SAFETY & TRANSPORT
FIRE TECHNOLOGY

Exposure from mass timber compartment fires to facades

Johan Sjöström, Daniel Brandon, Alastair Temple, Emil Hallberg, and Fredrik Kahl

RISE Report 2021:39

ISBN: 978-91-89385-24-5

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Abstract

Exposure from compartment fires to facades

Different countries world-wide have different legislation concerning the performance of facades exposed to fire and often significantly different ways to assess this performance.

Although it is recognized that standard façade fire testing aims to distinguish façade systems that limit fire spread to an acceptable level from systems that do not, it has historically been considered important that the fire exposure of such tests is representative for real fires.

In this study five real scale compartment fire tests, constructed of Cross Laminated Timber and Glued laminated timber were performed with instrumentation on a façade extension above the ventilation openings, providing a means to compare façade performance tests against the exposure generated by realistic compartment fires. The fuel load and openings of four of these tests were determined from a statistical analysis to represent severe fire exposure within a realistic range. Of these tests the surface areas of exposed Cross Laminated Timber and Glued Laminated Timber were varied, allowing an assessment of the influence having internal areas of exposed timber surfaces on the façade fire exposure.

For these tests, an increase of roughly 40 m^2 exposed surface area (from ~54 to ~94 m^2 or from 113 % to 196 % of the floor area) resulted in a temperature increase of roughly 100 to 130 °C at the façade at all heights up to 3.5 m above the opening. Additionally, an increased fire plume height of 0 to 1 m was observed. The most significant effect of increased exposed areas was a prolonged duration of the flashover phase.

The British BS 8414 standard façade fire tests and the recently proposed European façade fire test have been identified to be the most representative for the tested residential fire scenarios in terms of façade fire exposure. Temperature measurements of the North American methods (NFPA 285 and CAN/ULC-S134) are towards the end of the tests also close to the those of the compartment tests. The Swedish SP Fire 105 test imposes the lowest exposure for a relatively short duration to the façade. It should, however, be noted that a lower exposure in the standard test method does not with necessity mean lower threshold for regulatory compliance as the test criteria also differ between different countries.

One of the tests were characteristic of open plan office buildings and it was shown that the fire exposure is both shorter and lower compared to typical residential compartment tests. All standard tests that were used for comparison here exhibited both longer and higher exposure than the office building compartment test.

Key words: Mass Timber, CLT, Fire, Compartment fire, Glued laminated timber, façade, test

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Content

Preface

Fires spreading on or in the external façades between floors constitute a major problem, especially for high-rise buildings. There is a lack of data concerning fire exposure to façades from which we can learn to assess façade systems. Since full-scale experiments are expensive and time consuming the opportunity to add additional measurements and observations to already funded fire tests is a cost-efficient way to extract data which would have been difficult to fund in an isolated project. The research discussed in this report is the result of such addition of measurements of exposure to an external façade, funded by Brandforsk, to an ongoing experimental series of mass timber compartment tests, funded primarily by a grant from the United States Department of Agriculture.

Thus, this report presents the work done to collect, assess and compare the data of thermal exposure to façades from external fire plumes in compartment tests corresponding to severe but realistic scenarios for multi-storey mass timber buildings.

This Project (discussed in this report)

Project name: Exposure of modern compartment fires to façades

Project funder: Brandforsk (Swedish Fire Research Foundation)

Main objective: Collect experimental data of façade fire exposures for comparisons to standard assessment methods

Reference group members:

- Mattias Delin (Brandforsk, Sweden)
- Birgitte Messerschmidt (National Fire Protection Association, USA)
- Ulf Wickström (Sweden)
- Robert Jansson McNamee (Brandskyddslaget, Sweden)
- Leif Andersson (Sweden)
- Mats Björs (Swedisol, Sweden)
- Robert Jönsson (Sweco Sweden)
- Karlis Livkiss (DBI, Denmark)
- Jason Smart and Kuma Sumathipala (American Wood Council, USA)

The financial support from Brandforsk is acknowledged as are the comments to the work and the report by members of the reference group and the service from the training site of Södra Älvsborgs Räddningstjänstförbund (Guttasjön). The report and more information can be found at the Brandforsk website: https://www.brandforsk.se/

NOTE: The compartment design, testing and assessment is part of a separate project, with separate funders and partners and a separate reference group. Only the data relevant for the façade exposure is discussed in this report.

Parallel project (not this report)

Project name: Fire Safe Implementation of mass timber in tall buildings

Main project funder: United States Forest Service (USFS) - United States Department of Agriculture

Main objective: Design and execute five compartment fire test involving mass timber compartments with variable exposed surface areas of timber.

1 Background

Façade fire spread has led to a significant share of high-consequence fires in modern multi-storey buildings. Spread through and on the façade of multi-storey buildings shortcuts the compartmentation of fire cells which is usually ensured by the fire resistance framework of building codes. façade fire spread involves multiple issues, as it can enable many floors to be active in the fire simultaneously, it can impede egress and constitute major challenges for suppression. These issues are of greater concern for tall buildings and in recent years, a number of incidents have drawn much attention. These include the 2015 Baku dwelling fire (BBC, 2015), Azerbaijan (19 fatalities), the 2016 Neo-Soho project in Jakarta (Petrus, 2015), the 2017 Jecheon fire in South Korea (29 fatalities) (NPR, 2017), the Torch Tower fire Dubai (twice) (BBC, 2017) and the infamous 2017 Grenfell Tower fire in London (71 fatalities) (Potton et al, 2017).

The performance of façade systems in the event of a fire is usually evaluated by either evaluating the combustibility of the materials in the system or by exposing the system to a standardized full-scale façade fire test. Many different test methods exist all over the world, such as the NFPA 285 (USA), CAN/ULC-S134 (Canada), ISO 13785-2 and even within the European Union several different methods (such as SP Fire 105 in Sweden and Lepir II in France) and assessment criteria exist (Smolka et al, 2013; Boström et al, 2018). However, very few comparative studies, or studies assessing the representativeness of exposures have been performed.

Recent developments resulting from *i.a.* architectural trends and an increased focus on sustainability of the built environment have led to a growth of implementation of bio-based materials as façade materials or the structural material. The invention of mass timber products such as glued laminated timber and cross-laminated timber, made it possible to realize tall buildings with timber as the main structural material. Having visible wood is commonly desired and increasingly often implemented in these buildings, which requires consideration of additional fire safety challenges such as a potential impact on façade exposure. Research indicates that the presence of exposed combustible structural members within compartments could increase the fire exposure on the external façade in case of fire (Frangi et al. 2005). Increased surface areas of exposed timber surfaces can contribute to the external fire exposure with additional pyrolysis products which, in a ventilation-controlled fire cannot burn until they mix with the oxygen outside of the compartment. However, it is not known to which extent this has an influence in real scenarios. Knowledge of this would help to ensure safety and would also shine light upon the representativeness of the standard assessment test methods for fire safety of façade systems.

In this report we utilize an ongoing project including a series of full-scale mass timber compartment tests. As an add-on to that project, we assess the thermal impact to an inert external façade above the openings of the fire tests. Thus, this is an assessment of the fire exposure to a façade from several scenarios which are deemed realistic but severe for both dwellings and office buildings.

1.1 Compartment fire tests

The size and exposure of externally venting flames from compartment fires to building facades have been experimentally studied by a number of researchers (Yokoi, 1960; Seigel, 1969; Thomas and Law, 1972; Klopovic and Turan, 1998; 2001; Hasemi, 1984; Tang et al, 2012). The size of the fire plume has often been correlated to the width of the compartment openings and the combustion rate or heat release rate of an enclosure fire as proposed by for example Law (1978).

1.1.1 The influence of wind

The most significant series of experiments that studied the influence of wind on façade exposure is performed by Bechtold et al. (1978), where an old 4-storey building was used for multiple fire tests under natural wind velocities varying from 1 m/s to significantly over 10 m/s, with varying wind directions. The different wind scenarios in combination with differences of the compartment designs (balconies and positions of windows) lead to vastly different shapes of the fire plumes.

For compartments with openings on one side with wind directed perpendicular to the façade Hu et al. (2017) and Zhao (2017) found, in line with Bechtold's observations, through CFD modeling that the height of external flaming reduces as the wind increases (while the neutral plane lowers and the flames spread wider on either side of the opening). Both these studies indicate a lower fie plume due to hindered outflow of unburned combustibles for winds perpendicular to the opening and due to the plume being smeared out sideways for a parallel wind direction.

Experimental studies of compartment tests exposed to velocity-controlled external wind were published by Ren et al (2018). They performed small-scale compartment fire tests in airflows controlled using a wind tunnel. It was shown that both the maximum recorded temperatures and the height of elevated temperatures decreased with increasing wind velocity (0 to 2 m/s).

Tests by Anderson et al. (2017) demonstrated effects that wind can have on fire plumes of compartments with openings on one side. Brandon and Anderson (2018) compared temperatures at a height of 2.5 m above the opening with temperatures of indoor fire tests and concluded significantly lower temperatures occurred at this height because of wind in both tests. In both tests the fire plumes changed size significantly, during wind gusts. Figure 1 was presented by Brandon and Anderson to indicate how rapidly the fire plume can change size in conditions with regular wind gusts.

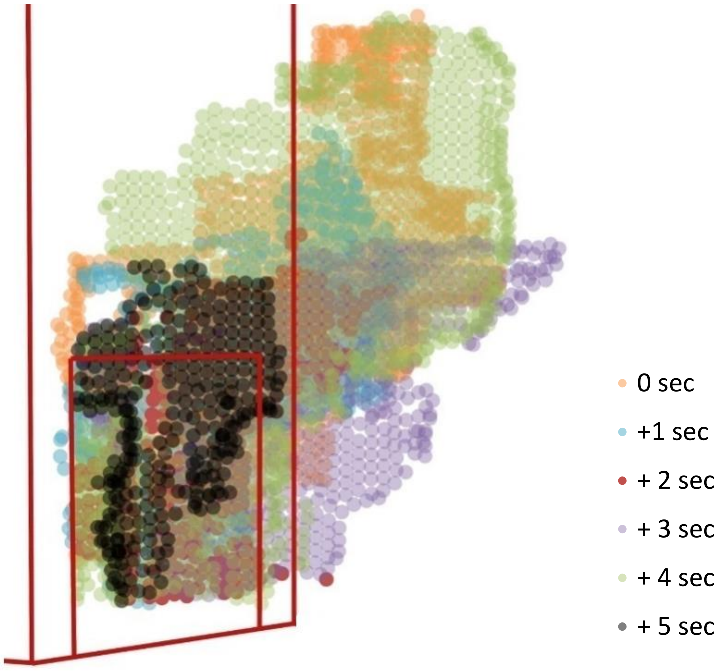


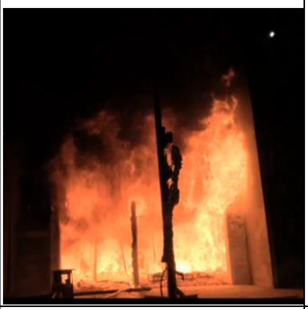
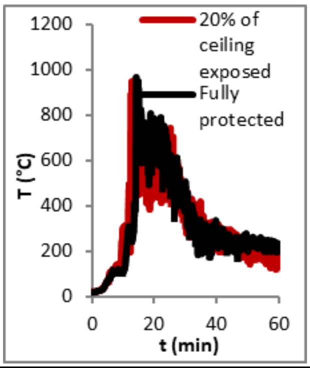
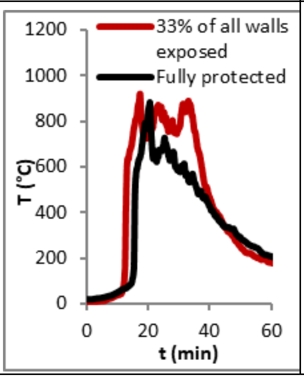
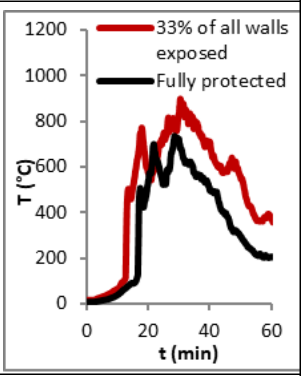
Figure 1. Fire plume shape at 5 consecutive seconds, (ignition + 20 min) *(Brandon & Andersson, 2018)*

1.1.2 The influence of internally exposed mass timber

The first compartment fire tests conducted with exposed mass timber were performed by Hakkarainen (2002). These tests, with relatively small openings, showed a significant difference of fire plume height for compartments with fully protected mass timber compared to compartments with fully exposed mass timber. Frangi and Fontana (2005), McGregor (2013) and Li et al (2014) have also performed test series of modules with combustible linings versus non-combustible linings and concluded that an increased external fire plume height can be a result of having exposed combustible linings in a compartment. A gap analysis by Gerard et al. (2015) indicated that there is a need to quantify any additional exposure to façades and the review of all available compartment fire tests (at the time) by Brandon and Östman (2016) confirmed this need. After those publications there have been a number of compartment fire test series in which the exposure to the façade has been measured and reported (Su et al, 2018; Zelinka et al, 2018). There is a correlation between the heat release rate of a fire and the dimensions of the corresponding external fire plume, however the influence is significantly dependent on the opening dimensions and especially the opening width. Brandon and Andersson (2018) provided an overview of tests series with different opening factors, in which each series consisted of a compartment fire test with non-combustible linings and a similar test with some exposed mass timber (Table 1). It was noted that the presence of exposed timber did not have a significant impact on the external fire plume of compartments that had larger and wider openings. For compartments with smaller and more slender openings, the influence of having exposed mass timber inside the compartment on the external fire exposure was notable.

The opening dimensions and opening width of previous compartment fire tests were, in general, not based on real building. Opening dimensions and the opening width implemented in compartment fire tests have in multiple previous occasions been limited by the capacity of the exhaust in laboratories and the dimensions of the available extraction hood.

Table 1. The influence of the opening factor and opening width

<table>
<tr><td></td><td>Comparison A: Fully protected versus 30 % of ceiling exposed</td><td>Comparison B: Fully protected versus longest 33 % of walls exposed</td><td>Comparison C: Fully protected versus longest 33 % of walls exposed</td></tr>
<tr><td>Reference</td><td>Zelinka et al. (2018)</td><td>Su et al. (2018a)</td><td>Su et al. (2018a)</td></tr>
<tr><td>Compartment dimensions (L x W x H)</td><td>9.1 m x 9.1 m x 2.7m
Or
30 ft x 30 ft x 9 ft</td><td>9.1 m x 4.6 m x 2.7m
Or
30 ft x 15 ft x 9 ft</td><td>9.1 m x 4.6 m x 2.7m
Or
30 ft x 15 ft x 9 ft</td></tr>
<tr><td>Opening dimensions (W x H)</td><td>3.7 m x 2.4 m (x 2 openings)
Or
12 ft x 8 ft (x 2 openings)</td><td>3.6 m x 2.0 m
Or
11 ft 10 in x 6 ft 7 in</td><td>1.8 m x 2.0 m
Or
5 ft11 in x 6 ft 7 in</td></tr>
<tr><td>Opening factor</td><td>0.105</td><td>0.065</td><td>0.032</td></tr>
<tr><td>Fully protected compartment (fully developed phase)</td><td></td><td></td><td></td></tr>
<tr><td>Compartment with exposed CLT (fully developed phase)</td><td></td><td></td><td></td></tr>
<tr><td>Time of photo after ignition</td><td>21 (min)</td><td>28 (min)</td><td>28 (min)</td></tr>
<tr><td>Temperatures at the facade at 3.5m (11 ft 6in) height from the floor</td><td></td><td></td><td></td></tr>
<tr><td>Note</td><td></td><td colspan="2">Delamination of CLT occurred during the tests. As it is currently required to use non-delaminating CLT in North America, the comparisons between temperatures after delamination are irrelevant and are not included in the comparison above.</td></tr>
</table>

1.2 Façade tests for regulatory compliance

In Europe different states have not only different legislation concerning the performance of facades exposed to fire, but also significantly different methods to assess this performance. Germany has different test methods in different states. France, UK, and Poland all use wood cribs as fuel source but have, other than that, vastly different tests methods to each other. Spanish regulations do not cite a full-scale method but base its safety level on the reaction-to-fire classification of the materials in the façade rather than the complete façade system itself (Hoffmann, 2016). In Sweden façades have been assessed using the SP Fire 105 method since the 1985. In that method, a flashover apartment fire is represented by 60 litres of heptane in a small burn chamber and a façade system passes the test if no burning or large objects fall and if charring or thermal damage is limited to a certain level above the chamber. Falling objects are also a criterion in Hungary (MSZ 14800-6), France (Lepir II) and Austria (Önorm B 3800-5) while in Poland (PN-90/B-02867) the objects must be burning to constitute a failure criterion.

Since many of the European methods are centred to one or, at the most, a few countries, very few comparative tests or further analyses have taken place. Consequently, most methods are rather arbitrary. As a result of the attention from façade fire incidents, several political initiatives have been taken to improve the performance of facades in case of fire. One such action is the work on completing a common European assessment method. This will assess exposure primarily via temperature measurements on facades and uses two different exposure methods based on the German DIN 4102-20 and the British BS 8414 test methods respectively. This work is ongoing, see the project website (ri.se, 2021) and is hereafter referred to as the *Proposed European Method*.

In North America there are two major large-scale assessment methods, the NFPA 285 and the CAN/ULC-S134. Both of these methods, which use gas burners as a fuel source, are performed by many laboratories and are applicable to larger markets compared to many of the national European methods.

An assessment method does not need to expose the system to a thermally realistic situation as long as the assessment criteria used for regulatory compliance takes the different thermal exposures of test and reality into account. However, setting such criteria are very difficult other than by correlating smaller test methods to outcomes in full scale situations. If thermal exposure resembles that which can be expected in a real situation the criteria can be set against the actual acceptable performance level of the system in case of a real fire.

There is a very small amount of data of exposure to façades that can be directly compared to multiple standard façade fire test methods, by having measurements in the same position relative to ventilation openings as the standard tests.

2 Objectives

A number of gaps are evident from the background:

- The relation between the fire exposure to facades in the regulatory compliance tests and that in real fires is unclear
- There is a lack of data from natural compartment fires where the exposure to the façade is assessed at positions that match with those of multiple standard test methods.
- The increase in external fire plume size due to exposing surfaces of mass timber in compartments has been assessed previously, but a focus on the representativeness of dimensions and openings representative to real modern buildings was lacking.

Thus, to help bridging these gaps the objectives of this study are therefore to take advantage of an ongoing test series of full-scale mass timber compartment tests and to:

1. Collect data of the thermal exposure (temperatures of thermocouples and plate thermometers, flame height, irradiation away from the opening) to the external façade in relatively severe fire plume scenarios.
2. Compare the impact exposed to the façade to that of a number of standard tests methods for regulatory compliance in North America and Europe.
3. Mapping the change of external fire plume as a consequence of exposing larger surfaces of mass timber.

The data gathered in this project is designed so that it can be compared to test data of assessment methods with standards for several different regulatory regimes. The test standards selected for comparison are:

- The proposed European method
- United Kingdom, BS 8414: 2020
- France, Lepir II
- Sweden, SP Fire 105,
- United States of America, NFPA 285
- Canada, CAN/ULC-S134

The data sources for each of these comparisons is discussed in more detail in Section 4.

3 Experimental

The opening factor and fuel load density for the tests performed in this study were selected on the basis of a probabilistic study using distributions of floor areas for the fire cells and opening factors from new constructions, both mass timber and non-mass timber buildings. 698 residential and 31 office compartments from a total of 31 different buildings in (UK, USA, Austria and Norway) were included in the study (Brandon et al 2021). Additionally, the distribution of fuel load densities from a recent Canadian study (Bwalya et al, 2010) were collected (Figure 2). The char depth resulting from flashover fires in a population of compartments following these distributions of area, fuel and opening factors was calculated assuming that the entire ceiling of the compartments comprised of exposed mass timber using the model by Brandon (2018). The floor area was chosen to be equal to the mean value from the statistical survey of Bwalya et al (2010), the fuel load density and the opening factors were chosen to represent the values producing a damage to the ceiling at the 85th percentile of (calculated char depth) in the total population of compartments.

Thus, the compartment size, openings and fuel load density were chosen to be representative of both residential and an office building but still with values that constitute the far end of damages to the mass timber structure in case of a fire. The choice of relatively small openings and a relatively high fuel load density will also produce severe conditions for the façade, but may not correspond directly with the arrangement that would be selected to maximise the façade exposure. Full details of the probabilistic analysis can be found in the summary report for the experimental series (Brandon et al, 2021) and an extended discussion is found in Annex A.

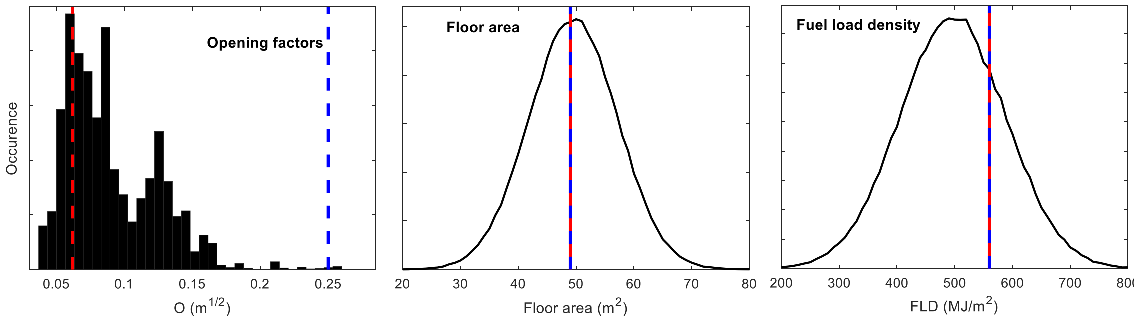


Figure 2. Distributions of newly constructed compartments in terms of opening factors (Brandon et al, 2021), Floor area and fuel load density (Bwalya et al, 2010) used to design the tests. The red and blue dashed lines are the values chosen for the tests representing residential (tests 1, 2, 3 & 5) and office buildings (test 4), respectively.

The properties of the external fire plume are governed by the geometry of the compartment and its opening, the composition of the moveable fuel and the structure, the external façade design, and the burning rate of all fuel in the compartment. These defining parameters are described throughout the rest of section 3.

3.1 Compartment

Five compartment experiments were performed as part of this test series. The compartments were built of 175 mm thick ANSI/APA PRG 320 (2018) compliant CLT provided by Katerra and KLH and Glued laminated timber provided by Boise Cascade. The mean moisture content of the CLT was 13 % during all tests, determined by hammering a resistive two-pin moisture meter, calibrated for spruce, at least 20 mm into the surface of the timber. All compartments had inner dimensions of 7.0 m x 6.85 m x 2.73 m. Four of the compartments had two ventilation openings at the front of the compartment (2.25 m x 1.78 m, width × height starting 324 mm above the floor level), see Figure 3 a. One compartment (Test 4) had 6 openings, 2 on the left and right sides (2.49 m x 2.1 m) and two in the front (2.44 m x 2.1 m) on the sides, see Figure 3 (b) and (c). These two different arrangements gave the compartments opening factors of 0.062 $m^{1/2}$ and 0.25 $m^{1/2}$, respectively (Figure 3).

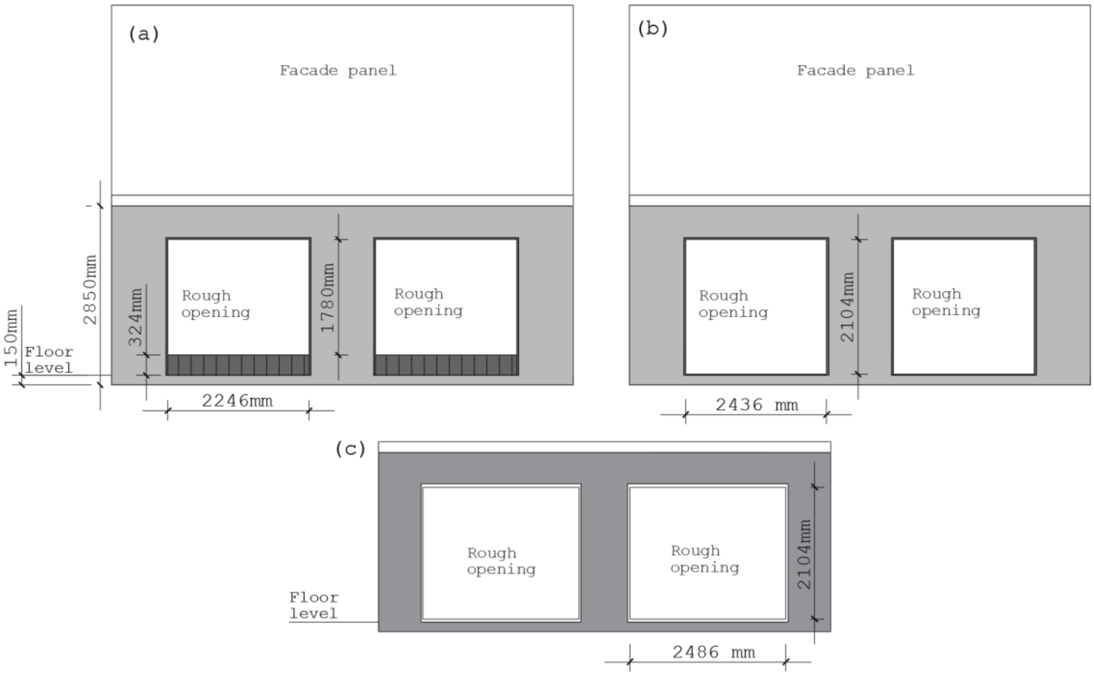


Figure 3. Outer dimensions of the structure showing (a) Front façade of test 1, 2, 3 & 5, (b) Front façade of test 4, (c) Side façade of test 4.

3.2 Moveable fuel and exposed surfaces

The moveable fuel for the tests consisted of typical apartment furniture (two small and one large sofa, 2 wardrobes, 6 bookshelves, 1 coffee table, 1 dining table, 8 chairs and 12 cushions), particle board sheets on the floor to represent a wooden floor and additional 380 kg of wood cribs with an average density of 435 kg/m^3 and an average moisture content of 13 %, representing fuel in storage spaces. Moisture content of the wood cribs was determined by overnight treatment in 105 °C. The target moveable fuel density for all five tests was 560 MJ/m^2, excluding the exposed surfaces of mass timber. Details regarding the internal layout of the fuel and variations between the different tests is summarized in Table 2 and can be found in the compartment test summary report (Brandon et al 2021).

In all tests, the timber ceiling was fully exposed. Of the small opening (residential) fires tests 1 had least exposure (54 m^2) followed by test 2 (91 m^2) and test 3 and 5 had almost identical exposed areas (96 m^2 and 97 m^2). The difference between test 3 and 5 was the distribution of exposed surfaces. In test 5 there was no corner with two exposed walls joining. In test 4, only the back wall was protected and everything else exposed (Table 2), on the other hand, test 4 had large openings in the three exposed walls.

Figure 4. Photos from the interior of the compartment for test 1. Both white couches, the dining table and the wardrobes contained additional wood cribs within. The setup was replicated for all tests.

Table 2. Summary of variation of conditions between tests

Test	Ventilation	Internal Exposed Timber
1	2 windows on front wall. 8 m^2 total openings.	100% ceiling and roof beam, total: 53.8 m^2
2	2 windows on front wall. 8m^2 total openings.	100% ceiling, left and right walls and roof beam, total: 91.2 m^2
3	2 windows on front wall. 8 m^2 total openings.	100% ceiling, left wall, beam and column and 78% of right-side wall, total: 96.2 m^2
4	2 windows on 3 sides. 31.2 m^2 total openings.	100% of ceiling, left, right and front walls, plus beam and column, total: 77.9 m^2
5	2 windows on front wall. 8 m^2 total openings.	100% ceiling, left wall, beam and column and 78% of right-side wall, total: 97.2 m^2

3.3 Façade

Two façade mock-ups were placed on top of each compartment above the opening. The facades were incombustible light weight concrete with nominal density of 575 kg/m^3. Blocks of 600 x 400 x 50 mm (width x height x thickness) were supported by a steel frame and could be lifted on and off the compartments for reuse during all tests (Figure 5). The moisture content was checked before test 1 on a reference sample to be 22 % (dry basis). For corrections of the mass loss calculation the façade was weighed before and after every test as discussed further by Brandon et al. 2021.

Figure 5. Placement of a façade mock-ups on the construction (left). Facades in place prior to test 1.

The façade structure was instrumented with a number of thermocouples (TC) corresponding to some of the assessment points in test standards (NFPA, CAN/ULC, BS 8414, ISO 13785-2, SP Fire 105 as well as the recently proposed European method) or location where additional measurements have been taken in available standard tests, as shown in Figure 6. In addition, four plate thermometers (PT), as used in standard fire resistance furnaces (Wickström, 1994) were embedded flush to the surface of each façade mock-up (Figure 7). A full list of instrumentation including their location and number can be found in Annex B.

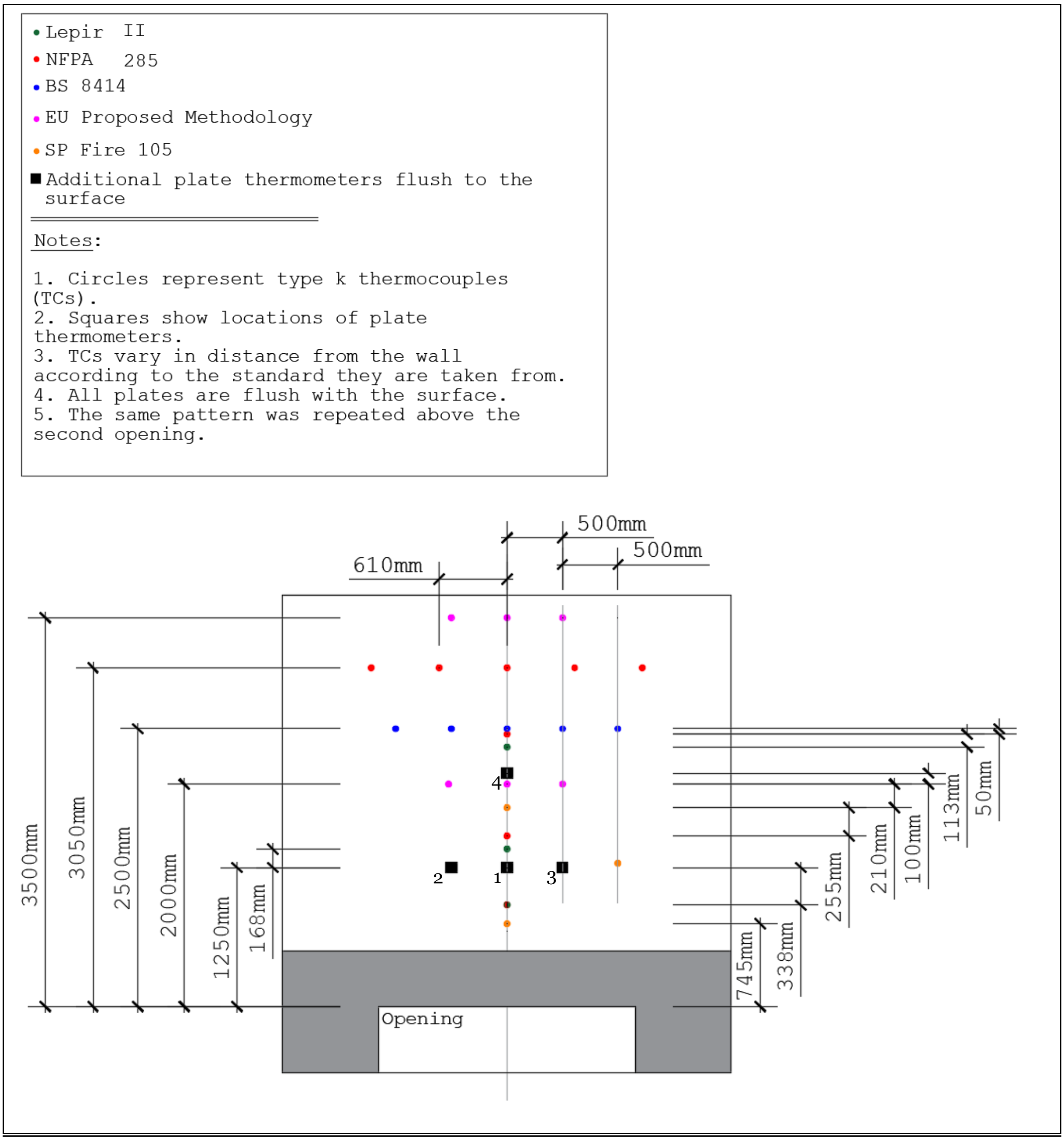


Figure 6. Placement of the PTs and TCs installed in each façade mock-ups above the opening. The same positions are repeated above the second front opening. The numbers next to the PTs are the same as in the nomenclature for Figure 13.

Figure 7. PT 4 embedded flush to the façade surface. Under the PT a 1 mm diameter TC (TC 7) extrudes 5 cm and above a 3 mm diameter TC extrudes 10 cm.

Additionally, four special plate thermometers with thicker, lighter insulation and thinner Inconel sheet were placed at 4.8 m and 8 m (the separation distance required in Sweden between buildings with no protection against external fire spread (Boverket's Building Regulations clause 5:61, Boverket 2020) in front of each opening at mid-height of the opening (1.3 m in Tests 1, 2, 3 and 5 and 1.1 m in Test 4) from the floor level. Such plates have previously been used for assessing the irradiance from fire to objects in ambient temperatures (Sjöström et al 2015). Additionally, at 8 m distance and at a height of 4 m one additional standard PT was installed to exemplify differences in irradiance with height.

At each opening a TC tree with 1 mm shielded Inconel TCs were placed a heights 0.6 m, 1 m, 1.4 m, 1.8 m and 2.2 m from the floor level.

Test 5 had reduced measurements above the façade with only the PTs and two TCs (5 and 25, see Annex B) included above the left-hand opening, and none above the right hand opening.

GoPro Cameras we placed at different angles and distances to evaluate the flame height and shape during the tests, recording at 120 fps.

Finally, the floor and the structure were placed on separate frames resting on load cells to assess the mass loss of the two during the tests, separately. The load cells (brand: ANYLOAD), had a maximum capacity of 50 kN and an accuracy of 0.02 %. They were well insulated and remained at ambient temperature during all tests. The 20 mm gap between the structure and the floor was insulated by ceramic wool insulation during the test to prevent fire spread in the cavity while still keeping the two separated in terms of load.

3.4 Mass loss and heat release rate

The heat release rate of the compartment fire is calculated from the mass loss rate and corrections of the mass loss of the concrete floor, gypsum boards and façade mock-ups using methods detailed in Brandon et al. (2021). The mass loss of the whole structure and all combustibles on the floor together with the calculated heat release rates are shown in Figure 8. The heat release rates are assessed assuming complete combustion of the pyrolysis gases.

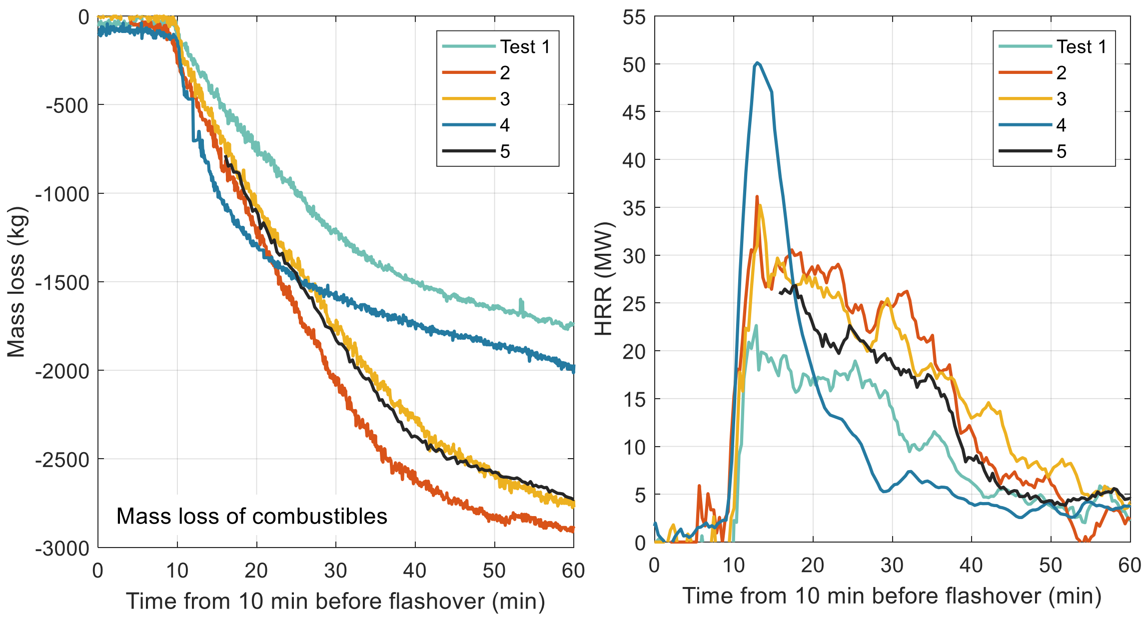


Figure 8. Left: The mass loss of the compartment fire, corrected for the loss of incombustible material such as the façade, gypsum boards and the incombustible floor. Right: Heat release rates calculated from the mass loss with the method explained in Brandon et al. (2021).

Since the structure and the floor were supported by individual frames on load cells the weight of the structure alone could be assessed at ignition and after the test. With the corrections for mass changes in the external façade and the internal gypsum boards (Brandon et al, 2021) the total mass loss of the structural timber could be assessed. These measurements were ongoing continuously throughout the tests but as buoyancy effects and pressure build-up during the course of events differ significantly the accuracy for each individual moment during the flashover is low[1]. The mass losses of the mass timber for the complete durations of each test are given in Table 3 together with estimated heat release assuming complete combustion during the whole test and the flashover phase.

Table 3. Mass loss of the structural timber and the estimated heat release of all combustibles during the test.

Test	Flashover duration (min)	Mass loss of mass timber during whole tests (kg)	Total heat release (GJ) of all combustibles (structure + floor)	
			Whole test	Flashover phase
Test 1	22	726	40 ± 1	29 ± 5
Test 2	28	2347	69 ± 1	47 ± 5
Test 3	31	2544[1]	72 ± 1[1]	44 ± 5
Test 4	5	1159	47 ± 1	26 ± 5
Test 5	30	2409	70 ± 1	44 ± 5

[1] Test 3 was terminated at t = 211 min.

3.5 Wind

The tests were conducted at days where the forecasted wind velocity was low. Measurements of average wind velocity on site during the test varied from 0.3 to 1.0 m/s and the wind in all tests was directed approximately perpendicular to the open façade. In Test 3 the measurements failed but based on measurements of the nearest weather station (18.3 km away) we expect the average wind velocity to have been 50 % higher (0.45 m/s to 1.5 m/s) than previous tests, which is in line with our experience at the test site.

3.6 Assessment of the sensors

3.6.1 Embedded PTs and TCs on the façade

The temperature measurements on the façade are mainly presented as raw data. No attempts were made to compensate TC temperatures for radiation and present calculated gas temperatures. Neither do we calculate assumed net heat fluxes to imaginative cold surfaces. Instead, this study compares the exposure to the façade of the compartment tests with that of standard façade test methods using the temperature readings directly.

One way of expressing thermal exposure to a surface is through the adiabatic surface temperature (AST), the surface temperature of a perfectly insulted surface exposed to a gas and radiation temperature (irradiation) and with a certain convective heat transfer coefficient and surface emissivity. AST can be expressed as an effective fire temperature, describing both the gas temperature and the radiation temperature that a surface is exposed to (Byström et al, 2013). PT measurements have been proven an efficient way of

[1] As an example, only a 40 Pa change in the compartment changes the measured mass by 200 kg for both floor and structure.

assessing AST since the plate already is comprised of an insulated surface. As the PT's in the façade are embedded the convective heat transfer will be similar for the plate and the rest of the façade.

We calculate the AST using a recursive formula for each time step, following the procedure in Byström et al (2013).

$$AST = T_{PT} + \frac{C\frac{dT_{PT}}{dt} - K(T_b - T_{PT})}{\varepsilon\sigma(AST^2 + T_{PT}^2)(AST + T_{PT}) + h_c}$$

where ε, σ and h_c are the surface emissivity, Boltzmann's constant, and the convective heat transfer coefficient, respectively. C and K are correction factors for storage and loss. T_b is the temperature behind the plate in the façade and is calculated using linear response theory, setting the façade temperature to that of the PT and assuming constant thermal diffusivity, following Sjöström & Wickström (2015):

$$T_b(t) = T_{PT}(0)\mathrm{erfc}\big(x/\sqrt{4\alpha t}\big) + \int_0^t \frac{dT_{PT}}{d\tau}\mathrm{erfc}\left(\frac{x}{\sqrt{4\alpha(t-\tau)}}\right)d\tau$$

where erfc is the complimentary error function, x is the depth of 15 mm and α is the thermal diffusivity of the façade (0.56 mm^2/s).

For this calculation we vary the correction factor for storage of C = 4200 W/m^2K (Häggkvist et al, 2013) of loss to the backside between $K = 0 - 10$ W/m^2K, the surface emissivity $\varepsilon = 0.8 - 0.9$ and the convective heat transfer coefficient between $h_c = 20 - 100$ W/m^2K. These variations of input parameters yield about ±20 °C difference in the calculated AST (Figure A3). Generally, the AST is also within 20 °C of the measured PT and for this reason we do not show the AST within the report but refer to Annex C for AST curves. (Figure A2)

3.6.2 PTs for irradiance assessment

Using plate thermometers (as used to control fire resistance furnaces) to measure irradiance (Incident radiation heat flux) in ambient air have been demonstrated as an affordable, robust method which enables the implementation of more sensors compared to if water cooled heat flux gauges (such as Gardon or Schmidt-Boelter) were to be used (Ingason & Wikström, 2005). To increase accuracy and response of the probes, an updated version of the standard plate thermometer was constructed with calibrated and proven response (Sjöström et al, 2015). This plate has a thicker but lighter insulation and a thinner exposed metal sheet.

The irradiance to a plate in a known gas environment (known gas temperature and convective heat transfer coefficient) can be assessed as:

$$\dot{q}''_{inc} = \varepsilon\sigma T_{PT}^4 + \frac{(h_c + K)\big(T_{PT} - T_g\big) + C\frac{\partial T_{PT}}{\partial t}}{\varepsilon}$$

For the four plate thermometers outside directed to the openings we use the corrections parameters used by Sjöström et al (2015) and Wickström et al (2019) of K = 5 W/m^2K, C = 2800 J/m^2K.

The elevated plate thermometer (4 m high) outside the left opening at a distance of 8 m was of traditional fire resistance design and the correction parameters for it are as defined in Häggkvist et al (2013), K = 8 W/m²K, C = 4200 J/m²K. The convective heat transfer coefficient was kept constant for all tests at 12 W/m²K. Even though a change in wind conditions would change this value it has been shown in previous studies that the change for wind speeds lower than 2 m/s is within the margin of error at 10 % (Sjöström et al, 2015).

3.6.3 Cameras for flame height

The flame height is determined by image analysis. All tests were filmed from a stationary front view position with GoPros recording at 120 frames per second. The camera is assumed to be completely parallel to the façade since the static pixel-meter conversion is used. Also, it is assumed that the highest flame is in the same plane throughout the video, and the measurement is converted in the same plane as the façade. To reduce the error caused by the camera's perspective, the camera was positioned relatively far at a distance approximately 15 m from the façade at 1.6 m high.

Because the flame has both high brightness and a colour that stands out from the background, it is possible to measure the flame size. A script is created that analyses each captured frame extracted as a numeric matrix. To improve the reading of the flame height the image is cropped so that the lower level coincides with the top of the opening in the front façade. To make an easier conversion to grayscale, the colormap of the image is altered by only using the red channel. The image is gray-scaled with a threshold determined by the brightness and colour of the background. This gray-scaled image is then converted to a binary image by a threshold depending on how much of the flame should be covered. By adjusting the threshold for the binary image, the "base" flame can be captured, and smaller flickering flames are ignored. The binary image contains only ones and zeroes, forming one or several areas in pixels. The largest area is used to determine the flame length by converting the pixel height on the y-axis to meters. The entire procedure after cropping the video to a suitable size is shown in Figure 9.

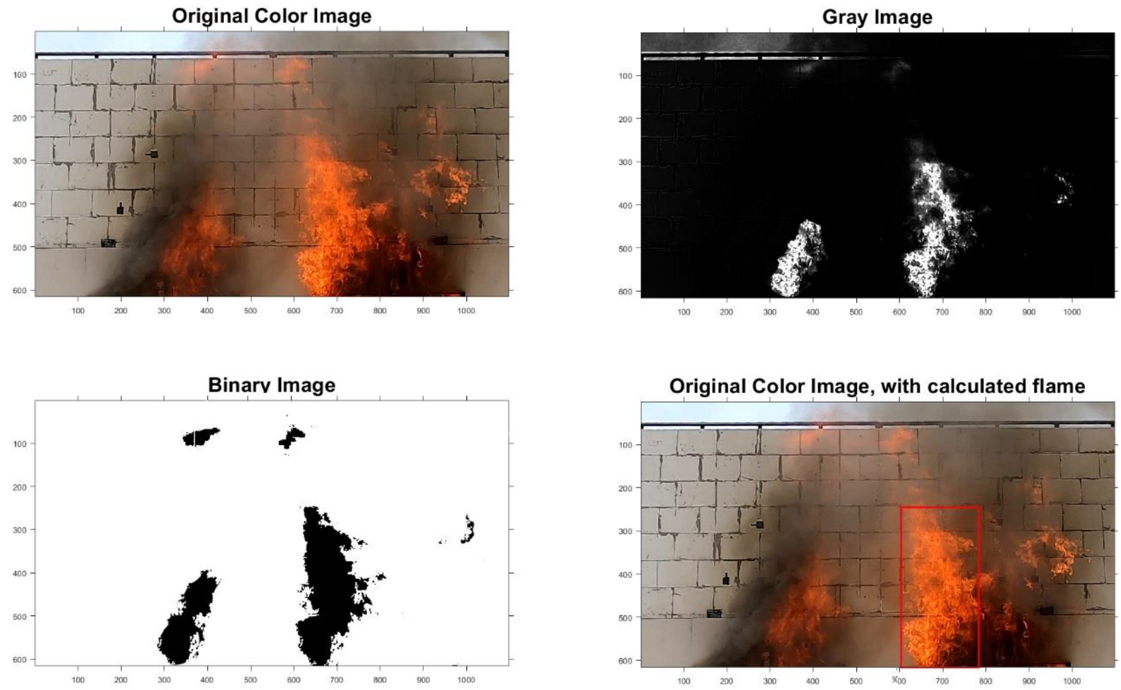


Figure 9. Top left: Original cropped image before processing. Top right: Grayscaled image above a certain threshold. Threshold is set to capture core of the flame. Bottom left: Binary image with from which the height is calculated. Bottom right: Original image with the bounding box used for calculating flame height added.

Since each second contains 120 frames and the flame height can change drastically between just a few frames the raw data is noisy. By applying a moving average, the characteristic of the flame size is obtained (Figure 10). Since the largest area in the binary image is used, smaller sections of the flame as seen in Figure 9 are ignored.

For some time-intervals, the cameras are either not working or cannot capture the full flame height. In those cases, a manual assessment of the flame height is done from other video recordings not parallel to the front façade.

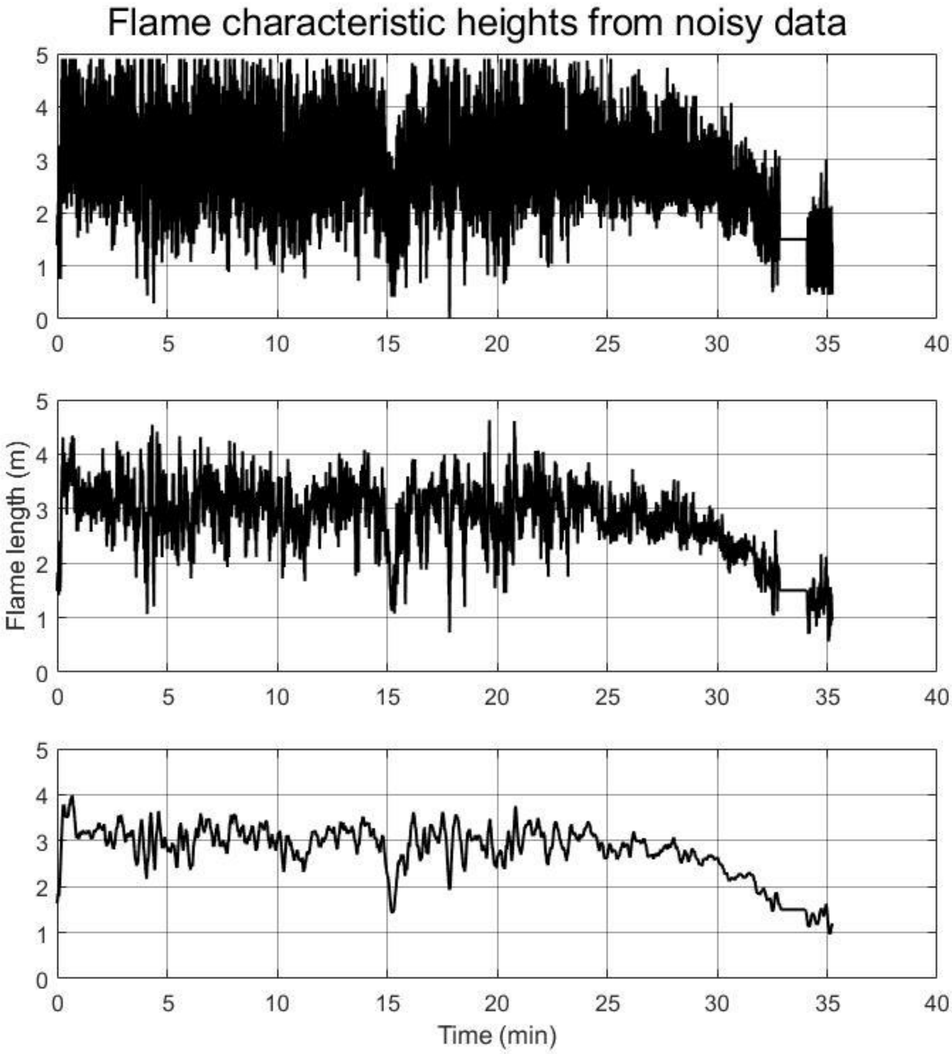


Figure 10. Flame characteristic from noisy flame data, test 3. Top Raw data. Middle: Moving mean of 120 frames (1 second). Bottom: Moving mean of 1200 (1 minute).

4 Reference data

To allow reasonable comparisons to be made between the compartment fires conducted in this project and the relative exposure of different façade test methods, data from tests conducted with inert facades (i.e. where there is no contribution to the fire from the façade) must be used.

4.1 SP Fire 105

The Swedish method of SP Fire 105, using 60 litres of heptane as a fire source, is the basis for regulations in Sweden, Norway and can also be used in Denmark. The data sets on inert façades used for comparison here are published by Boström et al (2016) and as a part of the SESBE project (SESBE 2017). Some other published data using SP Fire 105 on combustible facades with additional instrumentation are available but only the inert facades are used here.

These tests include limited external temperature measurements but a plate thermometer at 2.1 m above the opening that will be used as the basis for comparisons.

4.2 BS 8414 and proposed European Standard

No fully instrumented BS 8414 facade test with an inert façade has been found. However, as part of the ongoing project, named *Finalisation of the European approach to assess the fire performance of facades* (funded by the European Commission), tests have been conducted on inert facades at Efectis (France) with a BS 8414 compliant fuel source and combustion chamber. The full height of the BS 8414 façade is not included but only the first 2.5 meters above the combustion chamber. Also, the instrumentation differs from the BS test as these tests have been conducted primarily for the purpose of characterising the fire source (ca 350 kg of pine wood crib), and therefore have only a limited number of external temperature measurements. Measurements on the centreline at 1 m above the compartment opening, as shown in Figure 11, will be used as the primary basis for the comparison. The original crib in the BS 8414 method rests on a solid plate but here we also use data from a test where the crib rests on a grid, enabling more airflow through the fuel source.

In addition to the BS cribs and combustion chamber, 7 tests on different cribs used as candidates for the proposed European method are included in the comparison (Figure 11). These cribs vary in species (spruce and pine), density (411 – 547 kg/m^3) and moisture content (8.7 – 14.5) but have the same geometry. The same inert façade as the BS 8414 cribs discussed above was used (European Commission, 2021).

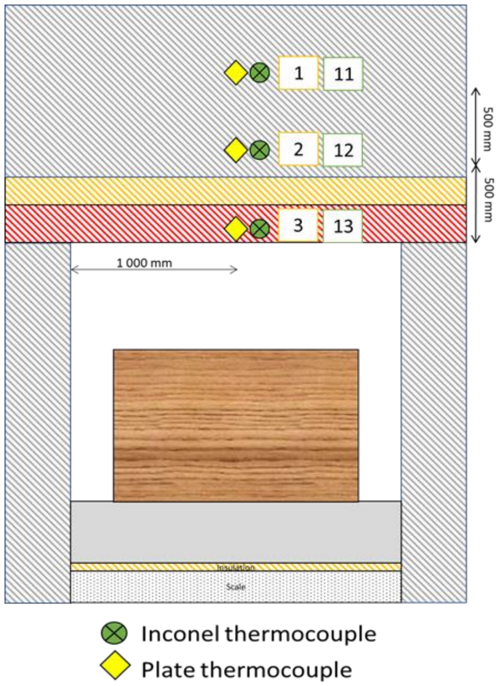


Figure 11. Locations of the measurements, external to the combustion chamber, taken in the tests for the *Finalisation of the European approach to assess the fire performance of facades* project. The combustion chamber was thereafter altered and chamber and cribs compliant to BS 8414 were used to assess the British method. Figure is taken from a project progress report (European Commission, 20121)

4.3 NFPA 285

Table 4. NFPA 285 calibration temperatures for external (0.8 mm type k) thermocouples (TCs)

TC location (mm above opening)	Temperature average of time period (°C)					
	0-5 min	5-10 min	10-15 min	15-20 min	20-25 min	25-30 min
305	317	466	511	533	563	581
610	359	546	605	639	674	702
914	341	521	591	634	674	712
1219	302	459	528	573	613	662
1524	272	407	469	509	542	597
1829	244	366	419	458	489	543

While no publicly available data for NFPA 285 tests on an inert façade has been found, prior to tests being conducted, a calibration exercise must be undertaken on a blank rig. As part of this calibration process, certain temperatures must be reached (with an acceptable error of -10 % and + 20 % in °F) at certain points during the 30-minute calibration. These temperatures provide a means by which a comparison can be made between the NFPA test and the exposure from the compartment fire. The calibration requirements used can be seen in Table 4. The shape of the temperature increase resembles the standard fire time-temperature and increases for the full duration of the test.

4.4 CAN/ULC-S134

No data for tests with inert facades to CAN/ULC-S134 has been found. However, reviewing a test (Gibbs et al., 2015) carried out by the National Research Council Canada (NRC) on a CLT wall covered with a non-combustible mineral-wool insulation (ROXUL, 2014) showed that none of the combustible elements of the wall behind the insulation became involved in the fire. This test can, therefore, be used as a reasonable source for a comparison between the severity of the CAN/ULC-S134 test and the exposure on the façade from the tests described within this report. TC temperatures at 1.5, 2.5 and 3.5 m above the combustion chamber opening have been extracted from Gibbs et al, (2015) and reproduced here.

4.5 LEPIR II

Experiments following the LEPIR II standard with inert construction (using a ground + 2 story concrete structure) have been carried out by Efectis in France (Drean et al.). This test included PTs at 0.2 m, 1.3 m and 2.05 m above the windows to the combustion room (as well as some offset TCs). These PTs are to be used as the basis for comparisons with the LEPIR II test.

5 Results

The following subsections contain an overview of the results. The full results from the instrumentation for all tests can be found in Annex B. All data for this project was recorded using 3 Fluke Hydra Series III loggers, each which record at a rate of approximately 1 reading every 4 seconds. The data as presented in this report has been resampled to 15 s timesteps from this raw data (using linear interpolation where the new timestamp falls between two recording points) and then smoothed via a moving mean of 1 min 30 s.

Large fire plumes were ejected from the openings during the flashover of all tests (Figure 12). Most flames were very luminous and not significantly shaded by smoke. The duration of the flashover phase differed between the tests with the exposed mass timber surface areas (Table 5).

Figure 12. Snapshots from each test at 2 minutes after flashover.

Table 5. Duration of the flashover phase for each test.

	Test 1	Test 2	Test 3	Test 4	Test 5
Duration of flashover phase	22 min	28 min	31 min	5 min	30 min

5.1 Temperatures of the façade instrumentation

An overview of the temperature histories for the plate thermometers measured from each test are shown in Figure 13 below. It can be seen that Test 1, 2, 3 and 5 all have similar exposures, both in terms of maximum temperatures and duration of the flashover period (although Test 1, which has the lowest proportion of exposed CLT, is slightly lower in peak temperatures than the other tests) while Test 4, with the increased ventilation has a much shorter duration of exposure due to the faster burning of the fuel and significantly lower temperatures since fire plumes are ejected from all six openings instead of the two openings in test 1, 2, 3 and 5. Finally, a comparison between the temperatures of the plate thermometers above each of the left and right openings from Test 1 shows small variations in exposure above each opening.

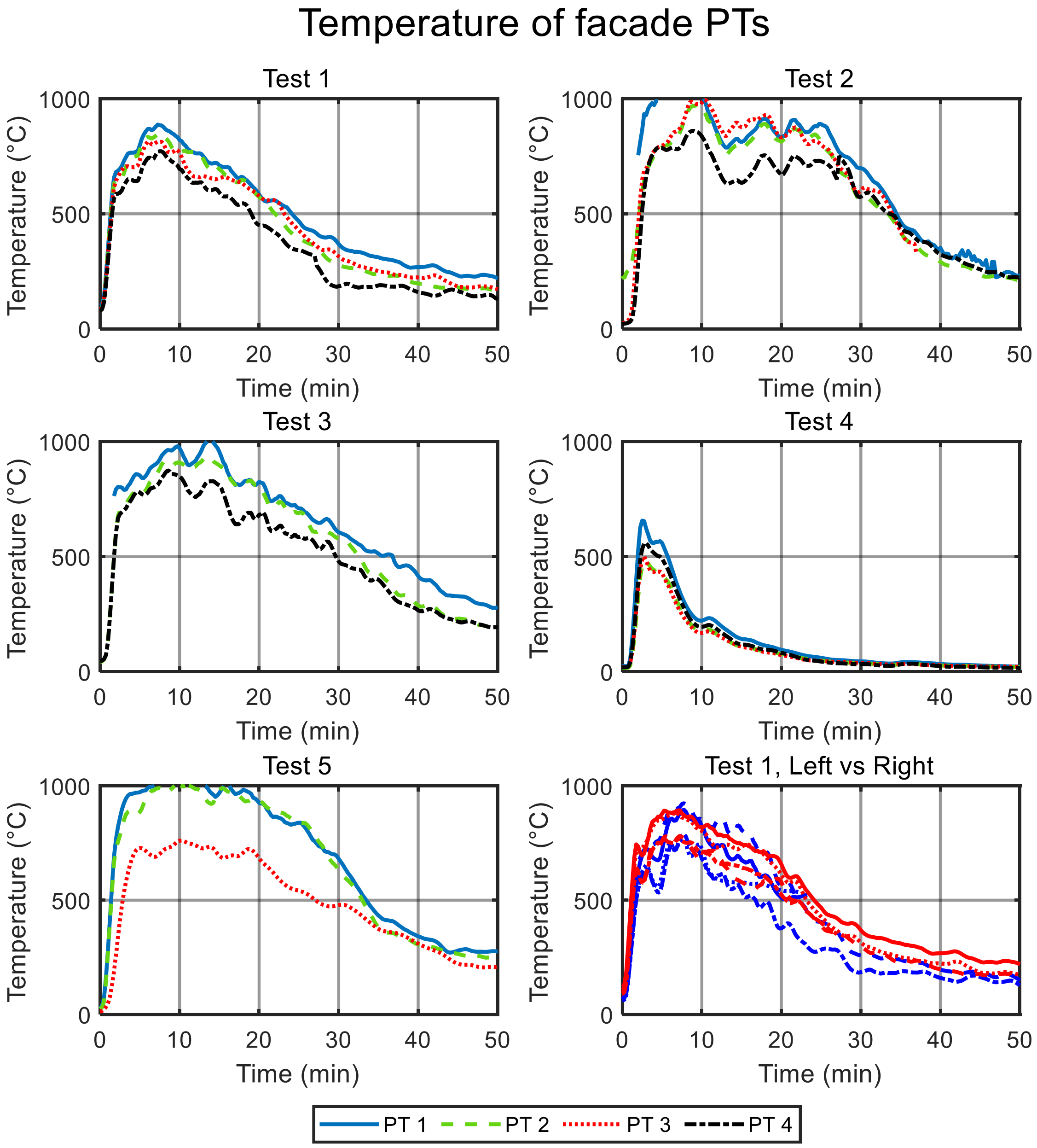


Figure 13. Temperature-time histories for façade PTs (all tests). PT1-3 are all located 1.25 m above the opening (PT1 central, 2 and 3 0.5 m either side) PT4 is 2.1 m centrally above the opening. The curves presented here are averages of the Left and Right opening for each test. The lower right panel shows the left and right openings for test 1 as an example. See Annex B for full location details.

The spacing of type k thermocouples from 790 mm above the openings to 3500 mm allows the estimation of the variation in temperature exposure over the height of the façade above the opening. The maximum 5 minutes average for tests 1 - 3, and maximum 3 minutes for the shorter flashover of test 4, has been plotted against height, see Figure 14. The similarity between the Test 1 to 3 can again be seen, with very similar variation with height and increasing temperatures with increasing area of exposed mass timber. Test 4 has significantly lower temperatures and reduces quicker with height. The average gradient for Tests 1 to 3 is -152.8 (°C/m).

Test 5 had a reduced number of measurements on the façade and so is not included. However, as the experiment is nominally the same as Test 3, and the PT results suggest similar peak temperature and duration, it is considered reasonable to assume it would follow have a similar relationship.

An overview of the temperature histories for all of the thermocouples in Test 1 can be seen in Figure 15, with full results for all tests available in Annex C.

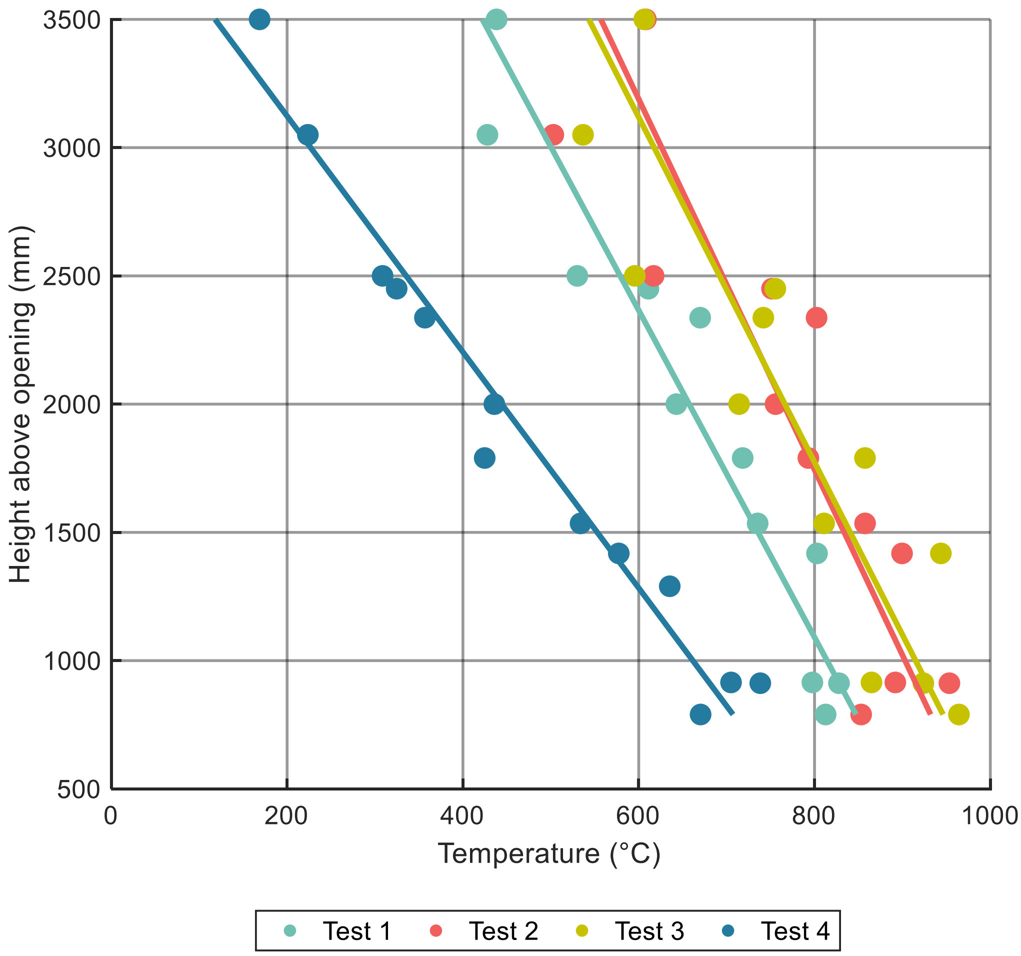


Figure 14. Variation in temperature recorded in façade TCs with height above the opening. Temperatures are the maximum 5 minutes average for tests 1-3, and 3 minutes for test 4. Lines are linear fits to the data.

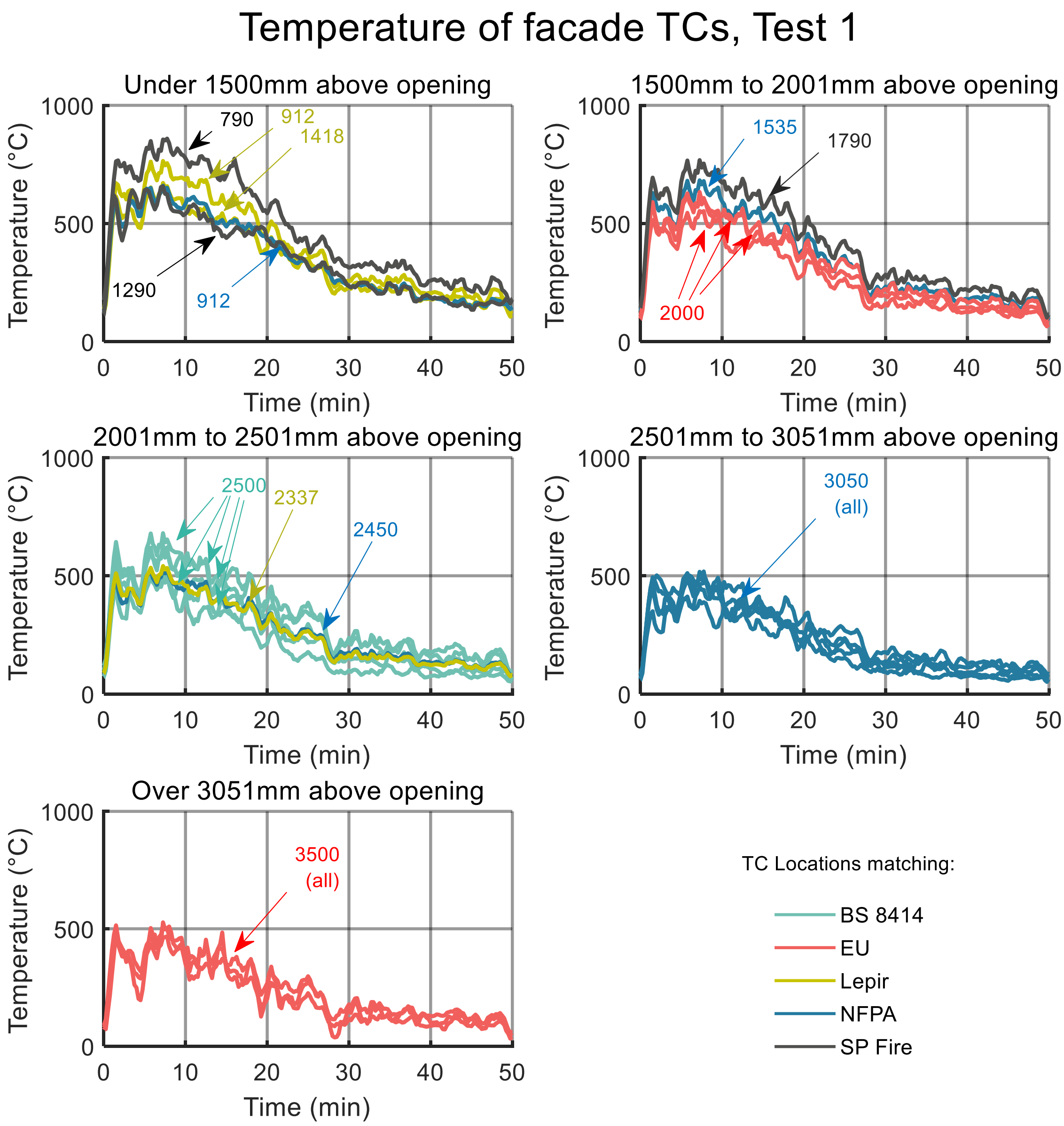


Figure 15. Temperature histories of façade thermocouples in Test 1. All curves are based on averages for the same thermocouple location above the left and right opening. Colours show the standard test methodology which has temperature measurements at each location and the number associated to each line is the height (mm) above the opening.

5.2 TC trees in opening

The temperature-time histories for the thermocouple trees placed in the openings for test 1 can be seen in Figure 16. The full results for the thermocouple trees in all tests can be found in Annex C.

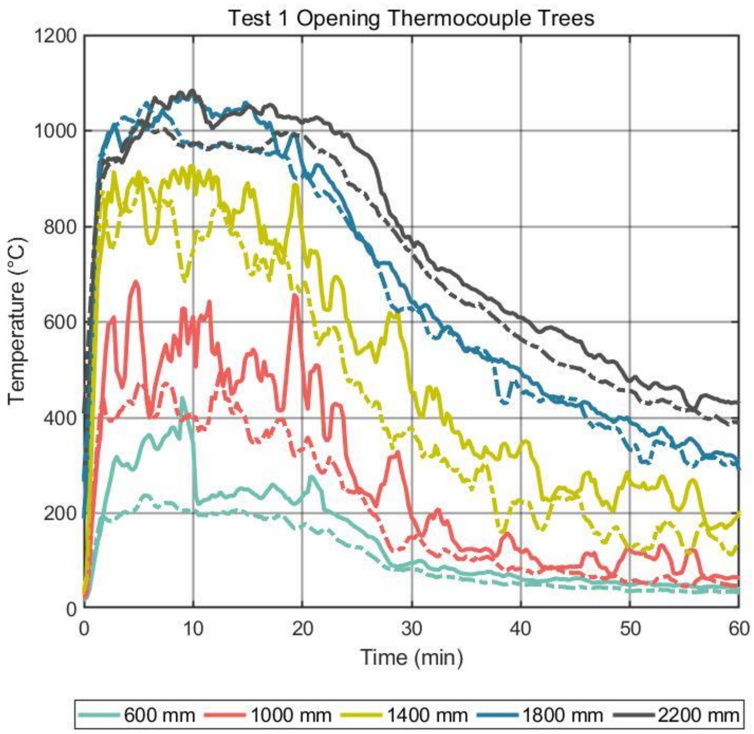


Figure 16. Temperature-time histories for the thermocouple trees in the opening. Heights are measured from compartment floor level; solid lines represent the left hand opening and dashed lines the right (as viewed from outside the compartment).

5.3 Flame heights

Comparing the flame heights show similar behaviour and height for small opening tests (1, 2, 3 and 5) while the large opening test show a significantly lower flame height and shorter duration (Figure 17). The differences that can be noted outside the scatter is that flame heights increased slightly from test 1 to test 2 with an increase in exposed timber surface area of 67 % (37 m^2). Test 3 exhibits the shortest flame height of the small opening tests, somewhat smaller than test 1 despite increasing the exposed area of timber by another 9.5 m^2. However, the wind was slightly higher in Test 3 compared to the other tests and also directed with a slight change in direction, more parallel to the front façade. For test 5, which was performed in completely still weather, the flame height is almost as high as test 2 and for a period (10 – 15 minutes) clearly higher.

Generally, the overall flame height characteristics are similar for small opening tests with average flame height between 3.5 and 4 meters and measurable flames for just shy of 35 minutes. The duration for the large opening test was 8 minutes (but significant flames for only 5 minutes) with maximum flame heights at 3 metres in the very beginning (Figure 17).

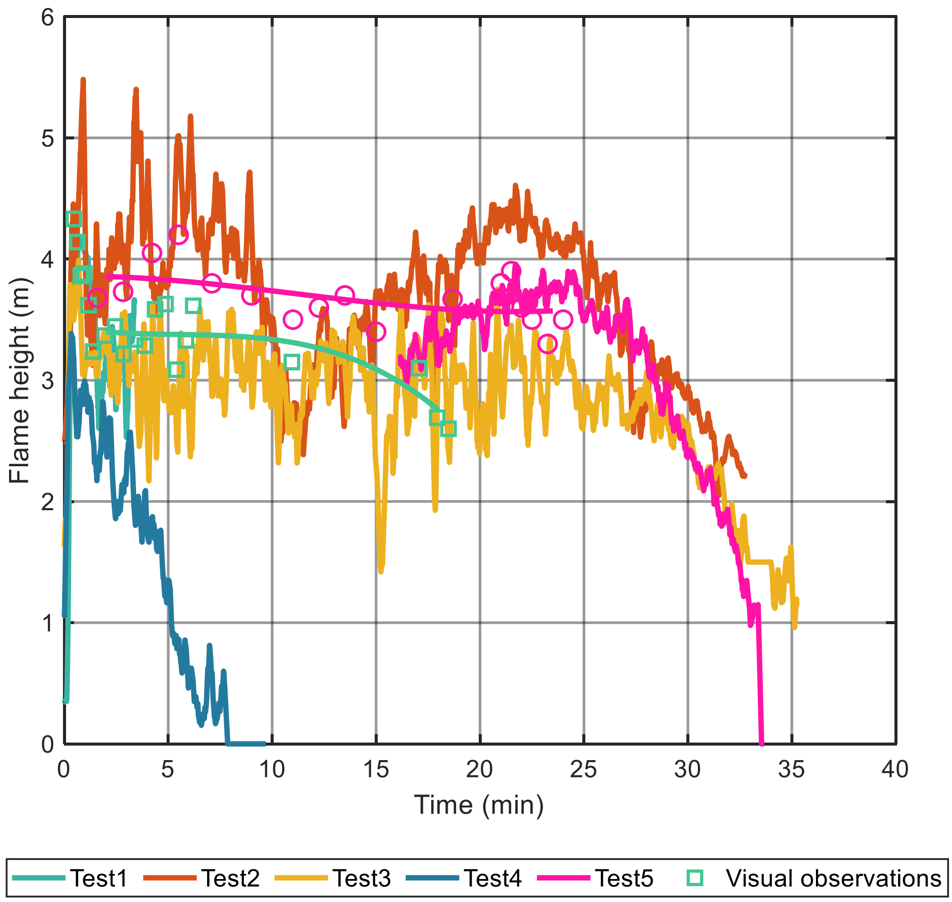


Figure 17. Flame height. Line are data obtained from image analysis on each frame. Dots are visually observed flame heights.

5.4 Irradiation from the opening

The radiant heat flux was calculated for the plate thermometers opposite the openings, as described in section 3.6.1. The maximum heat fluxes (based on a moving mean over 1.5 minutes for each test) received at each location for each test are shown in Table 6.

Table 6. Maximum radiant heat fluxes opposite the openings.

	Maximum Incident HF (kW/m²)		
Test	**4.8 m from openings**	**8 m from openings**	**Elevated at 8 m from openings**
1	17.1	7.5	-
2	17.1	9.0	11.0
3	15.2	6. 6	7. 7
4	9.0	6.3	5.7
5	-*	7.6	7.0
*Plates insulation wet and as such recordings ignored. For tests 2-3 only 1 plate affected, for test 5, both front plates affected.			

6 Comparisons to standard test methods

The following subsections show comparisons between the exposure from the CLT compartment test series and the standard tests identified in section 4. Where the comparison is based on TC temperatures and no device is located at the same position as those for the comparative data, the temperatures from the closest thermocouple is shifted based on the temperature-height dependency discussed in section 5.1 (Figure 14). A description of the methodology for completing this temperature shift can be found in Annex D.

6.1 Temperatures of the façade instrumentation

6.1.1 NFPA 285

A set of comparisons between the calibration requirements of NFPA 285 (see section 4.3) and the CLT compartment test results (TCs) can be seen in Figure 18. The comparisons show that the NFPA 285 test is nominally similar in peak temperatures to those from Test 4 (the large opening test) but with a longer duration. The growth rate is also slower than all tests. NFPA 285 does allow for variation in the temperatures (from 10 % below to 20 % higher, with respect to °F, than the nominal temperatures) and therefore it may be common for the actual maximum temperatures to be more akin to those of Tests 1 to 3.

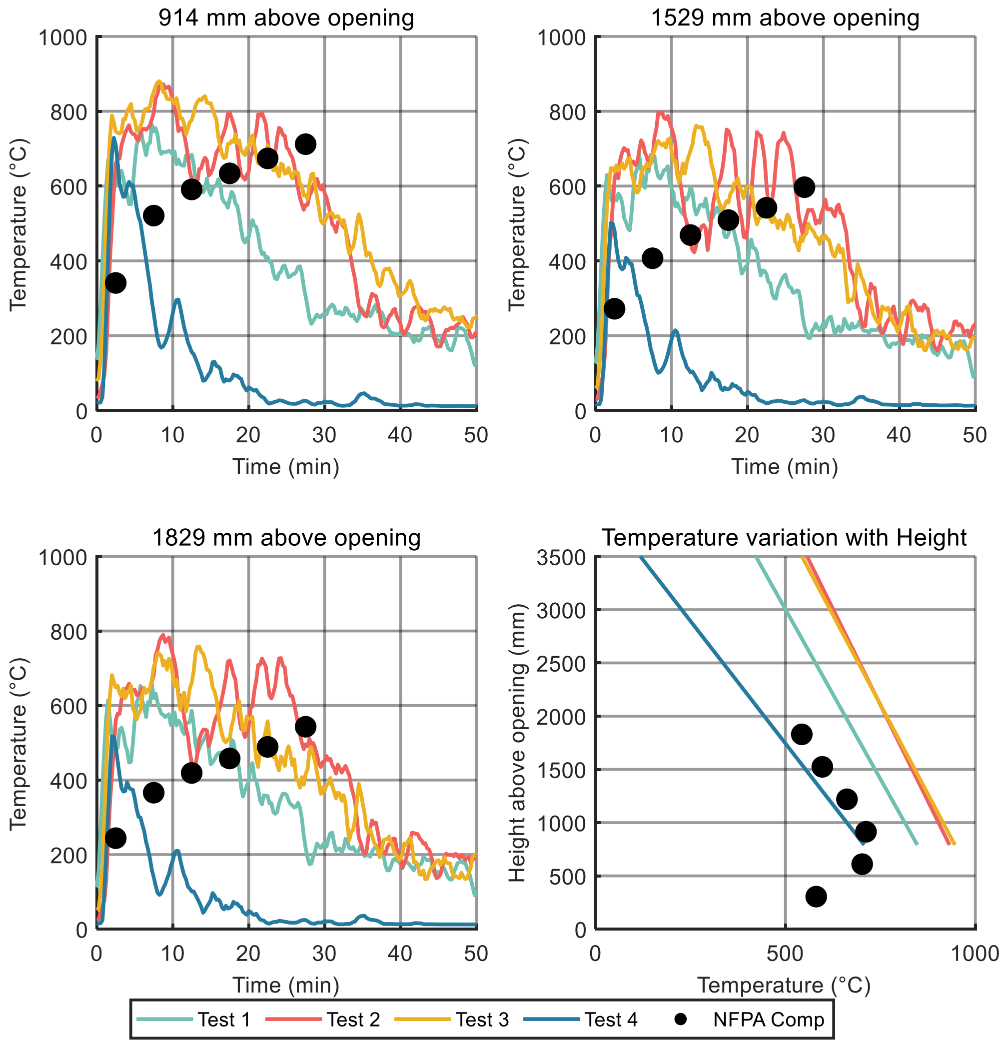


Figure 18. Comparison at varying heights of the facade exposure from the CLT compartment tests and the calibration requirements for NFPA 285. The final plot illustrating the temperature variation with height using the maximum temperatures from the calibration and the 10 minutes maximum averages during flashover for the compartment tests.

6.1.2 BS 8414 and proposed European standard

A comparison exposure from the CLT compartment tests with 2 BS 8141 compliant (in respect to their fuel source and openings, see section 4.2) experiments can be seen in Figure 19. From these comparisons it can be concluded that the fire exposure generated by BS 8414 is similar, in respect to peak temperatures and duration of the PT temperatures, to that of the CLT compartment tests, and therefore what can be reasonably expected from severe compartment fire. The TC temperatures are, however, almost 200 °C hotter in their peak values compared to the tests.

Additional comparisons against the other fuel sources and with a modified combustion chamber dimensions (with varying species of timber and cross sections) which are being trailed in the EU façade standard development project can also be seen in Figure 20. While these all differ from each other and the BS 8414 source, they are all a similar magnitude and duration. In all comparisons the data from the CLT compartment tests has been averaged across the measurements taken above each opening.

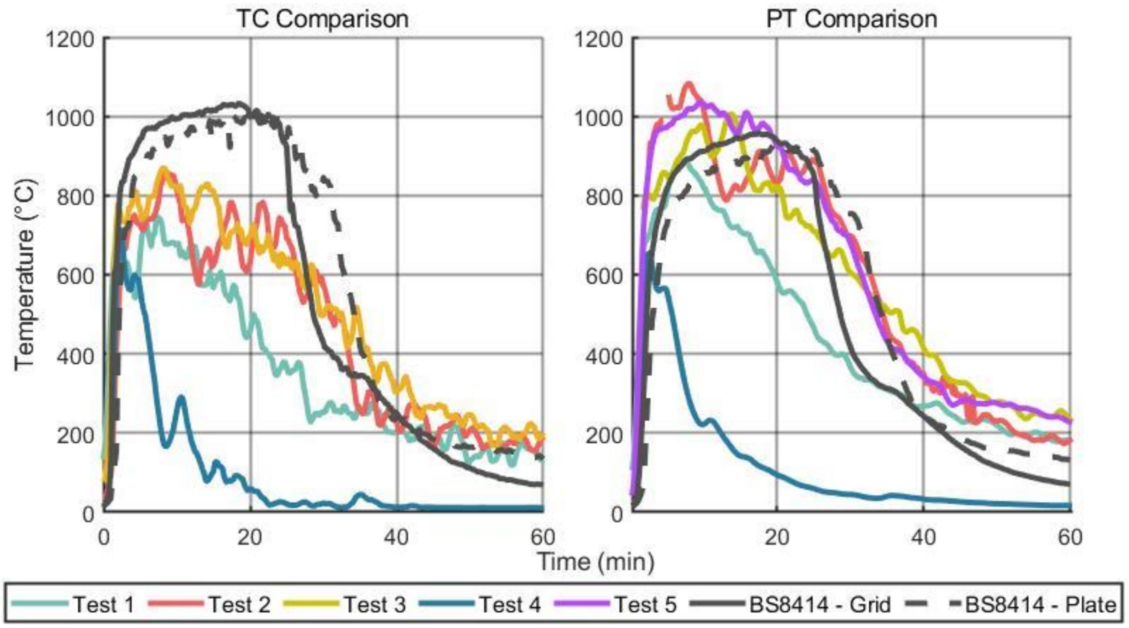


Figure 19. Comparison between test results and fire exposure from a BS 8414 compliant fire source. Left Comparison of TCs at 1m above the fire compartment opening. Right PTs at 1m above the fire compartment opening (BS 81414) against PTs at 1.25 m above the opening from the CLT compartment tests. The dashed line corresponds to the BS8414 test and the solid grey line is the same type of crib, in the same combustion chamber with a grid under the crib instead of a solid plate.

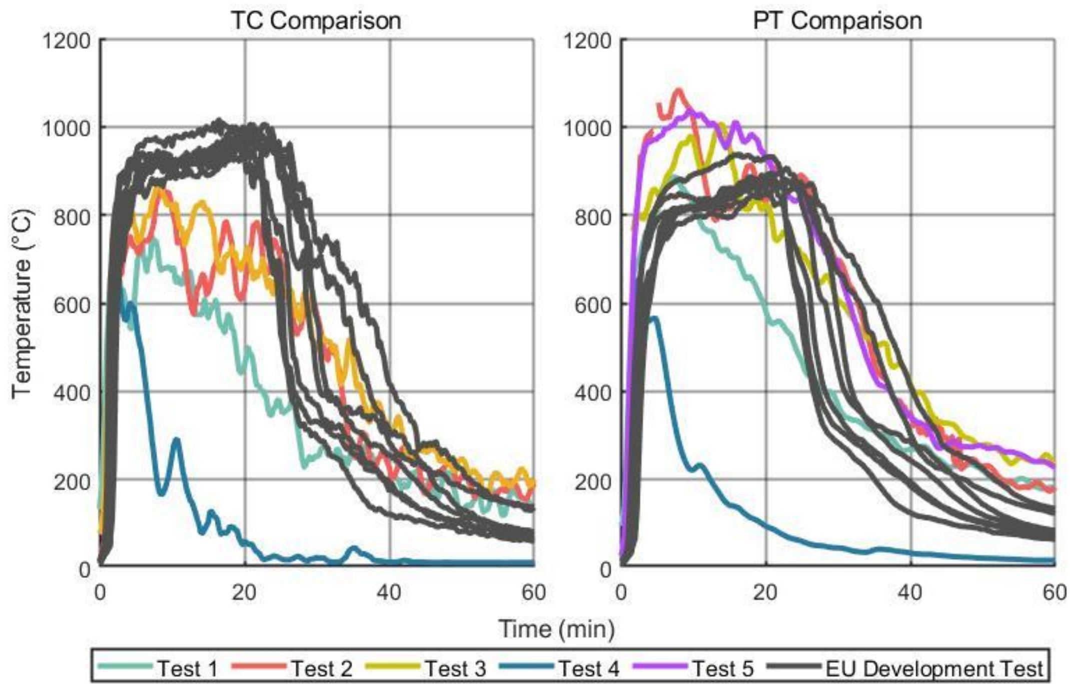


Figure 20. Comparison between test results and fire exposure from the proposed EU façade standard development tests. 7 different tests are included with varying timber species and section sizes used. Left Comparison of TCs at 1 m above the fire compartment opening. Right PTs at 1 m

above the fire compartment opening (BS 81414) against PTs at 1.25 m above the opening from the CLT compartment tests. See section 4.2 and the report for the European Commission (2021) for details on the variations on the cribs.

6.1.3 LEPIR II

A comparison of the exposure from the CLT compartment tests with a LEPIR II compliant tests carried out by Efectis France (see section 4.5 for further details) can be seen in Figure 21. These comparisons are made using PT temperatures as utilised in the LEPIR II test. The PTs are 50 mm different in height to those from the CLT compartment tests, however this will have minimal impact on the comparison (TCs vary ~7.5 °C over this range). From these comparisons it can be concluded that the exposure from LEPIR II is lower than that for the CLT compartment tests conducted.

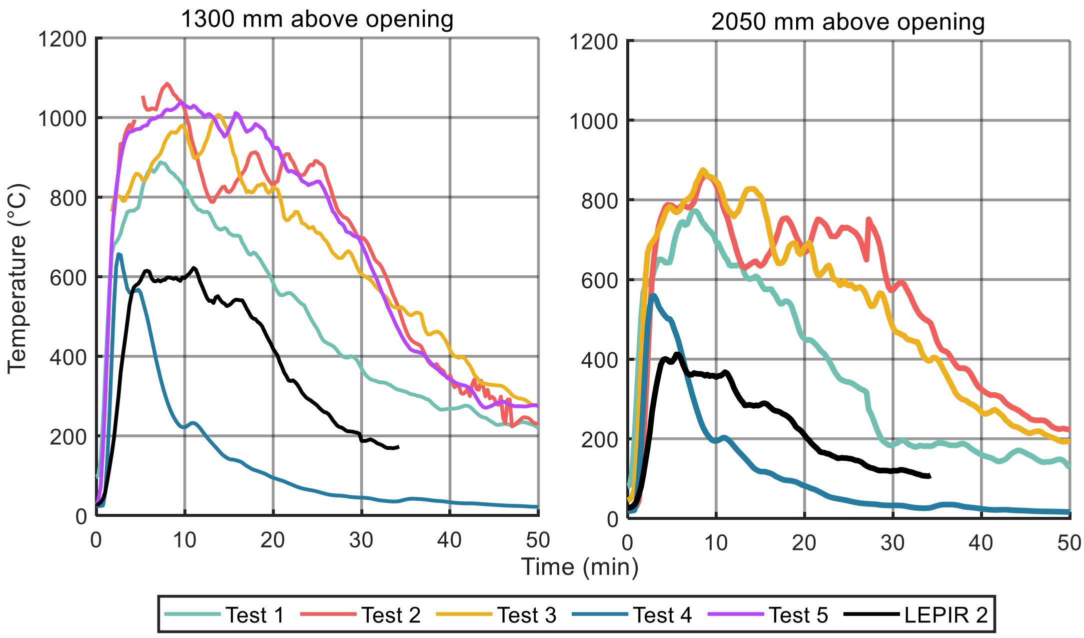


Figure 21. Comparison between plate thermometer (PT) temperatures from a LEPIR 2 test against those recorded for the CLT compartment tests. Left The LEPIR II results at 1300 mm vs CLT test at 1250 mm (above openings). Right The LEPIR 2 results at 2050 mm vs CLT test at 2100 mm (above openings).

6.1.4 SP Fire 105

A comparison of the exposure from the CLT compartment tests with 2 SP Fire 105 test on two different lightweight concrete façades can be seen in Figure 22, using PT temperatures at 2100 mm above the compartment opening. It is clear that the exposure from SP Fire 105 is both lower and shorter than that for the CLT compartment tests conducted.

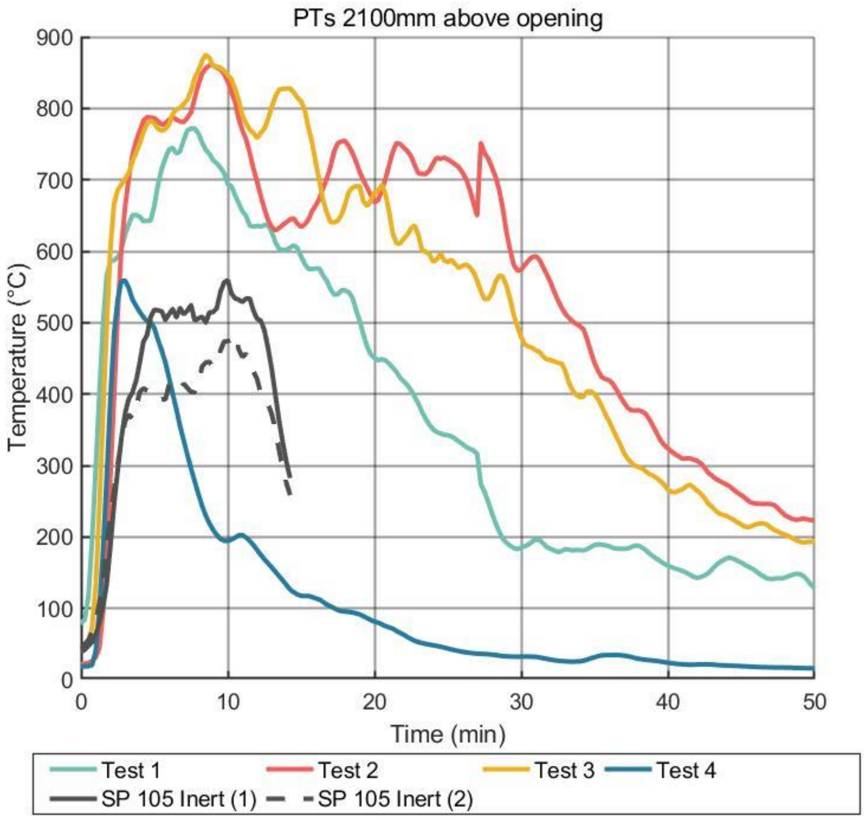


Figure 22. Comparison of PT temperatures over time at 2.1 m above the opening between tests 1-4 and two separate tests with SP Fire 105 compliant fires and rigs. The two SP Fire 105 curves shown are an inert reference test by Boström et al (2016), (solid line) and a test conducted with a lightweight concrete façade as part of the SESBE project (dashed line) (SESBE 2017).

6.1.5 CAN/ULC-S134

A comparison of the exposure from the CLT compartment tests with a test conducted in accordance with CAN/ULC-S134, see section 4.4 for further details, can be seen in Figure 23. This comparison makes use of TC temperatures at varying heights and shows comparable peak temperatures to those of Test 1 but with a slower growth rate than the CLT compartment tests.

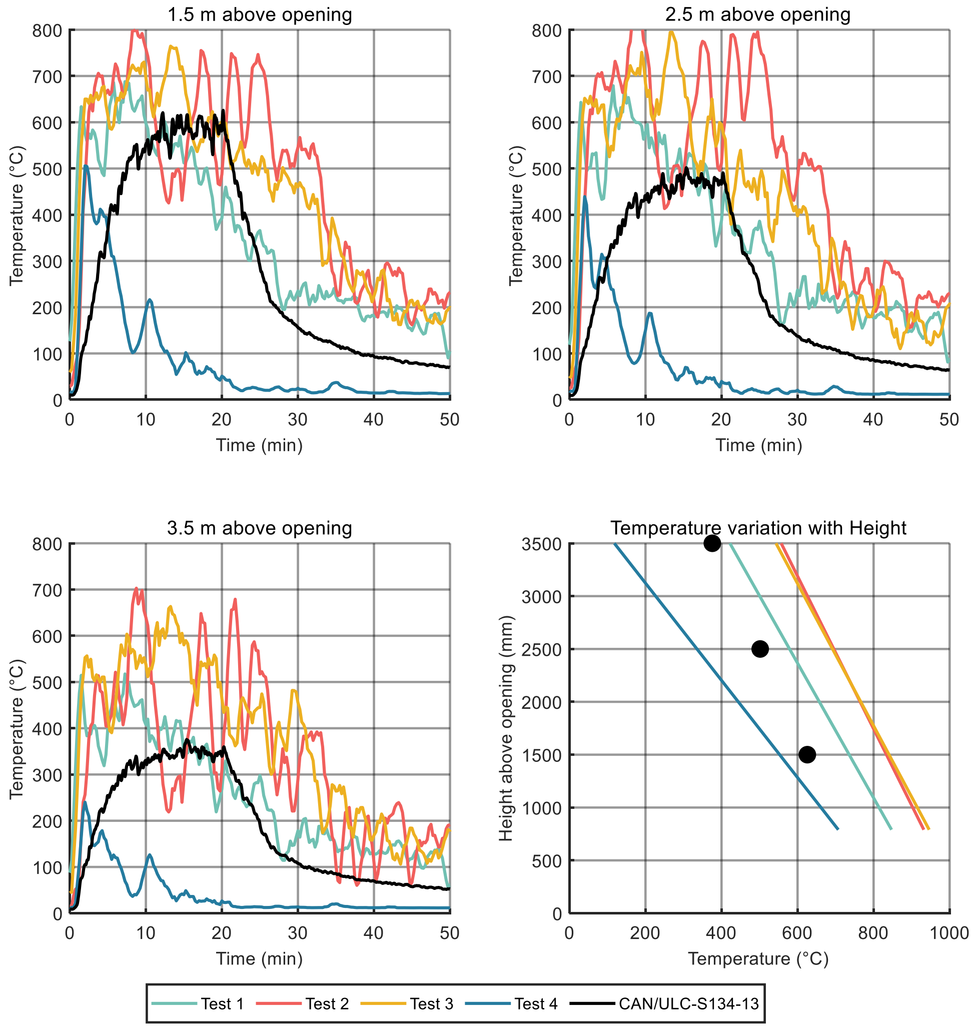


Figure 23. Comparison between TC temperatures from the CLT tests and a CAN/ULC-S134 test at varying hights.

6.2 Flame heights

To compare flame height and the facade exposure the same flame height analysis as for the CLT compartment tests is performed on a SP Fire 105 façade test on a lightweight concrete façade (Boström et al, 2016) and a BS 8414 test on a brick wall (Raketerm, 2020). The average flame height of SP Fire 105 is on par with Test 3 and the first two minutes of test 4, thus it is lower than the other small opening tests (Figure 24). However, the BS 8414 test is completely in line with observed flame heights of test 2 and 5.

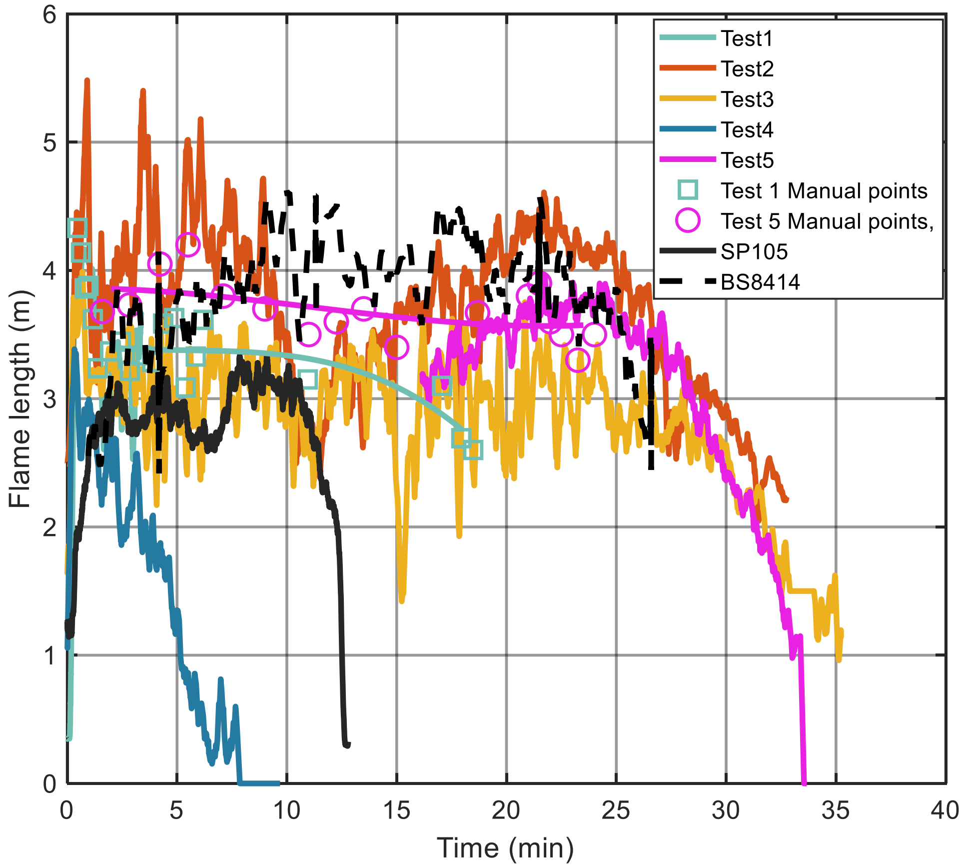


Figure 24. Flame height comparison including SP Fire 105 and BS 8414 compliance test. The BS 8414 test has no data until *t* =5 minutes.

6.3 Irradiation from the opening

Comparison of the radiant HFs opposite the compartment openings, the maximums of which can be seen in section 5.4, can be made against the limits set for external fire spread between buildings for various jurisdictions. A selection of the regulatory, or of "deemed to comply" guidance, are as follows:

- 15 kW/m² for at least 30 minutes at the relevant boundary– Sweden, *Boverket's general recommendations on the analytical design of a building's fire protection* (Boverket 2014)
- 12.5 kW/m² at the relevant boundary – United Kingdom, BR 187 (Chitty 2014).
- 30 kW/m² at the relevant boundary, and 16 kW/m² 1 m beyond it - New Zealand, NZ Building regulations (New Zealand Building Regulations 1992)
- Exposure to adjacent building based on a limit of 12.5 kW/m² - USA NFPA 80A (NFPA 2017)

Comparison of the heat flux time-histories (averaged across the two openings) with the limits for Sweden and the UK/NFPA as noted above can be seen for 4.8 and 8 m from the opening in Figure 25.

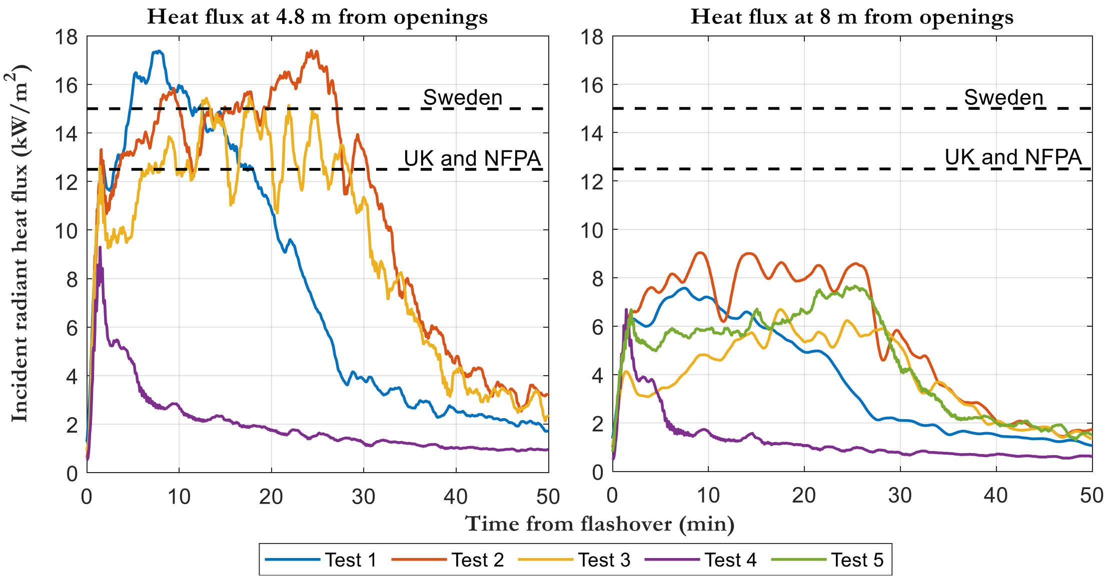


Figure 25. Comparison of the incident radiant heat flux recorded in front of the openings against regulatory limits (at the site boundary) for Sweden, UK and US (under NFPA guidance).

7 Discussion

The data collected here serves as a reference point of thermal exposures to façade from a few realistic but severe natural fires scenarios. The data will be publicly available at the following website: (https://www.ri.se/en/what-we-do/projects/fire-safe-implementation-of-mass-timber-in-tall-buildings). External fire plumes differ between different scenarios and the tests performed here only represent examples of four residential fire and one of an open plan office space. However, the designs of the tests are such that they represent severe cases, not only for the mass timber within the compartment but also for the external fire plume and its effect on the façade. See Annex A for a continued discussion on this topic.

When comparing the temperatures of TCs and PTs on the façade during these experiments and the standard assessment methods, it is clear that the range is wide between the different assessment methods. However, a test method does not necessarily have to represent a real scenario to be able to assess if a product is deemed safe to use or not. Assessment criteria can be chosen in relation to the impact on the specimen and therefore a "representative" test is not imperative. On the other hand, the acceptance of an assessment method is more easily obtained the closer the conditions of the test are to a real scenario and the rational to assess at a much lower exposure can be difficult to describe. The normal ways to determine criteria for a lower exposure are to correlate smaller exposure tests to larger exposure ones or to correlate smaller exposure tests to real fires. This type of data is not available for façade fire assessment and the importance that the fire exposure of such tests is representative for real fires has historically been highlighted (Law 1978).

The arguments above are the reasons many countries have chosen a "full-scale" method for assessing the façade performance in fires. However, it is therefore interesting to see how different the exposure to inert façades from the fire sources are between the different tests.

The duration of the test methods is usually around 20 minutes of high exposure, what would represent a fully developed phase. This is also the duration expected for the ventilation-controlled phase of these conducted tests had all mass timber surfaces been protected (Brandon et al, 2021). The SP Fire 105 method, with about 10 minutes of high exposure, is significantly shorter than e.g. the BS 8414 or the methods from North America while the Lepir II test is intermediate between these. The shape of the temperature evolution in the Lepir II test actually has the highest similarity to the compartment tests, although shifted to lower values (Figure 21). All other tests increase the exposure to the façade throughout the high intensity period. Since the compartment tests presented here involve a high degree of exposed mass timber, which chars most rapidly at the very start of the flashover, the tests have a peak followed by a decrease of external flaming with their maximum just after flashover. Contrarily, external flaming of the standardised test methods generally does not show the same decrease but could instead increase with time due to a hotter combustion chamber. In the NFPA 285 test the mass flow of the propane is even controlled to increase throughout the test (section 4.3).

In terms of the actual temperature readings on the façade, the PT temperatures which are closely related to the adiabatic surface temperature (AST) of the exposed façade, are highly similar between the compartment tests, the BS 8414 and the proposed European method. Thus, these tests assess the façade performance close to the conditions in these compartment fires. However, it is also noticed that the TC temperatures in the BS 8414 test is significantly higher throughout the test compared to those of the compartment tests (Figure 19). Since the TC is more sensitive to the actual gas temperature and velocity compared to a PT or an exposed façade surface, this indicates that the actual gas temperatures in the plume over the BS 8414 combustion chamber is higher compared the compartment tests. Concurrently, the exposure from the radiation of the flame is more severe in the compartment tests, which produce a thicker flame due to the larger amount of combustion. Note though, that for the combination radiation and convection, the PT temperatures are more relevant to the façade temperature itself than the small TC probes, as can be seen from the AST (Annex C).

The flame height of the compartment tests, between 3 and 4.5 m above the opening during the fully developed phase, is closer to the observed flame height of the SP Fire 105 test (around 3 m) than what was found when comparing temperatures. In line with observations on TC and PT temperatures, the BS 8414 test on the other hand exhibited a ~20 minutes long period with flame heights reaching 4 ± 0.5 m (Figure 24). This was in line with test 2 and 5 of the compartment test, which are the tests with much exposed mass timber (91 and 97 m^2, corresponding to almost the full ceiling and two full walls) and marginal wind during the tests. Similar results are found from visible observations on other façade claddings with low involvement in the fire (Dincel, 2019).

The incident radiant heat fluxes from the openings at 4.8 m from the opening reach maximum values which, for the small opening tests, exceeds both the UK, US and Swedish regulatory limits. At 8 m distance the calculated irradiances clearly fall under the limits. These limits are the maximum allowable heat flux to an adjacent site boundary (or typically half-way between buildings on the same site).

Comparisons between the façade exposure of Test 1 with the exposures of Test 2, 3 and 5, give an indication of the influence of the area of exposed mass timber on the façade fire exposure. Test 2, 3 and 5 had 37 m^2 to 43 m^2 more surface area of exposed mass timber than Test 1, which equates to an increase of roughly 70-80 %. The average temperatures measured between 10 and 20 minutes after flashover, increased by 100 to 130°C at all measured heights up to 3.5 m above the top of the opening (10-20 % larger temperature increase). Alternatively, this shift could be represented by shifting the TC temperatures vertically (Figure 14) which results in that the temperatures registered at a certain height for Test 1 are registered 0.65-0.85 m further up on the façade for test 2 and 3. The height difference involved in exposing more mass timber surfaces are also found for the fire plume height (Figure 17) which increases between 0 and 1 m for the first 20 minutes of the flashover (0-25 % increase). The fully developed phase (in which fire plumes were ejected from the compartment) was extended by 6 to 9 minutes, increasing the duration of the fire exposure by 30 – 40 %. As discussed in the analysis of Annex A, the opening width is in the low range of widths resulting from the survey. The effect of the exposed surface area of timber on the flame height is therefore on the high end of what could be expected in real buildings (Brandon & Andersson, 2018).

8 Conclusions

Façade extensions with roughly 60 measurements points were placed on top of 5 compartment tests which were designed to represent severe but realistic fire scenarios in residential and office mass timber buildings. The compartments had varying surface areas of exposed mass timber surfaces. The measurements and their locations matched those of several standard façade fire tests such that direct comparisons between temperature measurements on the façade between these tests and multiple standard assessment tests can be made. The data is available for download at the project website[2].

The following main conclusions can been drawn from the study:

- There is a large variation in the thermal exposure to façades at distinct heights above the openings in different full-scale façade tests for assessing compliance to national regulations.

- The proposed European method which is based on the British BS8414 method has a thermal impact which corresponds well to that found for the residential compartment tests presented here. In particular, the average plate thermometer temperatures (or the adiabatic surface temperatures) during the flashover phase are within 100 °C between the 3 more severe compartment tests (tests 2, 3 and 5) and the test standard (Figure 20). Also, the duration of the flashover phase for the standard method (23-30 min) coincides well with all residential compartment tests.

- The British method BS 8414 has close resemblance to the proposed European method and the exposure of this test is therefore also well in line with the compartment tests (Figure 19). Not only PT temperatures and duration but also flame heights are shown to be highly representative (Figure 24). The temperatures of thin TC are shown to be higher

[2] https://www.ri.se/en/what-we-do/projects/fire-safe-implementation-of-mass-timber-in-tall-buildings

than recorded in the tests but irradiation from the flames are larger for the compartment tests such that the PT temperatures agree.

- The French Lepir II test has a flashover phase of approximately 17 minutes which is lower than all the residential tests performed here but not far from that expected if no mass timber would have been exposed. The shape of the temperature evolution is, unlike all other tests, very similar between the Lepir II tests and the residential compartment tests with the highest exposure just after flashover (Figure 21). However, the temperatures are shifted to between 200 and 400 °C lower values at 1.3 m above the opening and 300 – 450 °C at 2 m height.

- SP Fire 105, which is used in Sweden and Norway, has the shortest duration of the high intensity period (~10 min). This is less than half of the flashover phase form the residential compartment tests. The temperatures measured on the façade is 200 – 300 °C lower in the assessment method compared to the residential compartments (Figure 22) although the flame heights are closing in on the lower end of those from the compartment testing (Figure 24).

- The North American NFPA 285 tests, mostly used in USA, exhibits a significant increase of the external temperatures during the 30 minutes exposure as exemplified in Figure 18. Peak TC temperatures are in the lower part of the average TC temperatures in the flashover phase of the compartment tests. Variations with height follow the same dependence as those of the compartment test.

- CAN/ULC-S134, the method predominantly used in Canada, exhibits a faster growth in temperatures compared to NFPA 285 and the TCs above the combustion chamber reach higher temperatures earlier than NFPA 285. Maximum intensity is however reached after only 20 minutes of testing followed by a five minutes cooling phase. The TC temperatures from the test are generally cooler than the compartment tests, coinciding with test 1 (the test with only ceiling and beam of exposed mass timber) after 15 minutes into the test (Figure 23)

- An increased surface area of exposed mass timber can increase the fire plume height and the temperature exposure to the façade. In the tested setup, an increase of roughly 40 m^2 exposed surface area (from ~54 to ~94 m^2 or from 113 % to 196 % of the floor area) resulted in a temperature increase of roughly 100 to 130 °C at the façade at all heights up to 3.5 m above the opening. Equivalently, the recorded temperatures are shifted 0.65 to 0.85 m up along the façade (Figure 14). Likewise, the increased exposed surface area yields an increased fire plume height of 0 to 1.0 m was observed (Figure 17). The main effect of the increased exposed area is the longer flashover phase (22 to ~30 minutes).

- A typical open plan office space will generate fire plumes which are well below those from characteristic residential compartment fires. The flashover phase will be significantly shorter, in the example here only 5 minutes, and the temperatures lower. All standard tests that are used for comparison in this report exhibit higher and longer exposure to the external façade compared to the office compartment test.

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Annex A – On the design of the fire tests

As described above, the aim of the tests was not to create a fire plume specifically severe for the façade above the opening but to design compartment fires which were severe in terms of expected damages to the mass timber in the compartment. This Annex serves to dwell on the chosen parameters from Brandon et al (2021) and how representative these can be in terms of exposure to the façade in modern buildings.

The area of the compartments was chosen based on the mean value from the statistical survey of Bwalya et al (2010). The moveable fuel load density (FLD) that was chosen for the experiments was 560 MJ/m^2, representing the 75^{th} percentile of 515 dwellings from the same study, Figure 2. Other values can of course be found for dwellings around the world and from different decades, a few examples are given below (Table A1). The design value for this study is very much in the scope of many empirical studies, slightly larger than the tests performed for the last code change of the IBC (Zelinka et al, 2018; Su et al, 2018) and larger than the median of all known mass timber compartment tests performed to date (Brandon, 2018). On the other hand, it is lower compared to e.g. the design value from Eurocode 1 annex E (mean value 780 MJ/m^2) or the design value for Swedish dwellings (Boverket states that design values for dwellings have FLD of *less than* 800 MJ/m^2 for simplified design or that the 80% percentile of the FLD-distribution should be 750 MJ/m^2).

Table A1. Mean fuel load densities reported in the literature (reproduced from Bwalya et al (2010).

Country	**Fuel load (MJ/m^2)**	**size of the survey (*n*) and type of room**	**Year & Reference**
US	450	*n* = 200 basement recreation rooms	1980 (Harmathy & Mehaffey, 1983)
US	500	*n* = 70 residential recreation rooms	1980 (Harmathy & Mehaffey, 1983)
US	500	-	1986, (Thomas, 1986)
Japan	670	214 homes	1965 – 1988 (Kose et al 1988)
Canada	410	598 main floor living rooms	2004 (Bwalya, 2004)
New Zealand	400	Recommended value Building code	2001 (Buchanan, 2001)
Eurocode 1	780	Mean value	2002

The severity, as per the damage to exposed timber surfaces within the compartment, was regulated using the opening factor after the fuel load density was fixed at 560 MJ/m^2 and the floor area at 49 m^2.

Not only the energy of the fuel but the composition of it will affect at which rate the fuel will burn. A thin and fast burning fuel (with a high pyrolysis rate) would most likely yield higher temperatures measured at the external façade but for a shorter duration compared to a thicker fuel. The fuel chosen here is from IKEA, the world's largest furniture retailer and the furniture was chosen to have a high energy content, such as the 106 kg (excl. any incombustible parts) *Friheten* couch. In addition, as 48 % of the energy was in the additional wood cribs and the wooden flooring, we take the composition of the fuel to be representative, and not overly severe for the external façade.

The opening of the structure is one of the most important factors for the exposure to the façade. The smaller the opening, the less oxygen enters the compartment and the more are the uncombusted pyrolysis products in the plume outside, igniting when exposed to the ambient air. The openings factors for the small opening tests correspond to the 25th percentile of the opening factors in the survey performed before the tests, Figure 2 (Brandon et al, 2021). However, not only the opening factors determine the size of the fire plume, the distribution of heights and width also play a role where narrower openings produce a taller fire plume. Thus, even compartments with identical linings and fuel load, no wind and same opening factor will, in theory, experience different thermal exposure to the external façade if the openings are distributed differently. The effective width of the openings in tests 1, 2, 3 and 5 was 4.3 m (taking into account the gypsum protection of the opening inner surfaces) which corresponds to the 22nd percentile of all 698 residential building in the survey (10th percentile of the mass timber compartments) (Figure A1). It could thus be argued that the openings are such that they represent a severe case for the external façade both in terms of opening factor and in terms of effective width.

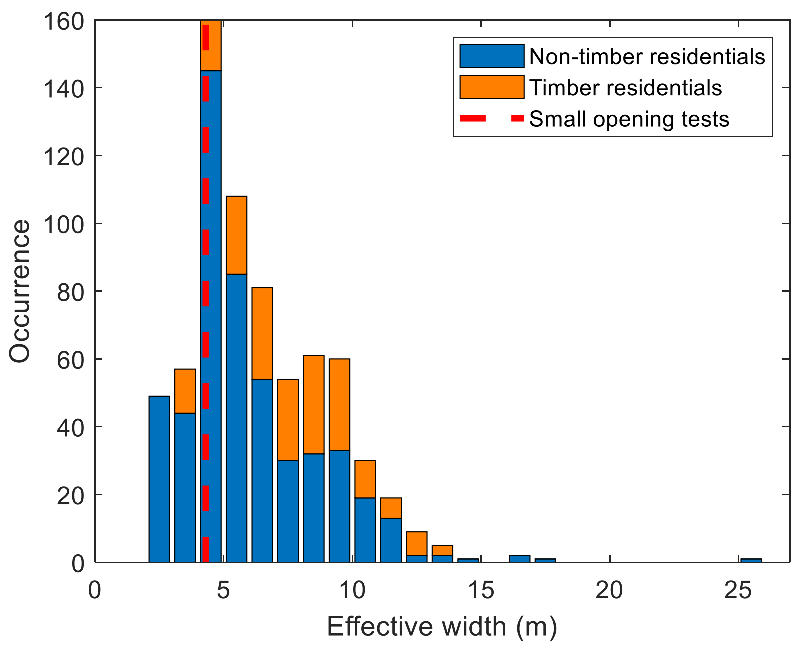

Figure A 1. The distribution of the effective widths of the openings for the 698 residential compartments in the survey by Brandon et al (2021) and the value for the small opening tests presented here.

Also, the exposed mass timber surfaces in the tests effectively act as additional fuel, with large surfaces which, during the flashover phase, produce extensive pyrolysis gases contributing to the external flaming. Additional live fuel corresponding to the same mass as the charred mass timber surfaces could however be argued to add more to the external flaming given the moisture content of the structure (13 %). The exposed surface areas were, in most tests, much larger than any recommendations for multi-storey dwellings and the HRR, which correlates positively to the façade exposure, was 550 ± 70 kW/m² for tests 2, 3 and 5 and 385 ± 35 kW/m² for test 1. This number can be compared with the maximum design HRR for dwellings in Eurocode 1, 250 kW/m².

The executions of the tests were only performed on days and times of days where low wind was forecasted and measured prior to the test. However, it was observed that an increased wind velocity and occasional wind gusts, directed approximately perpendicular to the open façade, lowered the average flame height, which is in agreement with previous studies discussed in Section 1.1.1. In addition to this after a wind gust passed, it was observed that after the fire plume height would increase again and can peak higher than the fire plume of tests with no or less strong wind gusts.

It is virtually impossible to quantify with a scalar just how severe the tests scenarios are for the façade exposure compared to that expected for the building population as a whole but given the individual discussions on fuel load density, opening factors, opening widths, HRR, exposed mass timber surfaces and wind we find these tests to be representative but clearly in the high severe range also with respect to façade exposure even though the designs were chosen based on severity for the mass timber itself.

Annex B – Instrumentation

This annex contains a detailed list of all instrumentation considered within this study, their types and locations.

Façade Measurements

The table below contains a full list of the thermocouple and plate thermometers, and their locations, used for measuring the exposure conditions to the façade above the openings. The origin for the X, Y and Z co-ordinates is the centre of the top of each respective opening. The X co-ordinate describes the distance left (-) or right (+) of the opening centreline; the Y co-ordinate describes the distance from the façade surface; the Z co-ordinate describes the height above the opening.

Description	Identifier	X (mm)	Y (mm)	Z (mm)	Type	Reference Test
External Façade Left TC1	TCEXL1		100	2337	Thick sheathed type K	Lepir II
External Façade Left TC2	TCEXL2	0	100	1418	Thick sheathed type K	Lepir II
External Façade Left TC3	TCEXL3	0	100	912	Thick sheathed type K	Lepir II
External Façade Left TC4	TCEXL4	0	25	915	Sheathed type K	NFPA
External Façade Left TC5	TCEXL5	0	25	1535	Sheathed type K	NFPA
External Façade Left TC6	TCEXL6	-500	50	2000	Sheathed type K	EU Test Proposal
External Façade Left TC7	TCEXL7	0	50	2000	Sheathed type K	EU Test Proposal
External Façade Left TC8	TCEXL8	500	50	2000	Sheathed type K	EU Test Proposal
External Façade Left TC9	TCEXL9	0	25	2450	Sheathed type K	NFPA
External Façade Left TC10	TCEXL10	-1000	50	2500	Sheathed type K	BS 8414
External Façade Left TC11	TCEXL11	-500	50	2500	Sheathed type K	BS 8414
External Façade Left TC12	TCEXL12	0	50	2500	Sheathed type K	BS 8414 - Canadian standard also has a TC here but against the wall's surface.
External Façade Left TC13	TCEXL13	500	50	2500	Sheathed type K	BS 8414
External Façade Left TC14	TCEXL14	1000	50	2500	Sheathed type K	BS 8414
External Façade Left TC15	TCEXL15	-610	25	3050	Sheathed type K	NFPA
External Façade Left TC16	TCEXL16	0	25	3050	Sheathed type K	NFPA
External Façade Left TC17	TCEXL17	610	25	3050	Sheathed type K	NFPA
External Façade Left TC18	TCEXL18	-1220		3050	Sheathed type K	NFPA
External Façade Left TC19	TCEXL19	1220		3050	Sheathed type K	NFPA

Description	Identifier	X (mm)	Y (mm)	Z (mm)	Type	Reference Test
External Façade Left TC20	TCEXL20	-500	50	3500	Sheathed type K	EU Test Proposal - Canadian standard also has a TC here but against the wall's surface.
External Façade Left TC21	TCEXL21	0	50	3500	Sheathed type K	EU Test Proposal - Canadian standard also has a TC here but against the wall's surface.
External Façade Left TC22	TCEXL22	500	50	3500	Sheathed type K	EU Test Proposal - Canadian standard also has a TC here but against the wall's surface.
External Façade Left TC23	TCEXL23	0	?	790	Sheathed type K	SP Fire/DBI
External Façade Left TC24	TCEXL24	1000	?	1290	Sheathed type K	SP Fire/DBI
External Façade Left TC25	TCEXL25	0	?	1790	Sheathed type K	SP Fire/DBI
External Façade Left PT 1 (flush)	PTEXL1	0	0	1250	PT	-
External Façade Left PT 2 (flush)	PTEXL2	500	0	1250	PT	-
External Façade Left PT 3 (flush)	PTEXL3	-500	0	1250	PT	-
External Façade Left PT 4 (flush)	PTEXL4	0	0	2100	PT	-
External Façade Right TC1	TCEXR1		100	2337	Thick sheathed type K	Lepir II
External Façade Right TC2	TCEXR2	0	100	1418	Thick sheathed type K	Lepir II
External Façade Right TC3	TCEXR3	0	100	912	Thick sheathed type K	Lepir II
External Façade Right TC4	TCEXR4	0	25	915	Sheathed type K	NFPA
External Façade Right TC5	TCEXR5	0	25	1535	Sheathed type K	NFPA
External Façade Right TC6	TCEXR6	-500	50	2000	Sheathed type K	EU Test Proposal
External Façade Right TC7	TCEXR7	0	50	2000	Sheathed type K	EU Test Proposal
External Façade Right TC8	TCEXR8	500	50	2000	Sheathed type K	EU Test Proposal
External Façade Right TC9	TCEXR9	0	25	2450	Sheathed type K	NFPA
External Façade Right TC10	TCEXR10	-1000	50	2500	Sheathed type K	BS 8414
External Façade Right TC11	TCEXR11	-500	50	2500	Sheathed type K	BS 8414

Description	Identifier	X (mm)	Y (mm)	Z (mm)	Type	Reference Test
External Façade Right TC12	TCEXR12	0	50	2500	Sheathed type K	BS 8414 - Canadian standard also has a TC here but against the wall's surface.
External Façade Right TC13	TCEXR13	500	50	2500	Sheathed type K	BS 8414
External Façade Right TC14	TCEXR14	1000	50	2500	Sheathed type K	BS 8414
External Façade Right TC15	TCEXR15	-610	25	3050	Sheathed type K	NFPA
External Façade Right TC16	TCEXR16	0	25	3050	Sheathed type K	NFPA
External Façade Right TC17	TCEXR17	610	25	3050	Sheathed type K	NFPA
External Façade Right TC18	TCEXR18	-1220		3050	Sheathed type K	NFPA
External Façade Right TC19	TCEXR19	1220		3050	Sheathed type K	NFPA
External Façade Right TC20	TCEXR20	-500	50	3500	Sheathed type K	EU Test Proposal - Canadian standard also has a TC here but against the wall's surface.
External Façade Right TC21	TCEXR21	0	50	3500	Sheathed type K	EU Test Proposal - Canadian standard also has a TC here but against the wall's surface.
External Façade Right TC22	TCEXR22	500	50	3500	Sheathed type K	EU Test Proposal - Canadian standard also has a TC here but against the wall's surface.
External Façade Right TC23	TCEXR23	0	?	790	Sheathed type K	SP Fire/DBI
External Façade Right TC24	TCEXR24	1000	?	1290	Sheathed type K	SP Fire/DBI
External Façade Right TC25	TCEXR25	0	?	1790	Sheathed type K	SP Fire/DBI
External Façade Right PT 1 (flush)	PTEXR1	0	0	1250	PT	-
External Façade Right PT 2 (flush)	PTEXR2	500	0	1250	PT	-
External Façade Right PT 3 (flush)	PTEXR3	-500	0	1250	PT	-
External Façade Right PT 4 (flush)	PTEXR4	0	0	2100	PT	-

Other Measurements

The table below lists the other measurement devices used for comparisons between the compartment fire and standardised façade fire tests. These are measurements external to the compartment, and the distance represents the horizontal distance from the respective opening, while the height refers to the height above compartment floor level.

Description	**Identifier**	**Distance (mm)**	**Height (mm)**	**Type**
Thermocouple tree Opening 1	TCT-O1-1		600	Sheathed type K
	TCT-O1-2		1000	Sheathed type K
	TCT-O1-3		1400	Sheathed type K
	TCT-O1-4		1800	Sheathed type K
	TCT-O1-5		2200	Sheathed type K
Thermocouple tree Opening 2	TCT-O2-1		600	Sheathed type K
	TCT-O2-2		1000	Sheathed type K
	TCT-O2-3		1400	Sheathed type K
	TCT-O2-4		1800	Sheathed type K
	TCT-O2-5		2200	Sheathed type K
Plate thermometer opening 1 close	PT-O1-cl	4800		Plate thermometer
Plate thermometer opening 1 far	PT-O1-fa	8000		Plate thermometer
Thermocouple PT opening 1 far	TCPT-O1-fa	8000		Glass fibre insulated type K
Plate thermometer opening 2 close	PT-O2-cl	4800		Plate thermometer
Plate thermometer opening 2 far	PT-O2-fa	8000		Plate thermometer
Test 4 left opening PT	T4-PT-O-L	4800		
Test 4 right opening PT	T4-PT-O-R	4800		

Annex C – Full Results

This annex contains a full set of the data utilised within this report for the first hour of each test after flashover. The data presented is not "raw" but has had some simple processing applied to improve its readability. The processing conducted is as follows:

- Resampling the data to every 0.25 s.
- Smoothing via a moving mean over a period of 5 samples (1 min 15 s).

Additionally, where there are clear malfunctions in the readings (e.g. due to a short-circuit in a thermocouple wire) these have been removed and are not presented.

The graphs presented are divided into three sections. First, the adiabatic surface temperatures, discussed in section 3.6.1, are displayed. Thereafter, all measurements of the façades in each tests are presented. Finally, measurement related to the openings (thermocouple trees and plate thermometers away from the openings) are presented.

Adiabatic surface temperatures (AST)

An example of the AST calculation at the position of PT2 in test 2 is given below. It is clear that the AST and PT only differ less than 20 °C in most of the stationary phase but that the TC temperature differ significantly from these. The temperature in the façade, behind the PT, (calculated as described in section 3.6.1) is lagging behind the surface or gas temperatures.

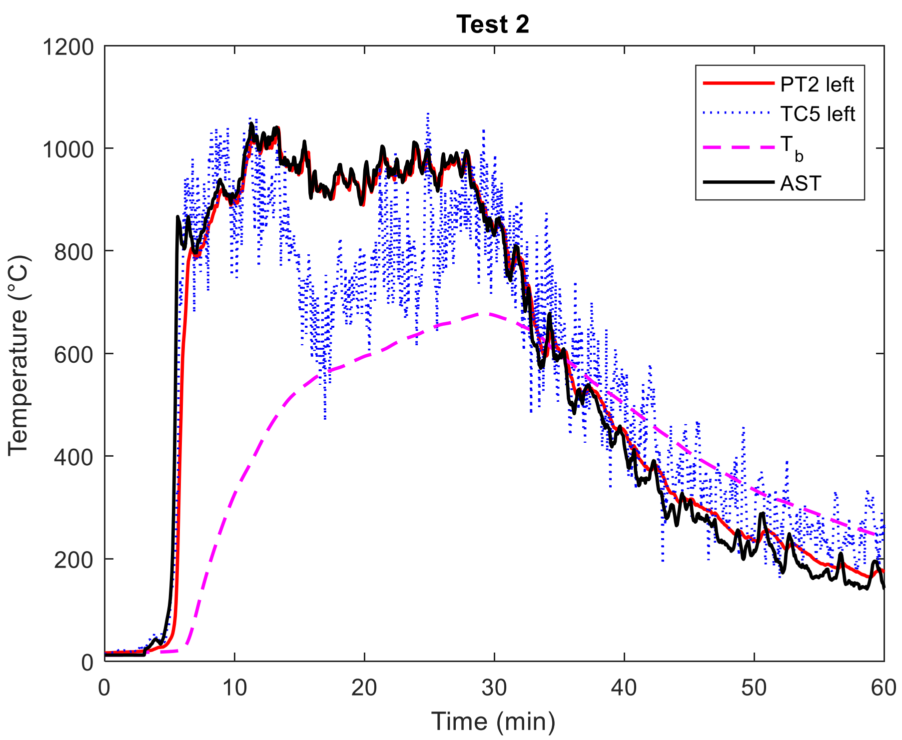

Figure A 2. Temperature of PT2 and the closest TC (TC5) on the left side of test 2. In the figure the calculated AST is also shown, almost overlaying the PT temperature. The temperature in the façade, behind the PT is represented by the dashed line.

The ASTs for all tests are shown in Figure A3. The figure closely resembles the PT diagrams (Figure 13). Also, the difference between calculated AST varying the input parameters K (0 – 10 W/m²K), h_c (20 – 100 W/m²K) and ε (0.8 – 0.9) is shown to yield only small variations in the assessment of AST.

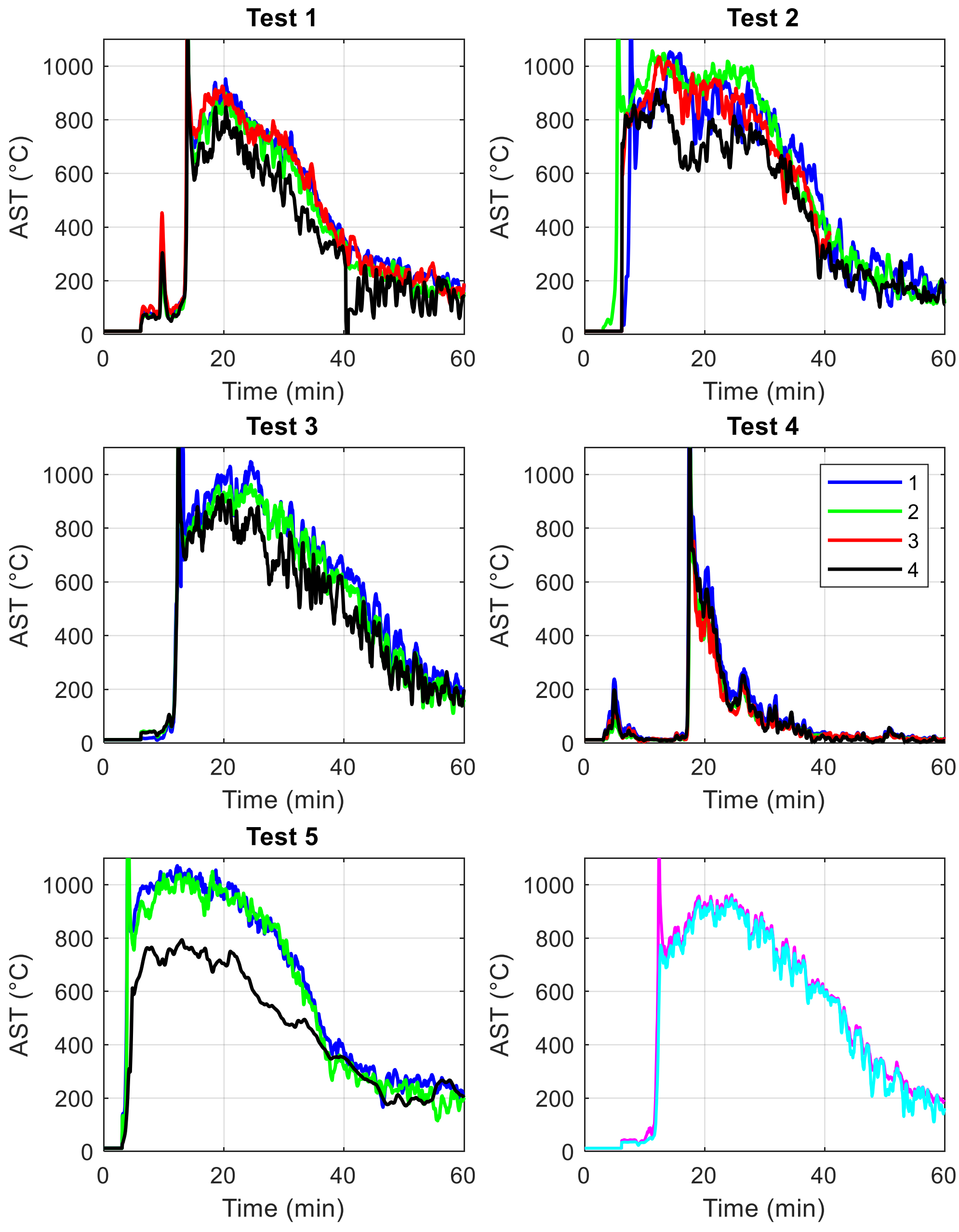

Figure A 3. Calculated AST for all PT locations in each test. The values are averages of the left and right position of each PT location and the legend refers to the denomination for the PT location (as in Figure 6). Lower left panel shows the maximum and minimum values of AST for test 2, PT2 (left).

Façade Measurements

The following graphs document the data measured via instrumentation on the façade (Thermocouples and Plate thermometers), as listed in Annex B "Façade Measurements" section.

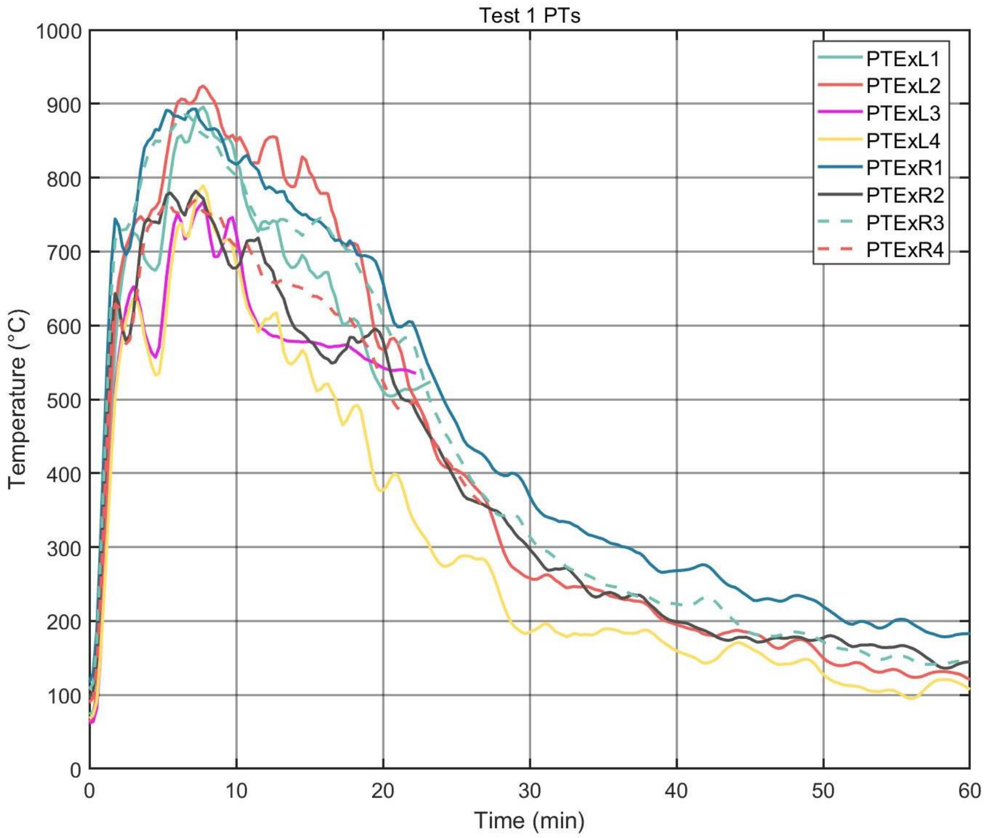

Figure A 4. PT temperatures of test 1. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening, respectively. See Annex B.

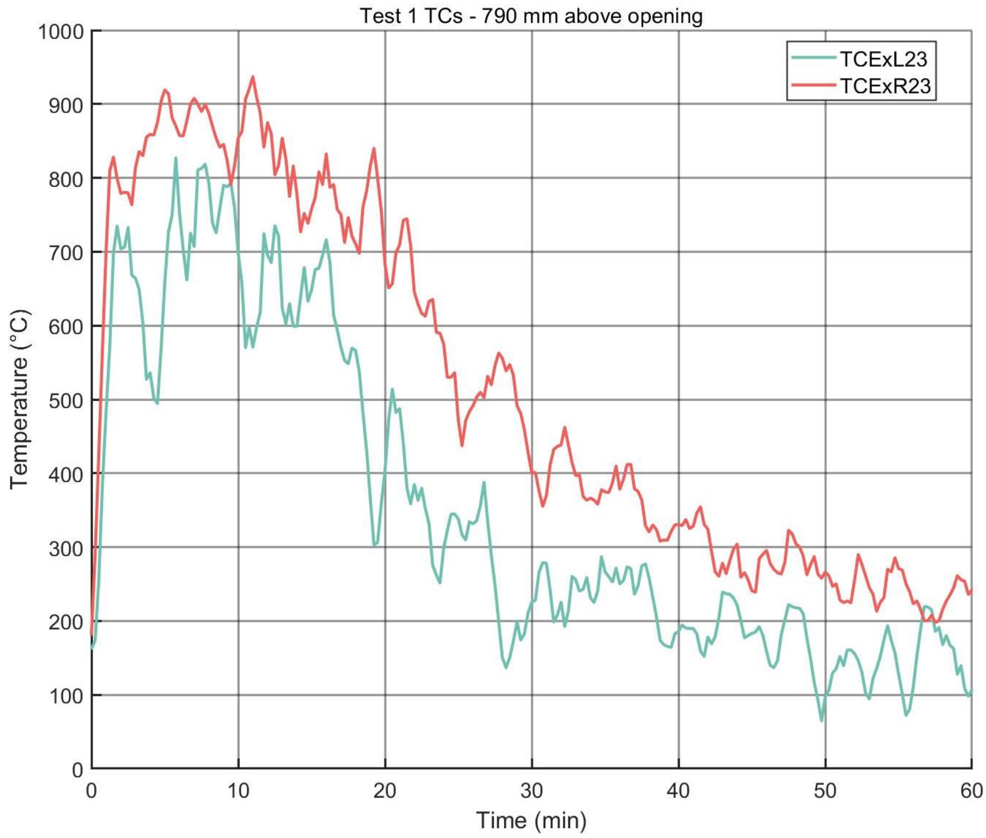

Figure A 5. TC temperatures of test 1 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

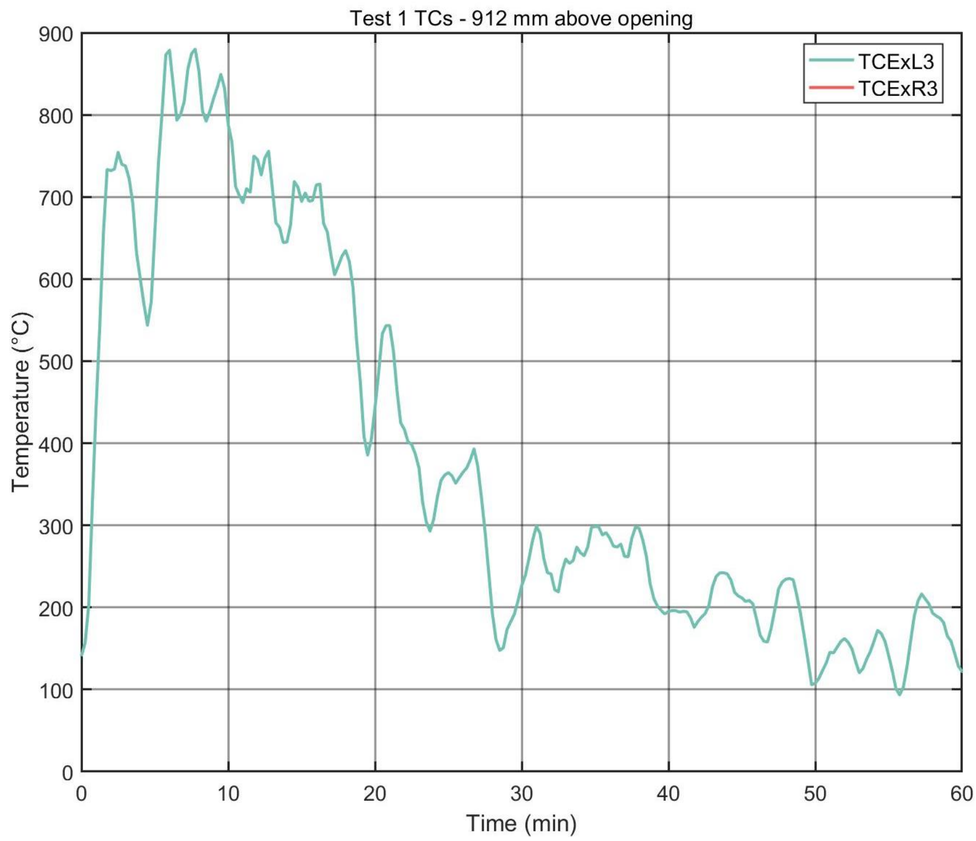

Figure A 6. TC temperatures of test 1 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

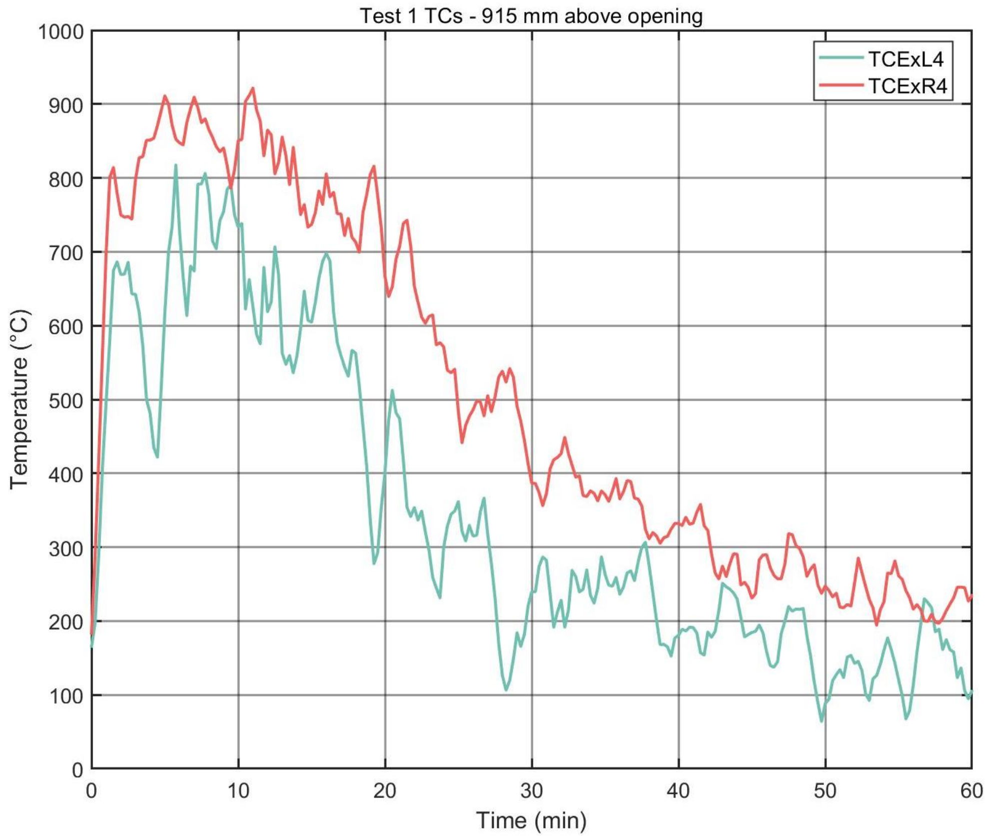

Figure A 7. TC temperatures of test 1 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

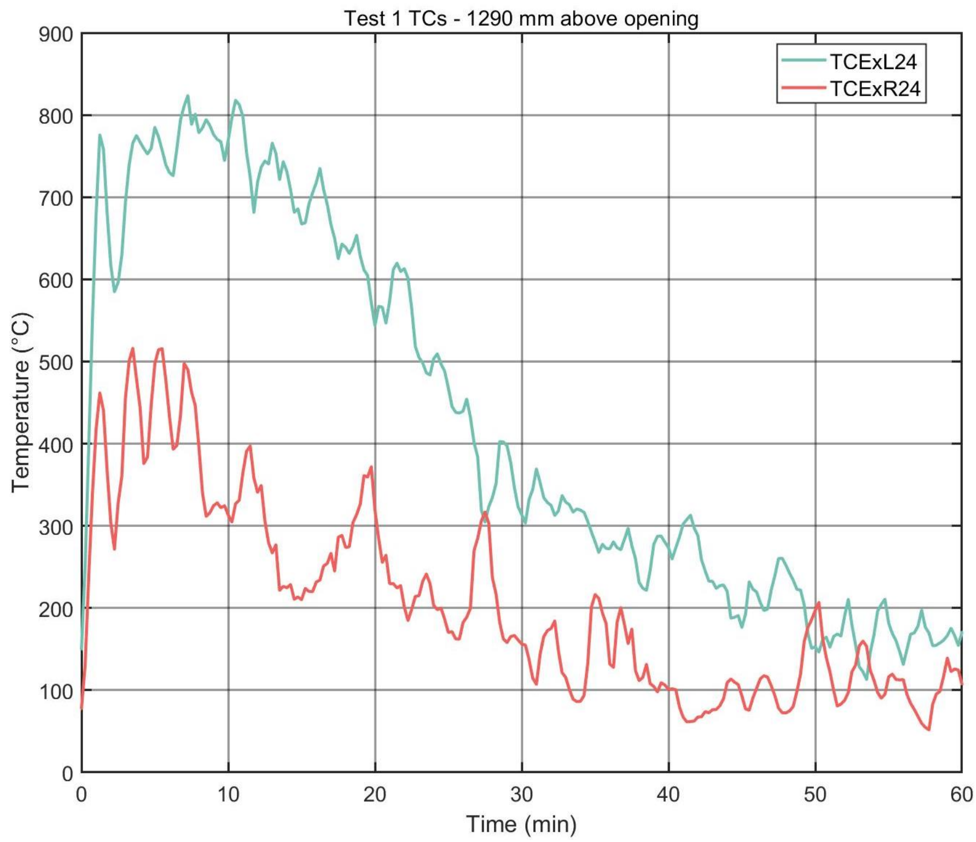

Figure A 8. TC temperatures of test 1 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

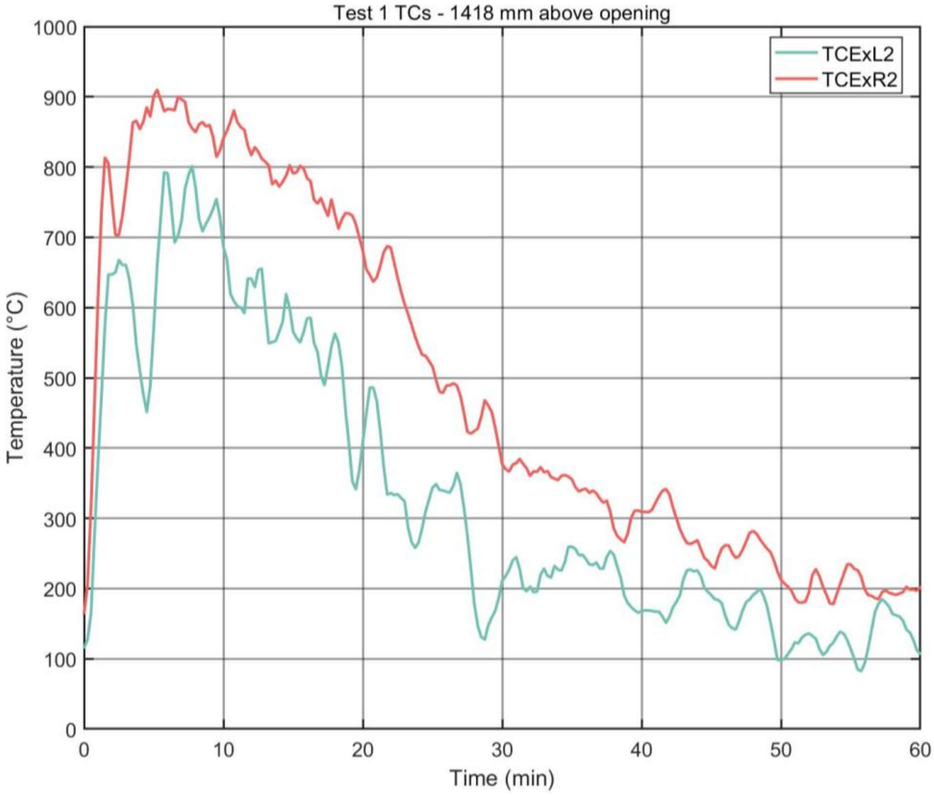

Figure A 9. TC temperatures of test 1 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

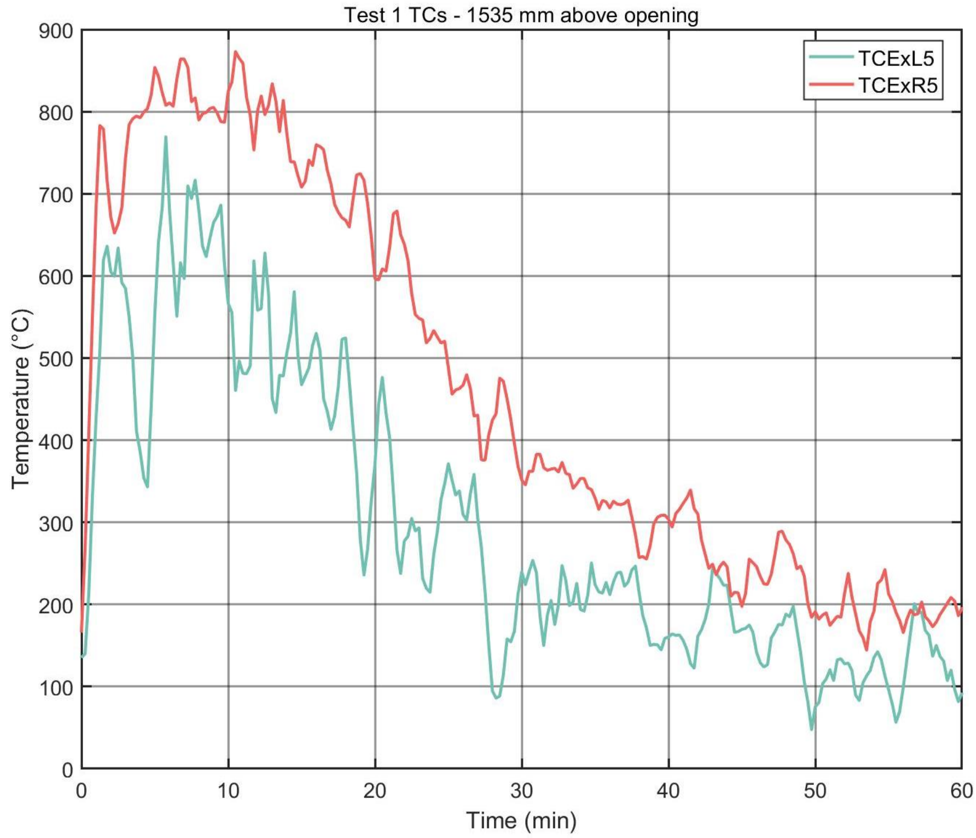

Figure A 10. TC temperatures of test 1 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

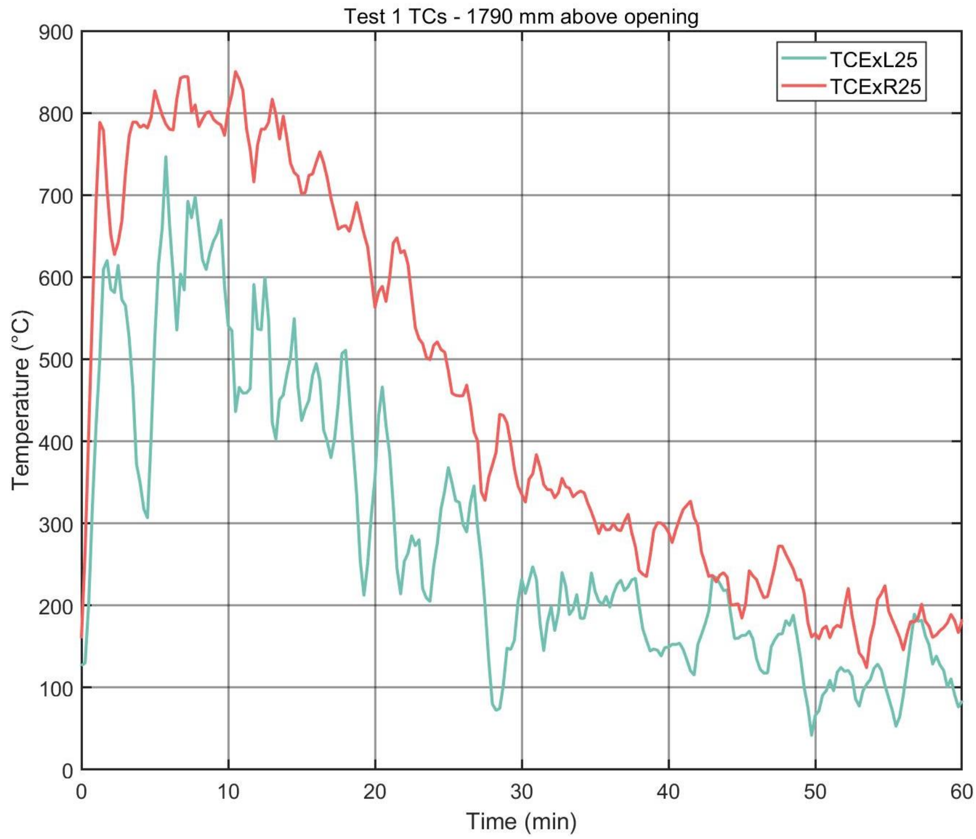

Figure A 11. TC temperatures of test 1 for comparisons to SP Fire 105. Ex refers to measurements being “external” (on façade), “L” and “R” refers to left and right opening. See Annex B.

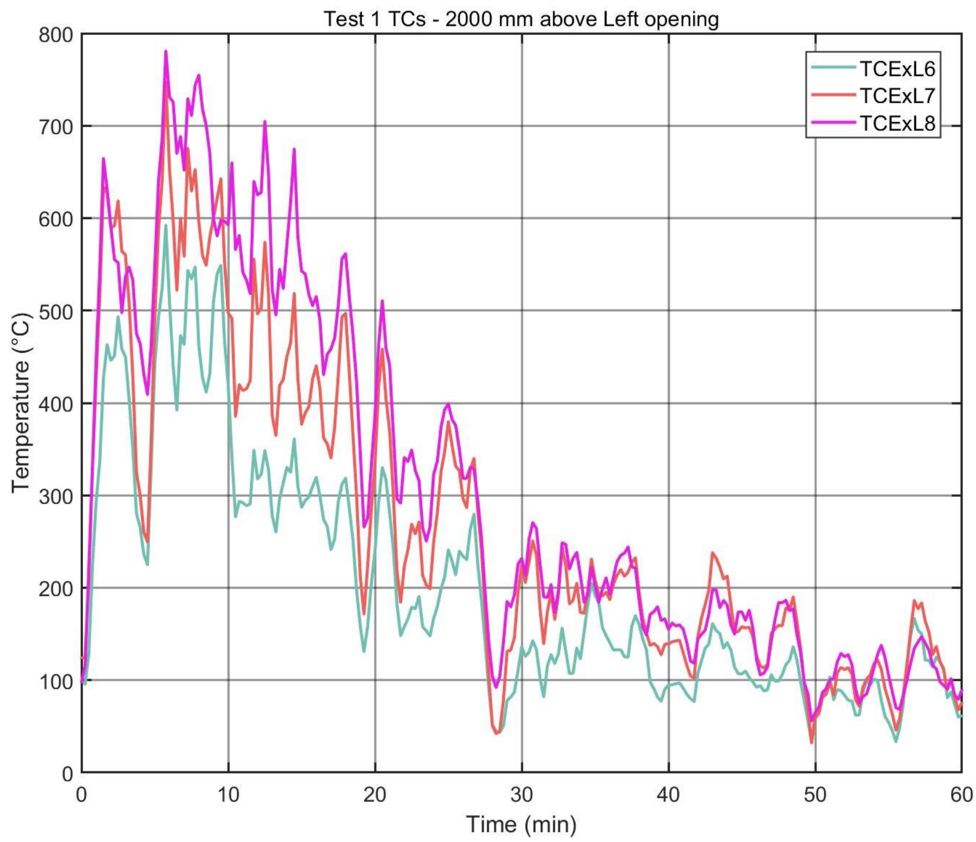

Figure A 12. TC temperatures of test 1 for comparisons to Proposed EU method. Ex refers to “external” (on façade), “L” refers to above left opening. See Annex B.

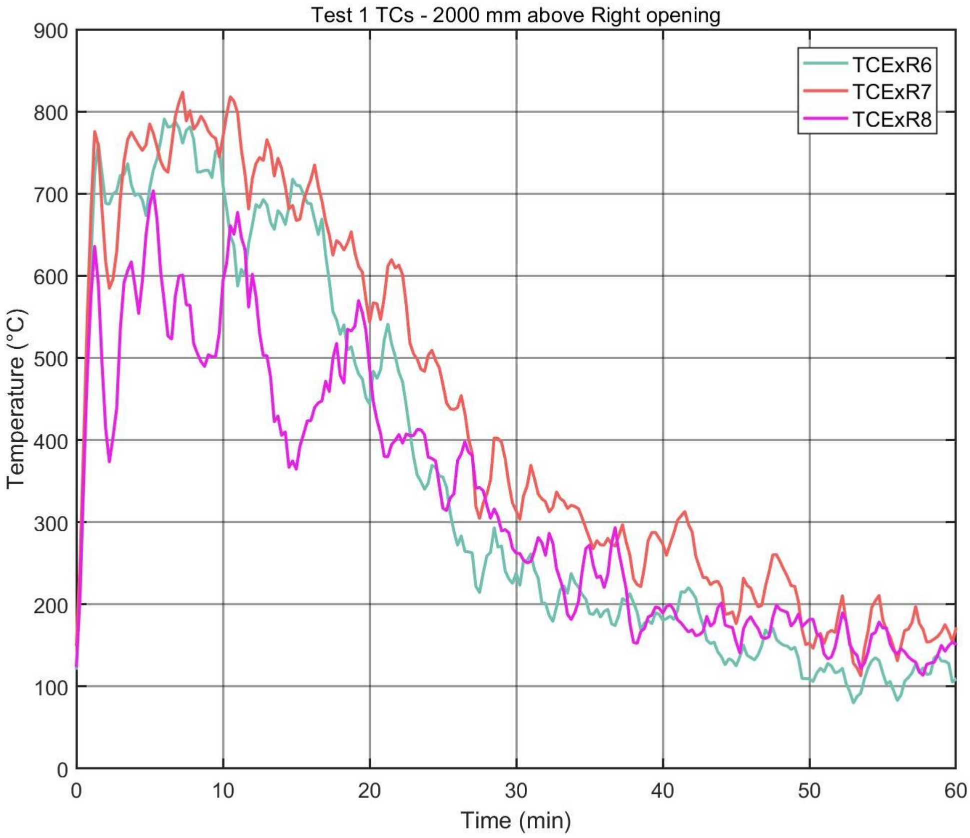

Figure A 13. TC temperatures of test 1 for comparisons to Proposed EU method. Ex refers to "external" (on façade), "R" refers to above right opening. See Annex B.

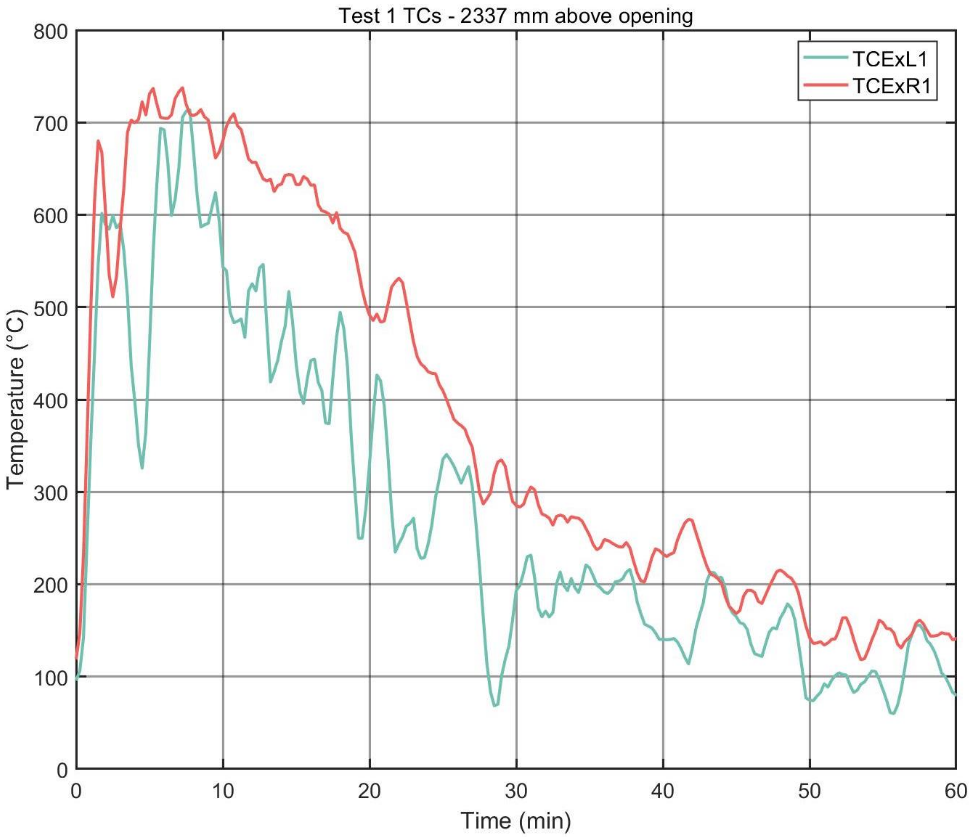

Figure A 14. TC temperatures of test 1 for comparisons to Lepir II. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

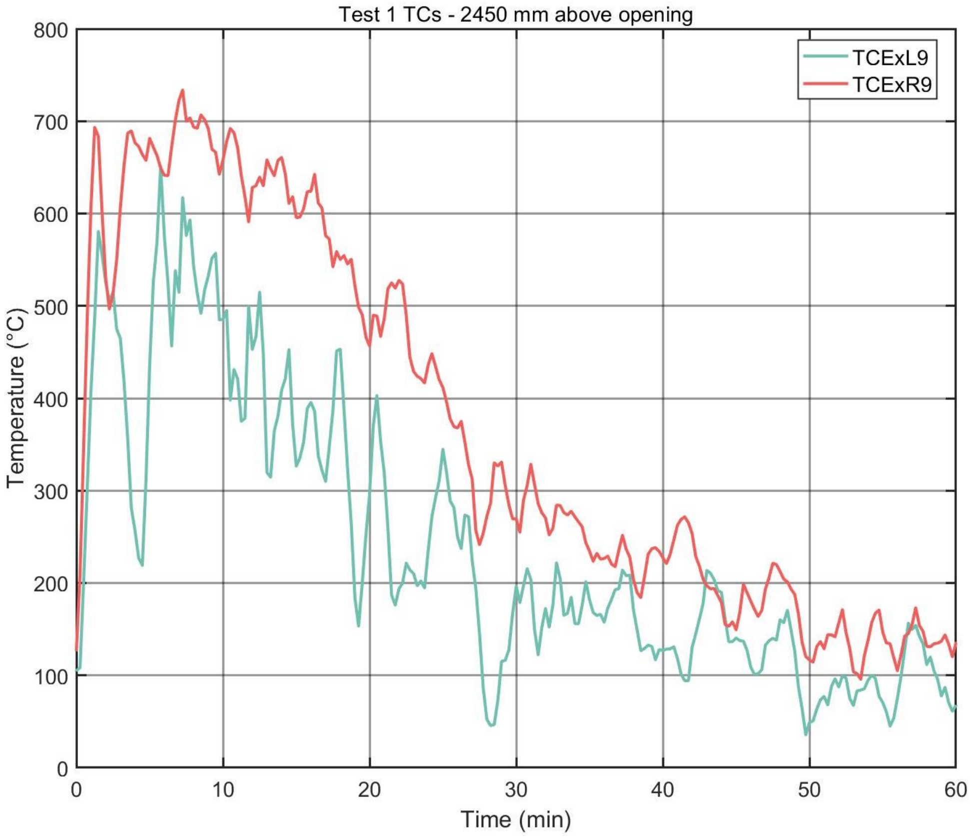

Figure A 15. TC temperatures of test 1 for comparisons to NFPA 285. Ex refers to “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

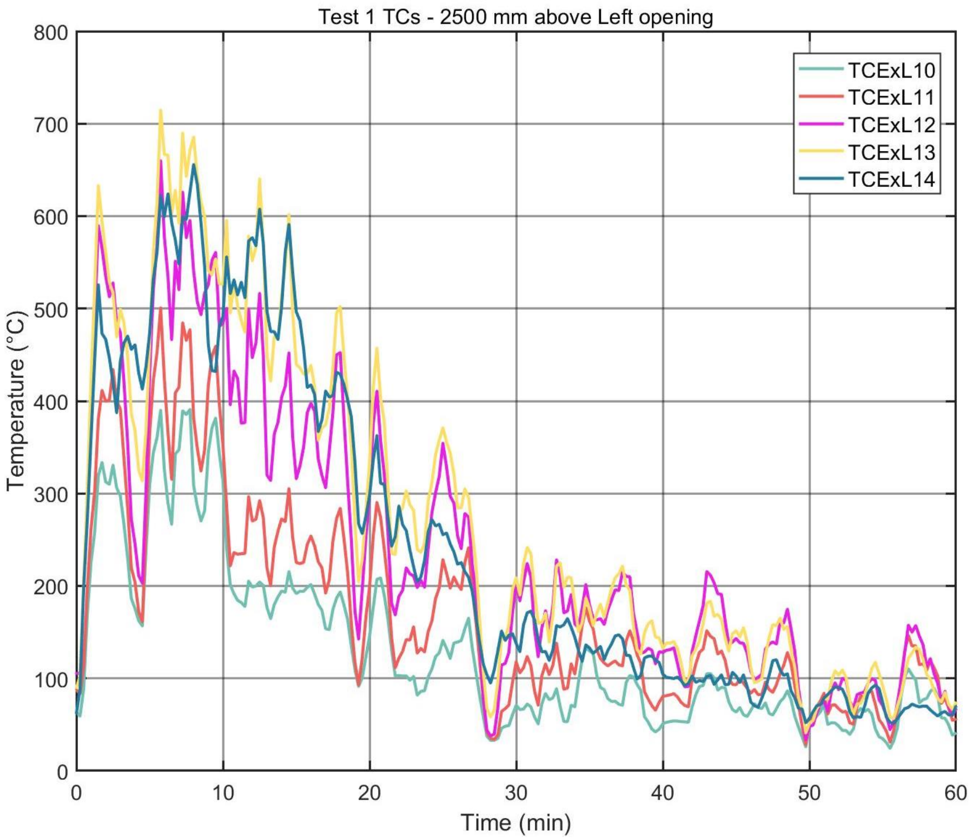

Figure A 16. TC temperatures of test 1 for comparisons to BS 8414. Ex refers “external” (on façade), “L” refers to above left opening. See Annex B.

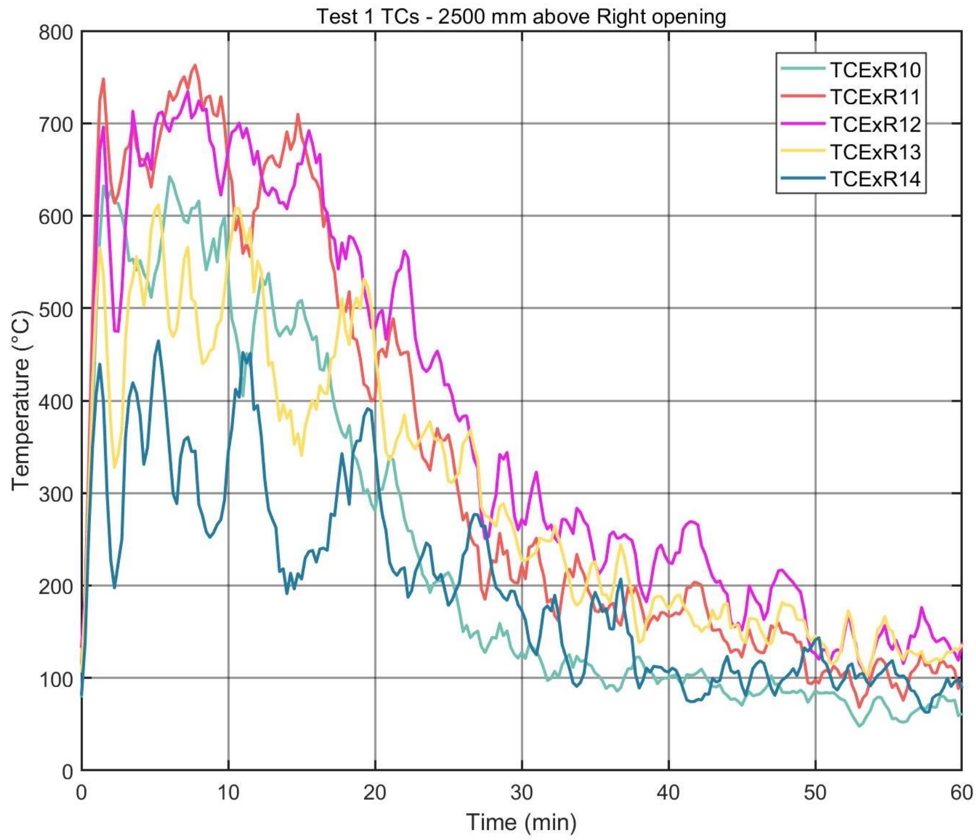

Figure A 17. TC temperatures of test 1 for comparisons to BS 8414. Ex refers "external" (on façade), "R" refers to above right opening. See Annex B.

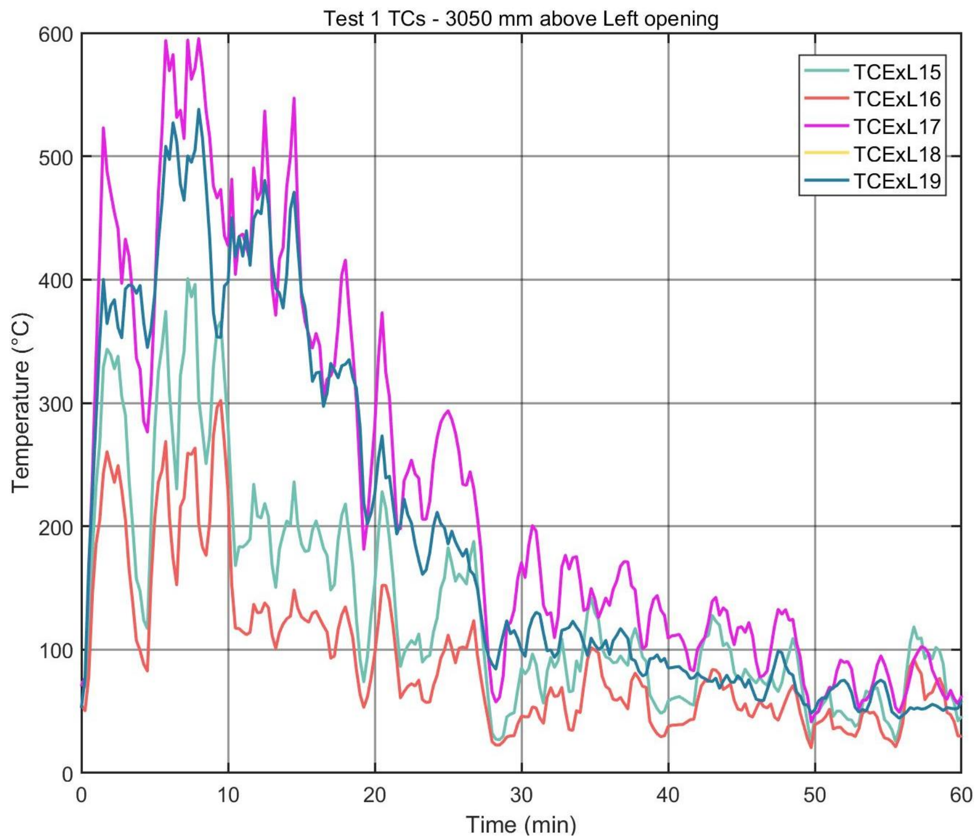

Figure A 18. TC temperatures of test 1 for comparisons to NFPA 285. Ex refers to measurements being "external" (on façade), "L" refers to above left opening. See Annex B. L16 is faulty

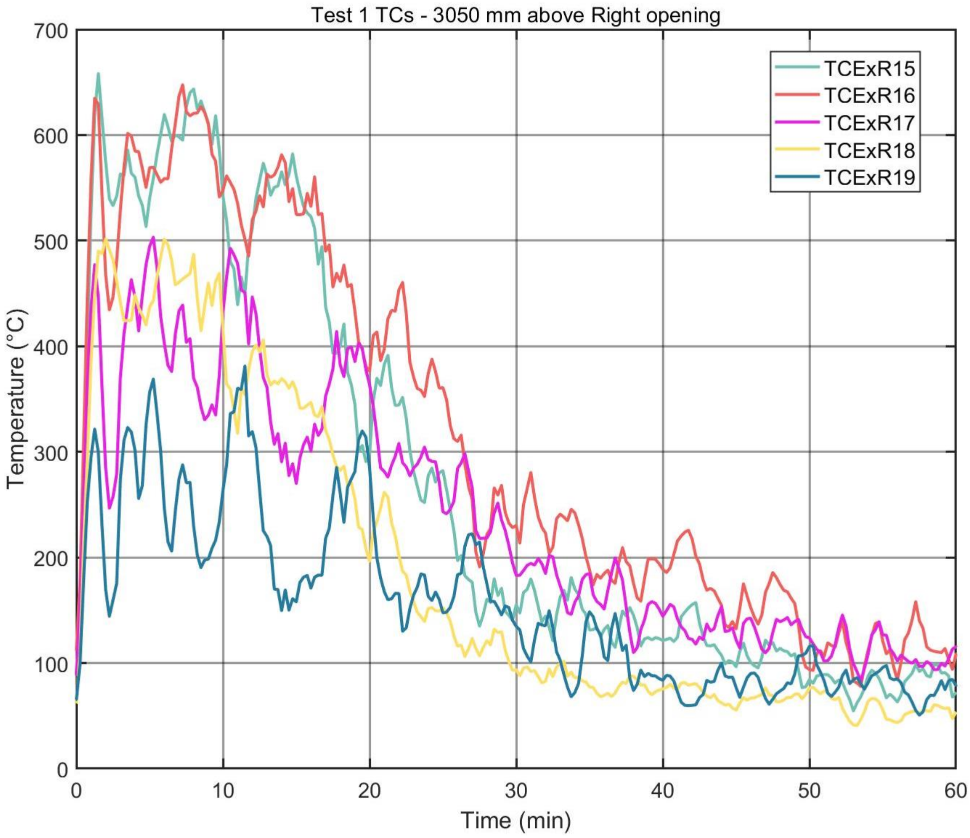

Figure A 19. TC temperatures, test 1 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

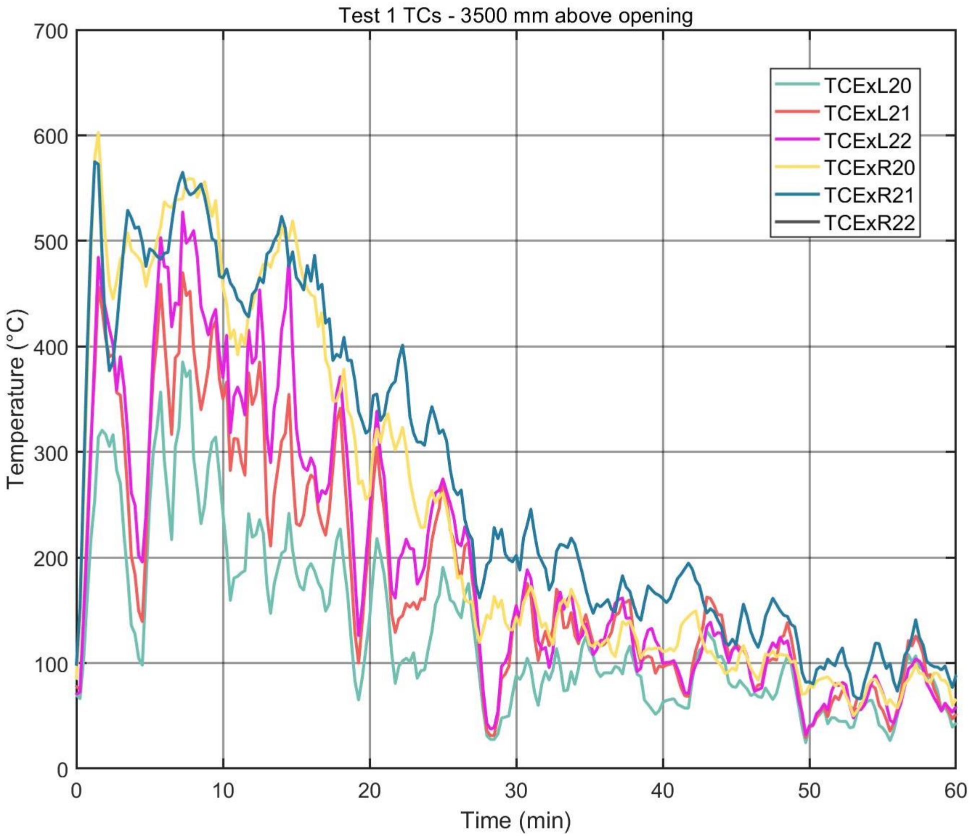

Figure A 20. TC temperatures of test 1 for comparisons to EU proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

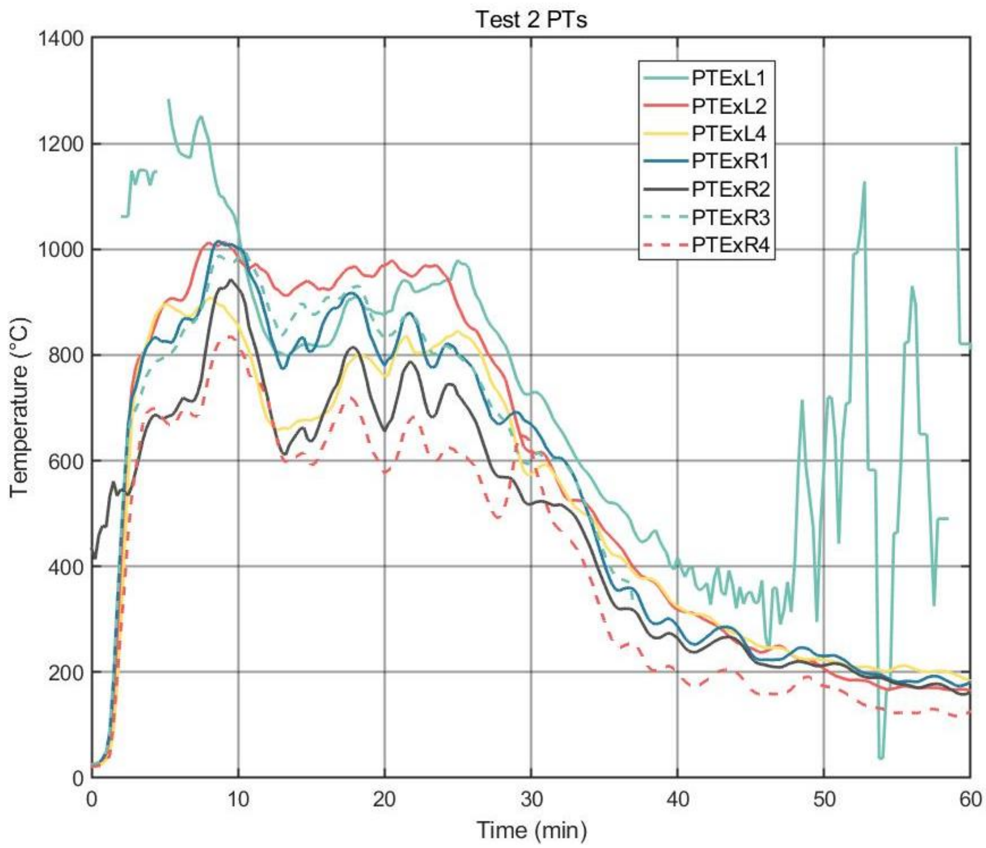

Figure A 21. PT temperatures of test 2. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

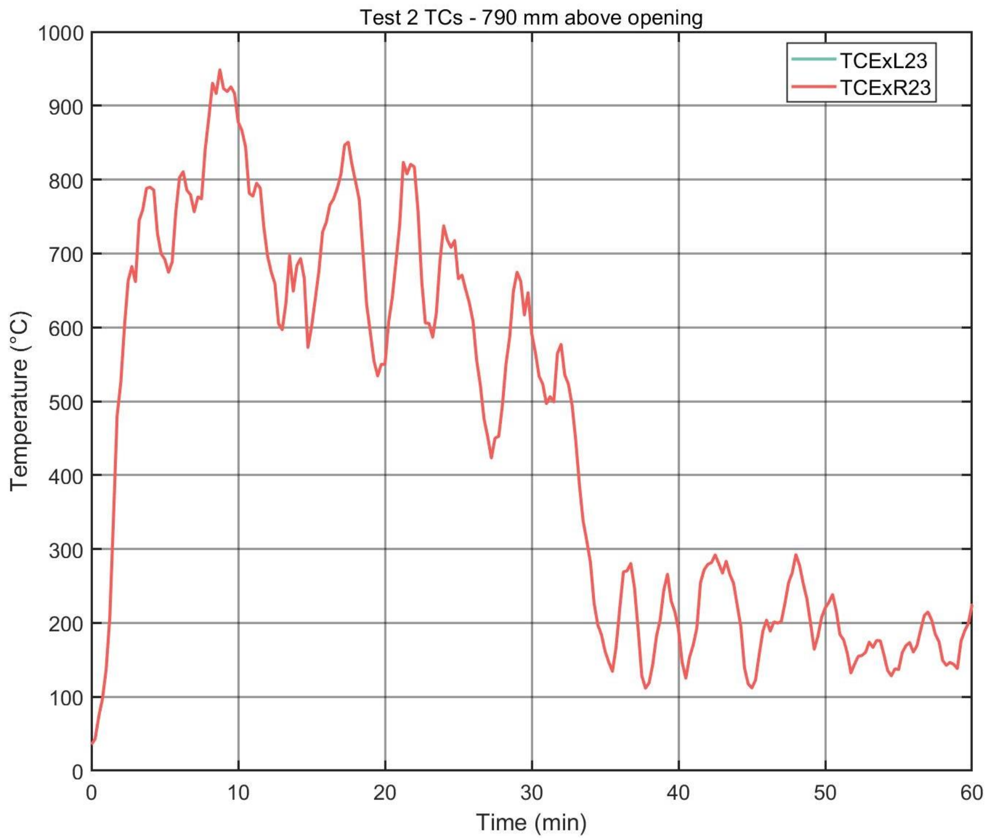

Figure A 22. TC temperatures of test 2 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

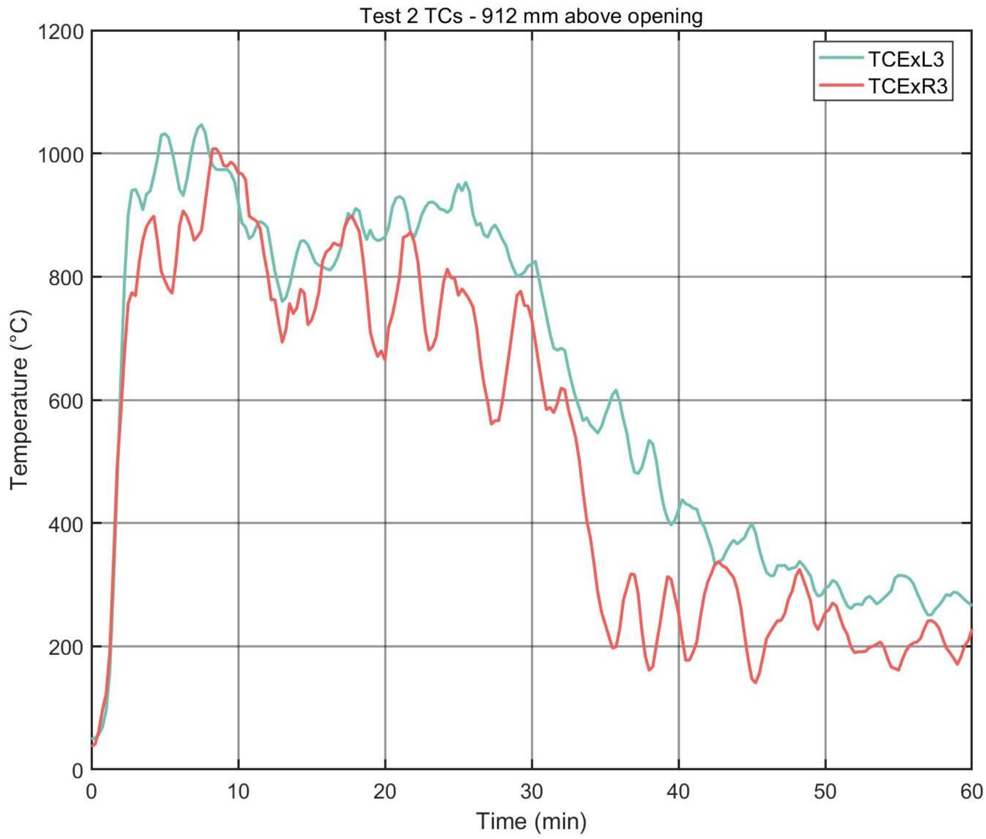

Figure A 23. TC temperatures, test 2 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

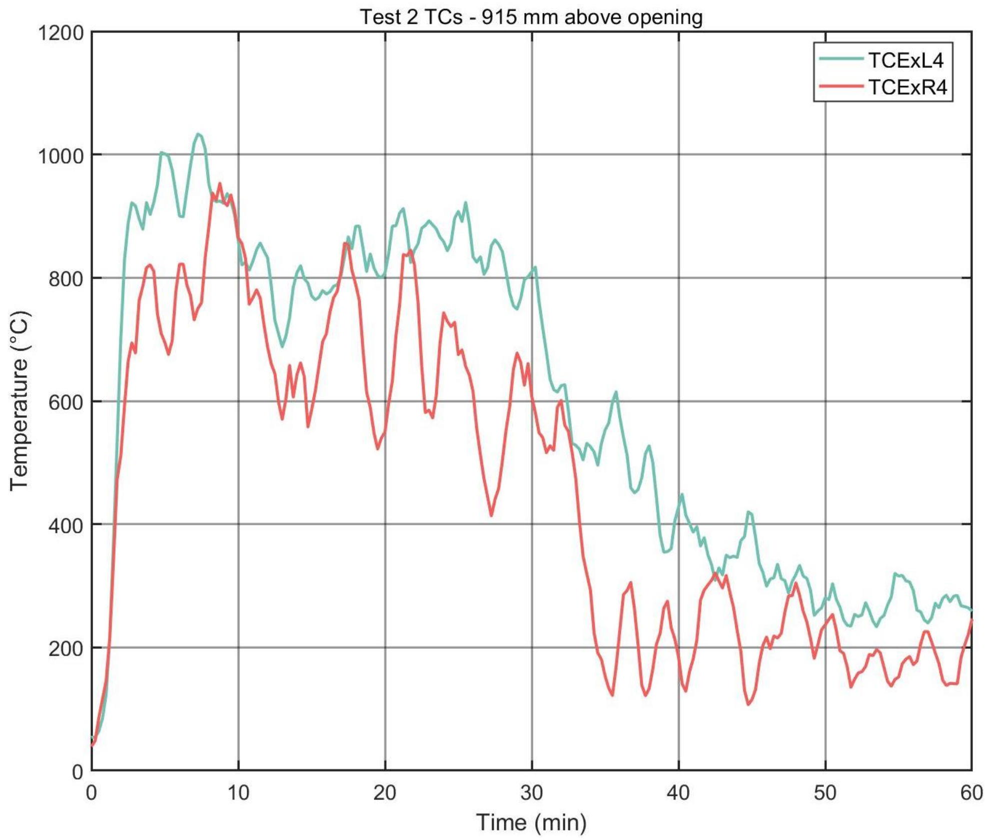

Figure A 24. TC temperatures, test 2 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

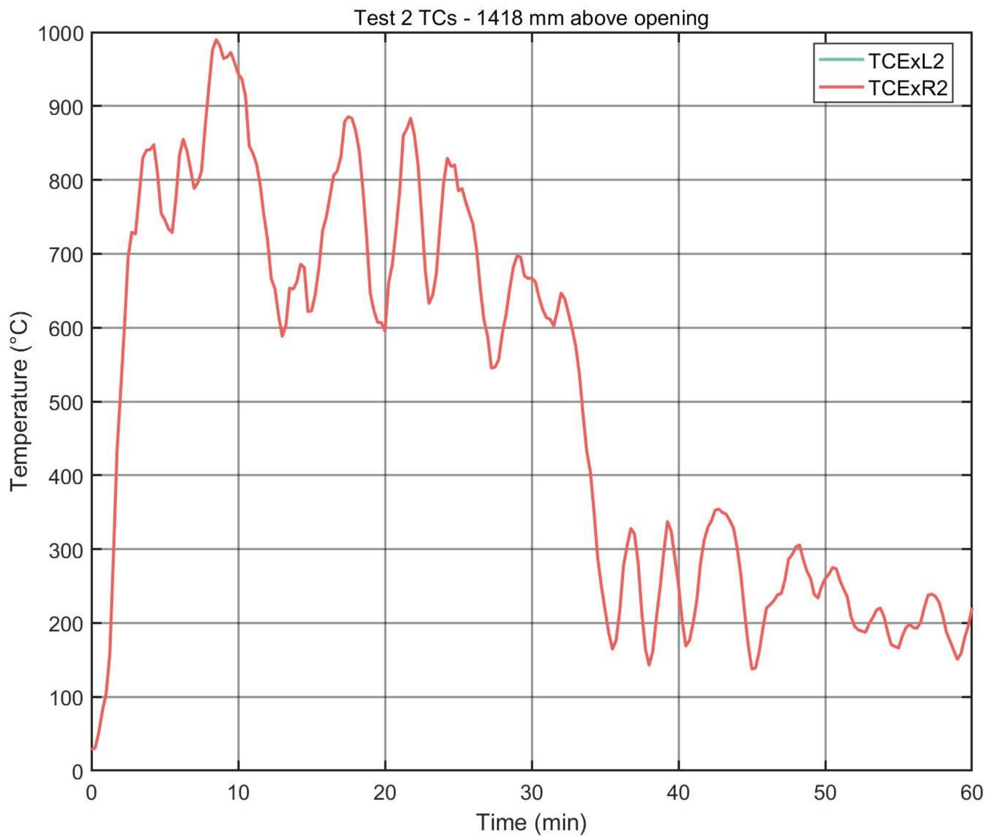

Figure A 25. TC temperatures, test 2 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

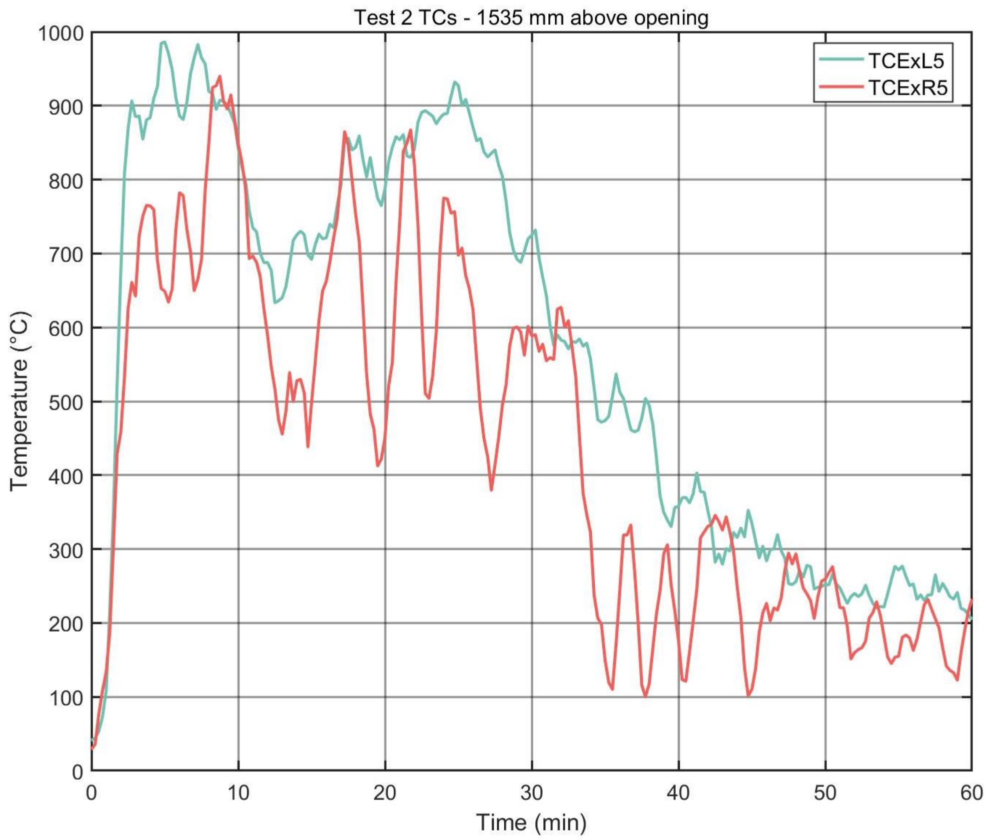

Figure A 26. TC temperatures, test 2 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

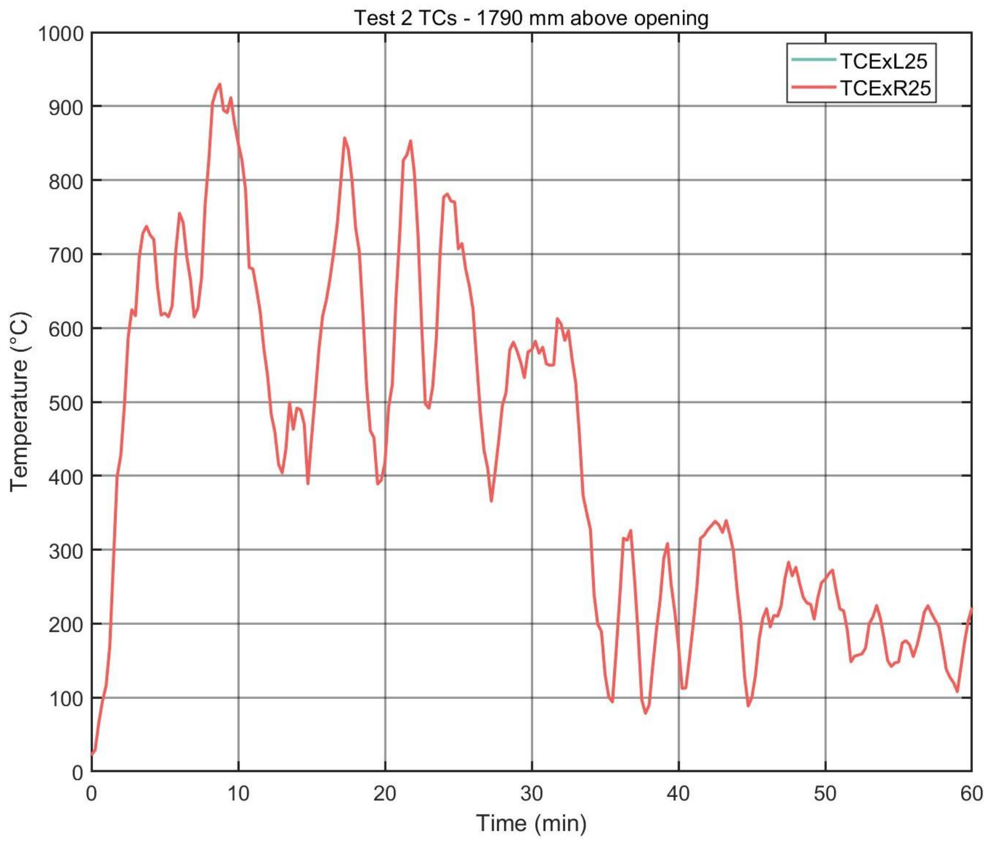

Figure A 27. TC temperatures, test 2 for comparisons to SP Fire 105. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

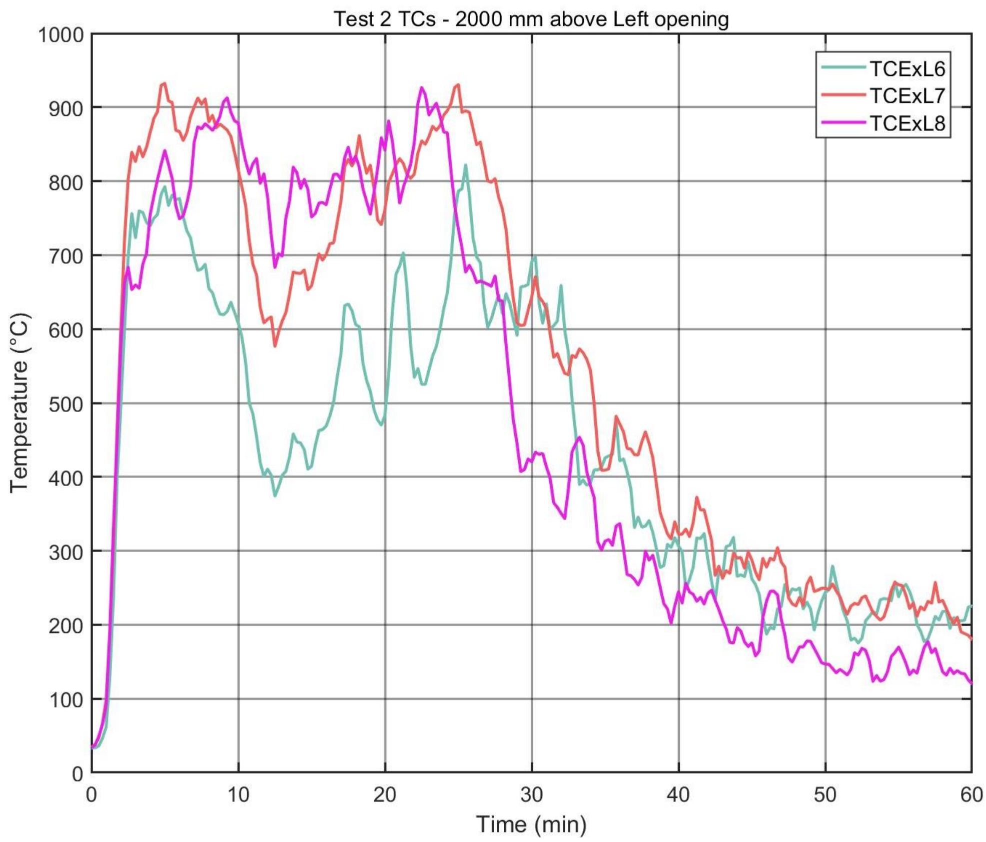

Figure A 28. TC temperatures, test 2 for comparisons to EU proposed method. Ex refers to “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

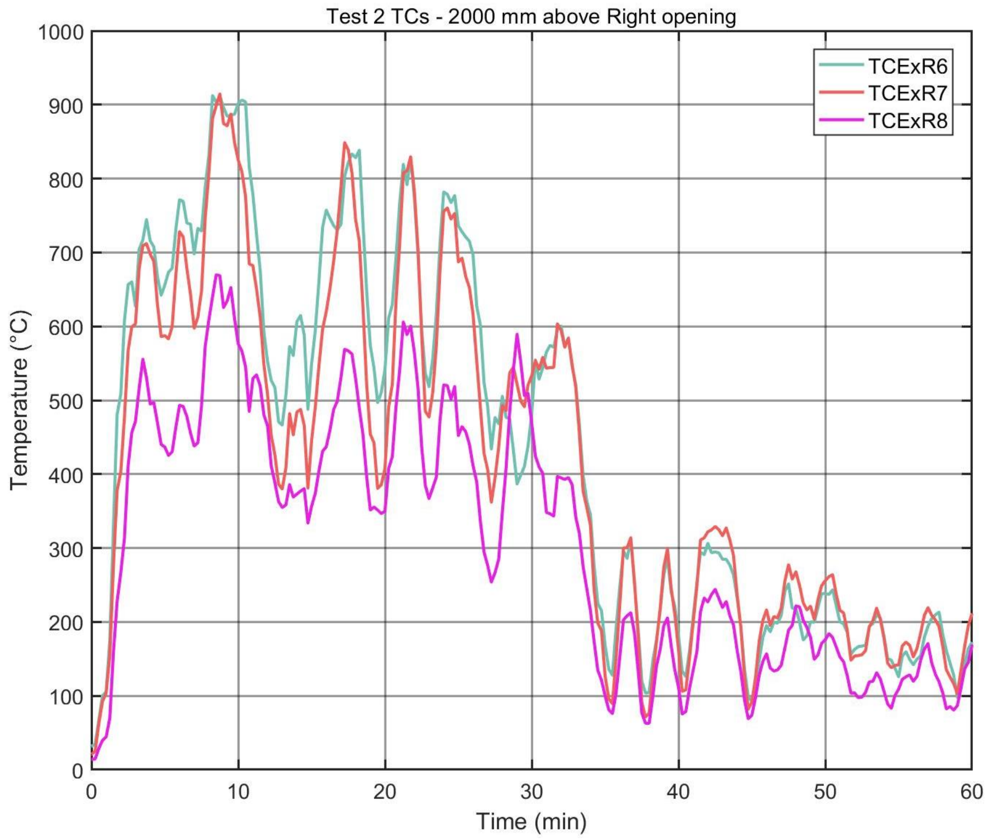

Figure A 29. TC temperatures, test 2 for comparisons to EU proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

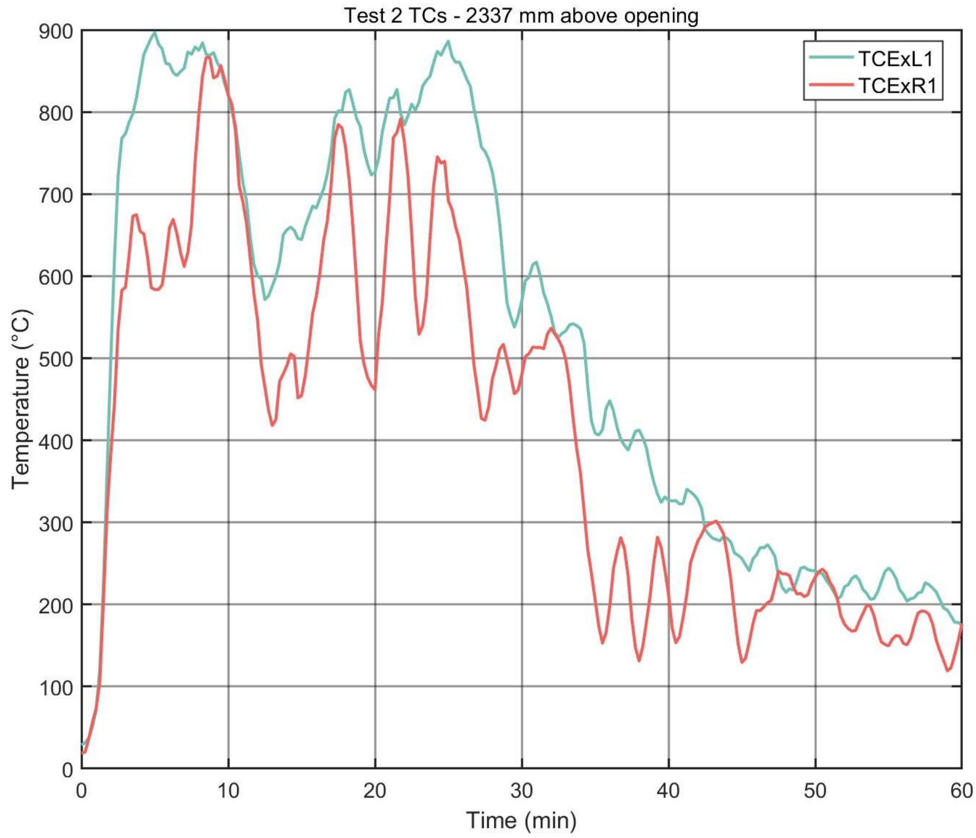

Figure A 30. TC temperatures, test 2 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

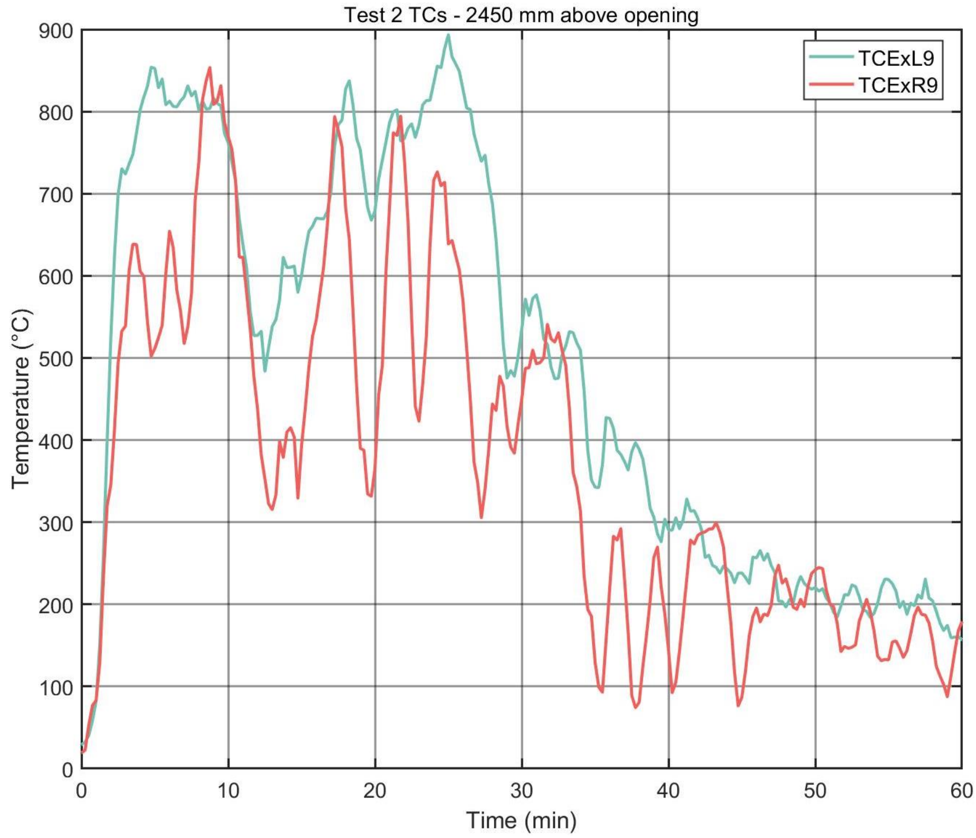

Figure A 31. TC temperatures, test 2 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

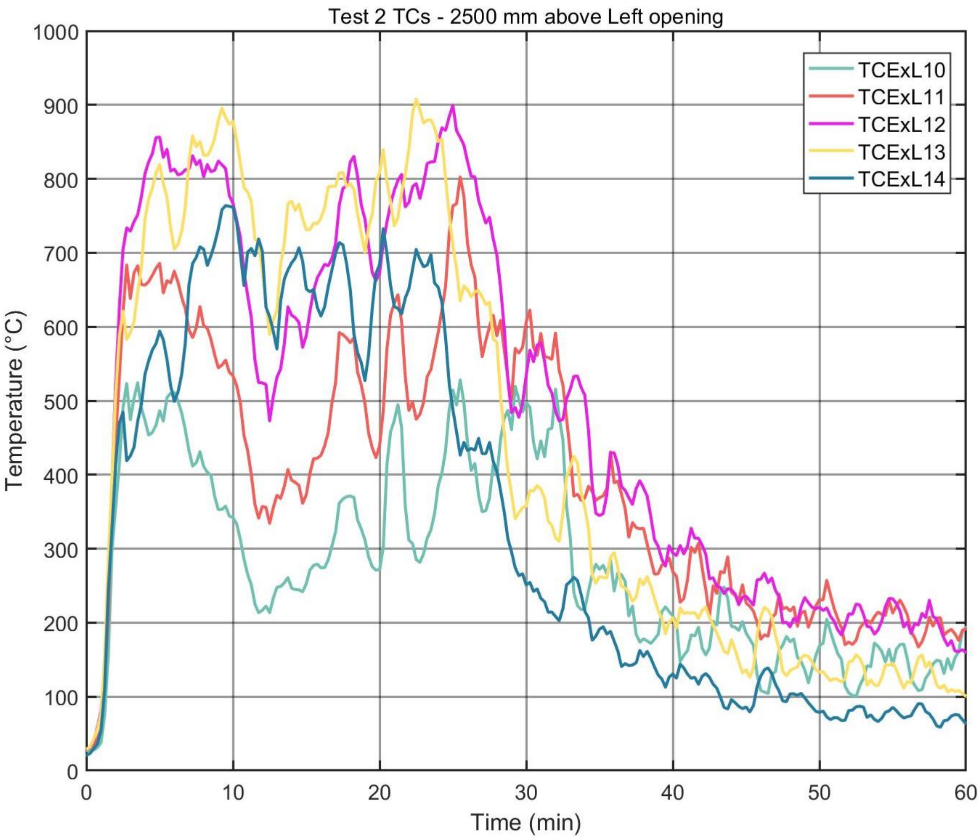

Figure A 32. TC temperatures, test 2 for comparisons to BS 8414. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

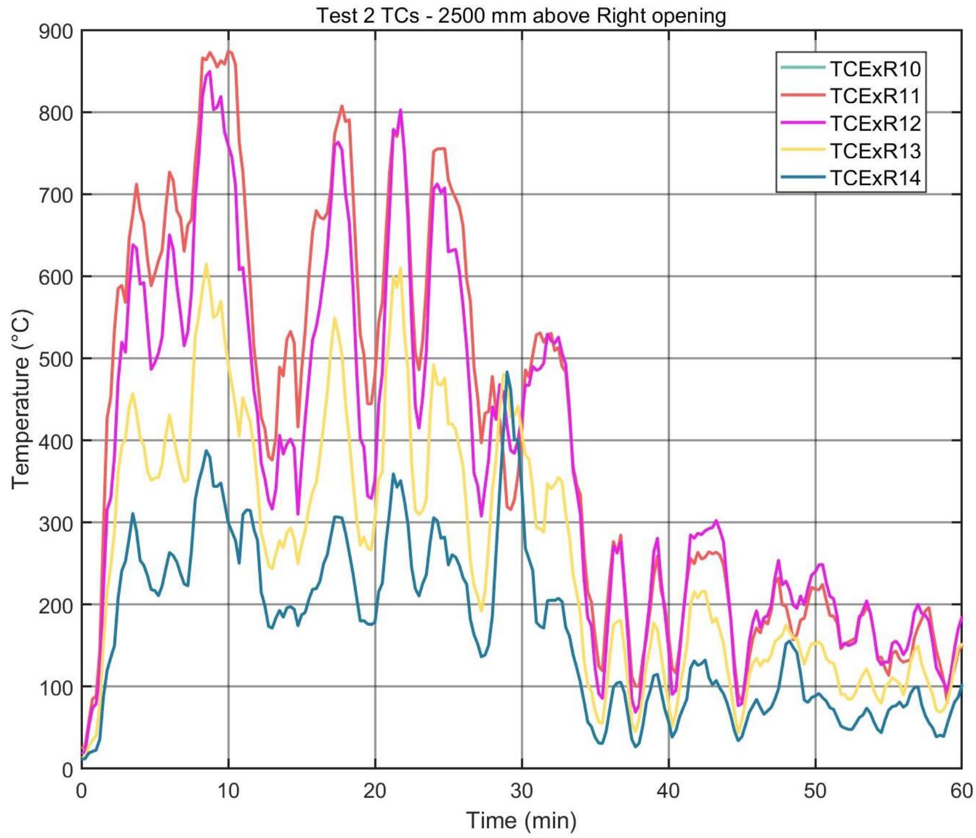

Figure A 33. TC temperatures, test 2 for comparisons to BS 8414. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

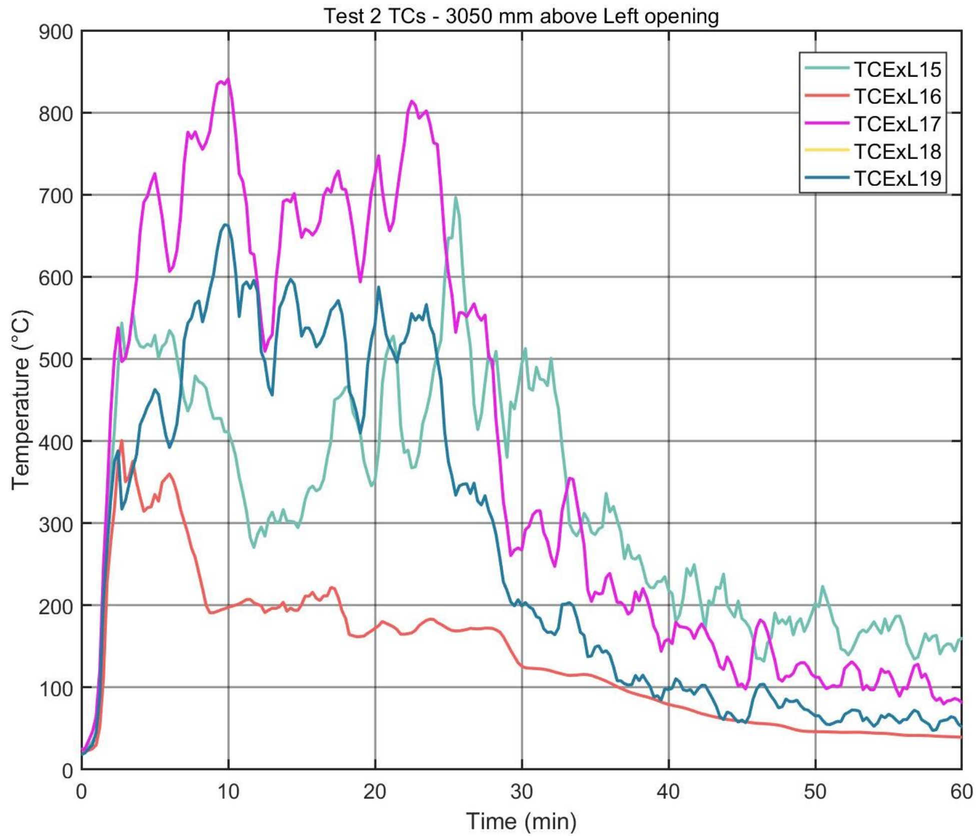

Figure A 34. TC temperatures, test 2 for comparisons to NFPA 285. Ex refers to "external" measurements (on façade), "L" and "R" refers to left and right opening. See Annex B. L16 is faulty

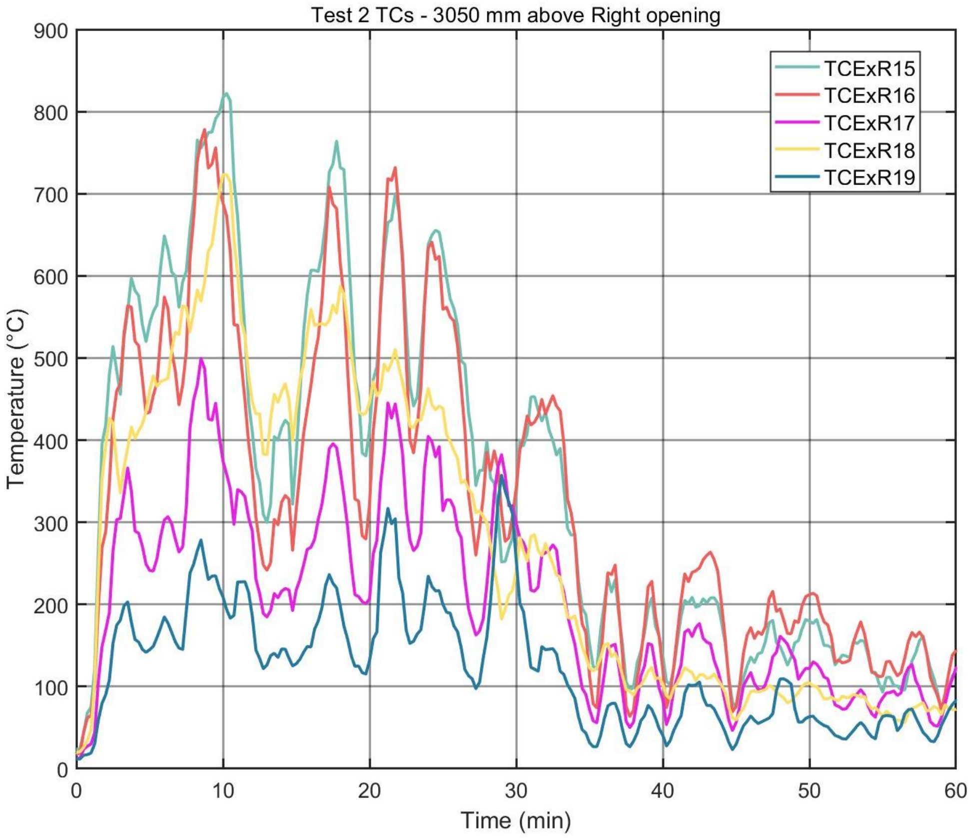

Figure A 35. TC temperatures, test 2 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

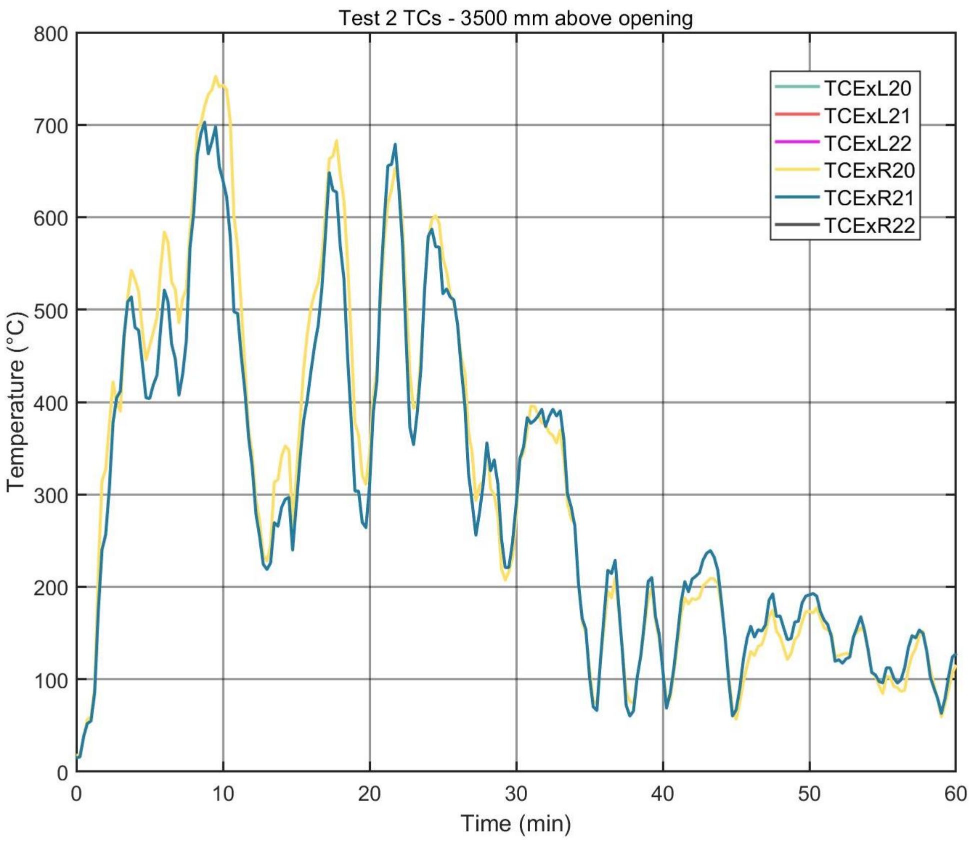

Figure A 36. TC temperatures, test 2 for comparisons to EU Proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

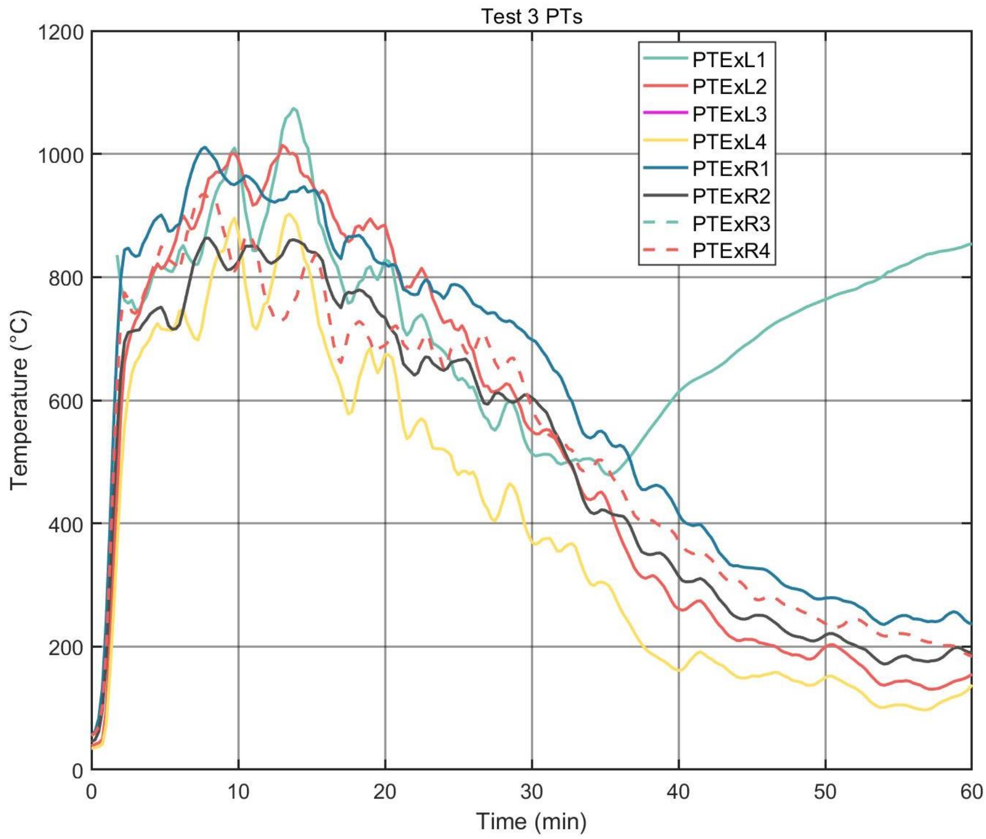

Figure A 37. PT temperatures, test 3. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

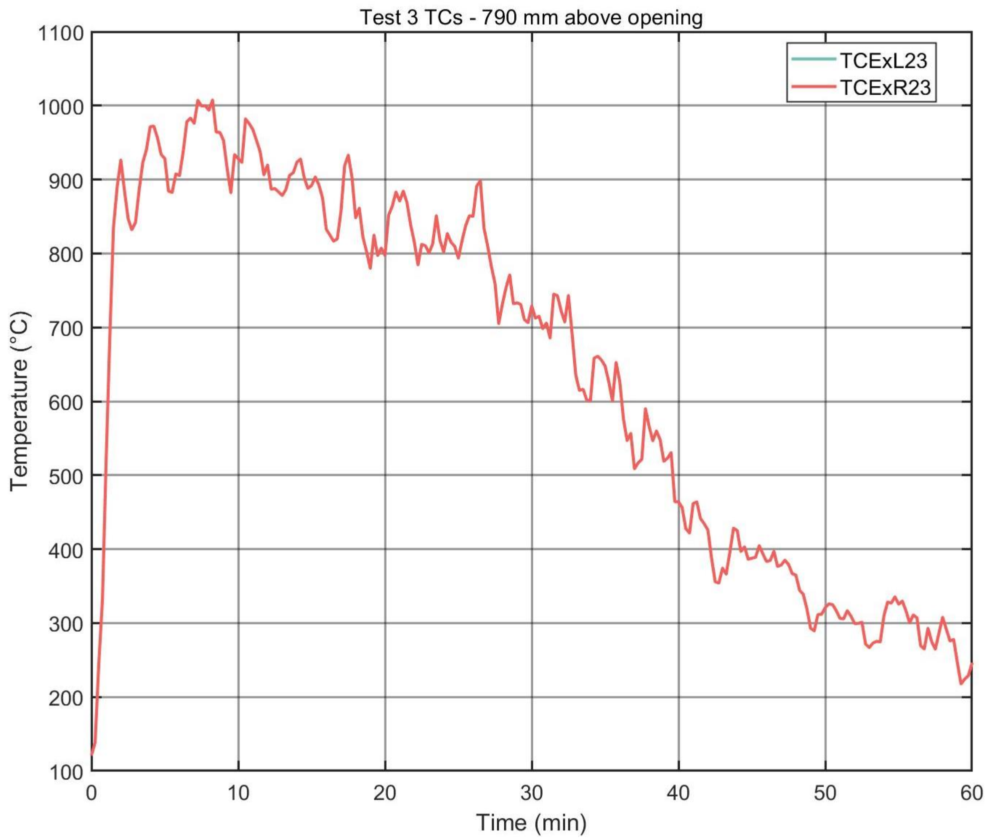

Figure A 38. TC temperatures, test 3 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

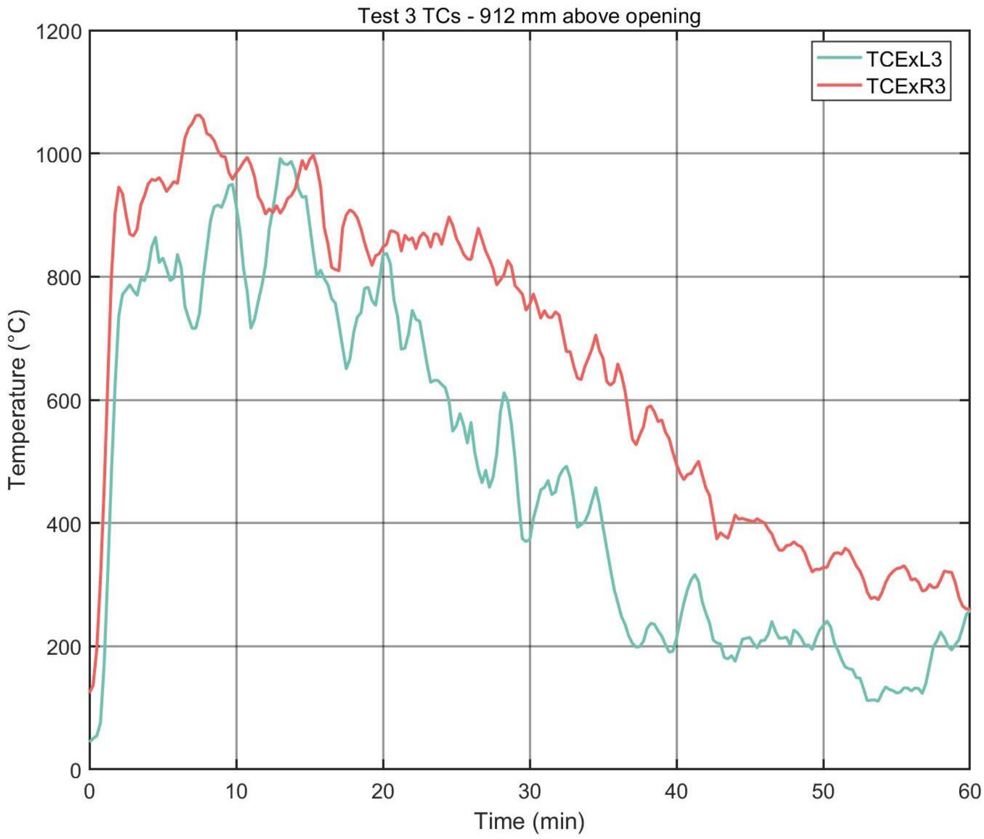

Figure A 39. TC temperatures, test 3 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

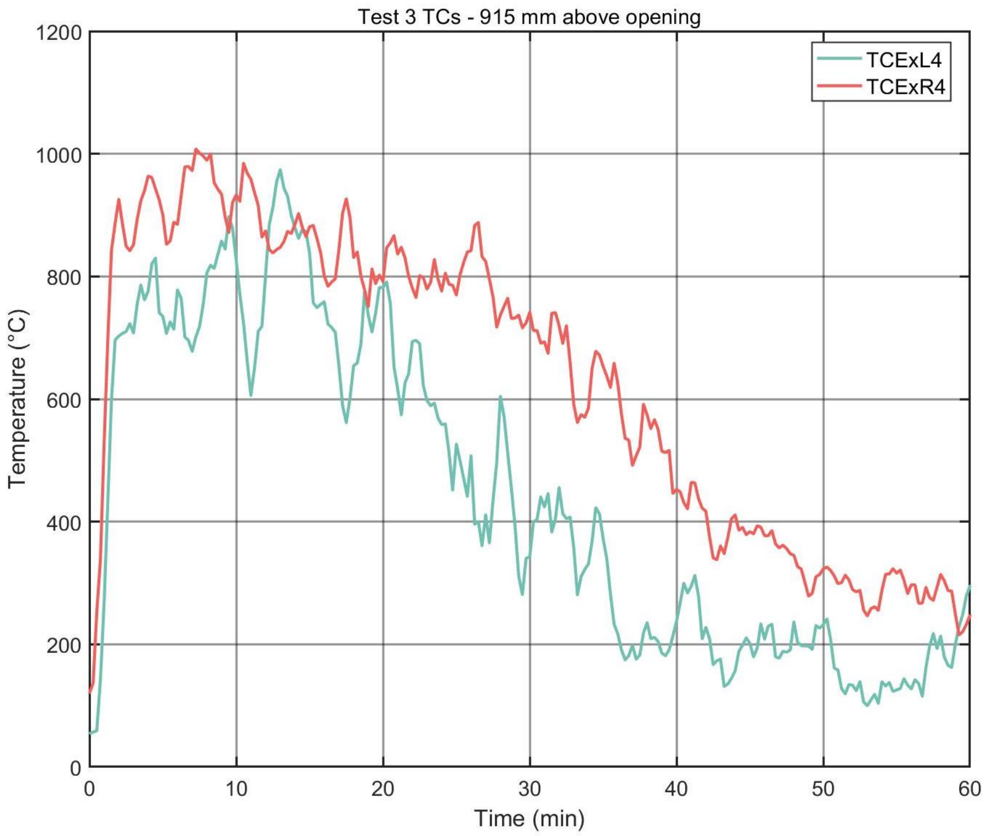

Figure A 40. TC temperatures, test 3 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

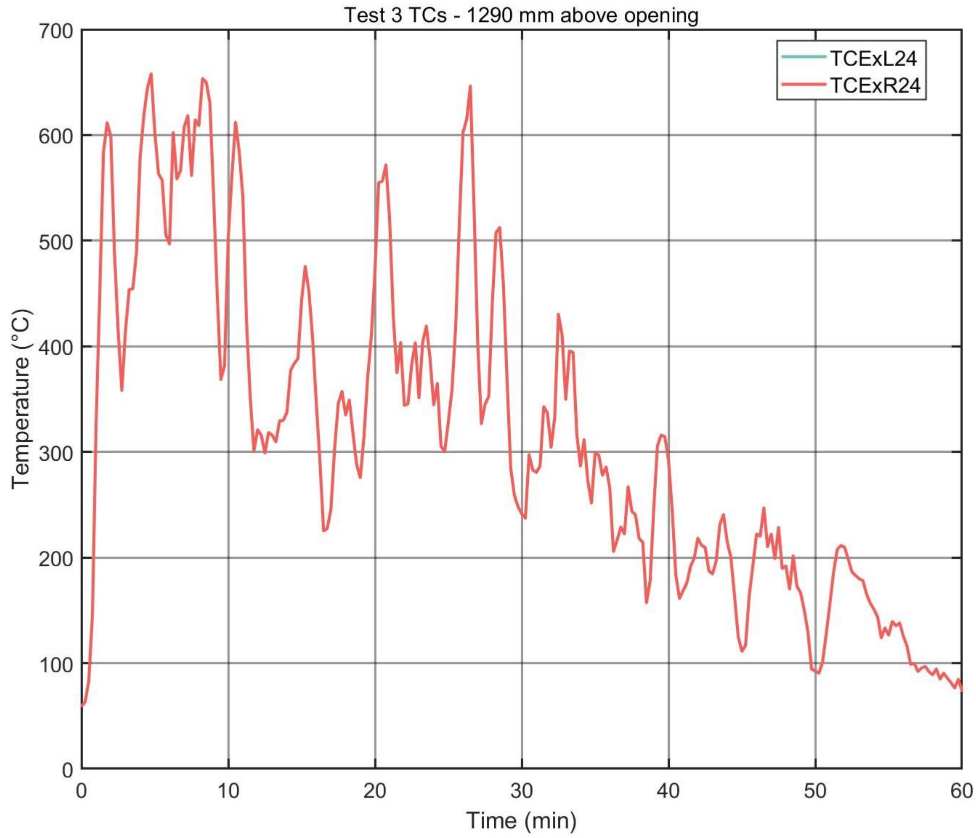

Figure A 41. TC temperatures, test 3 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

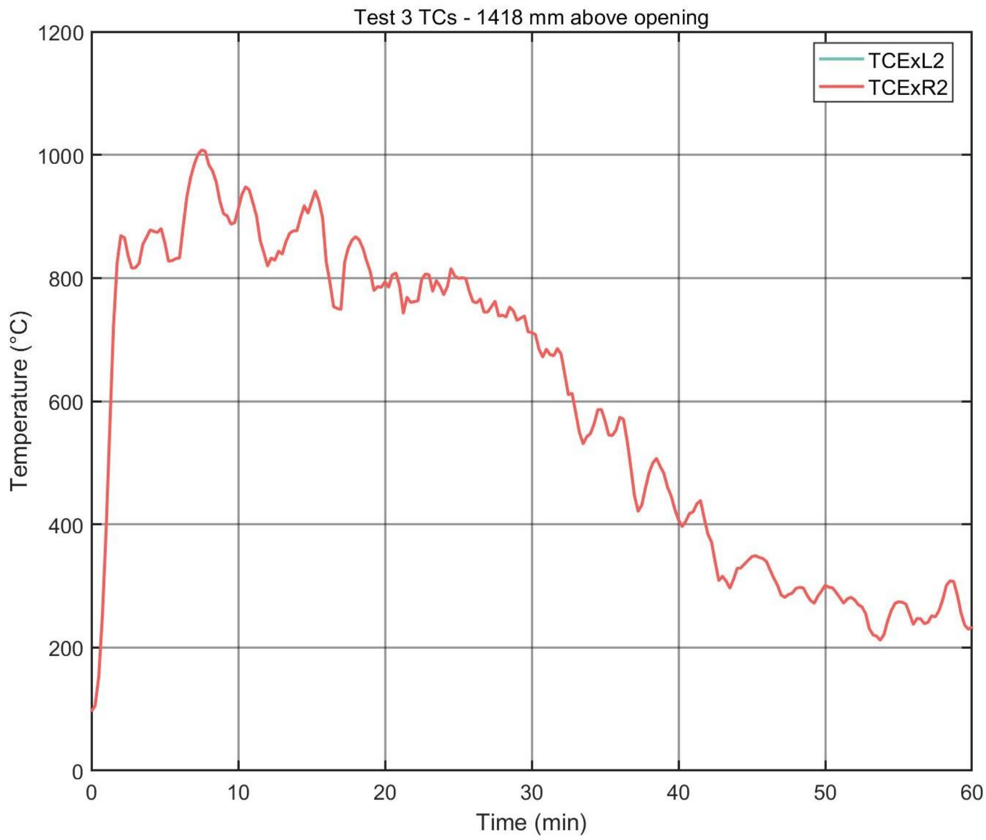

Figure A 42. TC temperatures, test 3 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

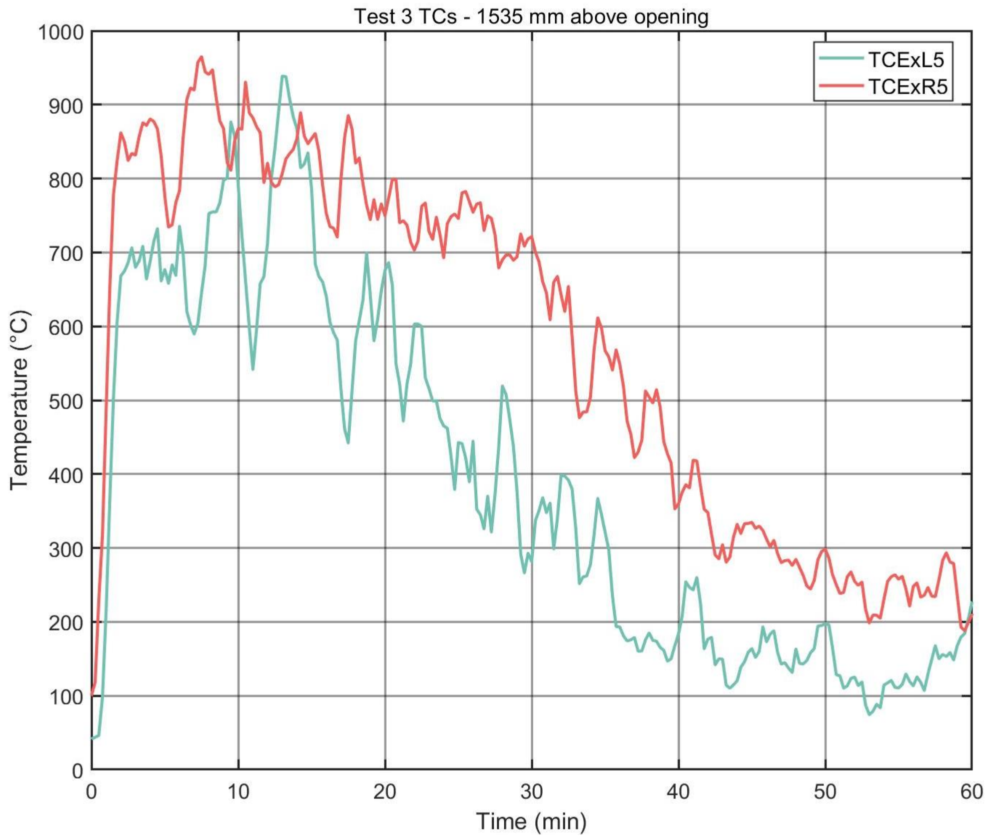

Figure A 43. TC temperatures, test 3 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

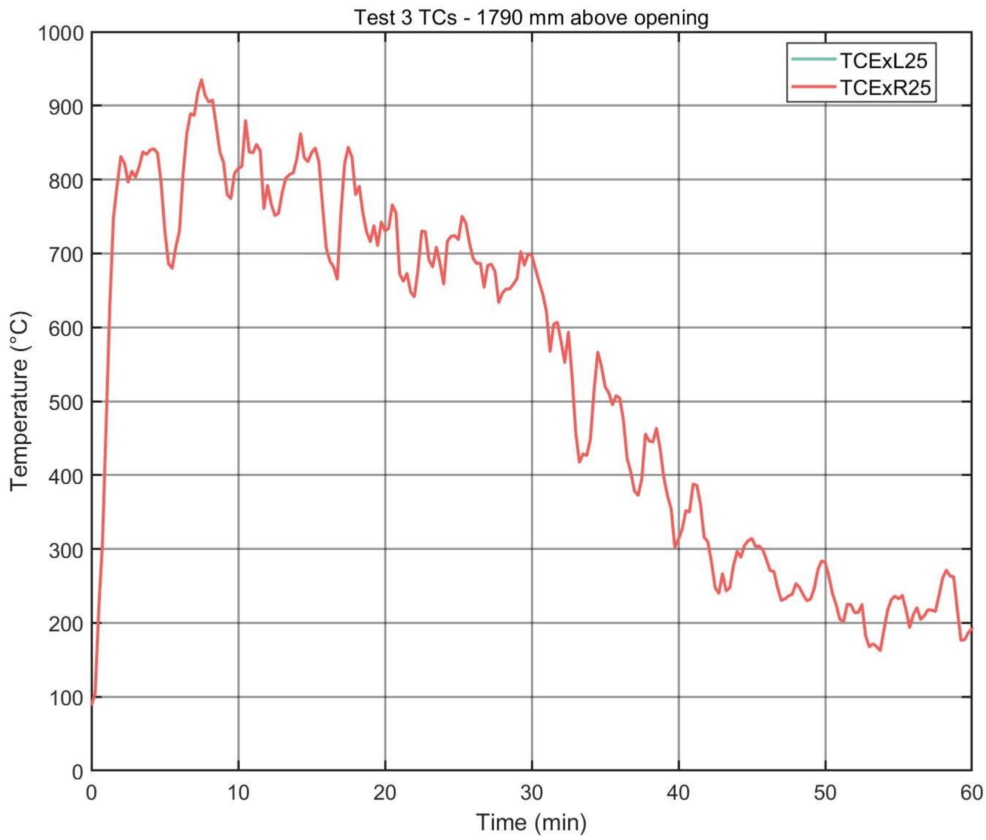

Figure A 44. TC temperatures, test 3 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

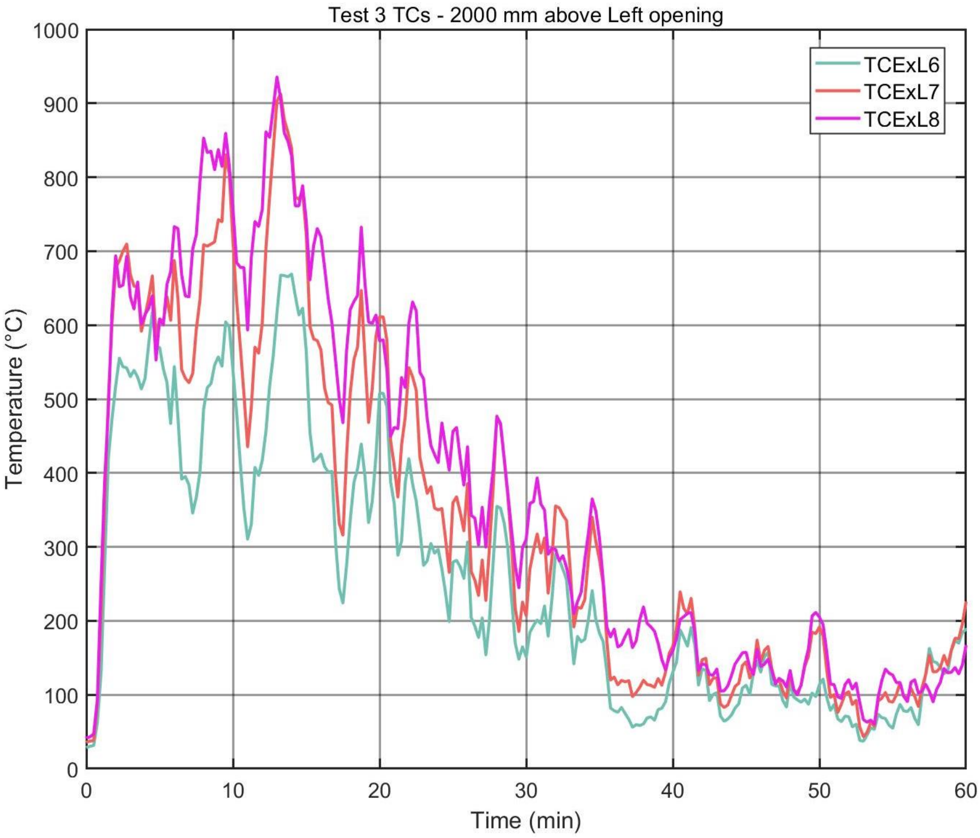

Figure A 45. TC temperatures, test 3 for comparisons to EU Proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

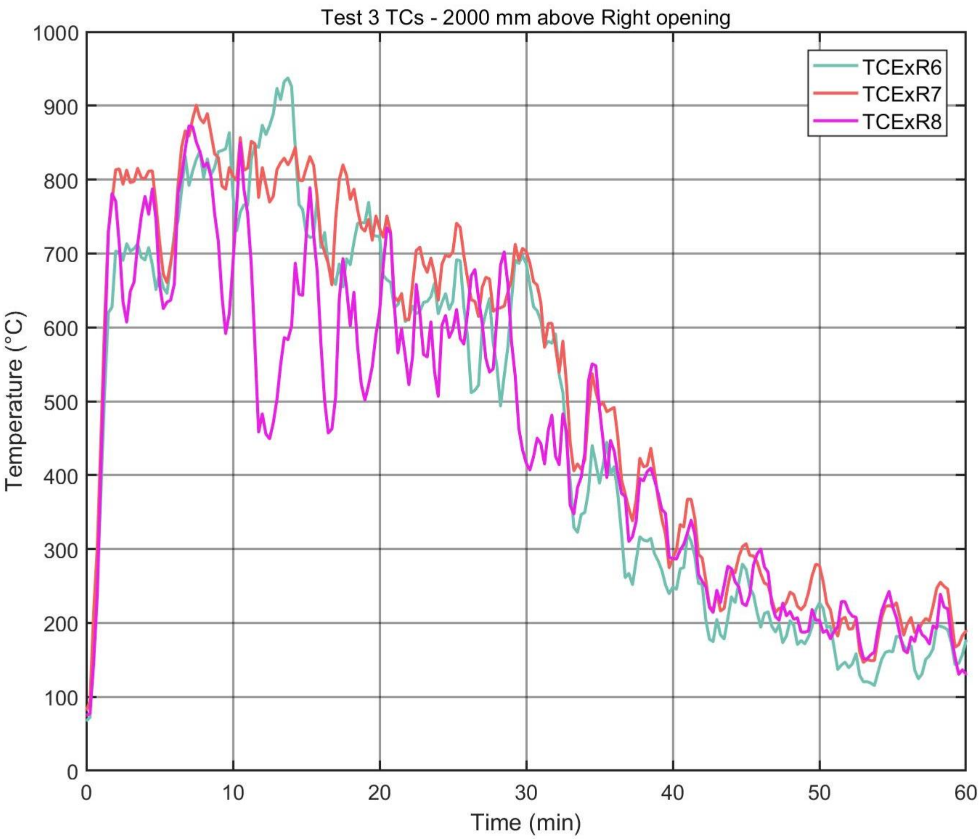

Figure A 46. TC temperatures, test 3 for comparisons to EU Proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

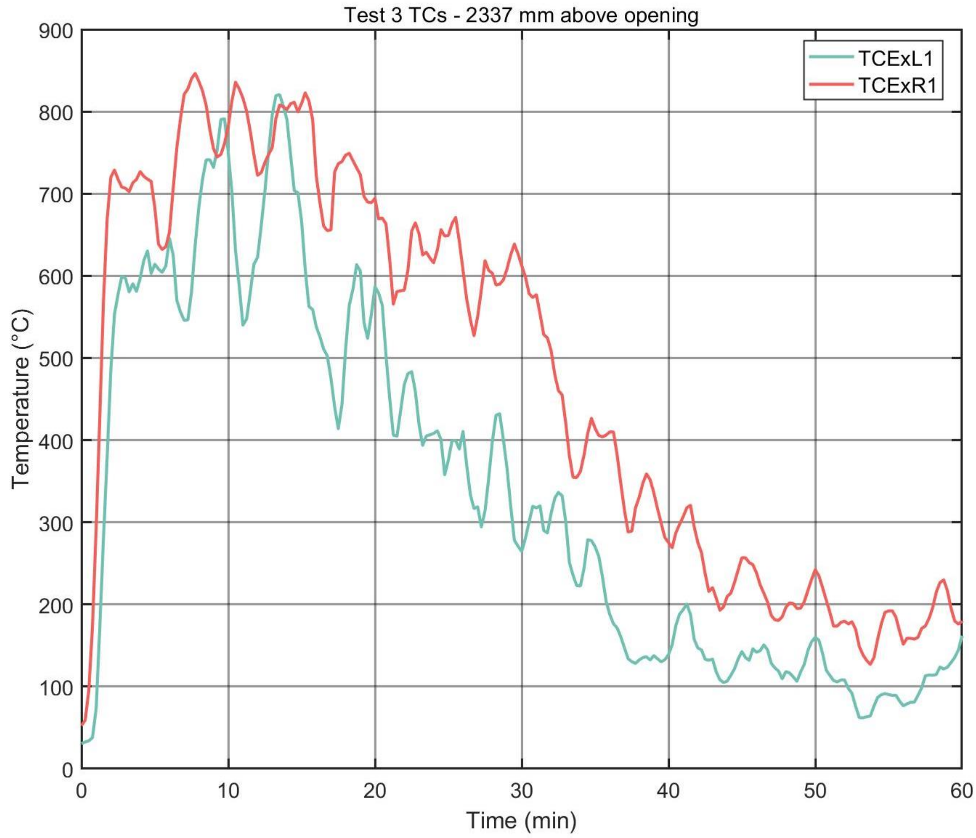

Figure A 47. TC temperatures, test 3 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

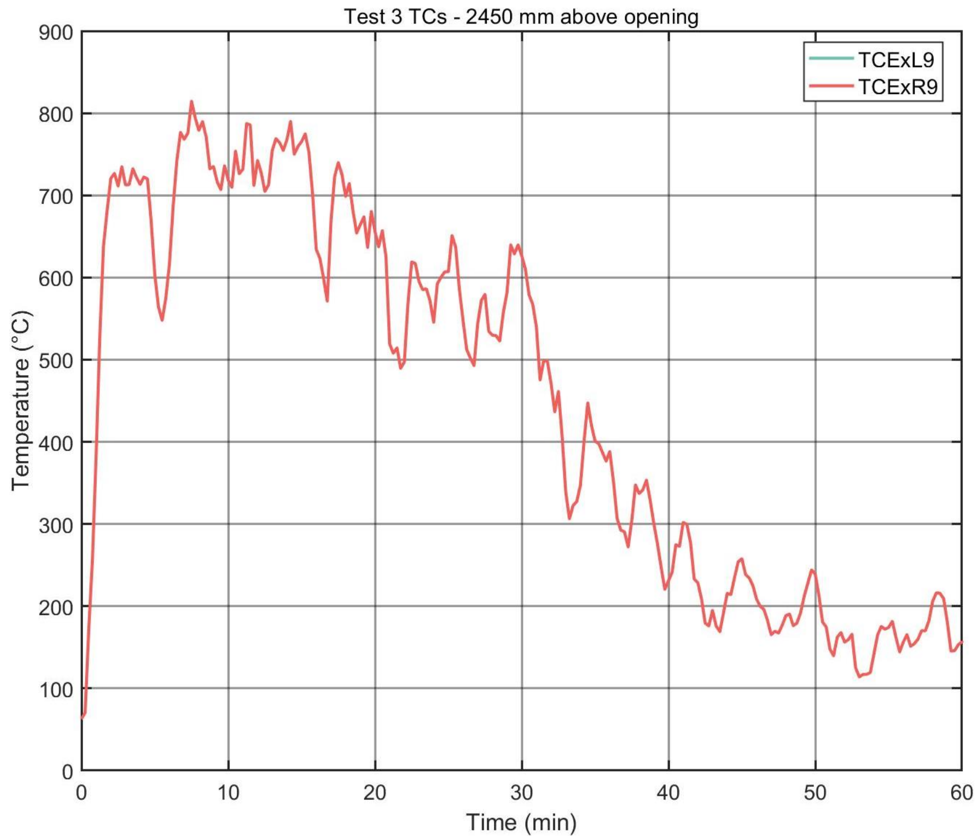

Figure A 48. TC temperatures, test 3 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

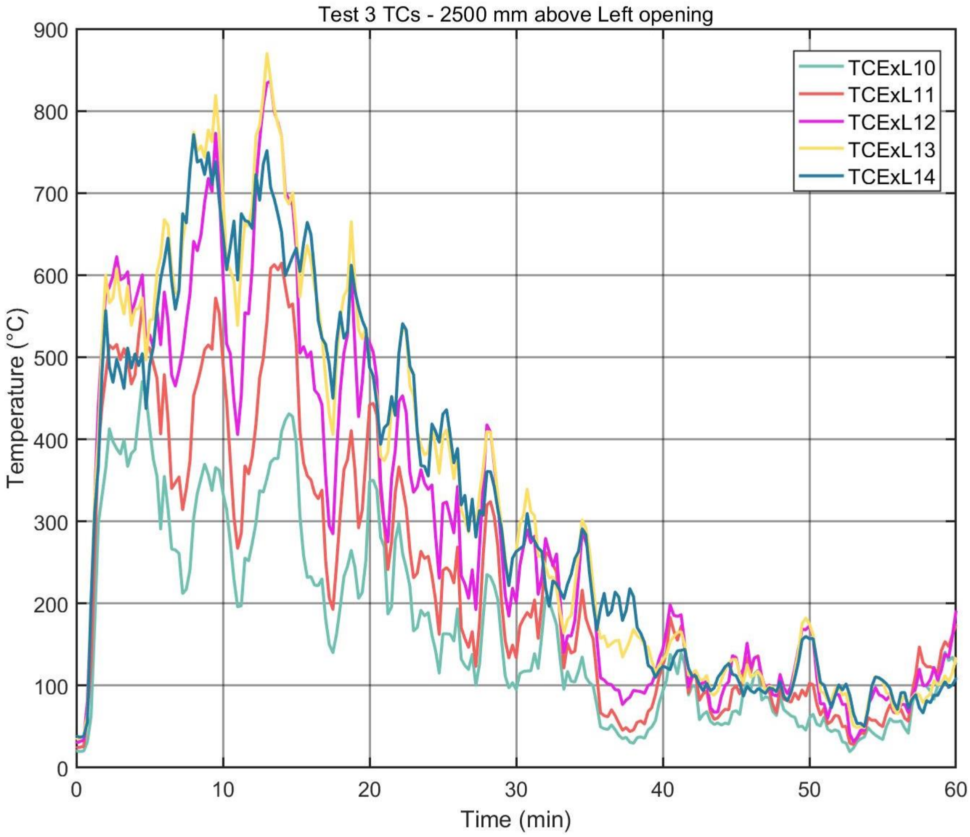

Figure A 49. TC temperatures, test 3 for comparisons to BS 8414. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

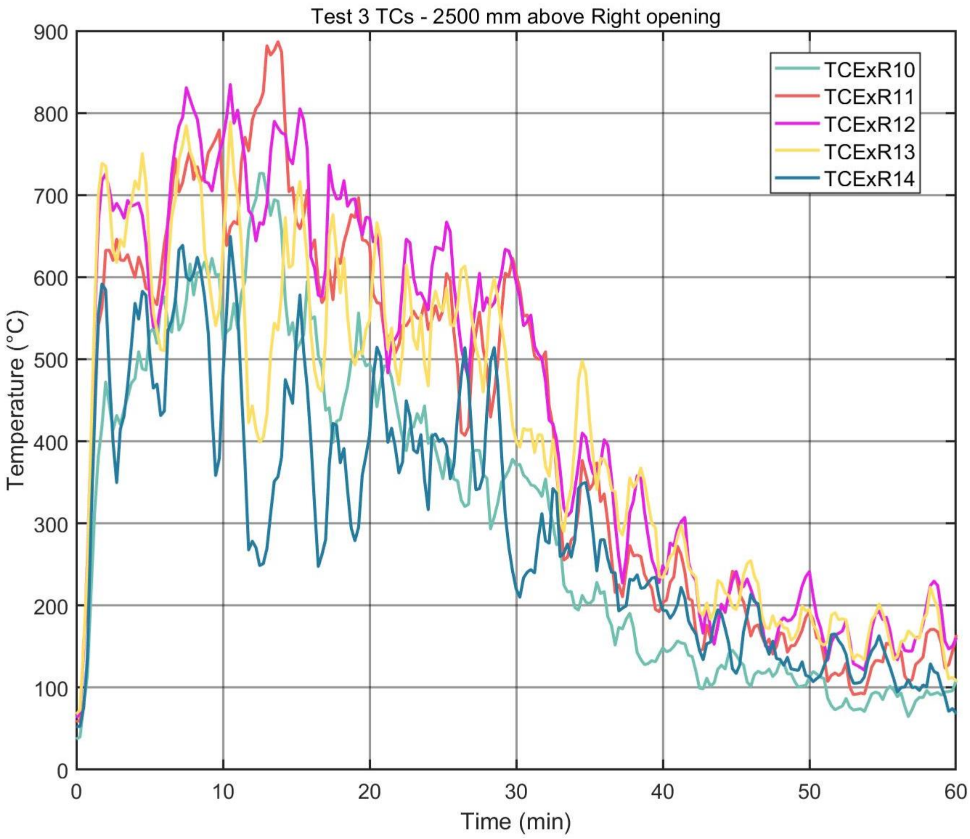

Figure A 50. TC temperatures, test 3 for comparisons to BS 8414. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

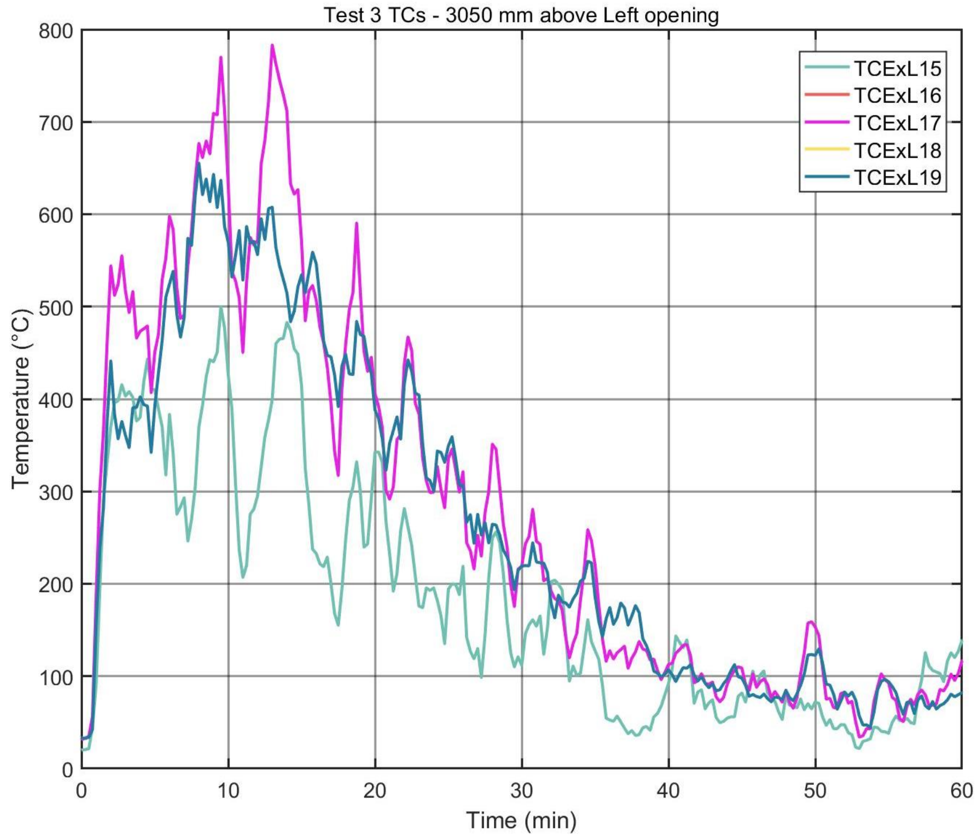

Figure A 51. TC temperatures, test 3 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

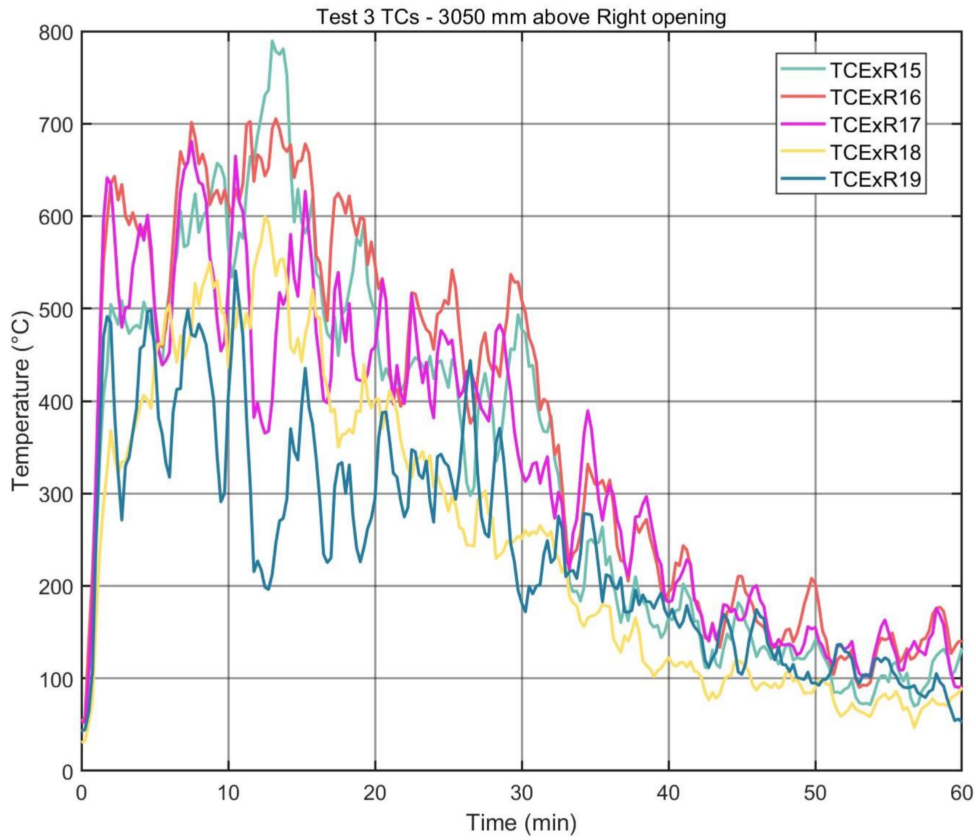

Figure A 52. TC temperatures, test 3 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

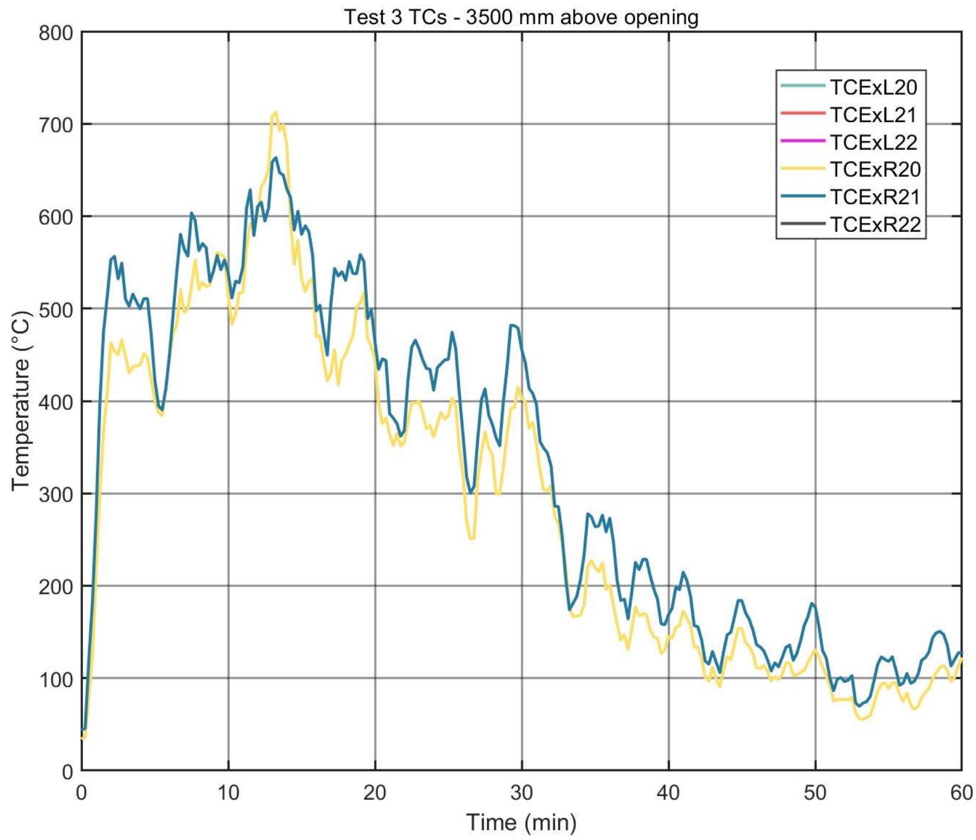

Figure A 53. TC temperatures, test 3 for comparisons to European proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

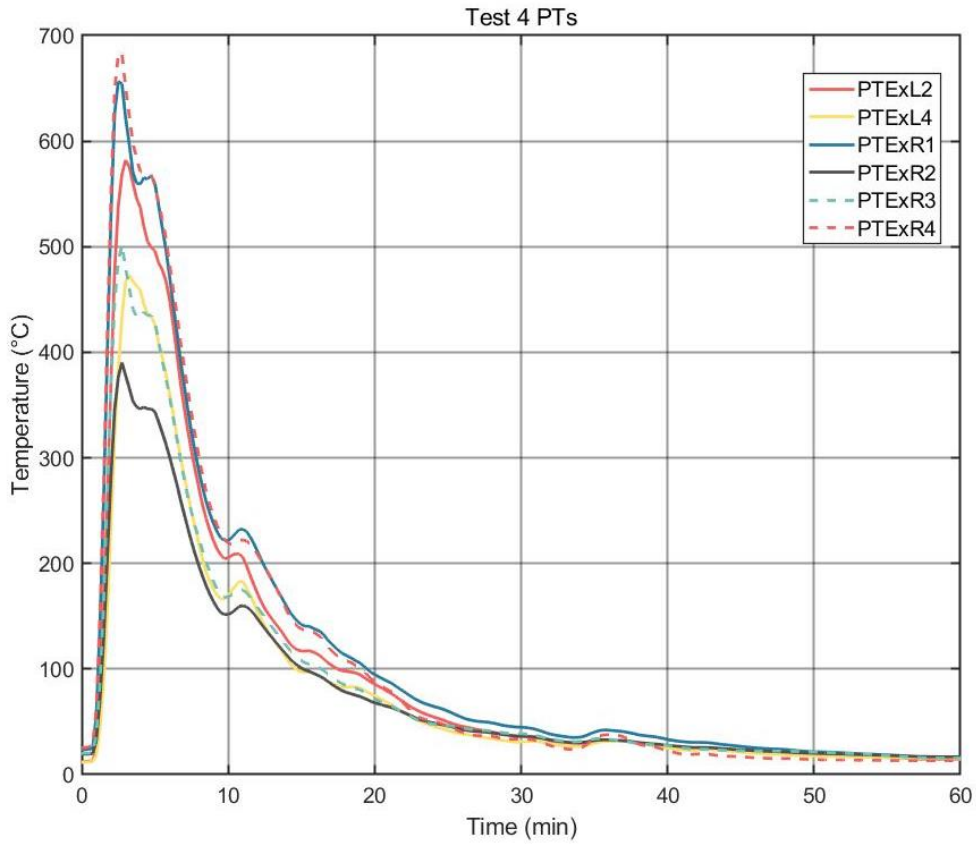

Figure A 54. PT temperatures, test 4. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

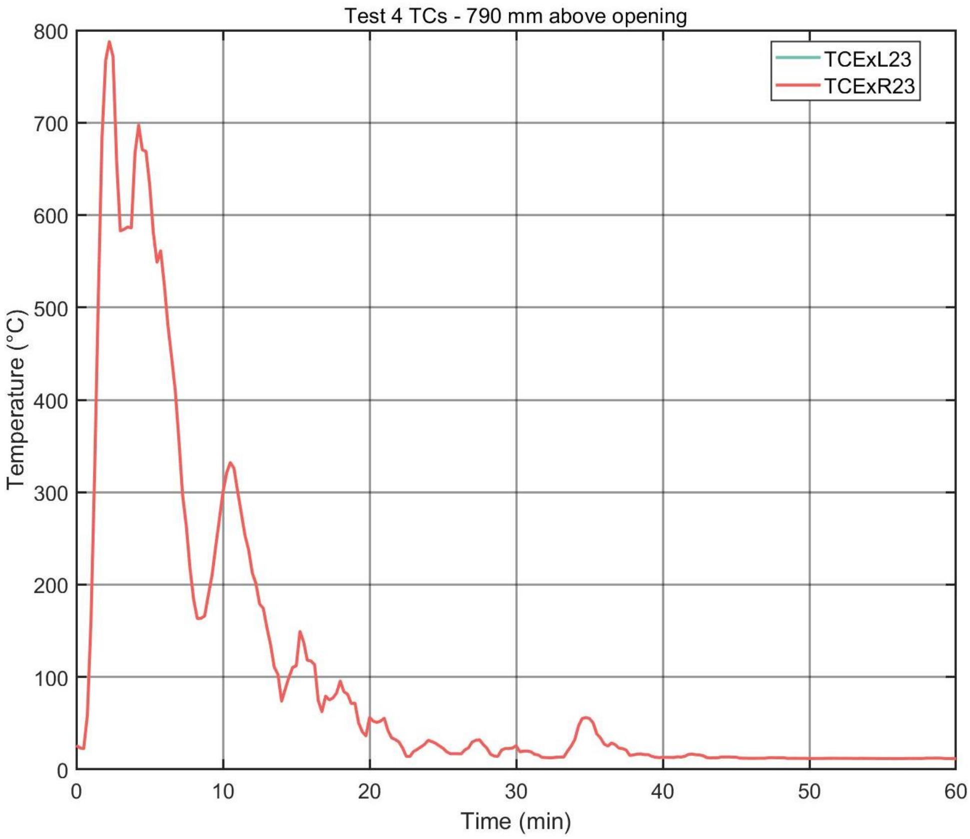

Figure A 55. TC temperatures, test 4 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

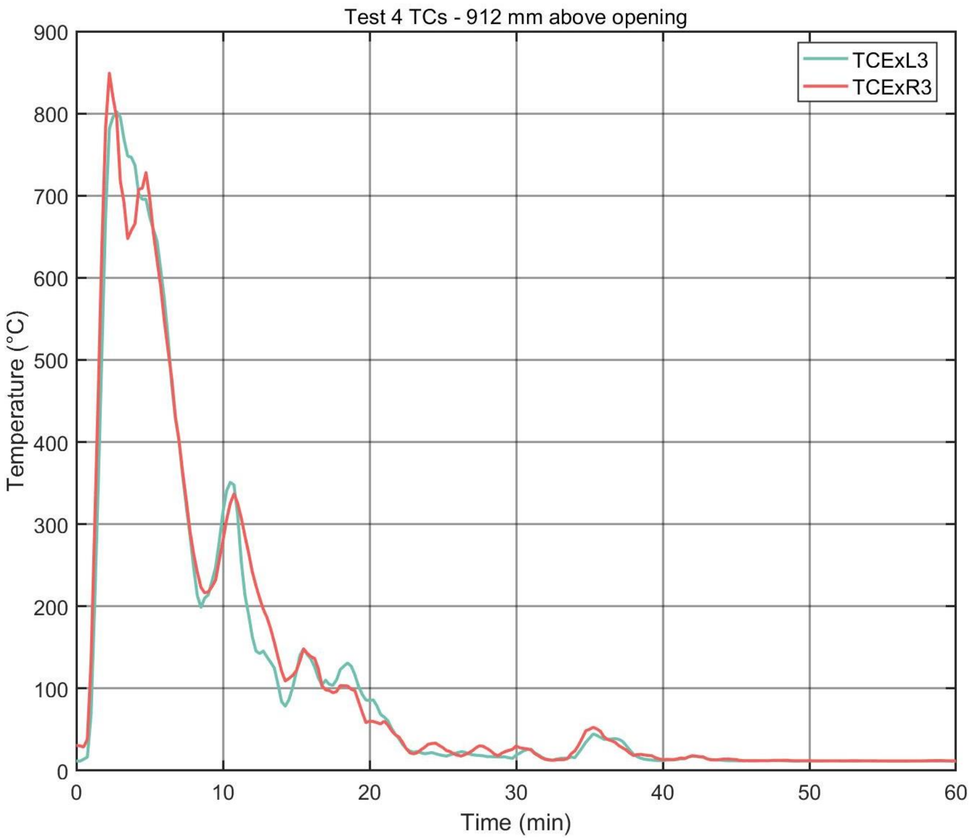

Figure A 56. TC temperatures, test 4 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

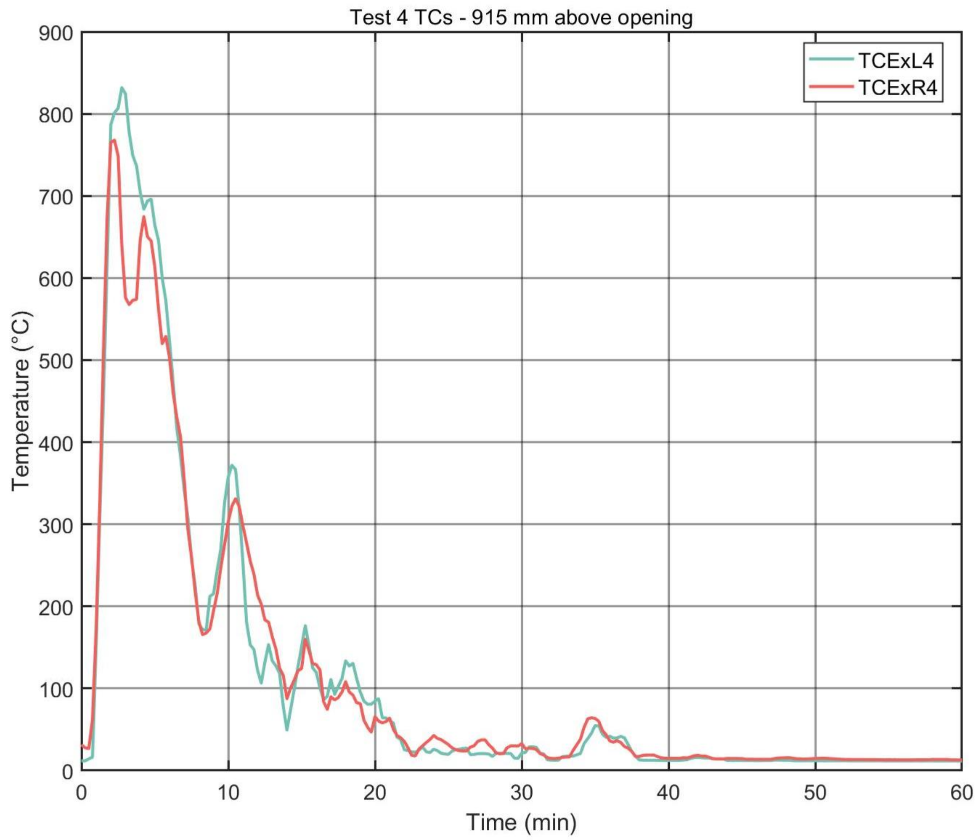

Figure A 57. TC temperatures, test 4 for comparisons to NFPA 285. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

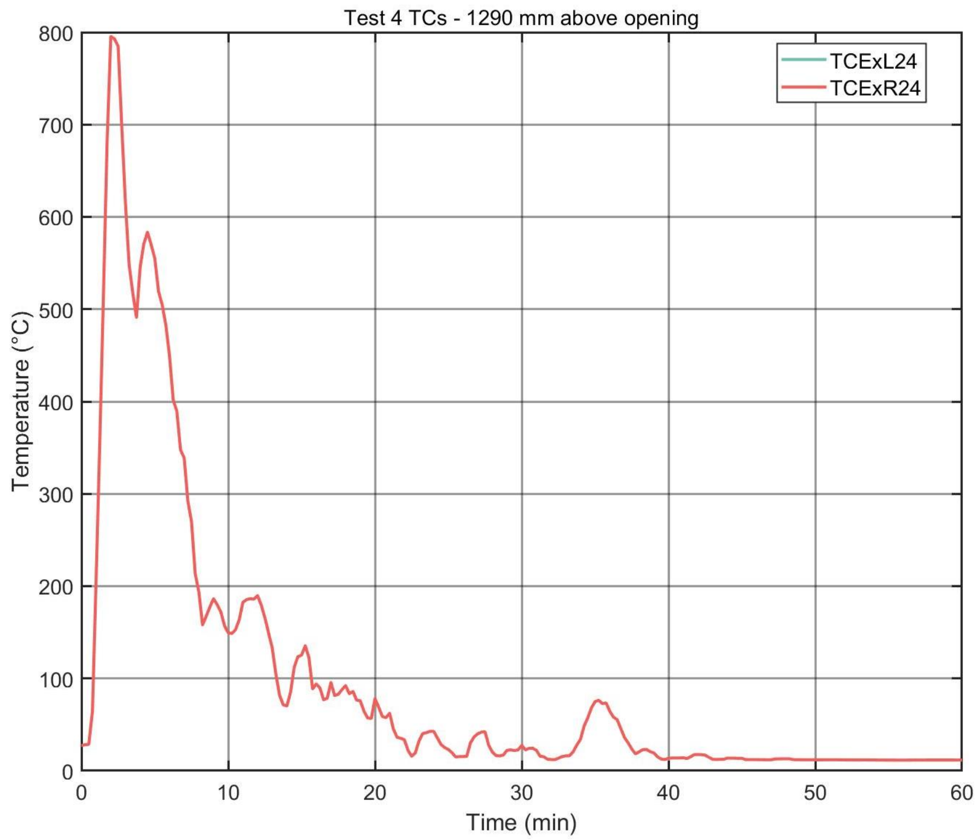

Figure A 58. TC temperatures, test 4 for comparisons to SP Fire 105. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

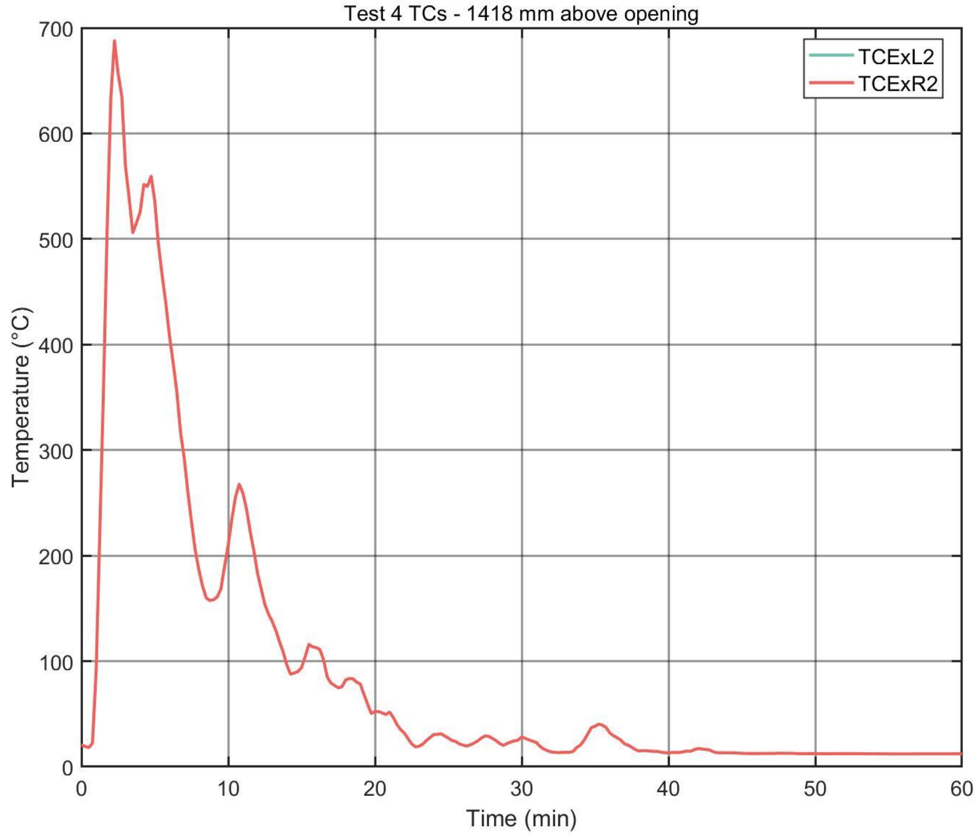

Figure A 59. TC temperatures, test 4 for comparisons to Lepir II. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

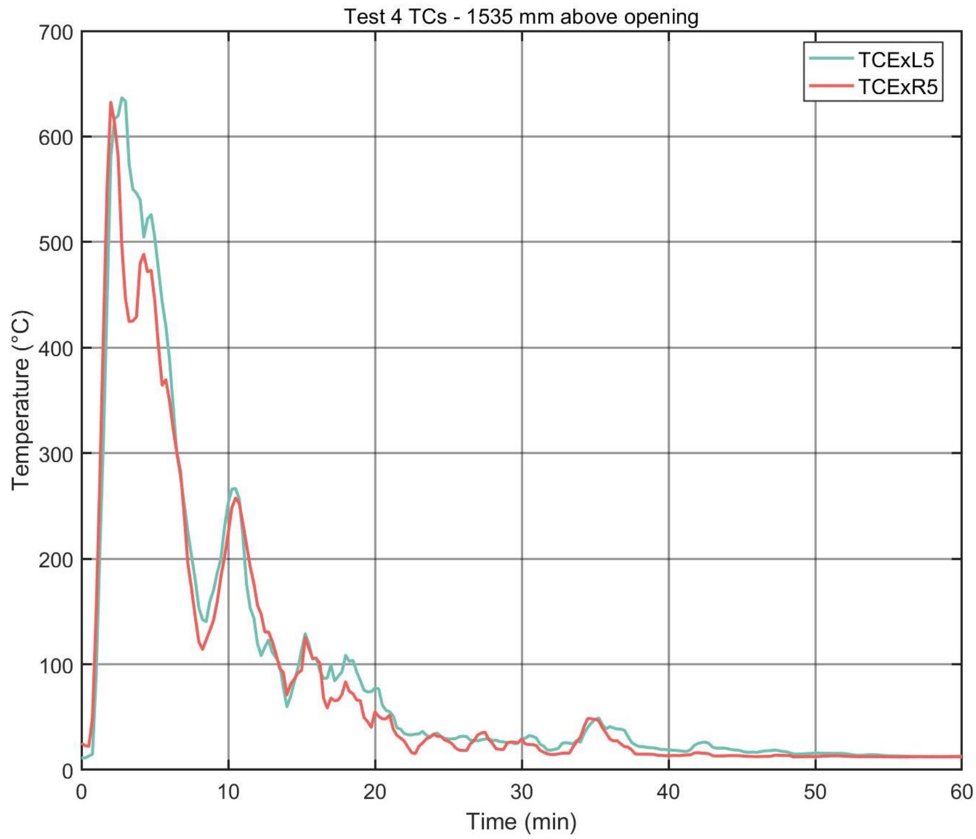

Figure A 60. TC temperatures, test 4 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

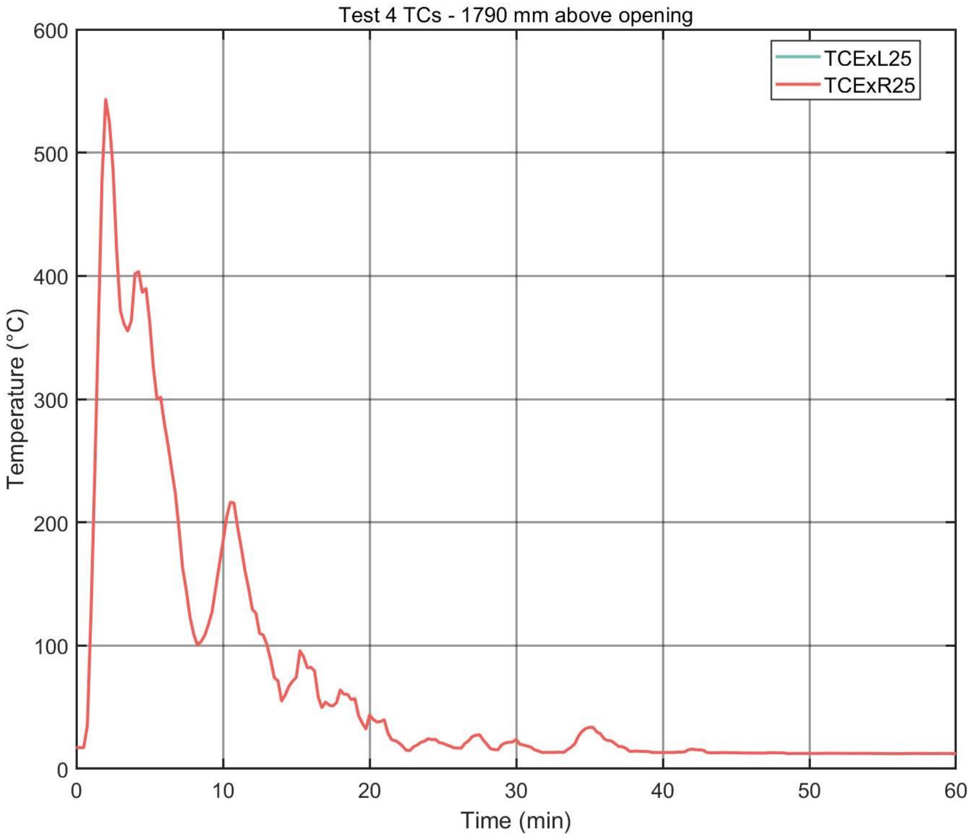

Figure A 61. TC temperatures, test 4 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

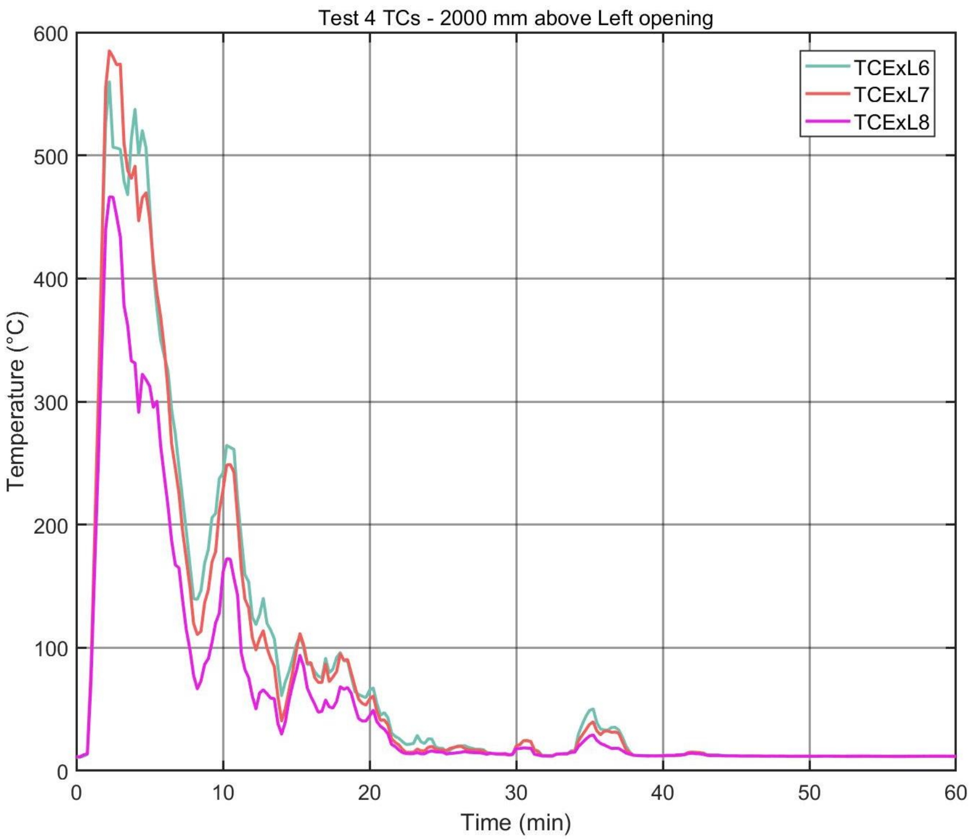

Figure A 62. TC temperatures, test 4 for comparisons to EU Proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

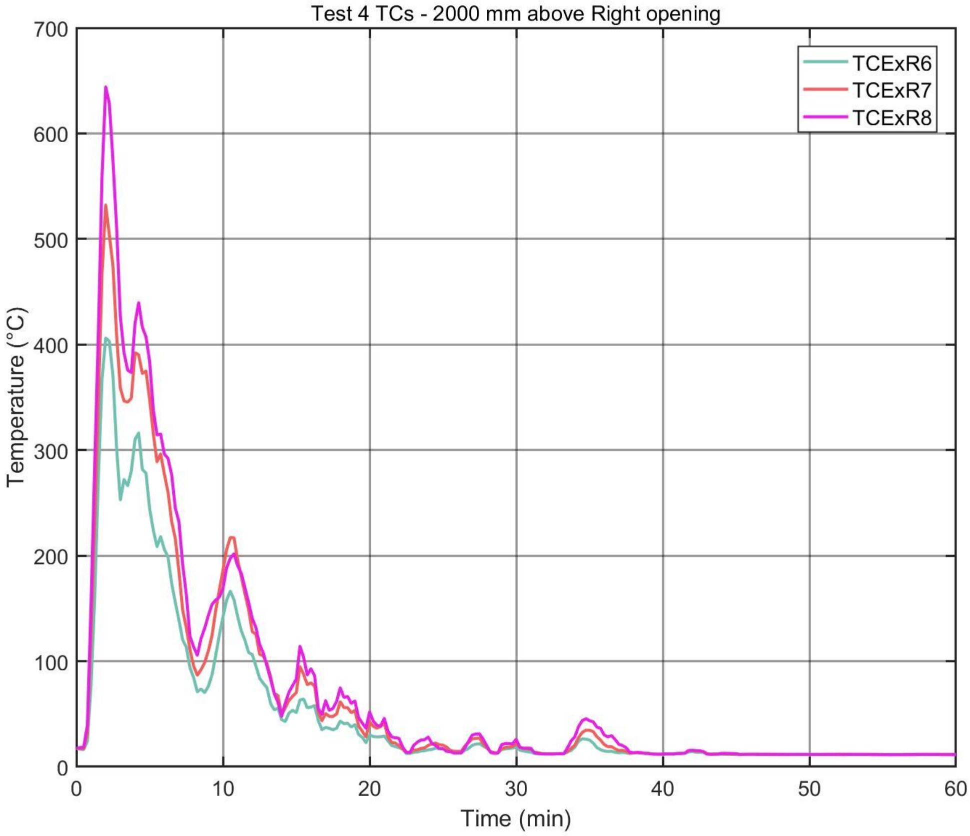

Figure A 63. TC temperatures, test 4 for comparisons to EU proposed method. Ex refers to “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

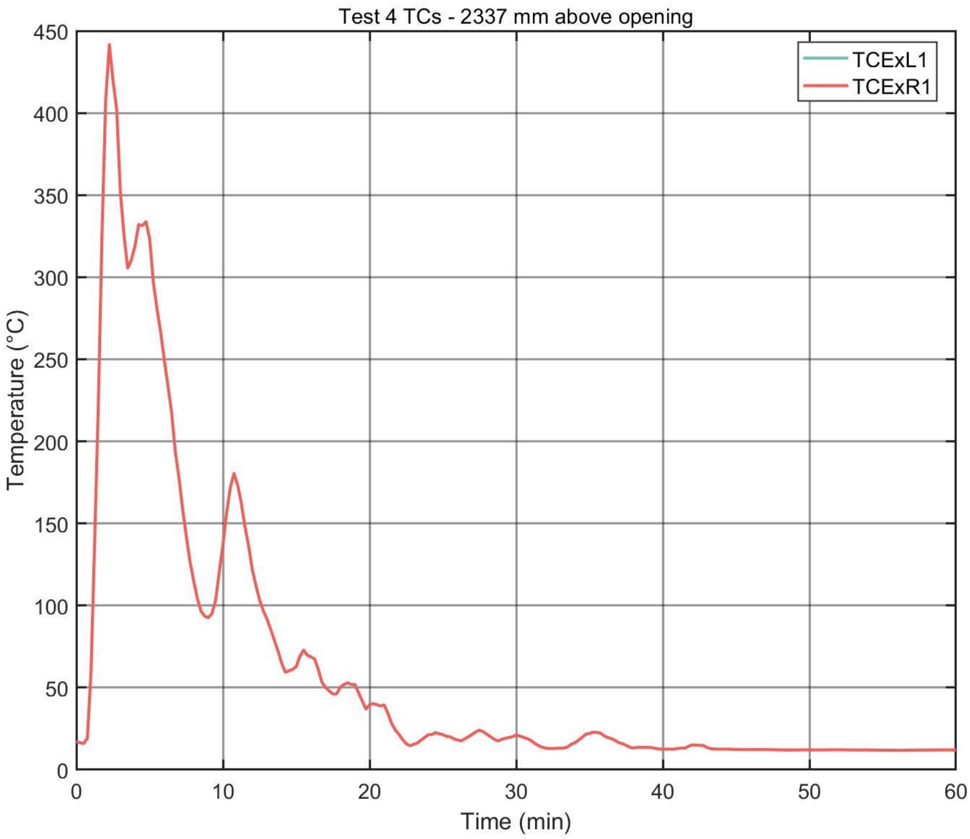

Figure A 64. TC temperatures, test 4 for comparisons to Lepir II. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

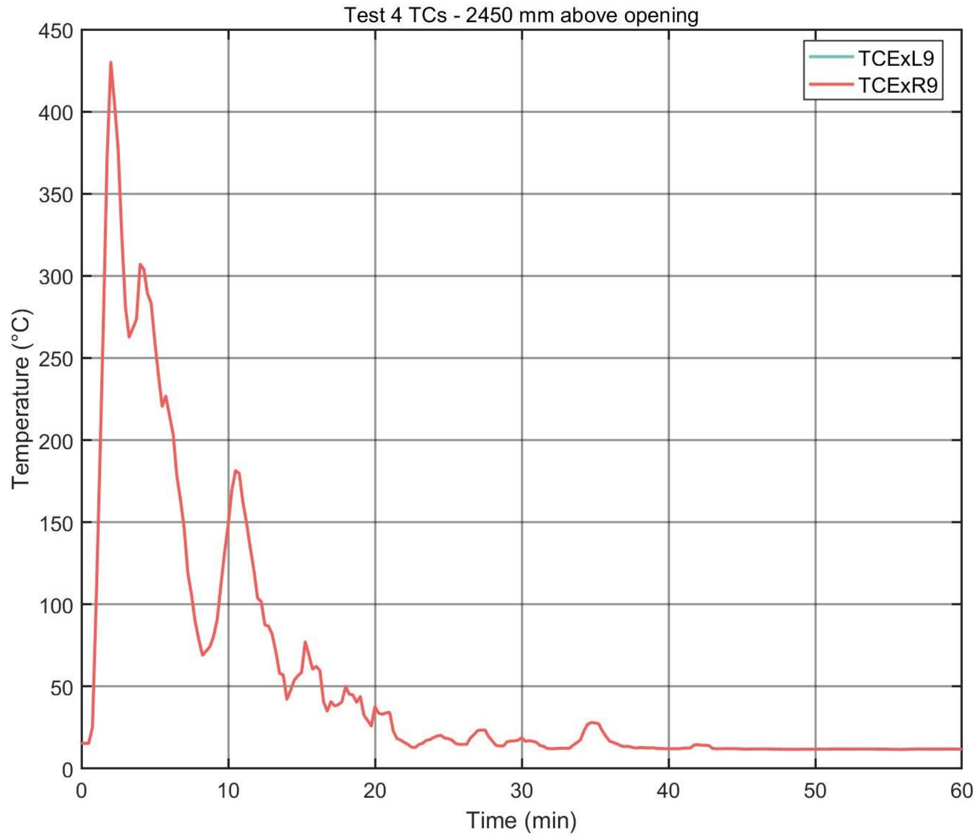

Figure A 65. TC temperatures, test 4 for comparisons to NFPA 285. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

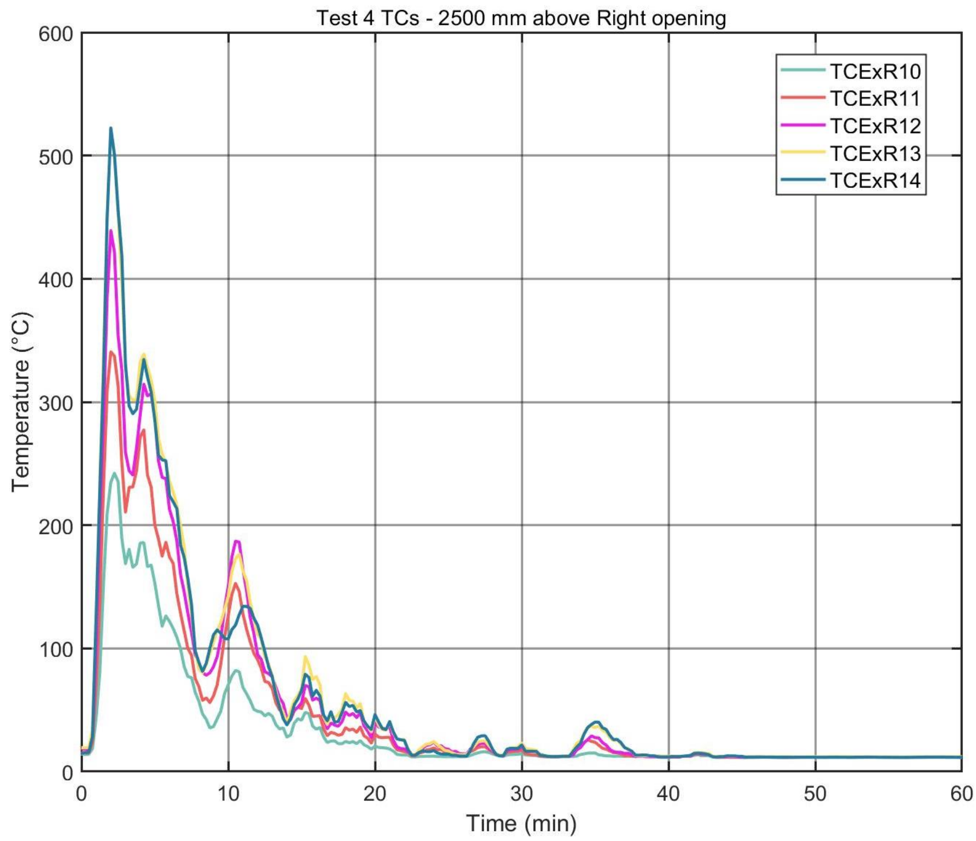

Figure A 66. TC temperatures, test 4 for comparisons to BS 8414. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

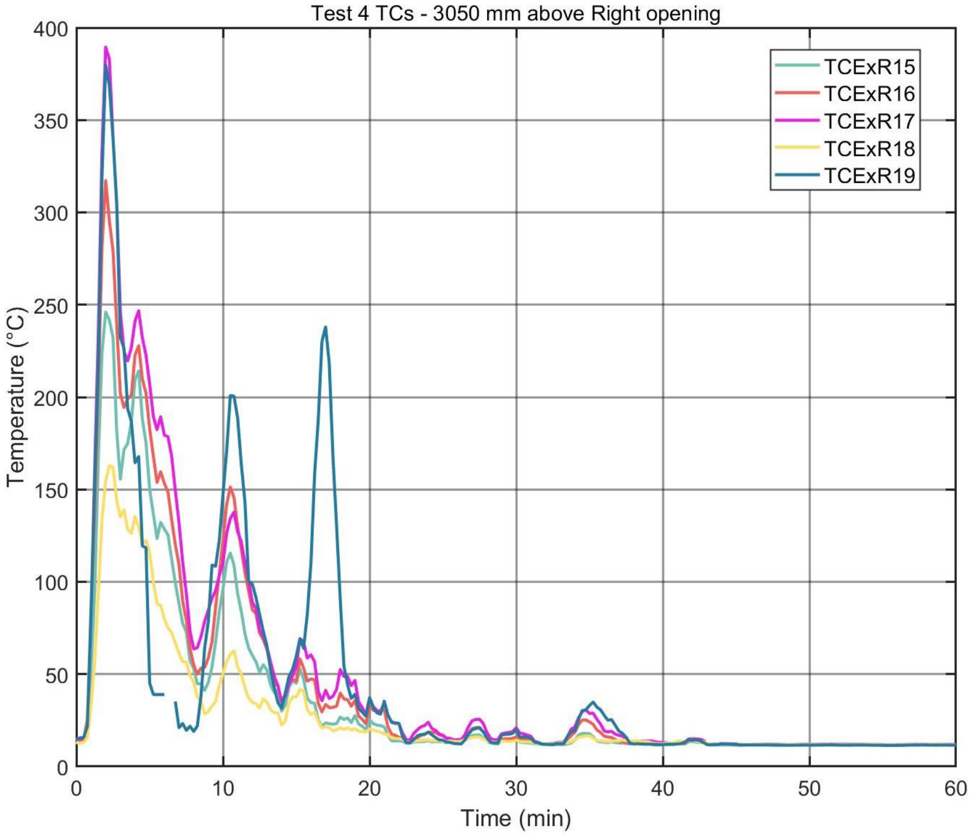

Figure A 67. TC temperatures, test 4 for comparisons to NFPA 285. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

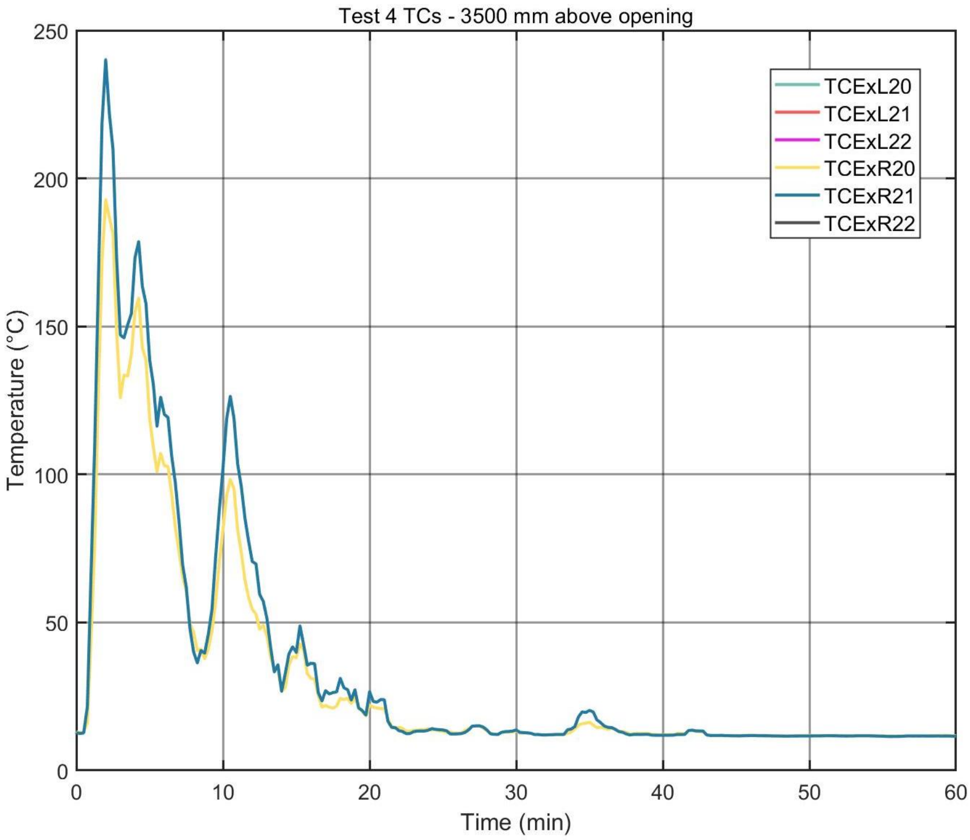

Figure A 68. TC temperatures, test 4 for comparisons to EU proposed method. Ex refers to "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

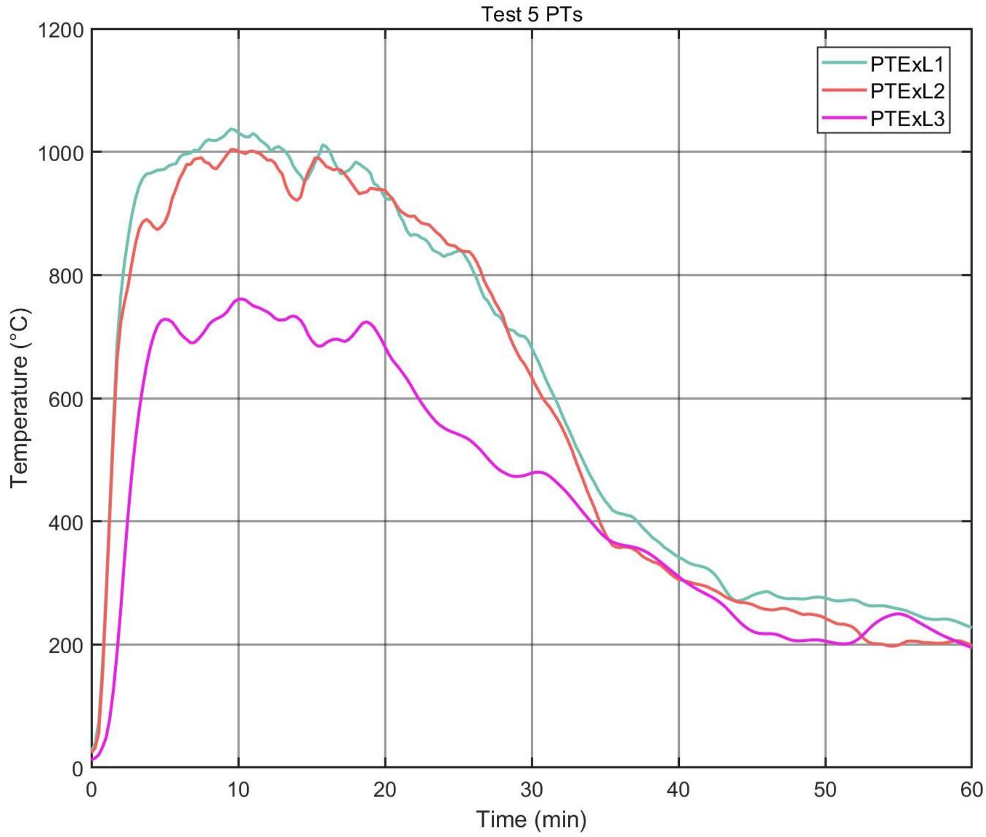

Figure A 69. PT temperatures, test 5. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

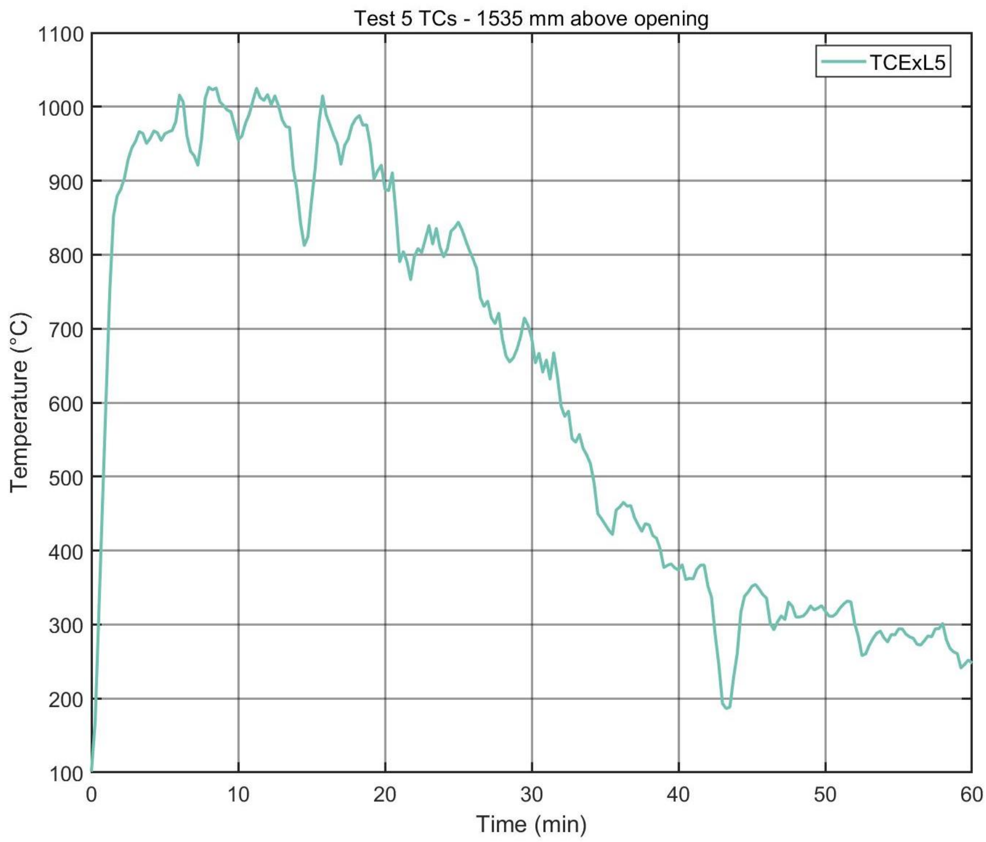

Figure A 70. TC temperatures, test 5 for comparisons to NFPA 285. Ex refers to the measurements being “external” (on façade), “L” and “R” refers to above left and right opening. See Annex B.

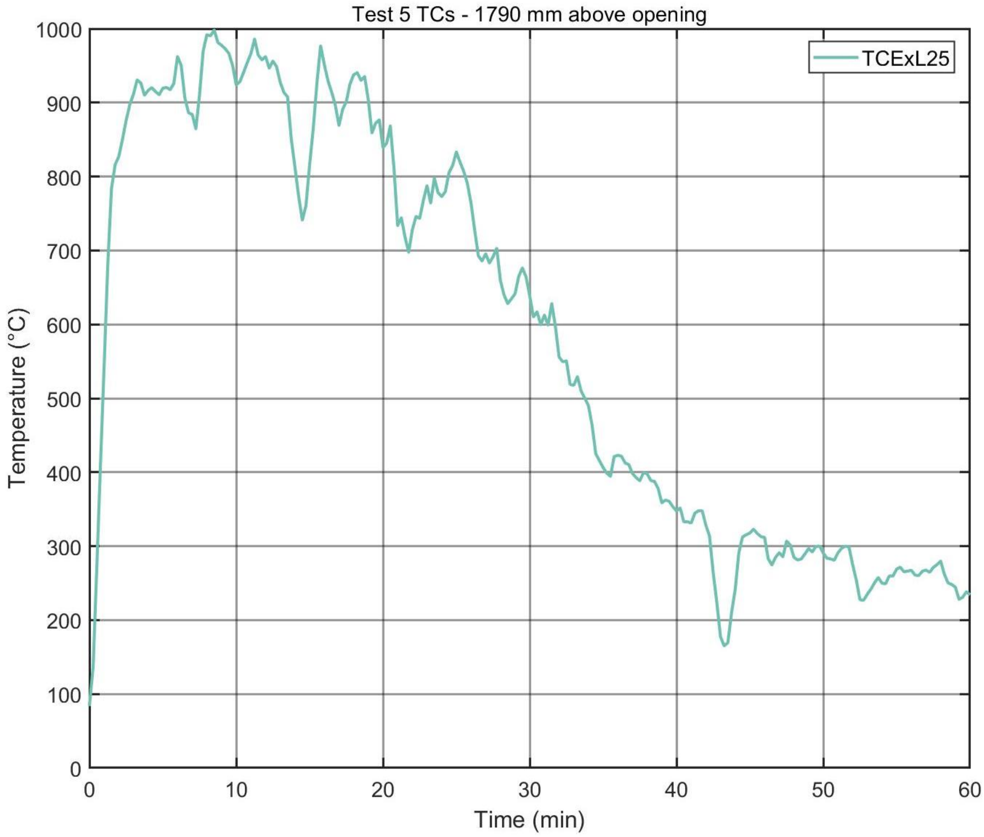

Figure A 71. TC temperatures, test 5 for comparisons to SP Fire 105. Ex refers to the measurements being "external" (on façade), "L" and "R" refers to above left and right opening. See Annex B.

Opening Measurements

The following graphs document the data measured via instrumentation in, or in front of, the two front openings, as listed in Annex A "Other Measurements" section. Legends for TC Tree data plots show heights measured from the floor level of the compartment. Opening 1 is the left-hand opening (when viewed from outside the compartment).

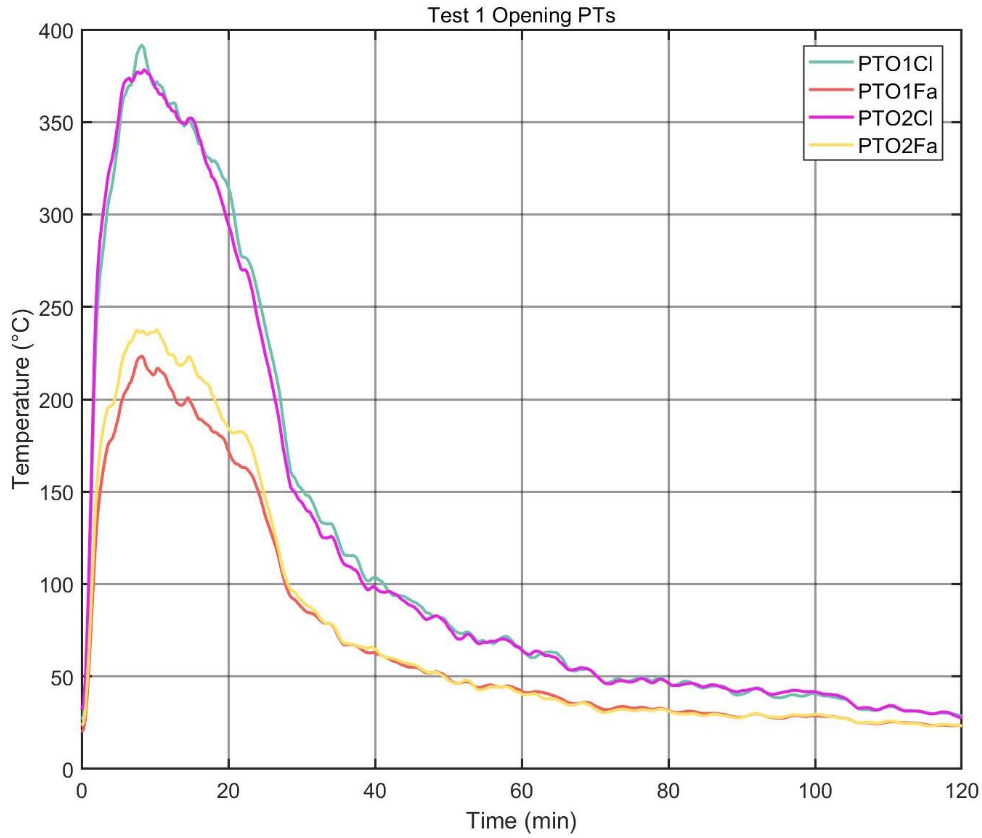

Figure A 72. PT temperatures, test 1. “Cl” refers to “close” – 4.8 m from opening. “Fa refers to “far” – 8 m from opening. O1 and O2 is left and right opening, respectively. See Annex B.

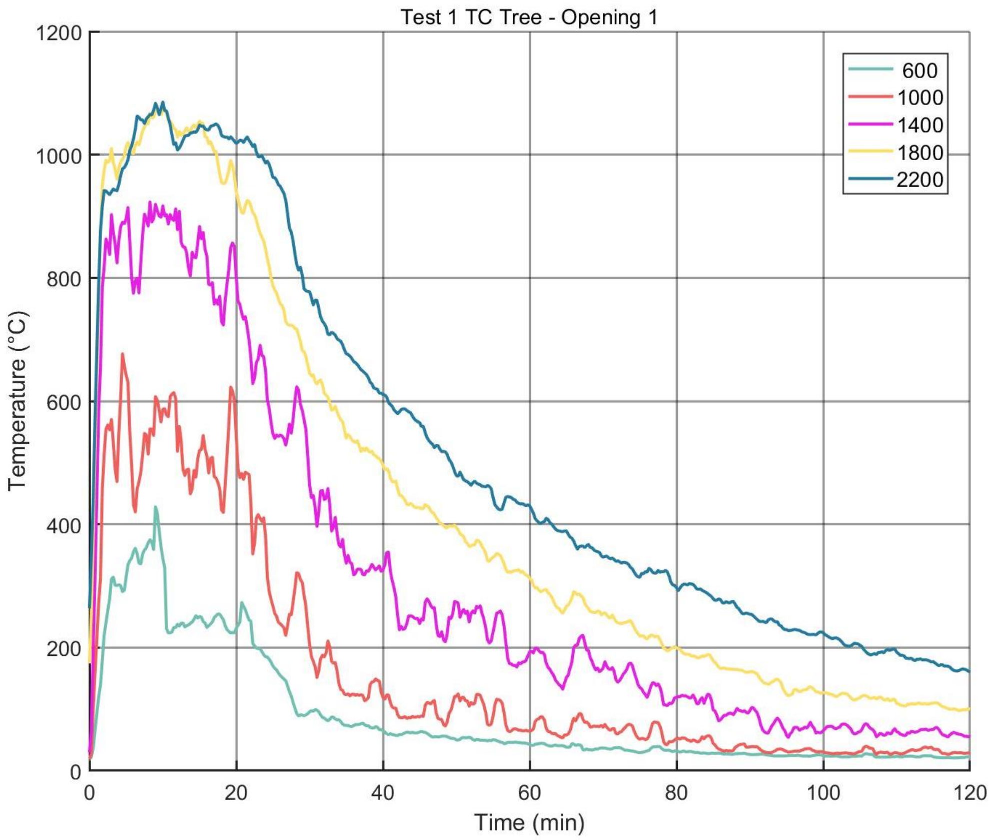

Figure A 73. TC tree openings (left) for test 1. Numbers refers to height from floor. See Annex B.

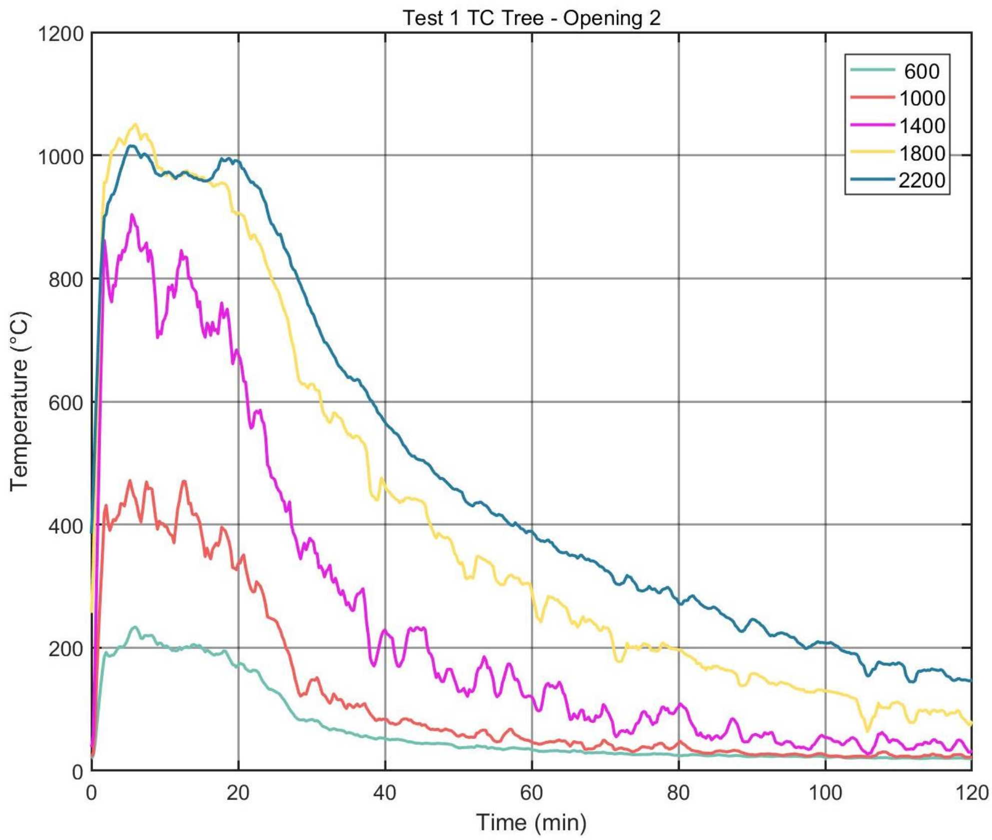

Figure A 74. TC tree openings (right) for test 1. Numbers refers to height from floor. See Annex B.

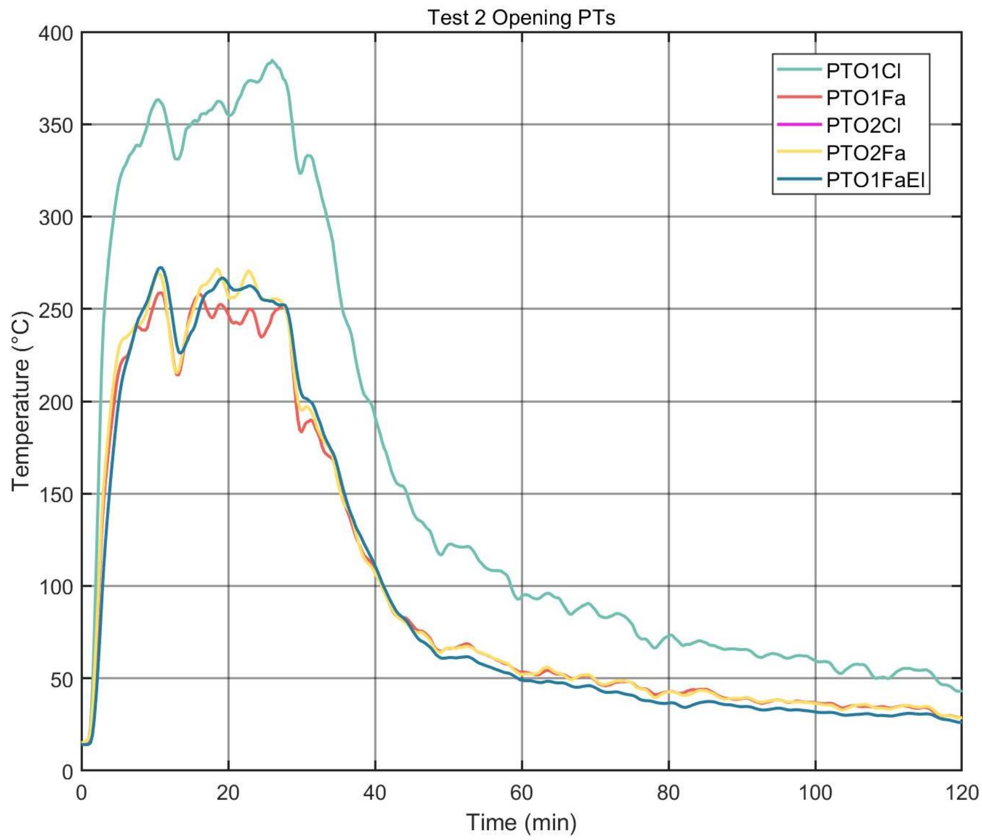

Figure A 75. PT temperatures, test 2. “Cl” and “Fa” refers to “close” (4.8 m) and “far” (8 m) from opening, respectively. “El” refers to “elevated” (at 8 m) O1 and O2 is left and right opening.

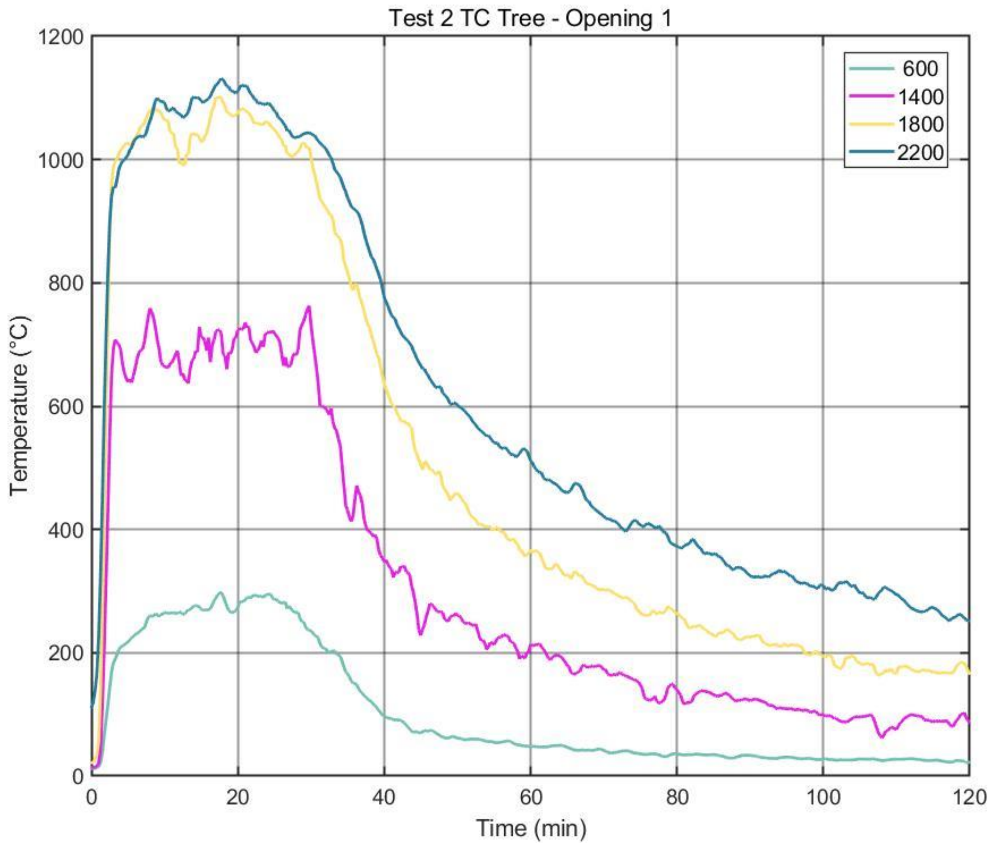

Figure A 76. TC tree openings (left) for test 2. Numbers refers to height from floor. See Annex B.

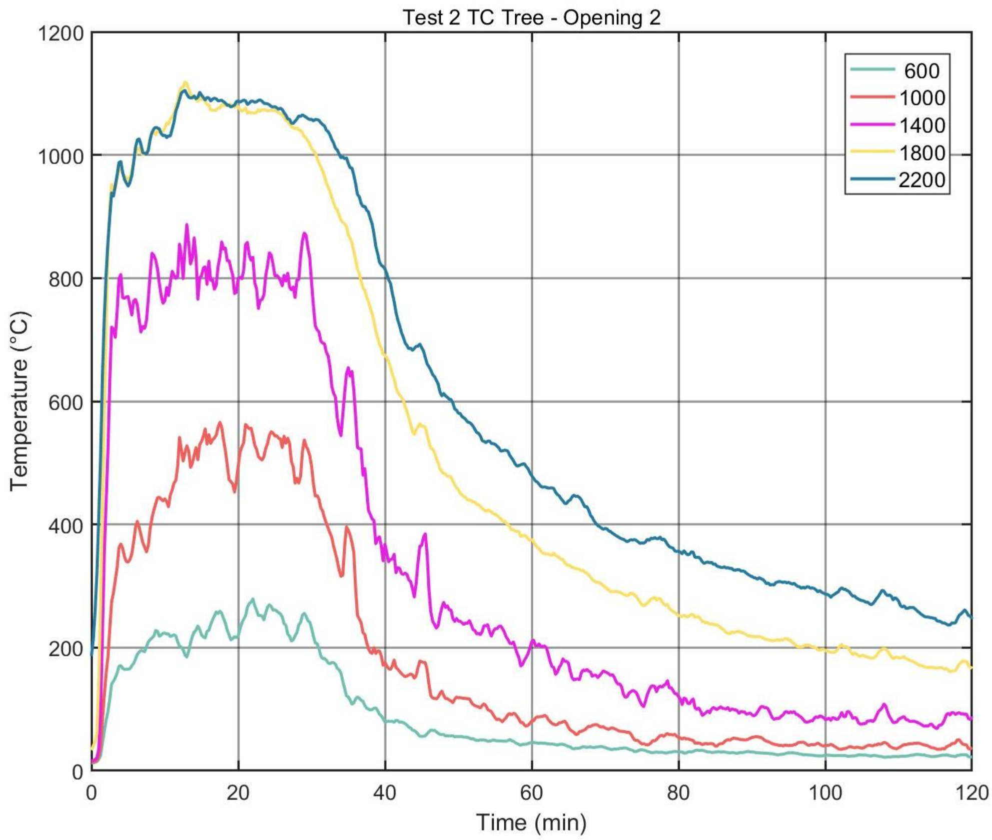

Figure A 77. TC tree openings (right) for test 2. Numbers refers to height from floor. See Annex B.

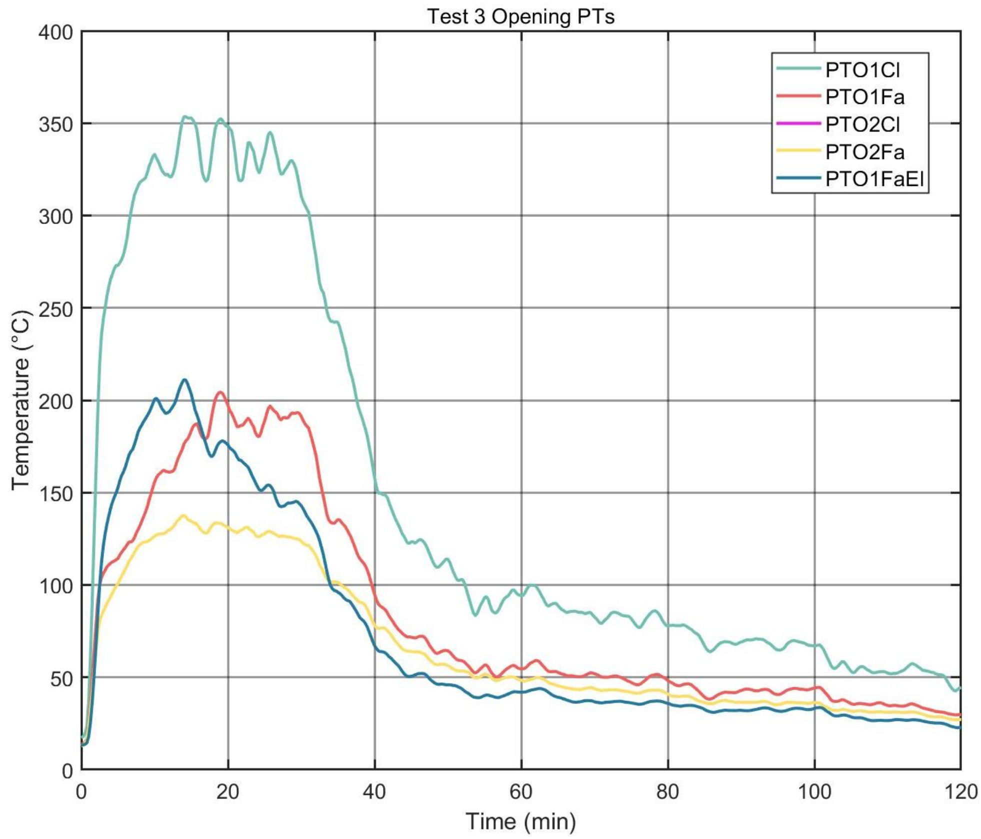

Figure A 78. PT temperatures, test 3. “Cl” and “Fa” refers to “close” (4.8 m) and “far” (8 m) from opening, respectively. “El” refers to “elevated” (at 8 m) O1 and O2 is left and right opening.

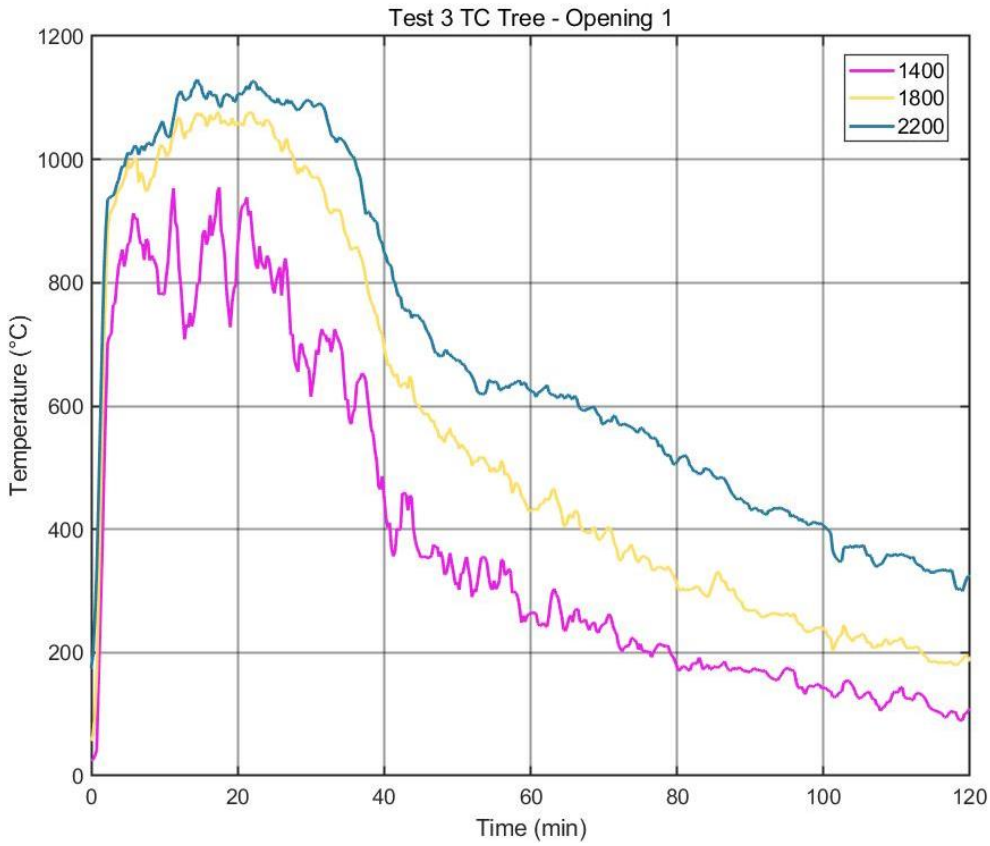

Figure A 79. TC tree openings (left) for test 3. Numbers refers to height from floor. See Annex B.

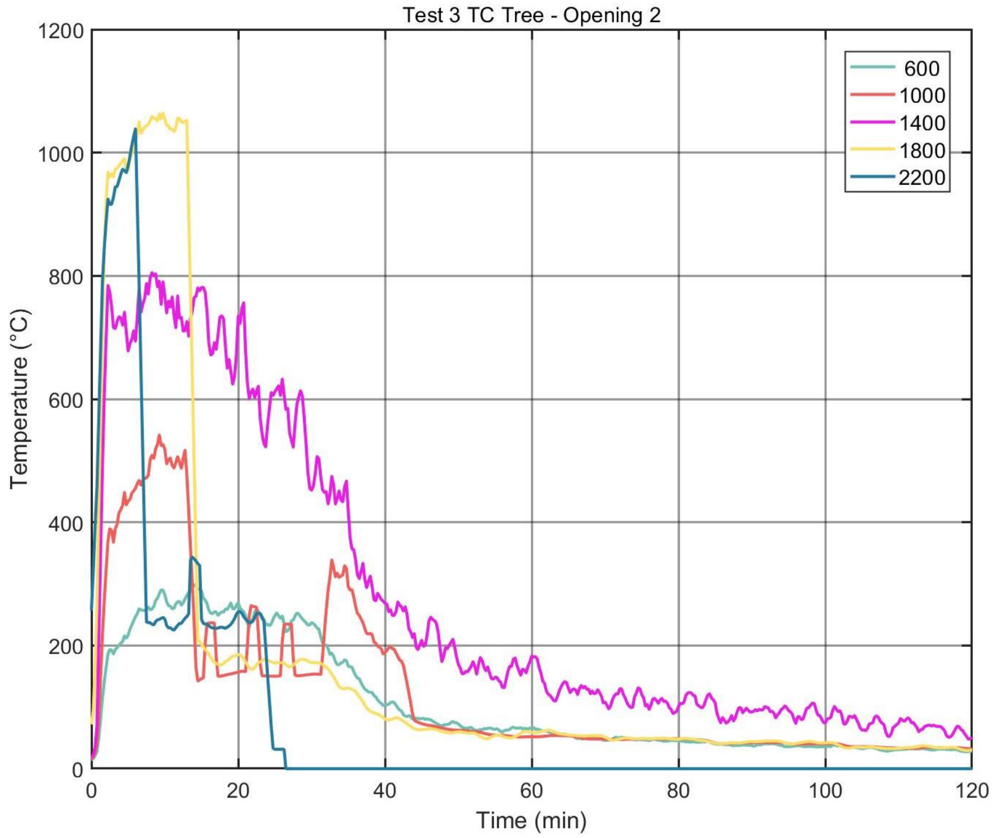

Figure A 80. TC tree openings (right) for test 3. Numbers refers to height from floor. See Annex B.

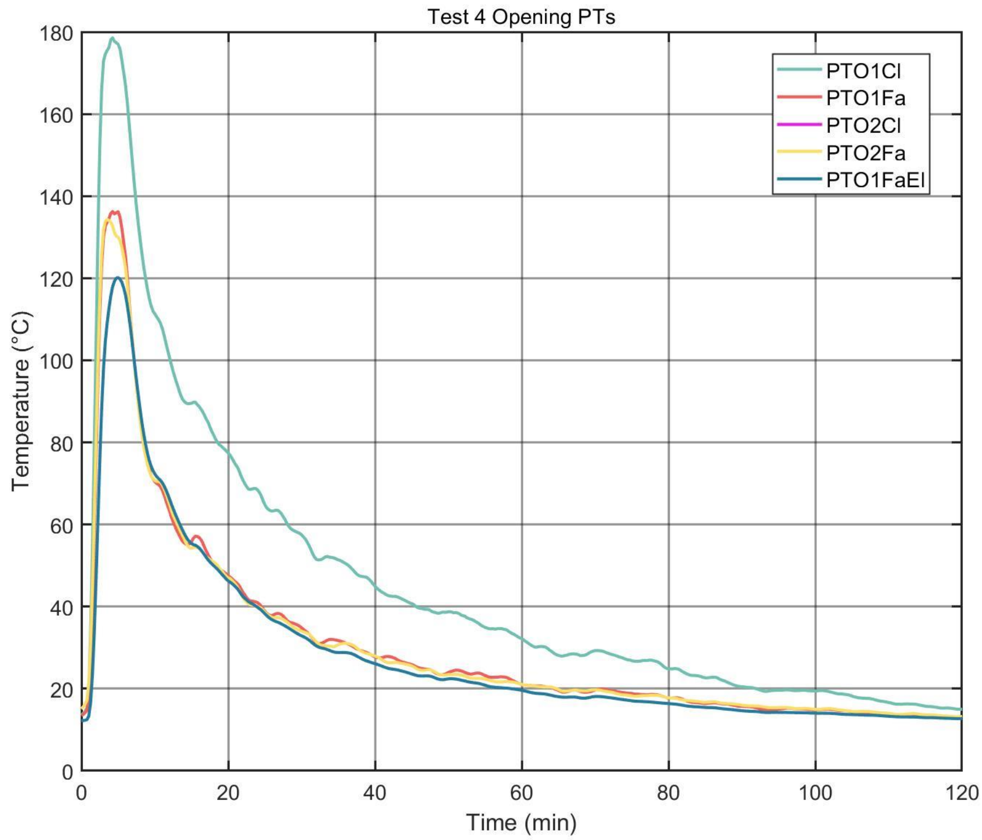

Figure A 81. PT temperatures, test 4. "Cl" and "Fa" refers to "close" (4.8 m) and "far" (8 m) from opening, respectively. "El" refers to "elevated" (at 8 m) O1 and O2 is left and right opening.

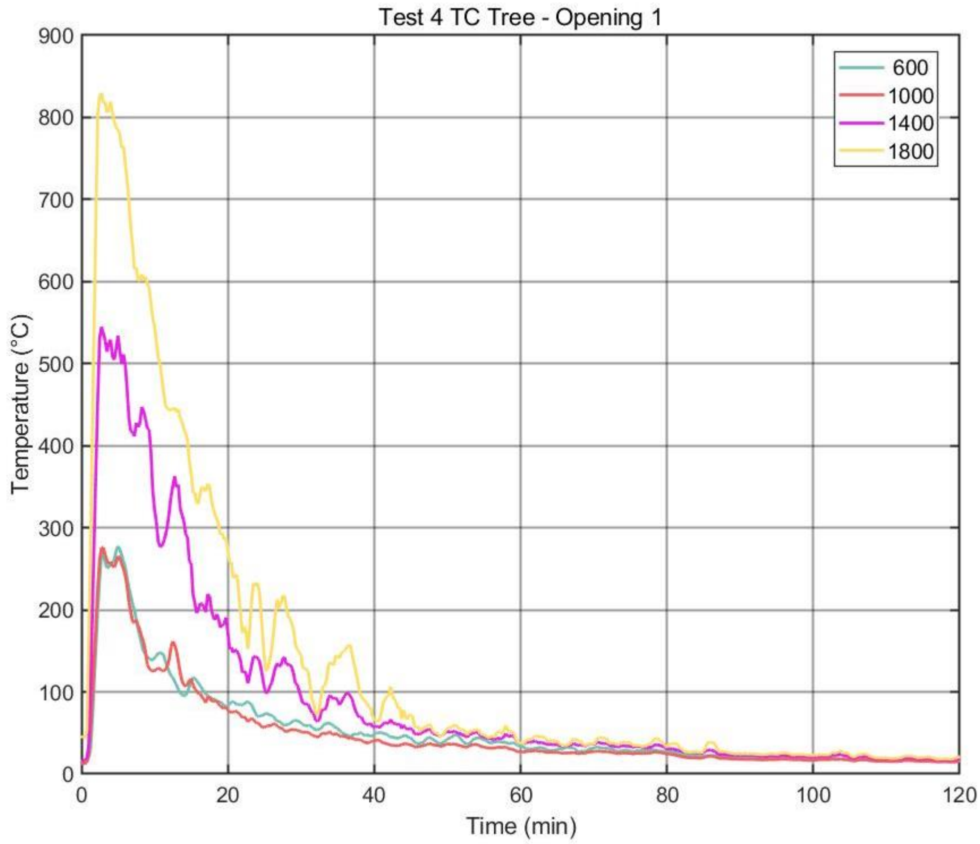

Figure A 82. TC tree openings (left) for test 4. Numbers refers to height from floor. See Annex B.

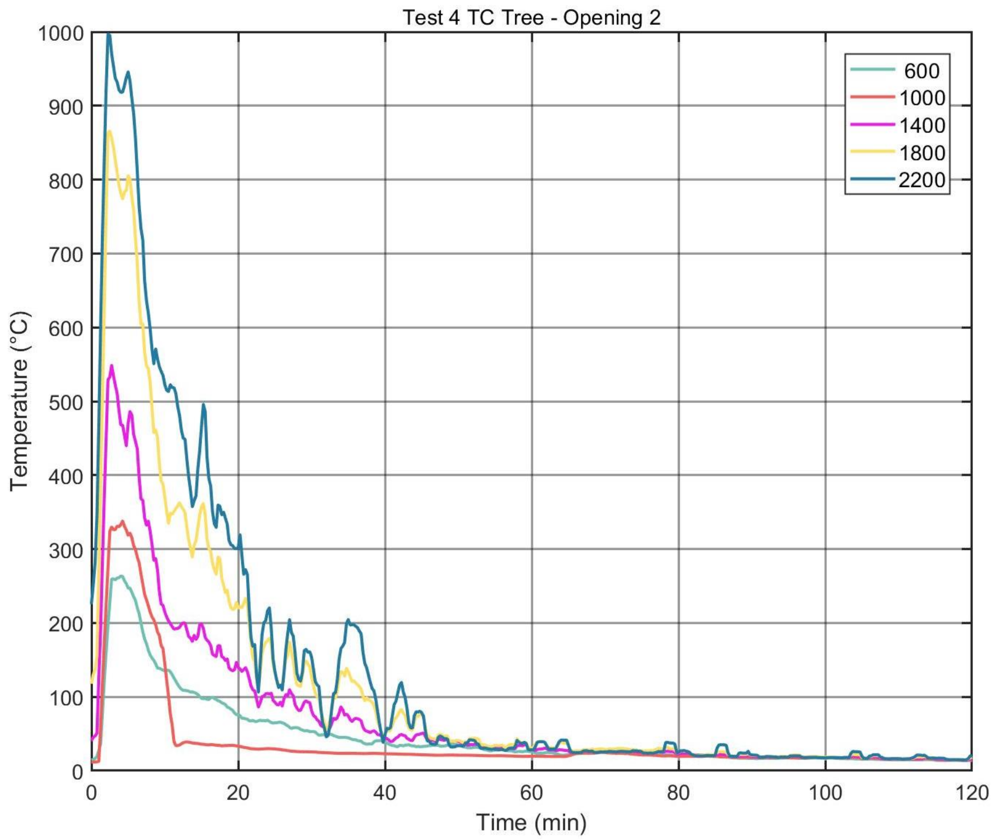

Figure A 83. TC tree openings (right) for test 4. Numbers refers to height from floor. See Annex B.

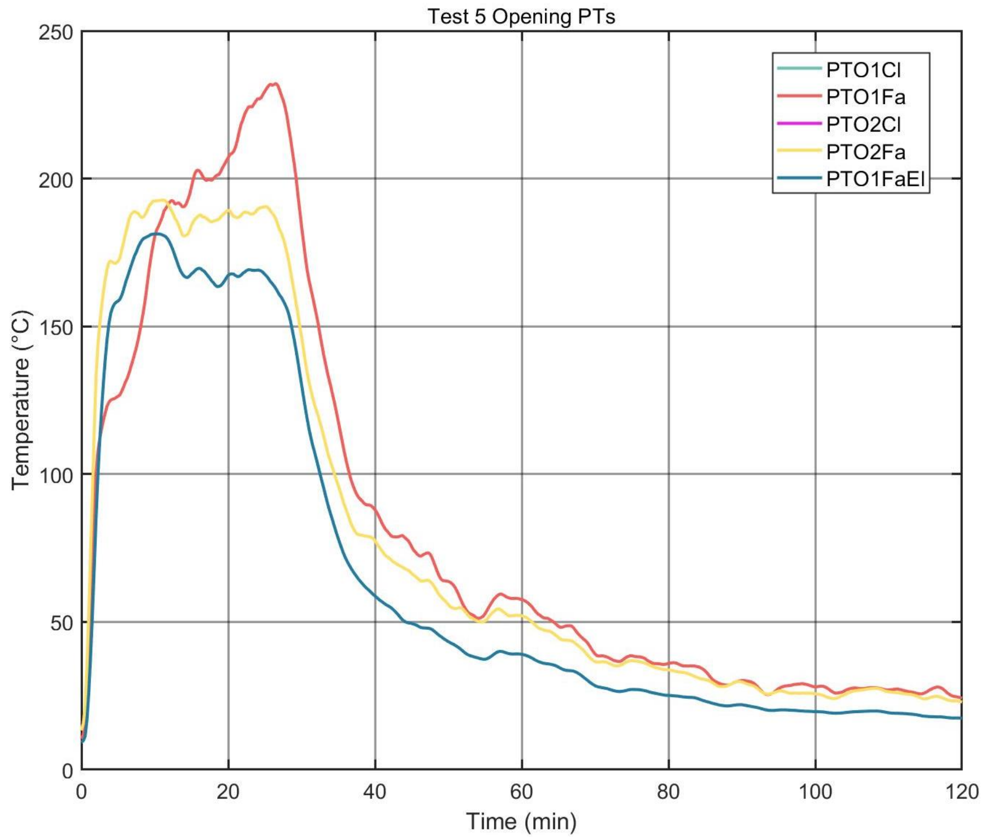

Figure A 84. PT temperatures, test 5. “Cl” and “Fa” refers to “close” (4.8 m) and “far” (8 m) from opening, respectively. “El” refers to “elevated” (at 8 m) O1 and O2 is left and right opening.

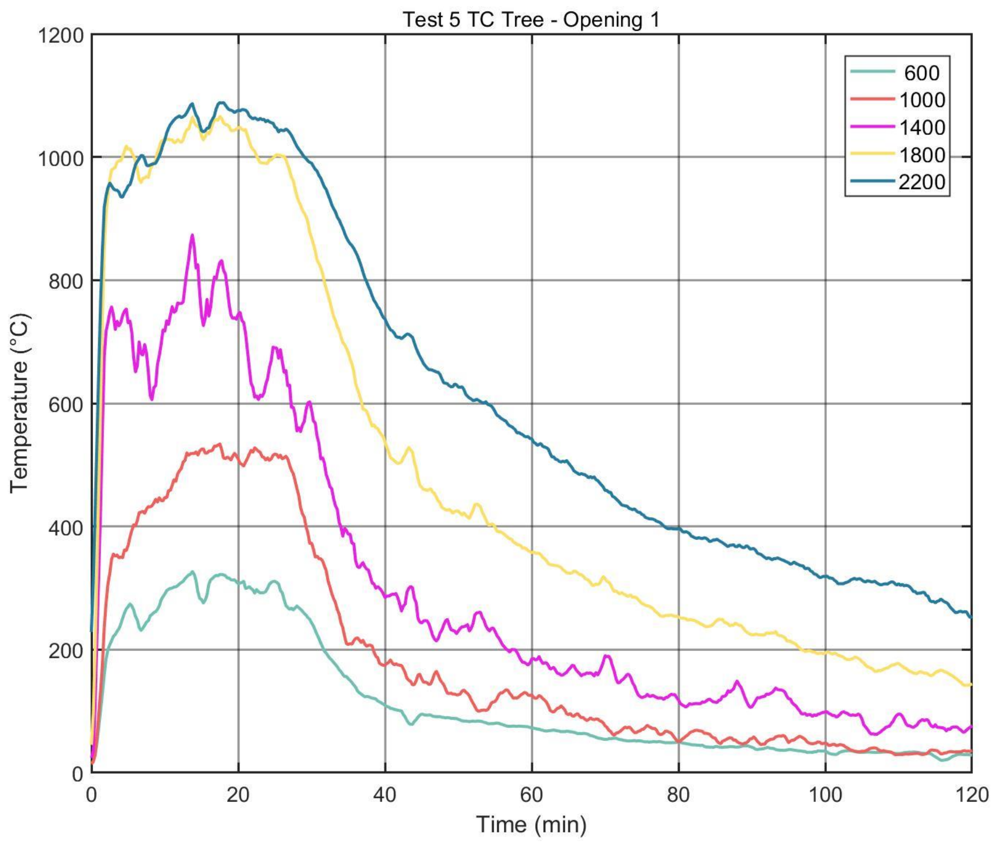

Figure A 85. TC tree openings (left) for test 5. Numbers refers to height from floor. See Annex B.

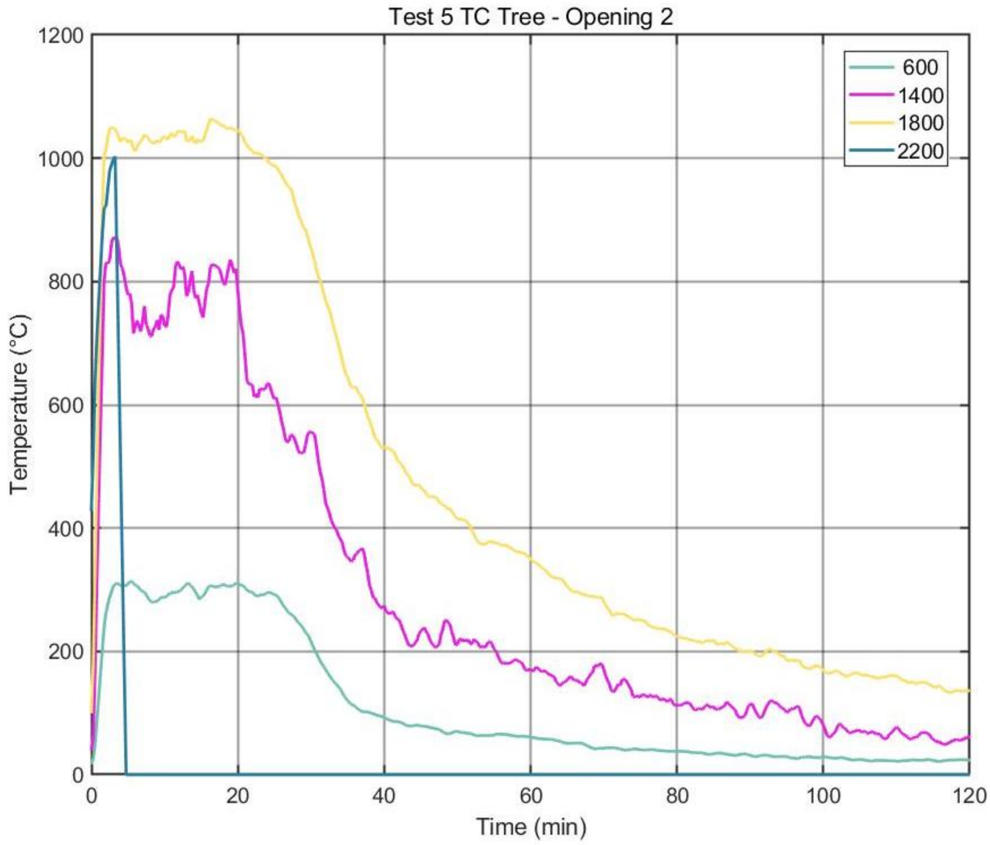

Figure A 86. TC tree openings (right) for test 5. Numbers refers to height from floor. See Annex B.

Annex D – Shifting Thermocouple Temperatures with Height

In a number of instances in the development of the comparison plots in section 6, thermocouple temperatures from the CLT compartment tests have been shifted to estimate their values at a height matching that of the data from the standard test.

The method by which this is achieved is as follows:

1. The maximum change in temperature between the two heights is calculated on using the average gradient of the temperature-height relationship for Tests 1-3 (-0.1528 (°C/mm), see Section 5.1). E.g. a shift from 2 m to 1.5 m would result in an increase in temperature of 76.4 °C during flashover.
2. As this temperature relationship is calculated based on the peak temperatures at flashover, the increase is scaled at each individual time measurement in relation to the maximum temperature at flashover, i.e.

$$\Delta T_{time=i} = (\Delta height \times -0.1528) \times \left(\frac{T_{time=i}}{max\ temp}\right)$$

This shift prevents outsized changes in temperature occurring in the post-flashover stage of the fire.

An example of the results of this temperature shift calculation for a change in height from 2 m above the opening to 2.25 m above the opening can be seen in Figure A 87.

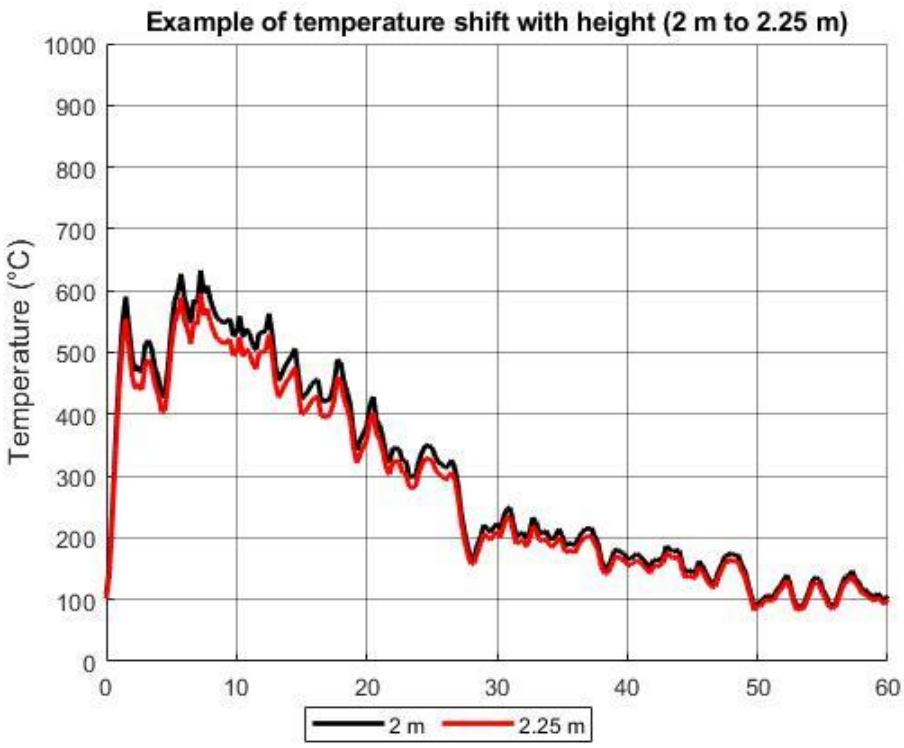

Figure A 87. Example of the temperature shift for a change in height between 2 m and 2.25 m above the opening.

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