlighting the importance of these parameters when representing BAPV fire conditions in a reduced scale test.

Overall, the modified configuration provides a useful basis for further development of a screening method for roof constructions used beneath BAPV systems. However, the present study does not establish a validated test or classification procedure. Further large scale testing is required to verify the repeatability of the PVC response, followed by investigations of additional roof constructions, including systems with combustible insulation materials, and corresponding medium scale testing.

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