BRANDFORSK 2016:5

The function of intumescent paint for steel during different fire exposures

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KEYWORDS

Intumescent paint, steel, alternative exposure

BRANDFORSK 2016:5
ISBN 978-91-88349-47-7

Abstract

In the present study the behaviour of four intumescent systems for steel was investigated experimentally. The main purpose of the study was to determine the behaviour of the systems during different fire scenarios including standardized furnace testing, tests in cone calorimeter and ad hoc tests including ceiling jets and fire plumes. The experimental campaign shows that two of the investigated systems did perform very poorly in the furnace tests compared to what they were designed for, despite being the systems having the best swelling in the cone calorimeter tests. This highlights the importance of adhesion at high temperature for this type of systems. Since adhesion is crucial a more relevant evaluation for this type of systems ought to be a test where the flows around the specimen can be characterized and controlled, i.e. a ceiling jet or a fire plume scenario. This is especially important as steel protected with intumescent systems are often used in large open spaces where local fire plumes and ceiling jets are expected.

Key words: intumescent paint, steel, alternative exposure

SP Sveriges Tekniska Forskningsinstitut
SP Technical Research Institute of Sweden

SP Rapport 2016:43
ISBN 978-91-88349-47-7
ISSN 0284-5172
Borås 2016

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Preface

The study reported here has been sponsored by Brandforsk, the Board of Swedish Fire research, project 310-131, which we gratefully acknowledge. Project leader for the project has been Dr Robert Jansson McNamee from SP Fire Research in Sweden. The experimental studies were performed at SP Fire Research AS in Trondheim, Norway.

We also wish to thank the following persons for valuable support during the project:

At SP Fire Research AS in Norway:
Per Gunnar Nordløkken for his great organization skills in the test preparation phase and for his work with the furnace test. Ulla Eidissen Jensen for her help with the cone calorimeter study included as a project work in her course TBA4521 - Building and Material Engineering, at the Norwegian University of Science and Technology, NTNU. Frode Løvik, Morten Daffinrud and Vidar Olsen, technicians at SP Fire Research AS, for their work with the test specimens.

At SP Fire Research in Sweden:
Dr Lars Boström for a valuable critical review of the text in the report and Dr Michael Försth, research manager at SP Fire Research, for valuable input.

We also want to thank the reference group consisting of Joakim Sender and Erik Almgren from the company Bengt Dahlgren for valuable discussions. And a special thanks goes to professor emeritus Kai Ödeen for reviewing the content and proof reading chapter 1.2.

Summary

In the present study the behaviour of four intumescent systems for steel from the Nordic market was investigated experimentally. The main purpose of the study was to determine the behaviour of the systems during different fire scenarios. The standard test used for this type of systems is EN 13381-8, from which all design tables for making a proper choice of thickness of the systems are developed. In this test method the test specimens are exposed to the standard time temperature fire curve in a furnace. This furnace exposure does only represent one possible scenario in real fires. Based on previous experience from fire testing of intumescent systems it is known that both heat exposure and the flows around the expanded products can influence the function. The following five different test scenarios were chosen for the experimental studies:

- Cone calorimeter test with incident radiation 30 kW/m^2.
- Cone calorimeter test with incident radiation 50 kW/m^2.
- Ceiling jet scenario where the specimens were exposed to a horizontal flow as in a ceiling jet, thermal exposure less severe than the standard fire curve
- Fire plume scenario where the specimens were exposed to a vertical flow as in a fire plume with a free flow velocity of around 10 m/s, thermal exposure less severe than the standard fire curve
- Furnace test with three side exposure hanging in the roof of the furnace exposed to a standard fire scenario

The four different protection systems used in the experimental study, A-D, was applied on hollow square cross section steel beams according to instructions from the suppliers. Thickness of the active component, the intumescent paint, was chosen from the suppliers design tables to maintain a fire resistance for 60 minutes with a design temperature of 550 °C. The design tables was according to the suppliers based on testing according to the current standard. Despite this, during the study it was discovered that the documentation regarding system A was not complete as the primer provided by the supplier was not the one that the certification was based on, but according to the supplier it was equivalent.

Results from testing in the fire resistance furnace showed that system A and B failed to maintain the insulation criteria for 60 minutes despite the fact that these two systems were the ones giving the highest expansion measured during the 50 kW/m^2 exposure in the cone calorimeter. When exposed to the fire plume and ceiling jet scenarios system A lost its adhesion to the steel surface leading to a rapid rise in steel temperature. Whether this was caused by the very high expansion of the system or the use of a non-certified primer (or a combination of this two) is not possible to determine. In summary, two out of four tested systems failed to protect the steel as intended which is a result that is not satisfying. As the performed test campaign only covered one cross section with protection designed for one hour fire resistance we do not claim that the study gives the full picture of the behaviour of intumescent paints. But as the thicknesses for all four systems was chosen to be far from the highest thickness allowed, which theoretically are the most critical for adhesion, the question of adhesion of intumescent paints deserves further attention.

The study did not show clearly that the chosen ad hoc scenarios with a ceiling jet or a fire plume was more severe than the standard furnace exposure but in these tests the flow situation can be defined compared with tests in a standard furnace. This gives these type of tests a potential for a more relevant evaluation of adhesion than traditional furnace testing. Adhesion is shown in these experiments and from previous experience from standardized testing to be crucial for the function of the systems.

Sammanfattning (Swedish summary)

I denna studie undersöktes fyra olika brandskyddsfärgssystem för skydd av stålkonstruktioner. Huvudsyftet med studien var att visa hur systemen fungerar vid olika brandscenarier som uppkommer i stora rum där brandskyddat stål är vanligt förekommande. Standardtestet för den här sortens skyddssystem är EN 13381-8 vilken används för att ta fram dimensioneringstabeller för skyddssystemet. Vid dessa tester exponeras provkropparna för standardbrandkurvan i en ugn. Denna standardbrandkurva representerar endast en sorts upphettning. Tidigare erfarenheter från brandtester av brandskyddsfärgssystem visar att både värmeexponeringen och flödesprofilen kan påverka systemens funktion. Följande fem olika exponeringsscenarier valdes för studien:

- Konkalorimetertest, infallande strålning 30 kW/m^2.
- Konkalorimetertest, infallande strålning 50 kW/m^2.
- Takplymsscenario där provkropparna exponeras för ett horisontellt flöde, termisk exponering något lägre än standardbrandsexponeringen.
- Brandplymsscenario där provkropparna exponeras för en brandplym med en flödeshastighet på runt 10 m/s, termisk exponering något lägre än standardbrandexponeringen.
- Ugnstester med tresidig exponering där provkropparna är monterade i taket på ugnen och exponeras för en standardbrand enligt den europeiska standarden EN 13381-8.

De fyra brandskyddsfärgssystemen som undersöktes i den experimentella studien, system A-D, var applicerade enligt leverantörernas anvisningar på slutna stålprofiler med fyrsidigt tvärsnitt. Tjockleken på den aktiva komponenten i systemen, brandskyddsfärgen, bestämdes med hjälp av leverantörernas dimensioneringstabeller för att ge ett brandmotstånd på 60 minuter vid en vald kritiskt temperaturer 550 °C. Enligt leverantörerna var samtliga system testade enligt den europeiska standarden för brandskyddsfärg. Trots detta upptäcktes det under studiens genomförande att ett av systemen som levererats, system A, inte var korrekt eftersom primern som användes inte var den som används vid den standardiserade provningen men enligt leverantören var primern likvärdig.

Resultat från ugnstesterna visade att system A och system B inte fungerade som det var tänkt då de inte kunde begränsa temperaturutvecklingen under 60 minuter trots att dessa två system var de som visade sig svälla mest under konkalorimetertesterna med infallande strålningsnivån 50 kW/m^2. Vid takplymstesterna och brandplymstesterna visade det sig att system A tappade vidhäftningen vilket ledde till snabb uppvärmning av stålet. Om detta primärt beror på den felaktiga primern som levererades med systemet eller den mycket kraftiga expansionen som uppmättes för system A vid konkalorimetertesterna är ej möjligt att avgöra. Sammanfattningsvis kan sägas att två av fyra system fungerade mycket dåligt. Tilläggas bör också att provningsserien endast gäller ett tvärsnitt dimensionerat för en timmas brandmotstånd vilket gör att studien är långt ifrån heltäckande. Men då tjocklekarna för samtliga system ligger klart under de tjockaste tillåtna enligt dimensioneringstabellerna, vilka teoretiskt ger störst problem med vidhäftning, visar studien att vidhäftningsfaktorn för denna typ av system måste undersökas mer ingående.

Studien visade att ad hoc testerna med tak- och brandplymscenarier ej tydligt var mer utslagsgivande då det gäller vidhäftning än det standardiserade testet. Men vid dessa tester har man möjlighet att karakterisera och reglera flödet kring provkropparna på ett mycket bättre sätt än vid standardiserade ugnstester där detta är i princip omöjligt. Detta gör att denna sorts tester är ett bättre verktyg för att utvärdera svällande brandskyddsfärgers vidhäftningsförmågan vid hög temperatur då det många gånger är det som bestämmer effektiviteten hos systemen.

1 Introduction

The parts of buildings where steel is visible are in many cases open spaces. It is attractive from an architectonic point of view to include visible slender members in the design. But in the case of fire this slender members needs to be protected. A way of doing this, but keeping the eye-catching visual appearance, is to apply an intumescing paint system to the steel surfaces. In most cases these type of systems consist of a primer, an intumescent paint and a top coat. Intumescent paint systems for protecting steel have been used extensively from at least the early seventies. It is, as shown in Figure 1, an almost invisible method of protecting steel as it due to its low thickness looks like an ordinary paint while substantially increasing the fire resistance of the member.

Figure 1 Application of a intumescent system on a steel column.

The word “intumescence” originate from the Latin word “intumescere” meaning “to swell up”. When reaching a critical temperature the material starts to foam and an outer char layer is created, protecting the underlying material. The first observation of intumescence was probably when using a toy called the “Fourth of July snake”. When heated a little pill starts to swell and foam and form a snake, the Fourth of July snake. But according to Vandersall (1971) it took many years to realize that this process could be used for fire protection systems.

In 1938 the first patent on using intumescent materials for fire protection of wood was launched by Tram et al. (1938). Since then intumescent materials have been used in a variety of different fire protection applications. Two key components are included in intumescent paints according to Goode (2004); (i) a resin binder and (ii) chemicals that decompose and release gas when heated. During fire exposure the material melts and a gas-producing reaction is triggered at a temperature corresponding to an appropriate resin melt viscosity. By this foaming process an insulating layer is created that may be 15 to 30 times the thickness of the initial layer[1].

Goode (2004) divides intumescent paints in three basic categories:

- Single part water based
- Single part solvent base
- Two part epoxy solvent free or solvent based

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[1] Higher expansion than 30 times the original thickness has sometimes been observed for this type of systems during standardized testing at SP.

Water based systems have a low odour but are more sensitive to humidity and temperature changes than other types. The solvent based intumescents, which are more resistant to temperature and moisture variations, are typically used outdoors, but is sometimes also used indoors. In more harsh environments like in chemical industries or offshore operations two part epoxy systems are used. These systems resist higher thermal and mechanical impact than the first two types. Charring increases the thickness approximately 5 times which is lower than the single part systems, and the original thickness is usually thicker, 5-25 mm, compared to 0.5-2 mm for the single part systems. The char that is formed in these systems are generally more compact and robust.

Intumescent paint systems are according to Goode (2004) usually designed to provide fireproofing during cellulosic type of fires, i.e. the standard time temperature exposure. During more severe exposure like hydrocarbon fires additional testing is needed as there can be problems with foaming which is driven by a balance between the viscosity of the resin melt and the gas evolution. During faster heating up the time for the foam to develop is reduced as the temperatures span where the viscosity change and gas production produces the foam is passed faster. Both the standard fire exposure and the hydrocarbon exposure can be seen in Figure 2.

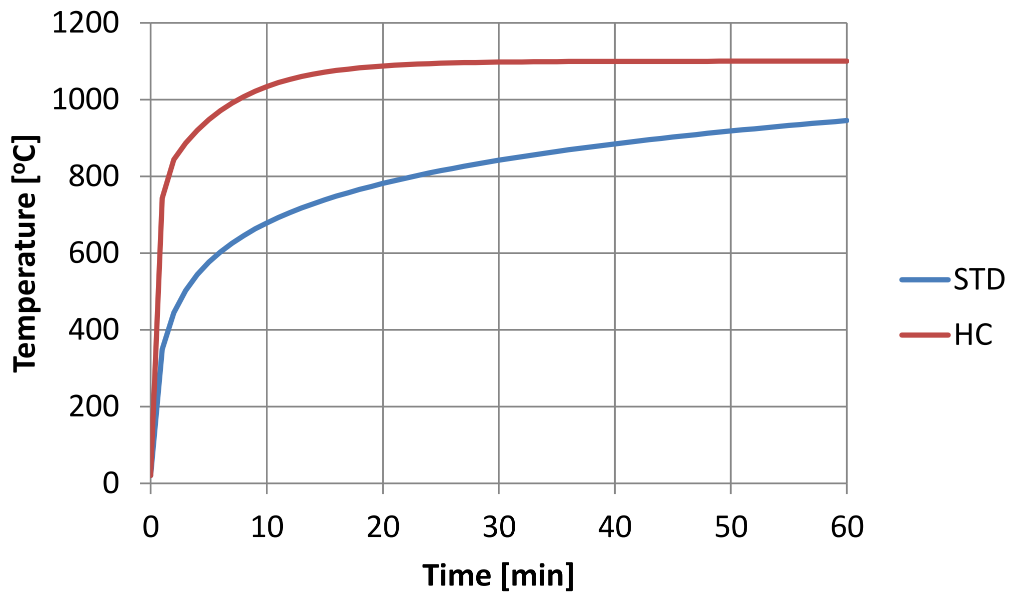


Figure 2 The standard fire exposure also called the "cellulosic" fire and the hydrocarbon fire exposure according to EN 1363:2012.

NT Fire 021 (1985) is the old test method for protection of steel in the Nordic countries. The method was developed in 1985 and based on a proposal made by Andersen and Wickström (1982). The background to this proposal was the identified need for

i. a test method that includes the influence of deformation on the tested products insulation properties and
ii. a methodology for making calculations of the heat development in protected cross sections based on a model calibrated by fire tests.

The test program in the study performed by Andersen and Wickström (1982) included tests of three protection systems made of Rockwool (mineral wool), Navilite and gypsum. No intumescent system was included in the test series but intumescent paints were included in the scope of the proposed method, as well as in the published NT Fire 021 (1985) standard. Later Andersen (1988) investigated the use of the NT Fire 021 method for intumescent systems and the main findings from this study were:

- Increased heating rate can have a very harmful effect on the foaming process, especially when combined with massive steel sections, i.e. section with low section factor. These tendencies were observed when testing with a fire exposure more severe than the standard fire curve but not as severe as the hydrocarbon exposure (standard exposures shown in Figure 2).
- Problems of applying an even thickness was highlighted and a large number of measurement points for checking the application was recommended.
- The film thickness and the section factor were found to influence the results but by introducing transformations for both parameters the temperature-dependent "modified thermal conductivity" could be created. This was needed as the NT Fire 021 method was originally developed for passive insulation products with thermal resistance proportional to thickness and independent of the section factor.
- A safety factor based on statistics assuming a normal distribution of results was introduced which includes a choice of how many of the test specimens having inferior results compared with calculations based on the developed model, i.e. the model could be calibrated to be more or less on the safe side compared with test results.

The present European test standard for intumescent systems for steel is EN 13381-8: 2013. One major difference between the new European standard and the old Nordic standard NT Fire 021 (1985) is that the device for measuring heat exposure in the furnace was changed from ordinary thermocouples to plate thermometers. A Round Robin performed with the old Nordic method showed very large deviations (Andersen, 1995) which partly could be explained with how the furnaces was previously controlled. The evaluation procedure included in the present European standard EN 13381-8: 2013 is designed to cover a range of:

- section factors
- thicknesses of the applied protection material
- design temperatures
- classification times

The first step in the procedure is to fire test a variety of steel sections defined in a test matrix in the standard. A lot of different test packages can be chosen which may include different numbers of loaded beams, unloaded beams, loaded columns and unloaded columns of different sizes. Then the assessment is performed in two main steps. First the **physical performance** which is in general determined by evaluating the difference in temperature data between loaded and unloaded sections monitoring if there is an negative influence from applying a load to the sections. From this evaluation a temperature dependent correction factor is calculated, which is applied to the variety of unloaded columns included in the test package. These unloaded columns are in accordance with the standard tests included in the **thermal performance** evaluation.

In large open spaces where visible exposed steel elements are used the conditions necessary for the evolution of a fully developed (ventilation controlled) fire are often not met. Instead the fire is spread between areas giving rise to many local phenomena. The moving fire may include three components that are not covered by traditional fire resistance testing in furnaces:

- Pre heating of the material from radiation and convection from a fire in the adjacent areas
- Exposure to very rapid convective heating in plumes
- Exposure to high fluid flow speeds in plumes

The aim of this project is to investigate if commonly used intumescent paints in the Nordic countries change their behaviour when exposed to non-standardized exposure scenarios as compared to standardized exposure. The main focus is to investigate the effect of flows around intumescent paint systems as this might influence the adhesion[2] but also two levels of incident heat flux are investigated by cone calorimeter tests.

1.1 Principal mechanism of intumescent materials

According to Lieff (1983) four types of compound interacts to form the insulating layer:

- a polyhydric compound to act as a carbon source,
- a dehydrating agent that is the intumescent catalyst,
- a blowing agent and
- a resin binder.

When the temperature is rising the compound provides carbon that reacts with the dehydrating agent to form char. At the same time gas is released from the blowing agent that causes the char to expand significantly. To keep the gases inside the foam the resin binder forms a thin layer to inhibit the gas escape. The timing, or the temperature sequence of these different processes is highlighted by Anderson et al. (1985) to be very important to achieve a good development of an expanded protective layer.

The different components included in intumescent systems are shown in Table 1. For a more detailed information regarding the chemistry and different components of intumescent coating systems a paper by Vandersall (1971) is recommended.

Table 1 The essential components of intumescent systems compiled by Kozlowski et al. (2007).

<u>*Carbone source*</u> Polyhydric alcohols (erythritol and its oligomers (pentaerythritol, pentaerythritol dimer and trimer, arabitol, sorbitol, inositol)), saccharides (glucose, maltose, arabinose) and polysaccharides (starch dextrin, cellulose), polyhydric phenols (resorcinol).
<u>*Dehydrating agent*</u> Phosphoric acid, its ammonium, aminic salt and esters (ammonium phosphate and polyphosphate, melamine and urea phosphate tributyl phosphate), boric acid and its derivatives (borax, ammonium borate)
<u>*Foam forming substance (blowing agent)*</u> Nitrogen or halogen compounds such as melamine and its phosphoric salts, urea, dicyanidiamide, guanidine and its derivatives, glycine, chlorinated paraffins.
<u>*Resin binder*</u> Amino, epoxy, acrylic, polyacetic-vinyl and polyurethane resins.

[2] The wording adhesion will be used in this report despite that it is called stickability in the test standard. Stickability is according to the definitions in EN 13381-8:2013 "ability of a fire protection material to remain sufficiently coherent and in position for a well defined range of deformations, furnace and steel temperatures, such that its ability to provide fire protection is not significantly impaired".

1.2 Real fires vs. the standard fire curve

The dynamics of an ongoing fire is based on the amounts of oxygen, heat and fuel. It is common during real fires that the main supply of oxygen comes from the atmosphere surrounding the volume that is in the fire zone. The buoyancy of the heated volume in the fire creates a rising fire plume over the fuel bed and air is supplied from the sides. This is the situation during fires outdoors in the open, in large rooms or during the early phase of fires in small rooms. The behaviour of fire plumes have been studied extensively by observations, as well as dimension analysis complemented by analytical models. A good overview on this research is given by Heskestad (2008). When hot gases from the fire plume reach the ceiling a ceiling jet flow is created as shown in Figure 3. According to Alpert (2008) this refers to the relatively rapid gas flow in a shallow layer beneath the ceiling, which is driven by the buoyancy of the hot combustion products from the plume. In large rooms a traveling fire can progress including a fire plume and a ceiling jet. A methodology for describing this for design purpose was developed by Stern-Gottfried (2011) by dividing the room into two separate moving regions, the near field where flames develops and the far field where smoke movement is heating the surrounding structure.

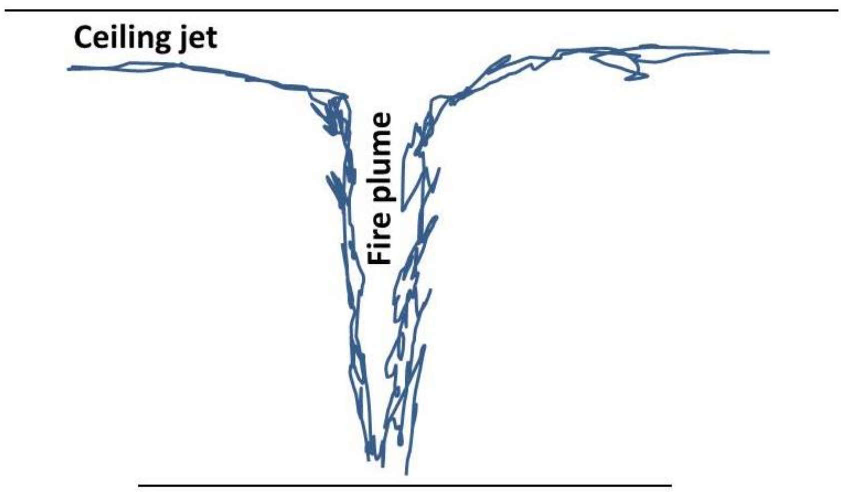


Figure 3 Principal sketch of fire plume and ceiling jet.

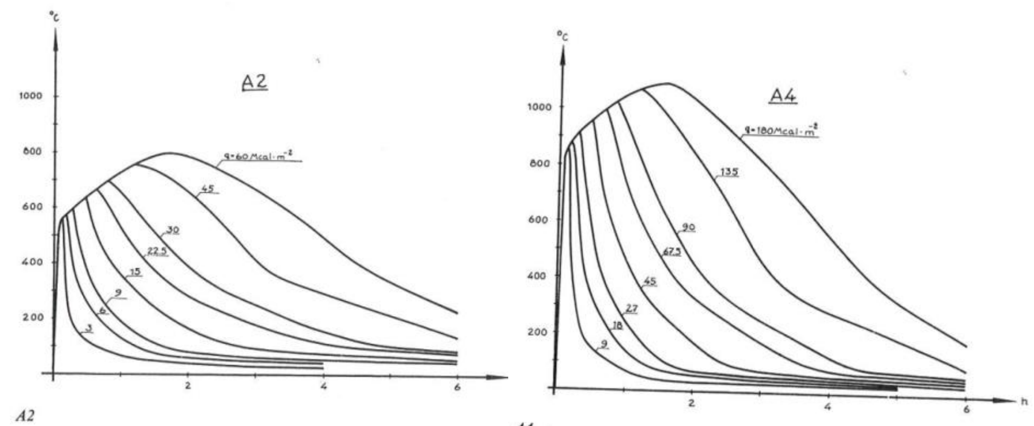
In smaller rooms the initiation phase is usually a fire plume with plenty of available oxygen for combustion. Depending on fire growth rate, geometrical factors and the thermal properties of the enclosure a fully developed room fire, or a flashover fire, can develop. This is a fire mainly controlled by the shortage of oxygen. In the fifties Kawagoe[3] suggested the empirical relationship shown in eq. (1), between the shape and size of a ventilation opening and the burning rate in this type of ventilation controlled fires.

$$\dot{m} = 5.5 A_w H^{1/2} \tag{1}$$

$\dot{m} = Burning\ rate\ of\ wood\ [\frac{kg}{min}]$
$A_w = Area\ of\ ventilation\ opening\ [m^2]$
$H = Height\ of\ opening\ [m]$

[3] The information about Kawagoes work in the fifties is from Karlsson and Quintiere (2000) as we do not have the original article.

The relationship in eq. 1, which is formulated around the *ventilation factor* $A_wH^{1/2}$, is however not enough to describe the fire dynamics and, as Ödeen (1963) and Kawagoe & Sekine (1963) found independently, there is also a dependence of the size and thermal properties of the enclosure on the fire development. The influence of enclosure size is included in the so called *opening factor* where the ventilation factor is divided by the total surface area of the enclosure. The dynamics in a lot of enclosures was calculated by Magnusson and Thelandersson (1970) and was presented in a systematic way which resulted in the so called "Swedish curves". According to this approach the standard fire curve corresponds approximately to the fire growth phase of an enclosure with an opening factor of 0.04 $m^{0.5}$ including walls with defined thermal properties of type A, a standard fire compartment[4]. Other enclosure types with alternative thermal properties of the walls give different fire development. In Figure 4 an example of the curves is shown where the first set of curves is with an opening factor lower than the one corresponding to the standard fire curve in an enclosure type A and the second set of curves is based on a higher opening factor. For the same load density larger openings to the fire cell give hotter but shorter fires.



A2
Type A enclosed space.
Opening factor 0.02 $m^{1/2}$.

A4
Type A enclosed space.
Opening factor 0.06 $m^{1/2}$.

Figure 4 Examples of the "Swedish curves". Calculated time-temperatures for a range of fuel-load densities, opening factors and enclosure types (Magnusson and Thelandersson, 1970). The left set of curves with opening factor 0.02 $m^{0.5}$ rise slower than the standard fire curve and the right set of curves corresponding to opening factor 0.06 $m^{0.5}$ rise faster than the standard fire curve.

The "Swedish curves" were further developed by Wickström (1985) who made a simpler mathematical formulation which now is the basis of the parametric fires in Annex A in the present Eurocode EN 1991-1-2:2002.

As described above many different fires scenarios are possible, from local plumes to more or less fast heating of enclosures during ventilation-controlled fires. Despite this, the totally dominant fire scenario in fire resistance testing is the so called standard time-temperature curve, or standard fire curve shown in Figure 2. The first standard for fire resistance testing was developed 1903 but there was a lot of different fire curves used so a unification process followed that led to the definition of the standard time temperature

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[4] *The standard fire apartment type A is an enclosure with a thermal conductivity of 0.81 W/mK and a volumetric specific heat of 1.67 MJ/m³. Simplified this can be said to correspond to a certain mix of concrete, brick and lightweight concrete.*

curve[5,6] that has become totally dominant in fire resistance testing. This standard time temperature curve is, as shown earlier in this chapter, only one possible thermal scenario in fully developed fires in enclosures as many geometrical parameters and physical properties influences the temperature development in real fires. Also, a natural cooling phase is not included in the standard time temperature curve. Through the years the relevance of using the standard fire curve for fire resistance tests during different durations has been questioned, see for example Ödeen (1969), Magnusson and Thelandersson (1970), Pettersson (1971), Malhotra (1974), Babrauskas (1976), Pettersson and Magnusson (1977) and Stern-Gottfried (2011).

[5] *According to Babrauskas (1976) the formulation of the standard fire curve was first published by UL in a description of column tests 1916.*
[6] *More information on the early development of fire resistance standardization and difficulties associated with temperature measurement can be found on pages 8-10 in Jansson (2013).*

2 Experimental study

The experimental study was divided in four different types of tests, cone calorimeter tests, standardized furnace tests, ceiling jet tests and fire plume tests, the two latter with a diffusion propane flame as the heat source. Four different intumescent paint systems, A-D, and an unprotected cross section, designated X only having a black top coat, were tested according to the test matrix shown in Table 2 below.

Table 2 Test matrix.

Test method	*Systems*	*Total number of test specimens*
ISO 5660-1:2015, Cone calorimeter, 30 kW/m^2 and 50 kW/m^2	A-D, X	24
EN 13381-8:2013, unloaded beams	A-D, X	10
Ceiling jet scenario	A-D, X	12
Fire plume scenario	A-B	4

2.1 Intumescent paint systems

Four commercially available systems were included in the test matrix. Through the report these systems are designated by the letters A, B, C and D (system X is unprotected). The commercial brands behind these letters are kept secret as the main point in this study is to investigate the behaviour in general and not to pinpoint the function of certain brands. All systems including the unprotected steel had a black top coat. In Europe intumescent systems are tested according to the standard EN 13381-8 which is a furnace test method including a variety of test cross sections as well as evaluation procedures for developing design tables. As one of the main parameters to investigate in this project is the adhesion during realistic non-standardized exposure the most onerous option[7] would be to test the highest thickness allowed for each system. This approach was not chosen as it might lead to conclusions only for a limited amount of situations where long fire resistance periods are the goal. Instead thicknesses prescribed to protect a square hollow section with section factor[8] of 105 in 60 minutes with a design temperature 550 °C was chosen for the four systems. This places the test specimens with protection in a very commonly used range. For the chosen cross section between 26-138 % thicker intumescent layer is possible to use according to the design tables for the four tested systems. All systems were applied according to the instructions by a professional painter with experience from such systems. The thickness of all layers were measured between application of the separate layers to ensure correct thickness. After the top coat had been applied, the systems were dried for more than three months in natural indoors climate before the tests in the cone calorimeter started the test campaign.

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[7] *It is known from standardized testing at SP that the highest thicknesses possible to use is limited by the fact that the system falls of if it is too thick.*

[8] *The section factor is the ratio of the fire exposed outer perimeter area per unit length divided by its cross sectional volume per unit length. A higher section factor gives a faster heating as more surface is exposed versus how much inner volume there is to heat up.*

2.2 Steel sections and instrumentation

Test specimens in the study were square hollow sections with dimensions 150 x 150 mm^2 with a steel thickness of 10 mm, giving a section factor of 105. In the cone tests the length of the sections were 150 mm and in the other studies 1000 mm, as shown in Figure 5. Before application of the four different intumescent paint systems the test specimens were sand blasted and instrumented with thermocouples type K with diameter 0.51 mm. The mounting were done in pre-drilled holes on the surface with quick-tip type AWG 20-22 as shown in Figure 6. Thermocouple positions on all test specimens are shown in Figure 7. During the tests in the cone calorimeter an extra internal thermocouple was placed inside the void.

Figure 5 Test specimens for furnace and ad hoc tests before application of the protection systems. Photo; Robert Jansson McNamee.

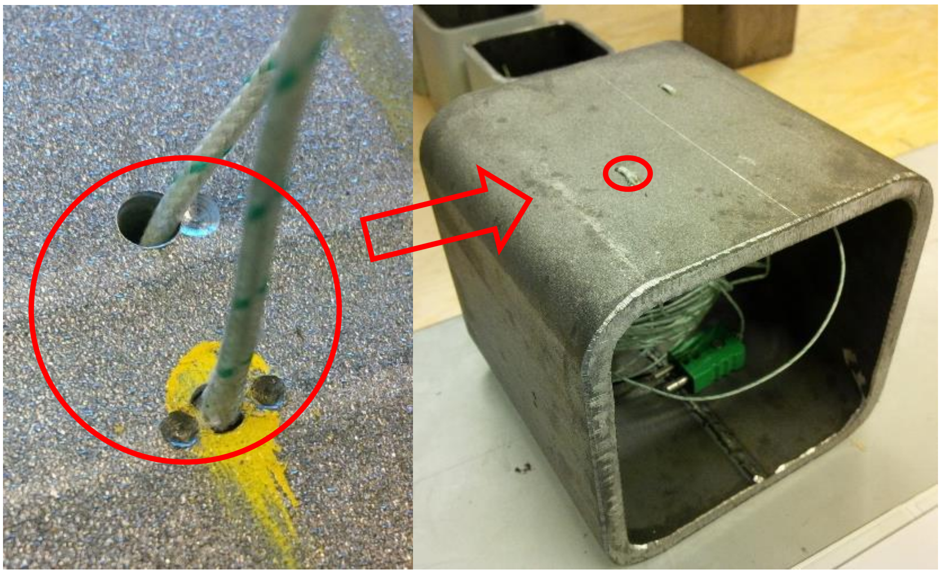

Figure 6 a) Quick tip mounted and TC wire routed through the specimen surface. After stretching theTC wire mounting is shown in figure b. b) Test specimen for cone calorimeter test with two TCs. Photo: Ulla Eidissen Jensen

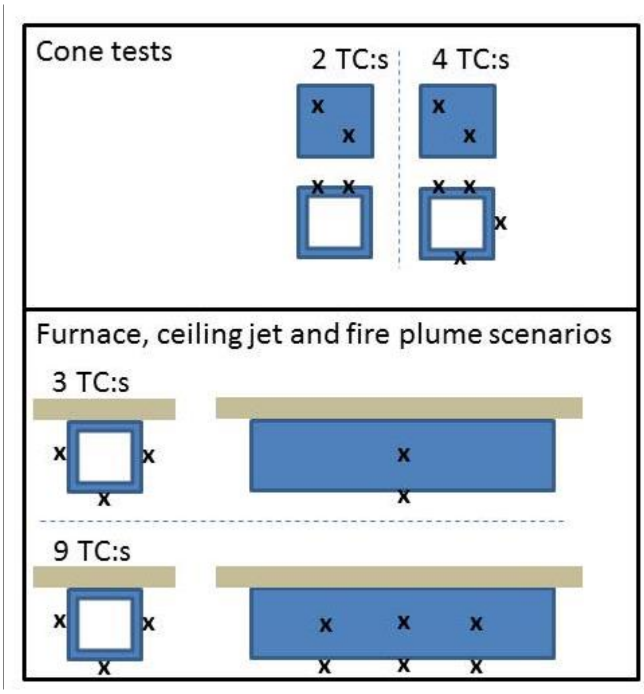

Figure 7 Thermocouple (TC) placement. In the cone tests the two upper TCs were placed in the centre of the quadrants of the surface.

2.3 Test methods and results

2.3.1 Cone calorimeter test method

Heat exposure tests at two levels of incident heat flux were performed in a cone calorimeter described in the test standard ISO 5660-1 (2015). In the tests the cone calorimeter was only used as a radiation source so no measurement of heat release rate was done. As the samples was of size 150 x 150 x 150 mm no sample holder was used. The setup during a test can be seen in Figure 8. The distance between the lower edge of the cone and the test sample during the start of the test was 55 mm. Two levels of incident heat flux was used, 30 and 50 kW/m^2. The net heat flux levels in a cone calorimeter can only be close to the exposure in standard fire condition in certain time intervals as this conditions have a much higher variation in net heat flux. The incident heat flux levels in the cone calorimeter were calibrated with a Schmidt Boelter gauge. As the expansion of the paint systems changes the view factor of the heater in the cone calorimeter the effective incident heat flux increased initially. To estimate this effect the heat flux was also measured 25 mm above the specimens surface during the calibration procedure. For the heat flux level 30 kW/m^2 (at the initial surface level) the heat flux 25 mm above the initial surface was 38 kW/m^2 and for the 50 kW/m^2 level the heat flux 25 mm above the initial surface was 62 kW/m^2.

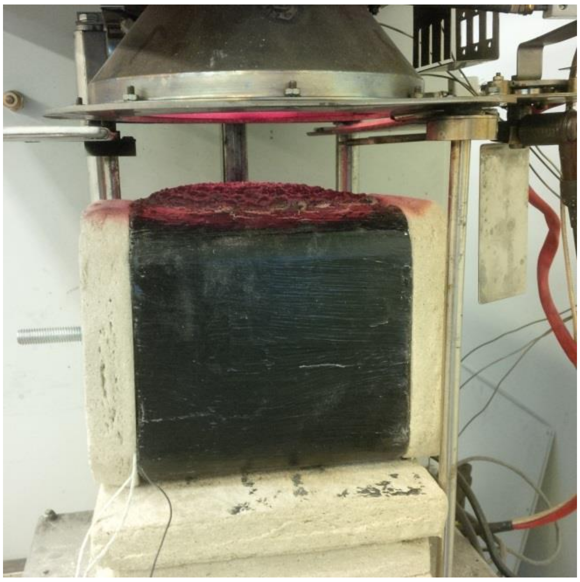

Figure 8 Test of intumescent system in cone calorimeter. The ends were insulated with stiff insulation board of 25 mm thickness. Photo: Ulla Eidissen Jensen

The test matrix including individual specimens for the cone calorimeter tests can be seen in Table 3. Two or four thermocouples was attached to each specimen, placement according to Figure 7. During the tests also a shielded 1 mm thick thermocouple was placed in the air cavity during each test. All tests were filmed together with a ruler to estimate the thickness development of the systems. The film camera was filming from the left side of the setup in Figure 8.

Table 3 Test matrix of cone calorimeter tests. A-D intumescent systems, X without intumescent. Specimens with 4 thermocouples marked in grey, the others had 2 thermocouples. During all tests an extra thermocouple was placed inside the void.

30 kW/m^2	X1	X2	AA	AB	AC	AD	BC	BD	CC	CD	DC	DD
50 kW/m^2	X3	X4	AE	AF	AG	AH	BG	BH	CG	CH	DG	DH

2.3.1.1 Test results from cone calorimeter tests

The analysis in this chapter includes the temperatures measured and the observations of expansion of the intumescent system on the heat exposed surface of the cross sections.

Results from additional measurements of temperatures on the non-exposed surfaces and inside the void can be found in the Appendix A. The intumescent systems were only expanding on the surface exposed to radiation, i.e. the conduction of heat in the cross section to non-exposed parts was not enough to activate the systems in these parts during the experiments.

Steel temperature measured on the exposed surface during the lower exposure level in the cone calorimeter, 30 kW/m^2, for all systems are shown in Figure 9. The delay in temperature development after one minute for specimen X1 is caused by a disruption in exposure due to a height adjustment as it was found that the heat source was too far away. When analysing the data the difference between the thermocouples TC1 and TC2 in each test was very low. This was expected since the exposure is supposed to be the same on both thermocouple positions and also since the thermal conductivity in the steel is high . At the incident radiation level 30 kW/m^2 protection system A and C are shown to insulate the steel better than system B and D.

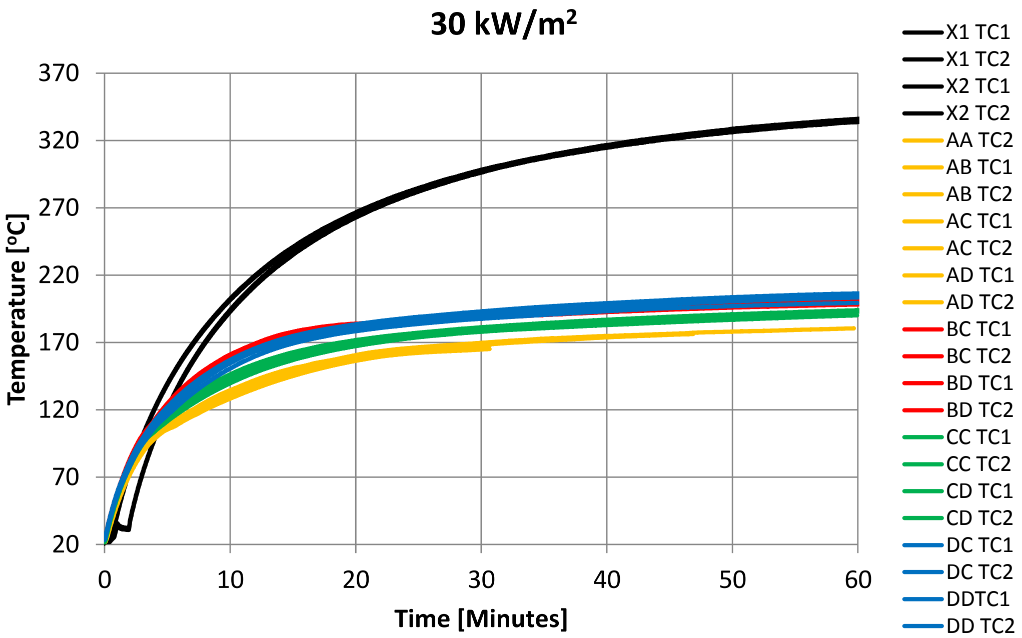

Figure 9 Cone calorimeter tests with incident heat flux 30 kW/m^2. Shown in the graph are steel temperatures on the heat exposed surface. All measurements can be seen in Appendix A.

During the higher exposure level 50 kW/m^2, shown in Figure 10, system A shows a better performance than the system B-D. The reason for the lower temperature in specimen AF compared with specimen AE, AG and AH during the first 20 minutes and after the 30 minutes duration of the test is not known.

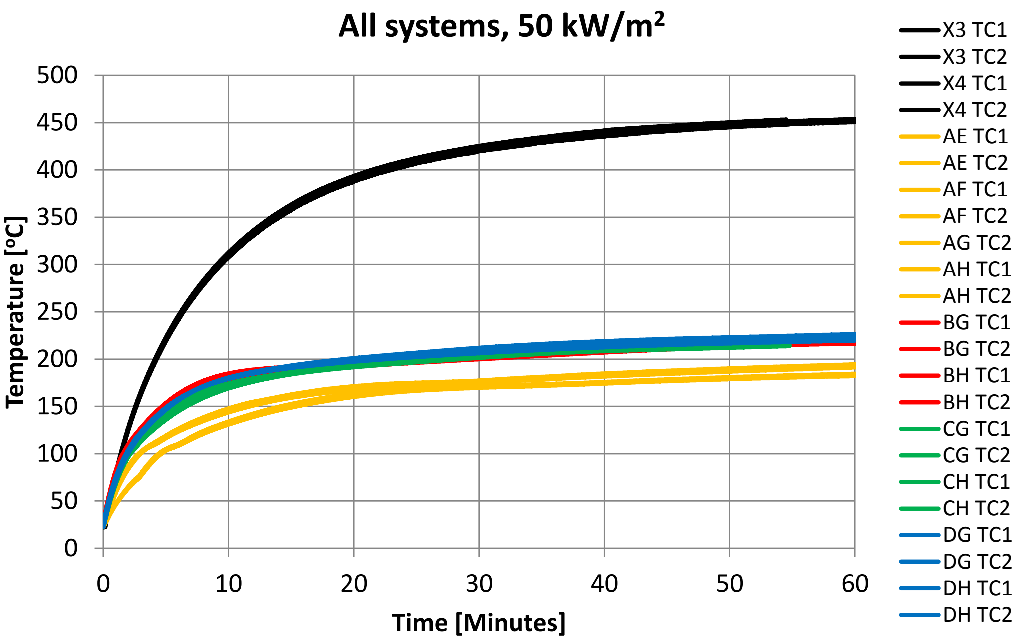

Figure 10 Cone calorimeter tests during incident heat flux 50 kW/m^2. Shown in the graph are steel temperatures on the heat exposed surface. All measurements can be seen in Appendix A.

The temperatures after 30 and 60 minutes of exposure in the cone calorimeter are shown in Figure 11. The behaviour of system A differs from the other systems as the temperature is higher after 60 minutes exposure at the lower radiation level compared with 30 minutes exposure with the higher radiation level. A possible explanation for this deviation from the behaviour of the other systems is seen in Figure 12 which shows that system A exhibits substantially higher expansion during the higher radiation level compared with the lower radiation level.

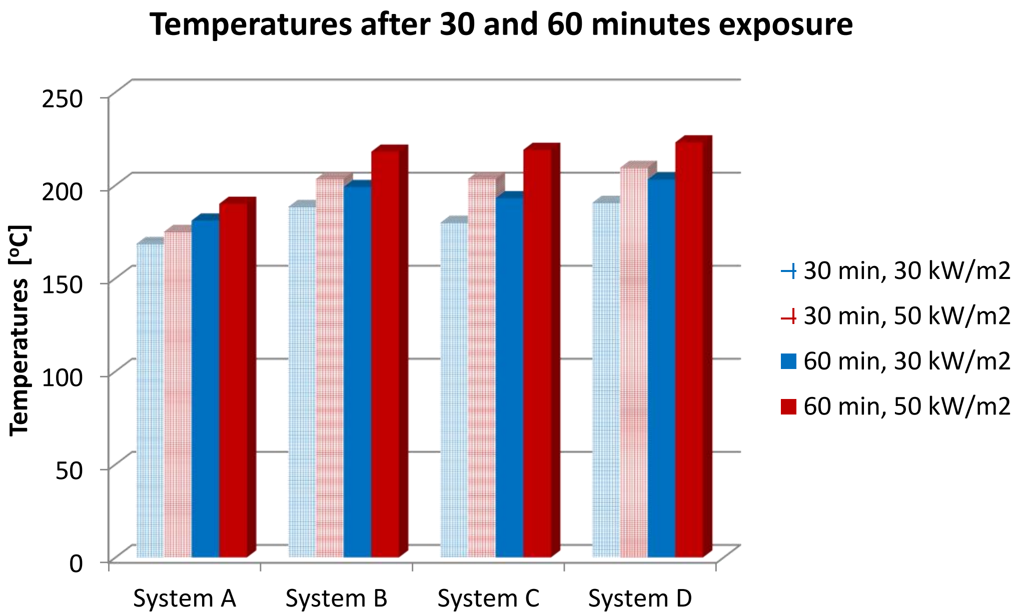

Figure 11 Temperatures after 30 and 60 minutes of exposure for all systems during both radiation levels.

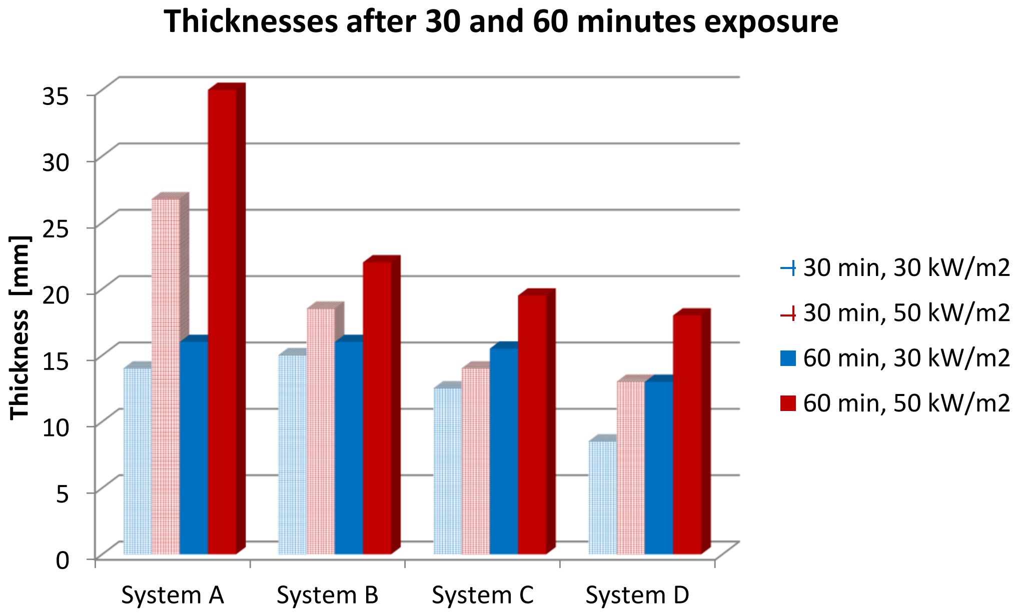

Figure 12 Thickness after 30 and 60 minutes of exposure for all systems during both radiation levels.

2.3.2 Furnace test method

Unloaded short hollow beams with the length one meter were tested in a horizontal furnace at SP Fire Research AS in Norway according to the description in EN 13381-8:2013[9]. During the test 10 test specimens were hanging from the roof of the furnace with 3-sided fire exposure. Figure 13 shows the specimens during mounting. The temperature in the furnace was controlled in accordance with the standard fire curve and the furnace temperatures were measured with plate thermometers.

Figure 13 Test specimens during mounting in the horizontal furnace at SP Fire Research AS in Trondheim. Photo: Per Gunnar Nordløkken

[9] *The performed test is not a full test for evaluation of the systems as only one type of test on one cross section have been performed. Several tests on different cross sections would have been necessary.*

2.3.2.1 Test results from the furnace test

The test matrix of the furnace tests can be seen in **Fel! Hittar inte referenskälla.**. All specimens was equipped with 9 thermocouples according to Figure 7.

Table 4 Test matrix of furnace tests. A-D intumescent systems, X without intumescent. Specimens with 9 thermocouples.

AI	BI	CI	DI	X1
AJ	BJ	CJ	DJ	X2

During the test the furnace was following the requirements on temperature development prescribed in the standard EN 1363-1:2012 but the pressure inside the furnace was outside the prescribed limits during the time period 5-10 minutes as shown in Figure 14. The pressure defined is the differential pressure compared with the surrounding air outside the furnace at the same height. In general different levels of differential pressure should not influence the function of an intumescent system but the rapid changes as recorded during the test is an indication of changes of the flow situation inside the furnace. Unfortunately the flow situation is not characterized during standardized testing, so its influence on the performance of the insulation systems is not known. This influence is one of the motivations behind doing this experimental studies in the first place.

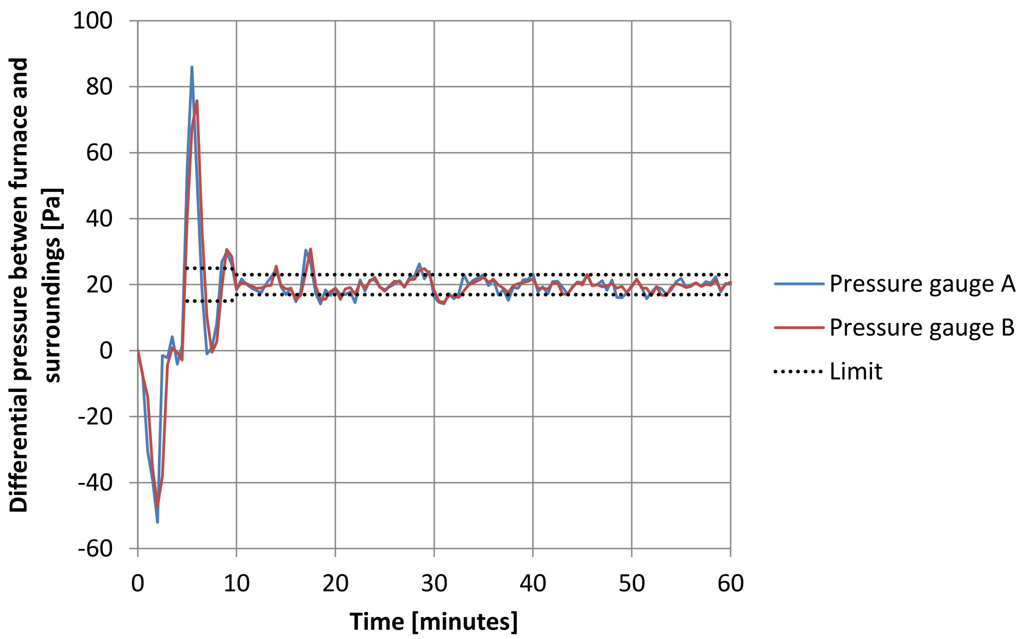

Figure 14 Pressure difference between furnace and surroundings on the height 100 mm beneath the furnace roof as measured with two different gauges. The pressure was outside the limits stated in the standard during the time 5-10 minutes.

During the test in the horizontal furnace two unprotected specimens were included as references. In Figure 15 temperatures of the unprotected specimens are shown. The design temperature 550 °C was reached after 15 minutes exposure at the bottom side of the 3-sided exposed specimens. At the end of the test (at 60 minutes) the temperatures in the unprotected steel were only approximately 50 degrees less than the furnace temperature 945 °C. This indicates that the specimens are approaching an equilibrium corresponding to the measured plate thermometer temperature.

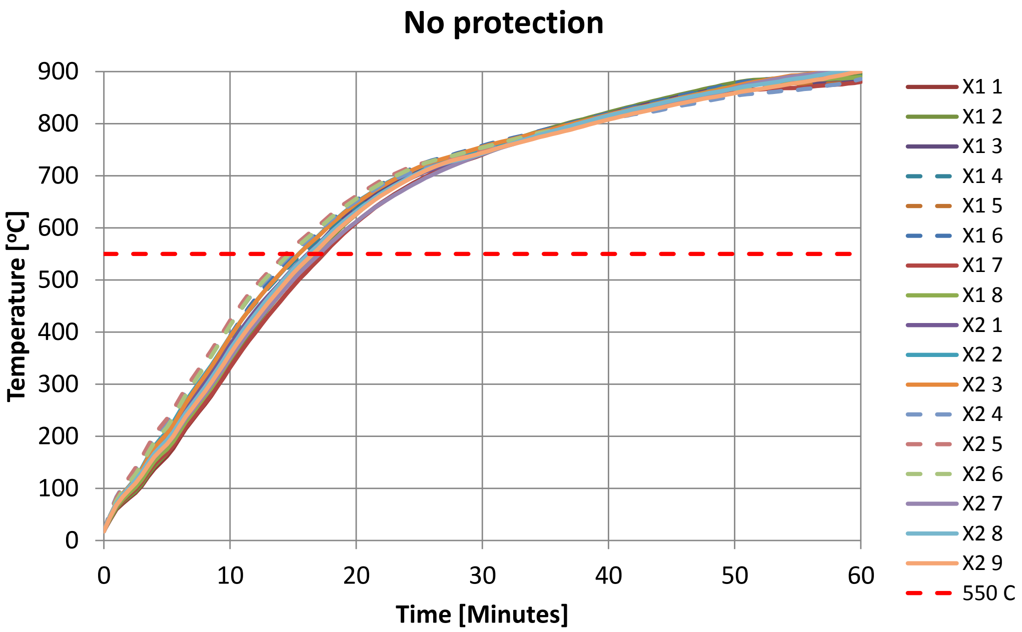

Figure 15 Temperatures in unprotected specimens X1 and X2 during furnace testing. The design temperature 550 °C is included as a reference. Measurements on the bottom side of the specimen are marked with dashed lines.

The temperature development during fire exposure in the furnace for two specimens protected with system A is shown Figure 16. The large spread of temperatures indicates partial loss of adhesion of the systems during the fire exposure. It is not possible to conclude with the limited amount of test data if the loss of protection is more pronounced on the horizontal or the vertical parts. The rise of local temperatures found in the temperature plots indicate that specimen AI first lost adhesion on the horizontal part, continues lines, while specimen AJ first lost adhesion on the vertical part, dashed line thermocouple AJ 6 . Unfortunately no visual observations was done during the test but there might be a link between the extra rise in temperature measured in AJ 6 and the fluctuations in pressure in the furnace between 5 and 10 minutes shown in Figure 14. Thermocouple AJ6 is the only one indicating on this possible connection.

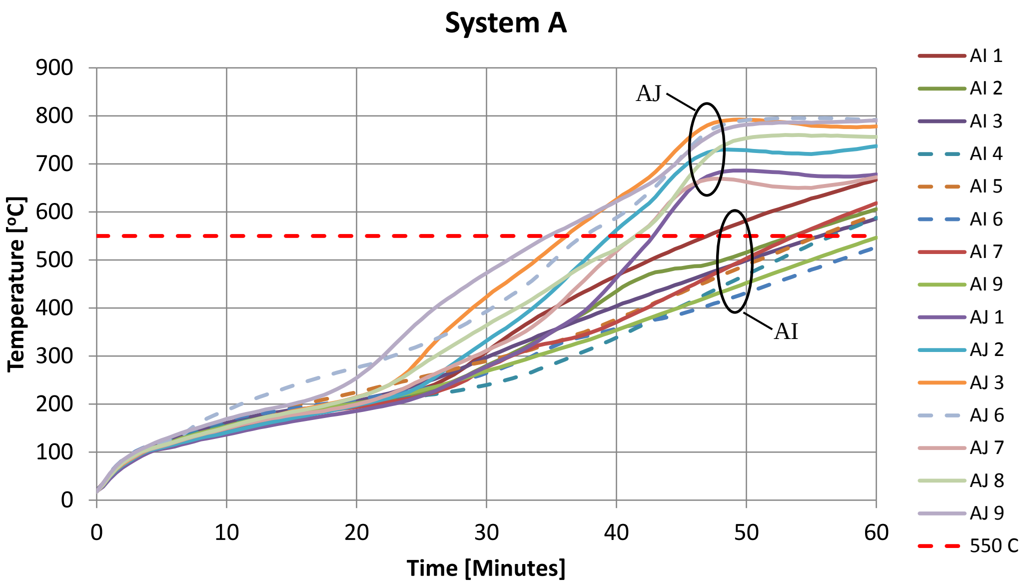

Figure 16 Temperatures in system A specimens during furnace testing. The design temperature 550 °C is included as a reference. Measurements on the underside of the specimen is marked with dashed lines.

The temperature development in two specimens protected with system B are shown in Figure 17. All thermocouples indicates a loss of adhesion for specimen BI after 45 to 50 minutes whereas for specimen BJ two thermocouples indicates loss of adhesion at the time around 50 minutes.

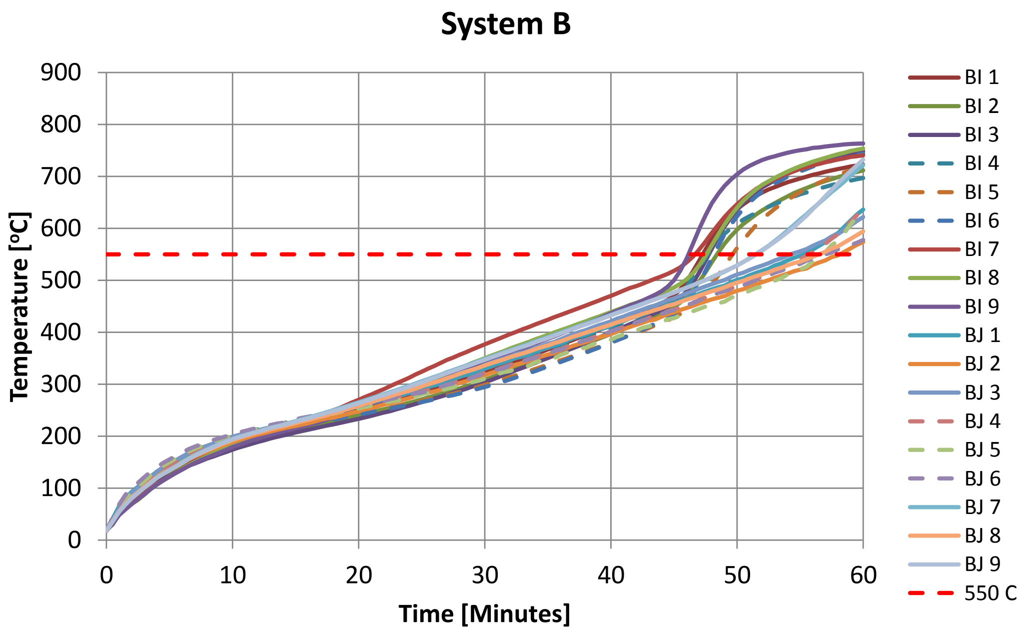

Figure 17 Temperatures in system B specimens during furnace testing. The design temperature 550 °C is included as a reference. Measurements on the underside of the specimen is marked with dashed lines.

As shown in Figure 18 the temperature development inside the two specimens protected with system C are very stable with no indication of loss of adhesion or rising over the design temperature[10].

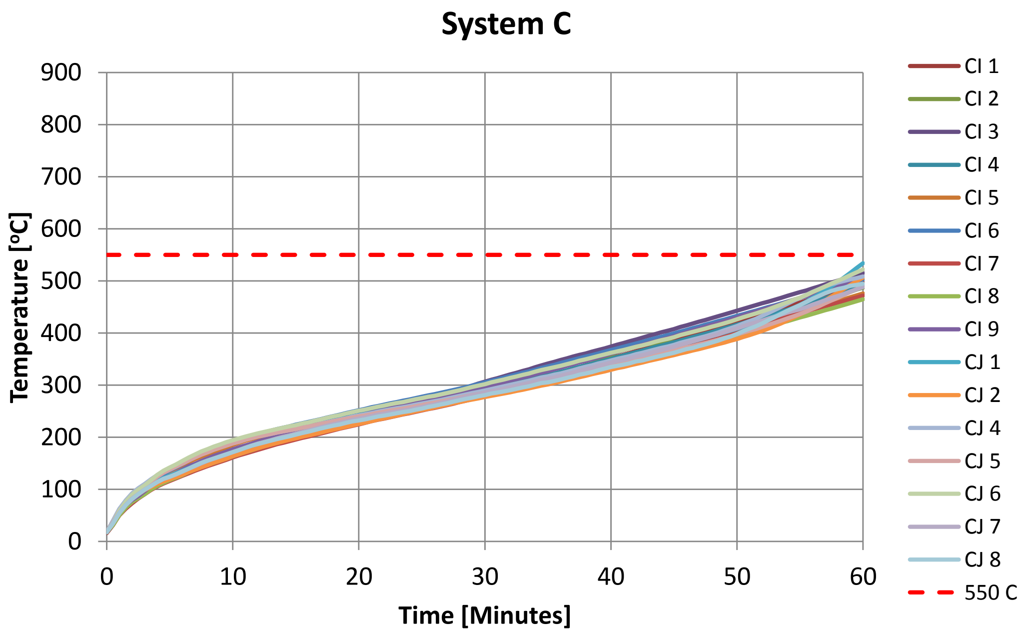

Figure 18 Temperatures in system C specimens during furnace testing. The design temperature 550 °C is included as a reference.

During the test of system D, shown in Figure 19, two thermocouples in one of the specimens indicate a local anomaly starting around 30 minutes from the start of the test. Thermocouple DJ4 is on the bottom surface of the specimen and thermocouple DJ7 is on one of the sides. This point toward some local loss of adhesion or cracking occurred in this region but due to continuous swelling of the remaining system it was later covered. It is not possible to know if this local phenomena was close to DJ4 since no visual observations of this were made during the test. If the position of the loss of protection is not exactly where the thermocouples were located, higher local temperatures than the measured ones would have occurred.

[10] *It is important to remember that in a protection assessment according to EN 13381:8 the prediction is to a certain degree allowed to be slightly non-conservative for single specimens.*

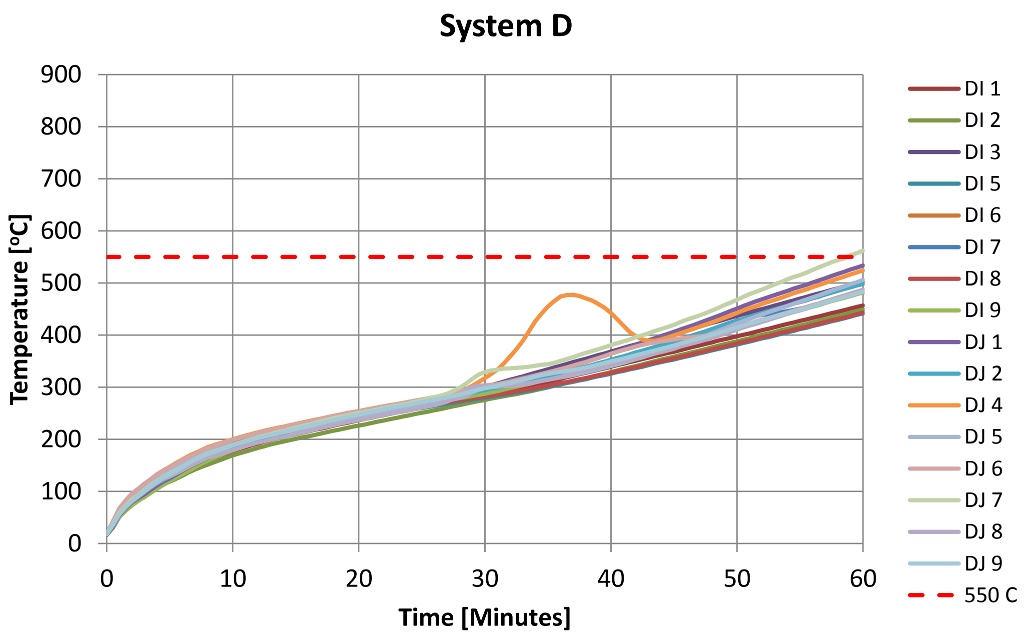

Figure 19 Temperatures in system D specimens during furnace testing. The design temperature 550 °C is included as a reference.

2.3.2.2 Summary of furnace test data

Results from the furnace test are summarized in Figure 20 and Figure 21. The two unprotected specimens, X1 and X2, reached the design temperature after approximately 15 minutes of fire exposure. System A and B did not perform as expected for a system with a fire rating of 60 minutes with the design temperature 550 °C. System C and D showed the expected performance by limiting the temperature development.

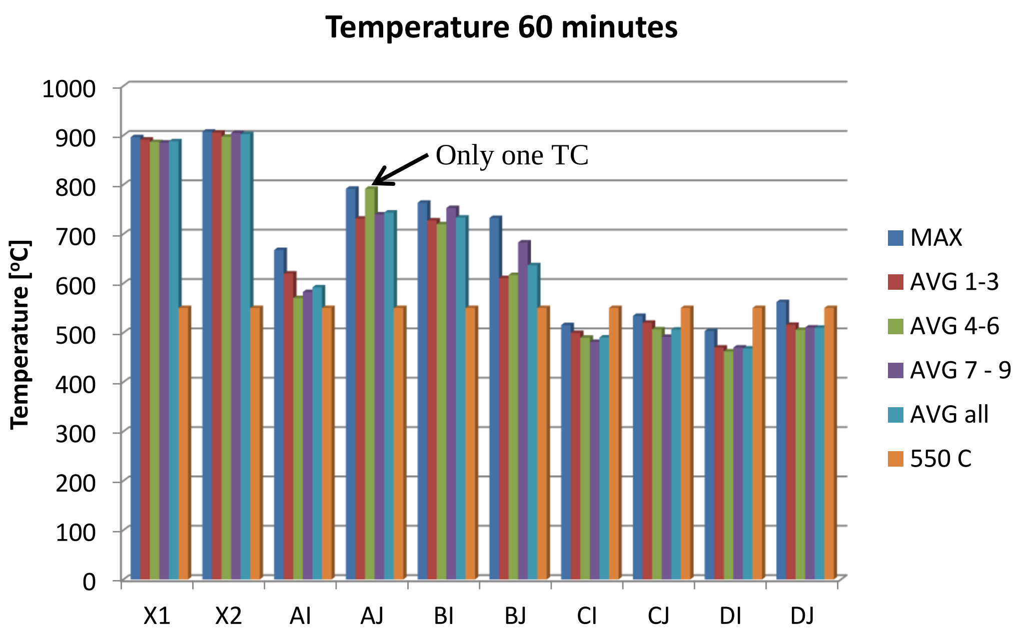

Figure 20 Maximum and average temperatures in all specimens after 60 minutes of standard fire exposure. Thermocouples 4-6 are on the bottom whereas 1-3 and 7-9 are on the horizontal part of the specimens.

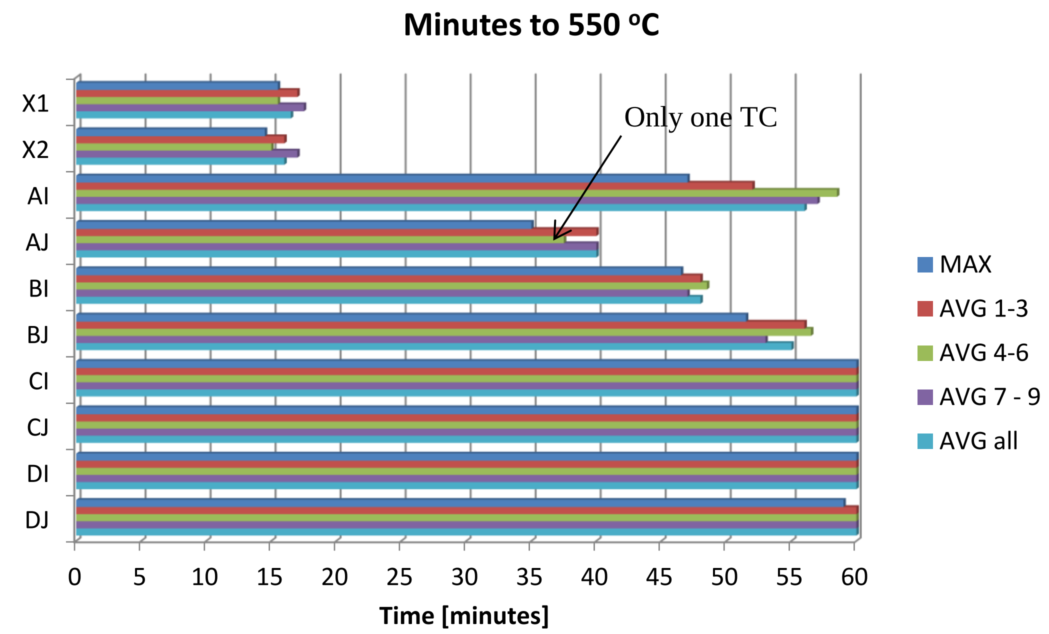

Figure 21 Time to reach the design temperature 550 °C during standard fire exposure. Thermocouples 4-6 are on the bottom, horizontal part of the specimens. Specimen CI, CJ, DI and average temperatures in specimens DJ did not reach 550 °C during 60 minutes.

2.3.3 Ceiling jet and fire plume test method

To investigate the behaviour of the insulation systems exposed to a fire scenario including plume flows a special purpose test rig was built. The test rig for ceiling jet tests is shown in Figure 22 and Figure 23. The burner was made of four steel pipes with the outer diameter 4 cm covering an area of 1 x 0.47 m^2 located 0.3 m above the floor level. The propane gas was released through two rows of holes in the steel pipes as shown in Figure 24. During the test the diffusion flame was regulated such that the plate thermometer (PT) above the fire source (see Figure 23) followed the standard fire curve. Also in pair with each PT a 1 mm thick shielded thermocouple was placed to illustrate the difference between thermal exposure influencing a flat surface[11] (the plate thermometer) compared with a traditional thermocouple that is not direction dependant and have a much higher heat transfer coefficient than a flat surface in all flow situations.

[11] *The plate thermometer can be seen as a small reference object for thermal exposure calibration used in fire resistance testing and in a variety of ad hoc fire dynamics tests. As the PT is direction dependant and its size makes the heat transfer coefficient close to that of a larger flat surface it gives a much better measure of thermal exposure of larger objects then any type of ordinary thermocouple.*

Figure 22 Test setup for testing two specimens in the ceiling jet scenario.

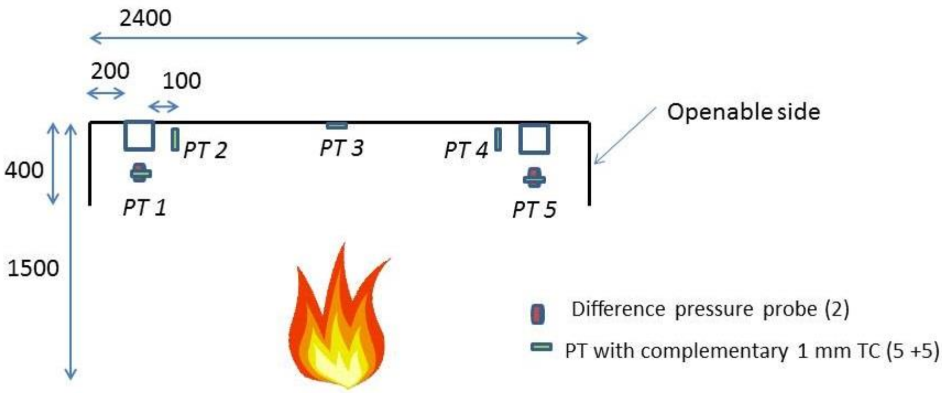

Figure 23 Cross section of test setup for testing two specimens with square cross section in the ceiling jet scenario. The depth of the rig was 900 mm. Instrumentation included plate thermometers (PT), 1 mm shielded thermocouples and differential pressure probes.

Figure 24 The fire source during ceiling jet and fire plume scenarios. Pipes slightly bent by thermal expansion.

Figure 25 Plate thermometer pointing downwards, paired with a 1 mm shielded thermocouple sticking out 3 cm from the plate.

The choice of the standard fire curve to regulate against was to not alter the thermal exposure except the flow situation compared with the furnace tests performed in the test campaign. However, as the plate thermometer used for regulation was in the centre of the test rig the thermal exposure of the two test specimens (situated on the left and the right side) became slightly less severe than during the standard fire exposure in the furnace. The test time was 30 minutes, and after 15 minutes of exposure the right part of the rig was opened to simulate a sudden change in flow around one of the two test specimens. This opening up procedure is shown in Figure 26.

Figure 26 Opening up of the test rig after 15 minutes of exposure during the ceiling jet scenario.

During the fire plume scenario the top slab of the test rig was taken away and the specimens were placed on each side of the plate thermometer in the centre of the test rig as shown in Figure 27.

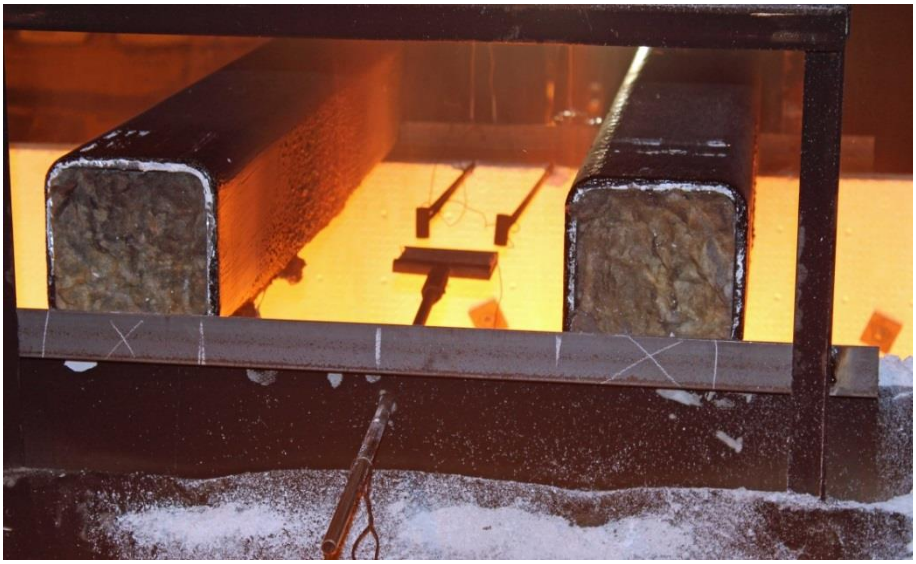

Figure 27 Fire plume scenario. Plate thermometer positioned in the centre and two differential pressure probes to estimate flow speed. An additional 1 mm shielded thermocouple was also protruding from each device. The distance between the two test specimens was 300 mm.

The velocities of the hot gases was estimated during the experiments by pressure measurements with bi-directional probes as described by McCaffrey and Heskestad (1976) and Olsson (1988). The bi-directional probe measures the pressure differences between front and back side when placed in a flow. The result from the measurement is related to the stagnation pressure so Bernoulli's equation together with a correction for density and a Reynold's number dependent correction coefficient k(Re) can be used to estimate the velocity. In the situation used, this coefficient, k(Re), is assumed to be 0.9. In eq. (2), T is the gas temperature, Δp is the pressure difference, ρ_0 is the ambient density and T_0 is the ambient temperature.

$$v = \frac{1}{k(Re)}\sqrt{\frac{2\,\Delta p\,T}{\rho_0 T_0}}.\ \text{[m/s]} \qquad (2)$$

2.3.3.1 Test results from ceiling jet scenario

The test matrix of ceiling jet tests can be seen in Table 5**Fel! Hittar inte referenskälla.**. The specimens was equipped with 9 or 3 thermocouples according to Figure 7.

Table 5 Test matrix of ceiling jet tests. A-D intumescent systems, X without intumescent.

Test no	1	2	3	4	5	6
Specimen close to not openable side of the setup	X1	AM	BM	CK	DK	X3
Specimen close to openable side of the setup	X2	AN	BN	CL	DL	X4
Number of thermocouples in each specimen	3	9	9	3	3	9

Plate thermometer PT 3 and thermocouple TC 3 were used to measure the temperatures in the centre of the test rig, see Figure 28. During the test, plate thermometer PT 3 was used to control the burner to follow the standard time temperature curve. In this position the ordinary thermocouple TC 3 shows a higher temperature which is indicating the presence of a higher gas temperature than the PT temperature. The opening of the test rig on the right side after 15 minutes of exposure is influencing the temperature readings of PT 5 and TC 5. These thermocouples are located under the right specimen and due to the opening up some of the hot gases trapped by buoyancy in the test rig are ventilated away, i.e. the smoke layer will rise.

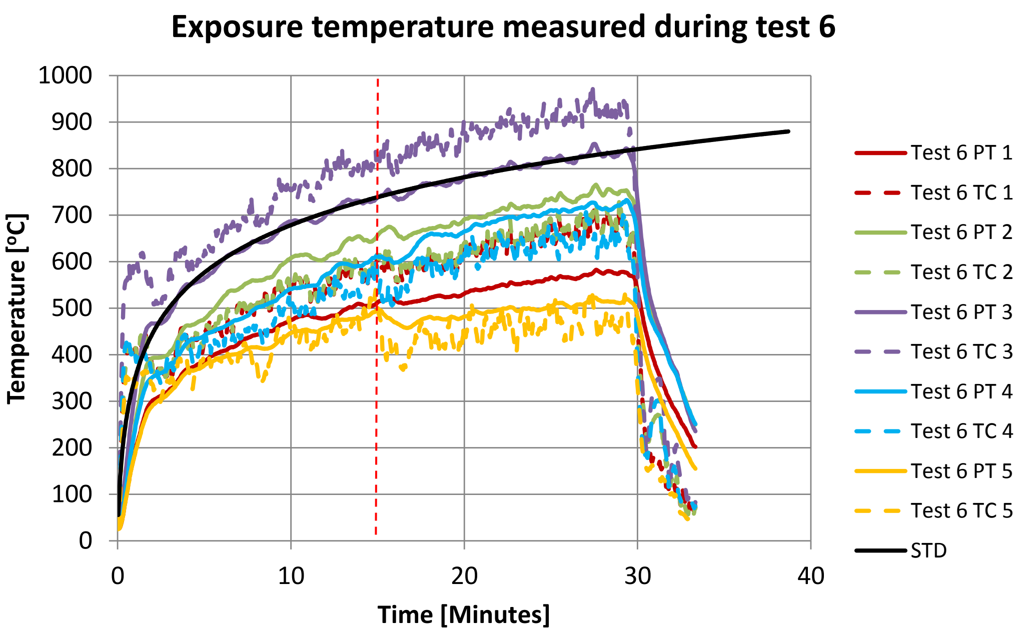

Figure 28 Example of temperature development during exposure according to the ceiling jet scenario with reference specimens without protection, measurements from all tests are shown in the appendix. The red horizontal line marks the time 15 minutes when the right side of the test rig was opened.

In Figure 29 and Figure 30 steel temperatures measured in the reference beams without protection are shown. These two experiments, reference number 1 and number 6, was the first and the last of the tests with this test configuration. From the graphs it is apparent that the thermal exposure of the specimen on the left side of the test rig was slightly more severe than the specimen on the right side, also before opening up of the rig on the right side. This difference can also be seen in the plate thermometer temperatures shown in Figure 28 where the temperatures measured under the left specimen PT1 is higher than the measurement under the right specimen, PT5. When comparing the steel temperature measured in the unprotected cross sections during this test with the furnace test it is clear that the thermal exposure in these tests is less severe compared to the furnace test. The design temperature 550 °C was passed by the first thermocouples after around 22 minutes of exposure in this ceiling jet scenario compare to around 15 minutes in the furnace test (see Figure 21). There are two main explanations for this difference, (i) the temperature in the ceiling jet scenario is regulated just above the fire plume feeding the ceiling jet and (ii) the exposure to thermal radiation is much less severe on the vertical side not facing the fire plume in the centre of the test rig during the ceiling jet tests.

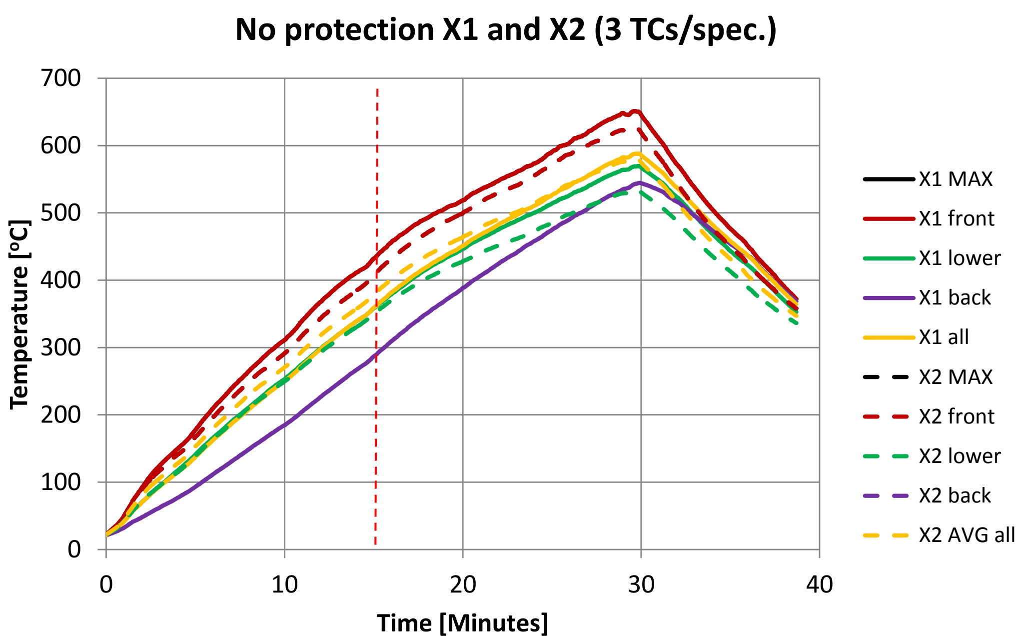

Figure 29 Measured temperatures in the steel section during test 1, test specimen X1 and X2 exposed to the ceiling jet scenario. The thermocouple on the back side of specimen X2 was defect. This makes the average temperature "X2 AVG all" less representative for comparison with other tests. The red horizontal line marks the time 15 minutes when the right side of the test rig was opened. Exposure temperatures during test 1 can be found in Appendix A.

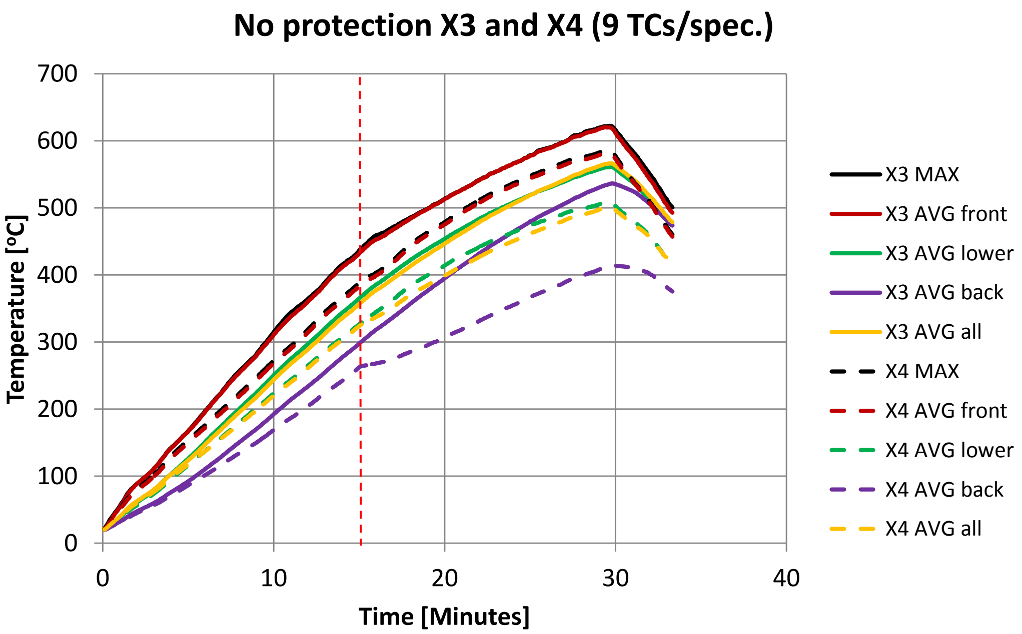

Figure 30 Measured temperatures in the steel section during test 6, test specimen X2 and X4 exposed to the ceiling jet scenario. The red horizontal line marks the time 15 minutes when the right side of the test rig was opened. Exposure temperatures during test 6 can be found in Appendix.

After 8.5 minutes of exposure it was observed that parts of the protection of system A lost its adhesion and were starting to fall off. Photographs from the test show unprotected steel after 11 minutes of exposure. Unfortunately also some large chunks of expanded paint that was falling down was hanging on top of the instrumentation as shown in Figure 31. It was decided to not try to remove this paint by shaking it down as it would be impossible to know how much of the still attached (functioning) paint that also might fall off. As a result it is assumed that the temperature measured in the steel is lower than if this was an equivalent real fire without instrumentation as the insulation was held in place by the instrumentation.

Figure 31 Release of parts of system A during ceiling jet scenario. Photo taken after the opening of the side, chunks of paint on the instrumentation 100 mm below the surface (red arrow) and on the floor.

Steel temperatures measured in specimens protected with system A can be seen in Figure 32. After around 10 minutes of exposure the plots of maximal temperatures in each specimen starts to deviate from the average which is a result of the loss of adhesion visually observed.

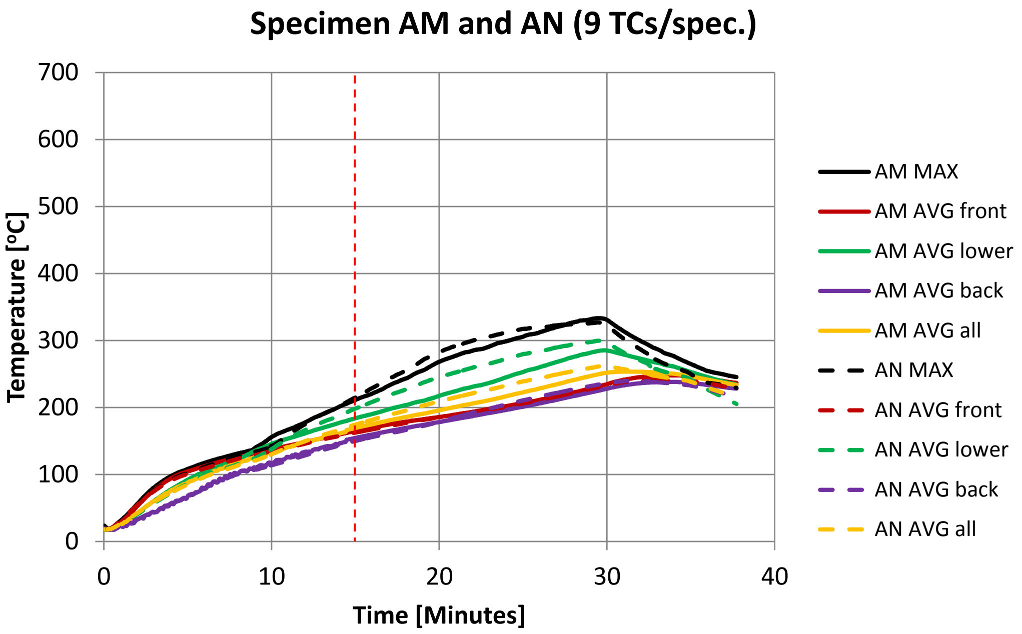

Figure 32 Measured temperatures in the steel section during test 2, test specimen AM and AN exposed to ceiling jet scenario. These temperatures show an overestimation of the function since paint falling down on the instrumentation was shielding it from radiation from the fire. The red horizontal line marks the time 15 minutes when the right side of the test rig was opened. Exposure temperatures during test 2 can be found in Appendix A.

Steel temperatures measured during tests of system B, C and D are shown in Figure 33 to Figure 35. Common for these tests is that no paint was falling down on the floor and no indication of loss of adhesion was observed. The maximum temperatures in the steel are around 250 °C after 30 minutes of exposure.

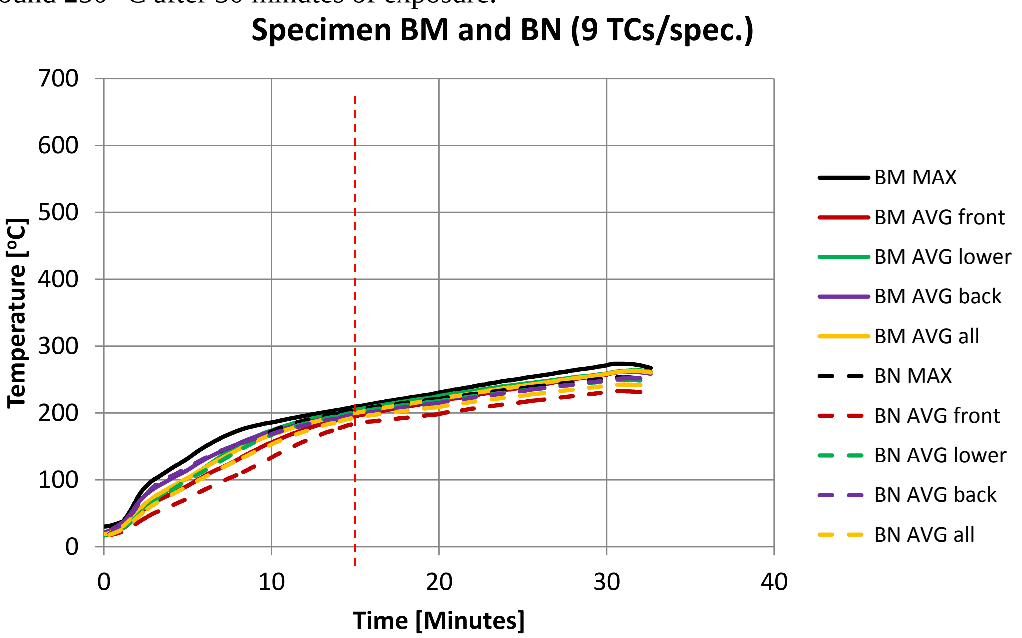

Figure 33 Measured temperatures in the steel section during test 3, test specimen BM and BN exposed to ceiling jet scenario. The red horizontal line marks the time 15 minutes when the right side of the test rig was opened. Exposure temperatures during test 3 can be found in Appendix A.

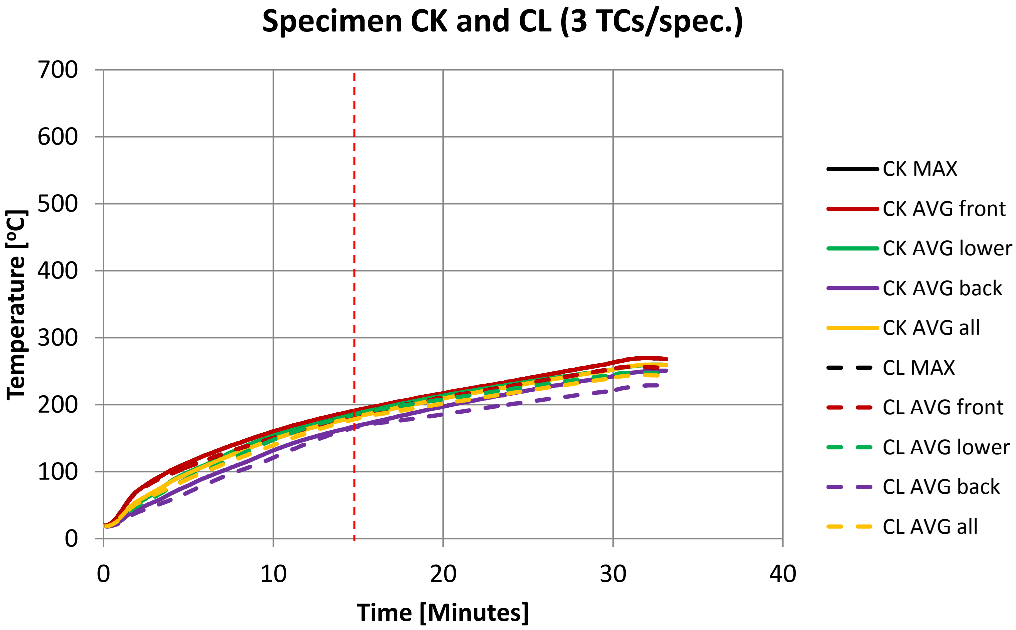

Figure 34 Measured temperatures in the steel section during test 4, test specimen AM and AN exposed to ceiling jet scenario. The red horizontal line marks the time 15 minutes when the right side of the test rig was opened. Exposure temperatures during test 4 can be found in Appendix A.

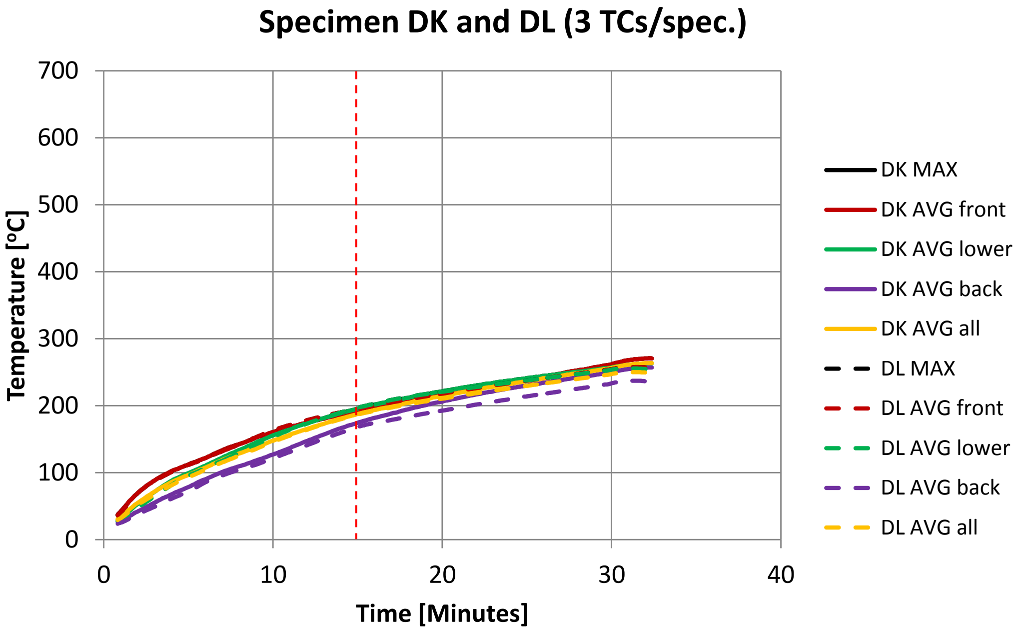

Figure 35 Measured temperatures in the steel section during test 5, test specimen AM and AN exposed to ceiling jet scenario. The red horizontal line marks the time 15 minutes when the right side of the test rig was opened. Exposure temperatures during test 5 can be found in Appendix A.

During the tests with the ceiling jet scenario differential pressures was measured for estimation of velocities around the specimens. However, due to experimental difficulties, including leakage in the system during some tests, these measurements are not presented.

2.3.3.2 Test results from fire plume scenario

The test matrix of fire plume tests can be seen in Table 5. The specimens was equipped with 3 thermocouples according to Figure 7.

Table 6 Test matrix of ceiling jet tests of system A and B.

Test no	7	8
Specimen to the left in the symmetrical test rig	BK	AL
Specimen to the right in the symmetrical test rig	AK	BL
Number of thermocouples in each specimen	3	3

For the fire plume scenario tests the test rig was opened up and two specimens were put on top of the rig as shown in Figure 27. Two tests were performed with this setup. During the first test system A was in the right position in the rig and during the second test system A was on the left position in the test rig. Temperatures measured in the fire plume can be seen in Figure 36 where the gas flow is controlled in order for the exposure to follow the standard fire curve in plate thermometer PT 3. In this position the ordinary thermocouple TC 3 shows a higher temperature which is indicating the presence of a higher gas temperature than the plate temperature.

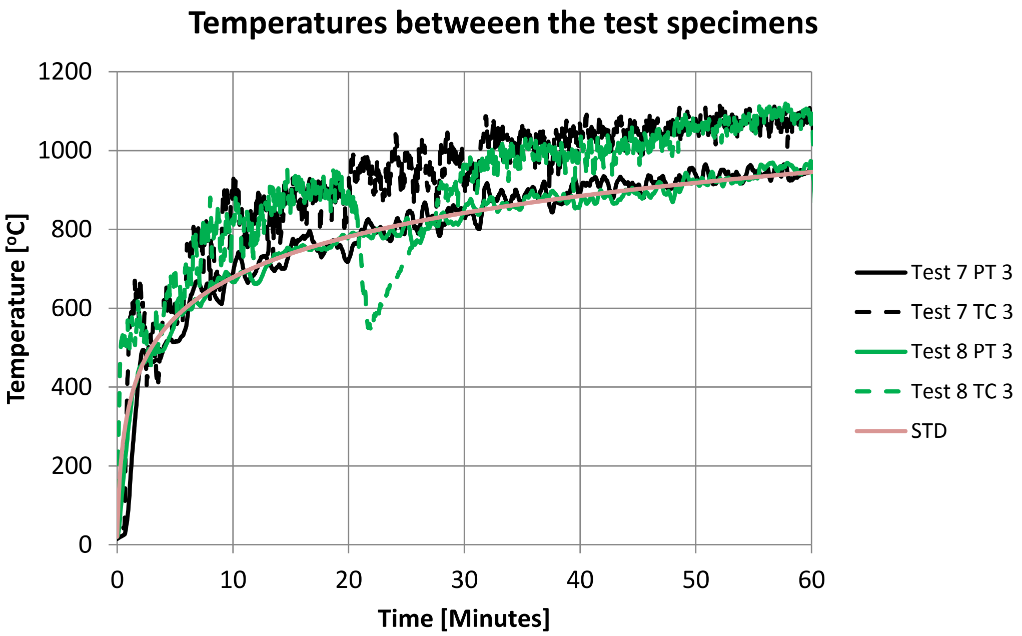

Figure 36 Temperatures measured between the test specimens in the fire plume. The dip in temperature for TC 3 in test 8 was due to large chunks of intumescent paint from the type A system resting against it.

The calculated upwards velocities based on differential pressure probe measurements are shown in Figure 37. These velocities can be compared with theoretical values from the McCaffrey plume equation[12]. When using this plume equation with the height 1.2 m and flow rate of propane of 0.4-1.6 kg/minute, as in the experiment, the theoretical upwards velocity is determined to 7.4 m/s. In this calculation the height chosen, 1.2 m, is from the top of the burner to the object. As the flow of fresh air from underneath in this setup, see

[12] *Equation 4.30 and table 4.1 in the book "Enclosure fire Dynamics" by Karlsson and Quintiere, dated 2000 was used for this calculation.*

Figure 24, is not the same as a plume over an open tray, which probably is the standard case, the plume equation was also tested with the height 1.5 m, which is the distance from the floor to the measurement point. This gave a slightly higher theoretical upwards velocity of 8.3 m/s. When comparing the estimation based on measurements, the McCaffrey plume equation gave lower velocities but they are surprisingly close despite the non-conventional shape of the fire source.

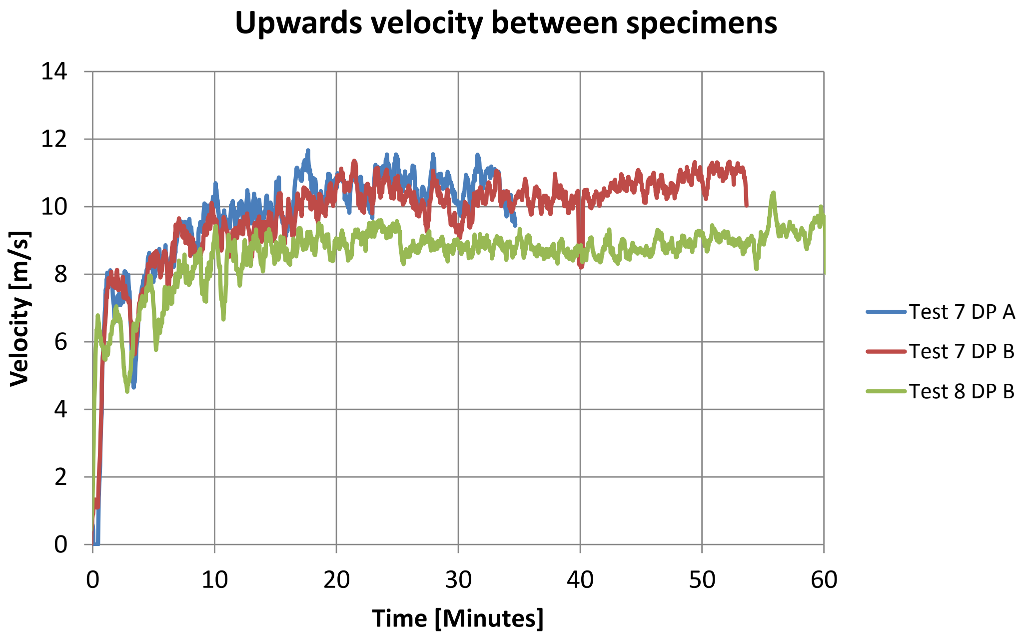

Figure 37 Estimated upwards velocities between the specimens during the fire plume scenario. DP in figure means Differential Pressure probe. The calculation procedure for calculation of velocities based on differential pressure probe measurement can be found in Chapter 2.3.3.

Steel temperature measured during exposure to the fire plume scenario can be seen in Figure 38. During the tests the following visual observations were made:

- Specimen AL, after 4.5 minutes of exposure the paint system lost its adhesion and started to fall off from the steel.
- Specimen AK, after 6 minutes of exposure steel was visible in two cracks formed in the foaming material on the underside of the specimen. After 26 minutes of exposure many cracks had opened, exposing the steel.

When comparing the observations with the measured temperature it can be seen that the start of a fast increase in temperature for specimen AL corresponds to the visual observations made. Regarding specimen AK the agreement between observations of exposed steel and temperature increase cannot clearly be seen, although the development of a larger spread in temperatures compared with results for the two specimens painted with system B indicates anomalies in the function. An obvious explanation for the unclear indication of loss of protection for specimen AK is the small number of thermocouples used in this test (3), two in the centre of each exposed vertical surface and one in the centre of the exposed underside. This makes the chance of measuring close to a crack in the system low. Temperatures locally, close to an opening in the insulation, may have been significantly higher than the temperatures measured.

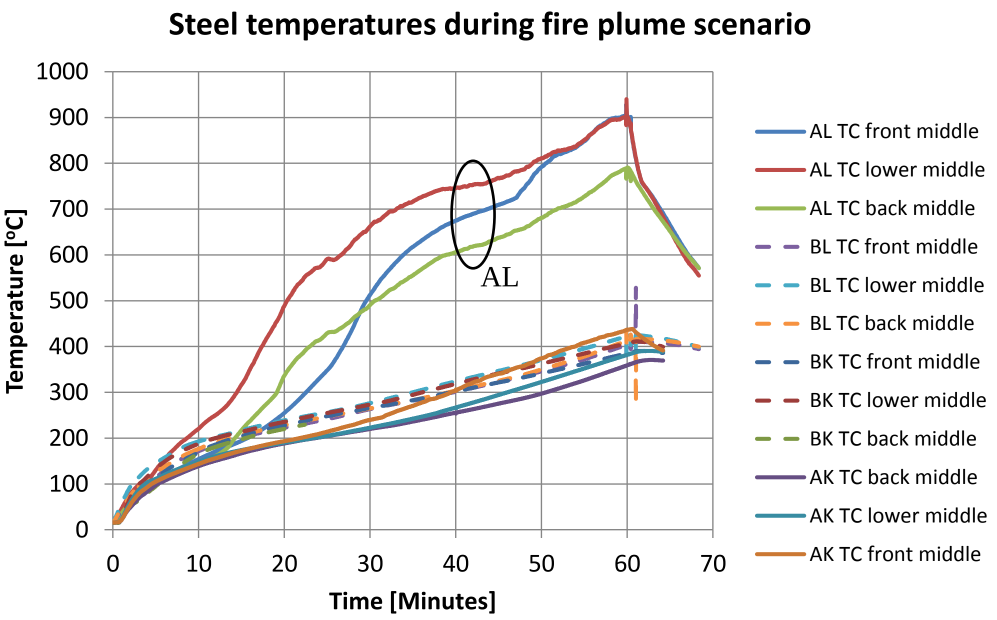

Figure 38 Temperatures measured in the steel sections during fire plume scenario. Specimen AL and BL were tested during test 8 and specimen BK and AK were tested during test number 7. The exposure data during test 7 and 8 can be seen in Figure 36.

3 Discussion

When doing standardized testing of intumescent paint systems, furnace tests are performed. In the furnace tests the "physical performance", as discussed in the introduction chapter, is evaluated by comparing results from loaded and unloaded sections. The relevance of this physical performance evaluation for intumescent systems are to the authors knowledge not proven by any studies. It seems as if this is a heritage from developing the test method for board systems[13] where this factor of deformation may be critical for the mounting system.

The main hypothesis behind the experimental studies performed in this project is that the standardized tests, EN 13381-8, lack important components of real fire scenarios. Real fires include large variations in;

- oxygen content,
- pre heating and
- fluid flows.

These are all components that can be assumed to have a low impact on the fire resistance in general for structures but in the case of intumescent paint systems, they may be important factors influencing the performance.

Cone calorimeter tests by Griffin et al. (2005) showed that the level of oxygen content of two types of epoxy based coatings was clearly influencing the insulation properties[14]. When a high level of oxygen content, 21%, was used the protective layer was consumed faster than when testing in a reduced oxygen atmosphere, 8-10%. When testing fire resistance in furnaces according to the European methods the oxygen content in the furnaces shall be over 4% when testing non-combustible materials. Although there is no upper limit on the oxygen concentration it is always much lower than the concentration in the atmosphere since low oxygen content gives better economy due to the fact that less air needs to be heated. Obviously this reduced oxygen content is representing an under-ventilated fire but as intumescent products are often used in rooms of large volume the heat transfer by radiation in a normal oxygen content environment is a possible scenario. The relevance of these findings regarding systems on the market in Europe is not known but it is a factor that may influence real behaviour of some systems. This factor was not further investigated in the present study.

The effect of pre heating, or slow heating, was to some extent investigated in the experimental study. Two levels of incident radiation, 30 and 50 kW/m^2, was used in cone calorimeter tests. When comparing the reaction behaviour between the systems during the low radiation level, 30 kW/m^2, system A, B and C expanded in a similar way and system C expanded less. When testing with the higher radiation level the expansion of system A was very much higher than the other systems giving a better thermal protection compared to the other systems. Thus the expansion of system A was more dependent on the level of exposure than the other systems when comparing these two radiation levels.

Higher level of fluid flow around the test specimens, as compared to the cone calorimeter tests, was investigated with two types of flow scenarios. During the first type of test the ceiling jet scenario, system A lost its adhesion and was falling off from the surface which did not occur for systems B, C and D. This is despite the fact that the thermal exposure

[13] *At least this was clearly the case when developing the previous Nordic standard NT Fire 021. See discussion in Chapter1.*
[14] *Tests on a waterborne vinyl acetate-based material did not show this influence.*

during this test was shown by reference specimens without protection to be less severe compared to a standardized test in a furnace.

The function of two of the systems were also investigated in a fire plume scenario. In these experiments the specimen was placed inside a fire plume with a flow speed around 10 m/s in the free flow exposed to a thermal exposure similar to the ceiling jet scenario (as indicated by the results of system B). In the experiments, system A lost its adhesion and was falling off while system B was intact. During this experiments one of the beams protected with system A showed the worst behaviour in the whole test campaign as the average temperature was passing the design temperature 550 °C already after 30 minutes which is half the time that the system was designed for.

To obtain a reference to the cone calorimeter tests, ceiling jet and fire plume scenarios described above, the systems were also tested in a standard furnace test. During these tests no visual observation were done but the temperature plots indicated loss of adhesion for both system A and B. The loss of adhesion during the experiments is summarized in Table 7. It is indicated in this summary that the tests performed with the furnace is more severe compared to the ceiling jet and fire plume tests designed for including flows around the specimens but the specimen showing the worst behaviour was one of the specimens of system A in the fire plume scenario. There is also a chance that the severity of the furnace test might have been extra high because of large pressure changes in the furnace during the early phase of exposure[15] making conclusions regarding severity of exposure difficult. Despite this deviation in the furnace test condition it seems that the materials are not very robust to varying fire conditions when some fail in half the time they are designed to function for.

Table 7 Summary of loss of adhesion or cracking phenomena indicated by temperature development or observations. Grey areas shows the occurrence of the phenomena, lighter grey is less distinct observations. OK means no indication.

	System A		System B		System C		System D	
Ceiling jet scenario			OK	OK	OK	OK	OK	OK
Fire plume scenario			OK	OK	No tests		No tests	
Furnace test					OK	OK	OK	OK

When doing tests with ceiling jet or fire plume scenarios the flow situation can be much better characterised and closer to what can be expected in real fires in open spaces than in a standard furnace situation. This gives these tests a potential for a more relevant evaluation of adhesion than traditional furnace testing.

All steel temperature measurements for the reference and the four different systems are summarized in the following five figures. In the first diagram, Figure 39, the temperature development in all reference specimens are summarized. Here it can be seen that during the furnace tests the design temperature 550 °C was passed after 15 minutes of exposure, which means that the systems investigated in this study were designed to extend the fire resistance time of the chosen cross section from 15 to 60 minutes. The reference tests on unprotected cross sections also show that the heating during 50 kW/m^2 incident radiation in the cone calorimeter corresponds fairly well with the standardized furnace test during the first 8 minutes of exposure, after which the exposure in the cone calorimeter is less severe. This correlation is only true for the chosen cross section and exposure conditions. In the cone calorimeter test the exposure was one sided whereas in the furnace test the exposure was three sided. Further on, the diagram shows that the thermal exposure in ceiling jet scenario is less severe than during furnace test.

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[15] *See further discussion in chapter 2.3.2.1.*

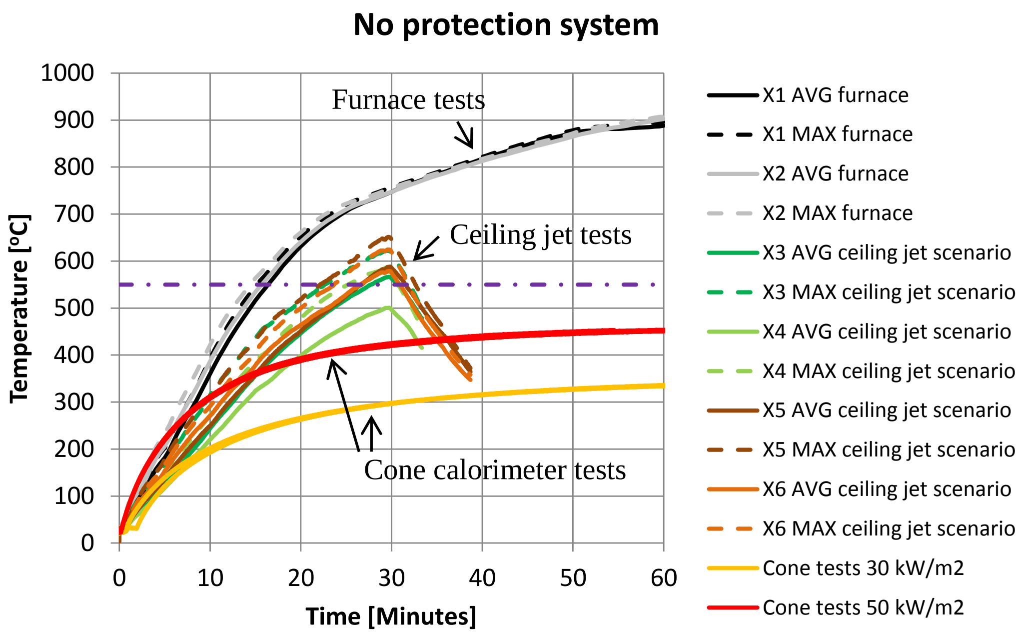

Figure 39 Summary of temperature development in reference specimens during furnace, ceiling jet, fire plume and cone calorimeter tests. The design temperature 550 °C is marked with a horizontal line. Fire plume exposure of unprotected steel was not included in the study.

Temperature plots from tests with protection system A are shown in Figure 40. During tests in the cone calorimeter system A exhibited a smaller difference in temperature development between the two radiation levels compared with the other systems, illustrated in Figure 11. This is caused by a much higher expansion during the higher radiation level compared with the other systems.

During all types of tests except the cone calorimeter tests loss of adhesion was indicated when testing system A which shows a fire resistance that did not correspond to 60 minutes with the critical temperature 550 °C that was given by the documentation of the product. When investigating the documentation supplied from the manufacturer of system A more in detail it was discovered that this product, that is available on the Nordic market, is sold without proper documentation of the function of the primer used (but the supplier claim the primer is equivalent). Whether the poor performance is caused by a direct problem with the primer or the very high expansion together with the choice of primer is not possible to assess. The chosen film thickness of intumescent paint in the protection system during the test is not the thickest allowed according to the design tables as between 26-138 % thicker intumescent layer is possible to use according to the design tables for the four tested systems. Hence, this is not a question of testing “on the limit” of performance as from experience from standardized tests at SP the largest chances of loss of adhesion is for the highest thicknesses tested.

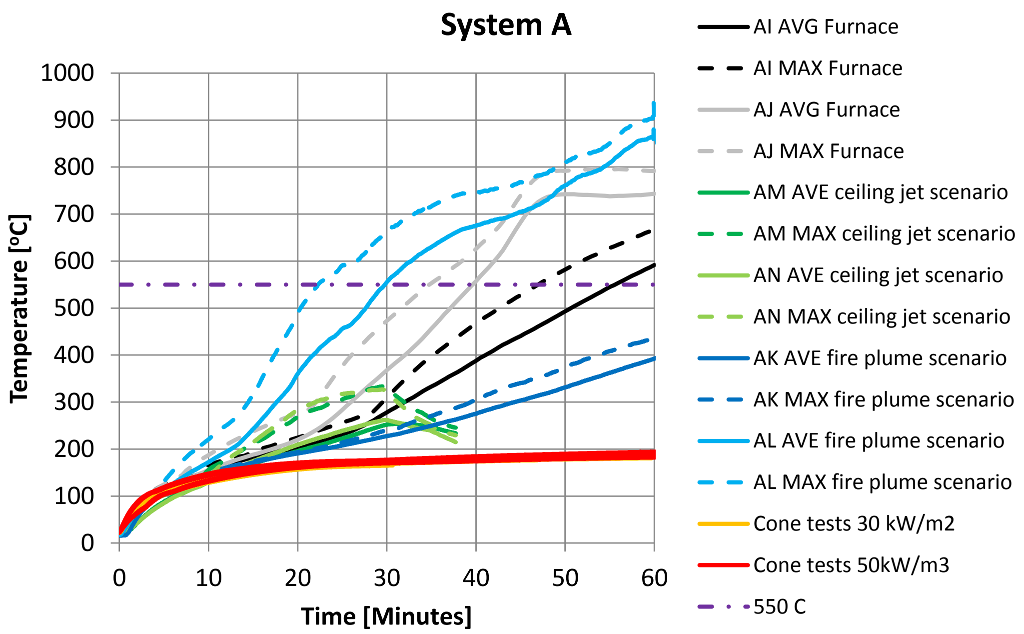

Figure 40 Summary of temperature development in specimens protected with system A during furnace, ceiling jet, fire plume and cone calorimeter tests. The design temperature 550 °C is marked with a horizontal line.

Protection system type B also showed an unexpected poor performance during the furnace tests. As illustrated in Figure 41 the paint on specimen BI started to rise after approximately 45 minutes of fire exposure with reduced fire resistance as a result. This increase is probably caused by loss of adhesion. Also in Figure 41 it appears that the thermal exposure during the plume fire scenario is less severe than the furnace exposure. The reason for this is not known in detail but one reason might be that the plate thermometer is placed in the centre of the flame compared with the specimens that “see” more of the cold surroundings. Despite this specimen AL, exposed in the fire plume scenario, was the specimen that had the lowest fire resistance which shows that loss of protection is crucial for the performance.

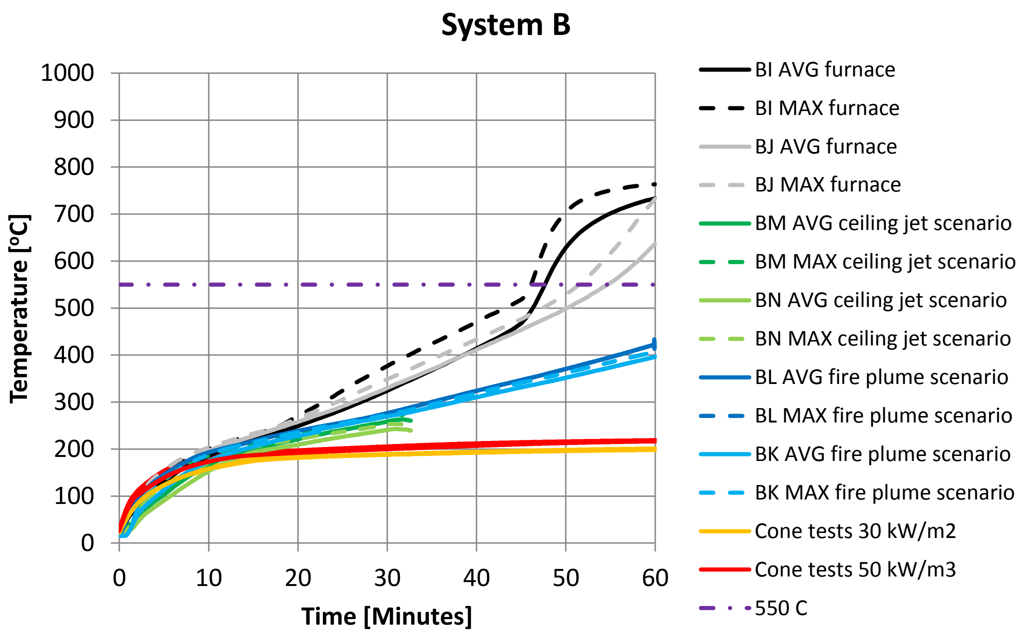

Figure 41 Summary of temperature development in specimens protected with system B during furnace, ceiling jet, fire plume and cone calorimeter tests. The design temperature 550 °C is marked with a horizontal line.

System C performed as expected during all tests as illustrated in Figure 42. No large deviations in temperatures measured in single points compared to the average and the insulation criteria was maintained for the test duration of 60 minutes in the furnace tests.

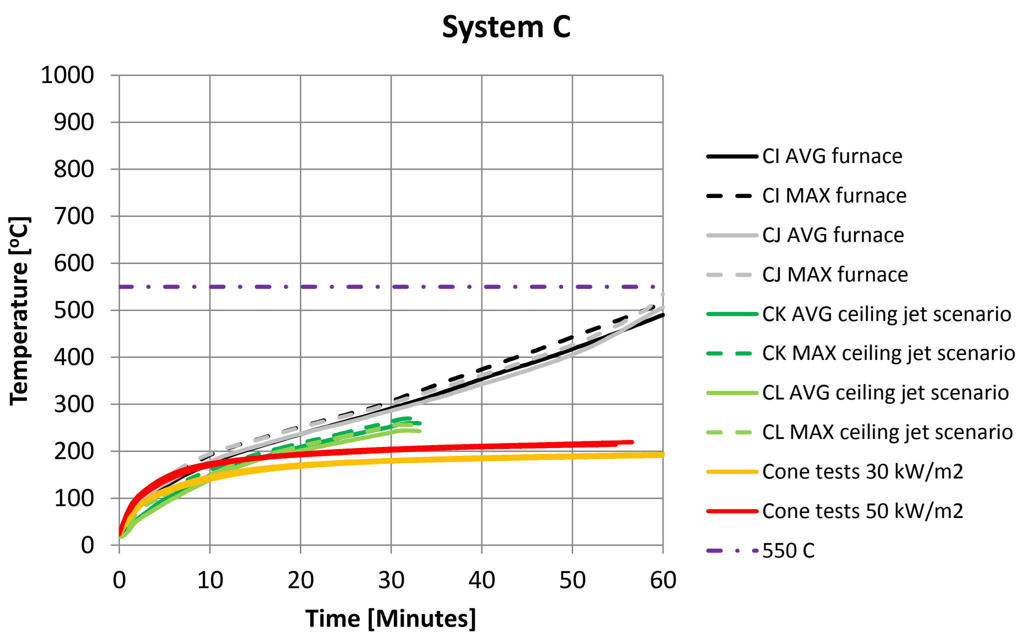

Figure 42 Summary of temperature development in specimens protected with system C during furnace, ceiling jet, fire plume and cone calorimeter tests. The design temperature 550 °C is marked with a horizontal line. Fire plume exposure of system C was not included in the study.

System D did also show a good performance, but as illustrated by Figure 43 there was a bump in one of the temperature plots in specimen DJ during the furnace test. This might be a crack in the materials or small loss of material that was later covered again by the surrounding material that continued to swell.

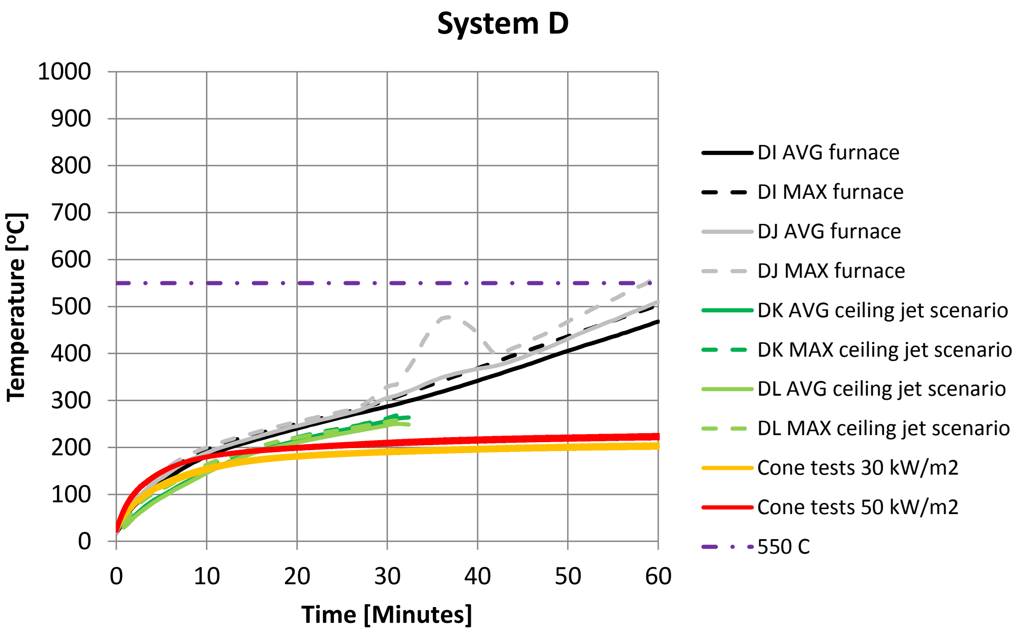

Figure 43 Summary of temperature development in specimens protected with system D during furnace, ceiling jet, fire plume and cone calorimeter tests. The design temperature 550 °C is marked with a horizontal line. Fire plume exposure of system D was not included in the study.

4 Conclusions

Four different protection systems available in the Nordic market, A-D, were in the present study exposed for the following heating scenarios:

- Cone calorimeter test with incident radiation 30 kW/m^2.
- Cone calorimeter test with incident radiation 50 kW/m^2.
- Ceiling jet scenario where the specimens were exposed to a horizontal flow as in a ceiling jet, thermal exposure less severe than the standard fire curve
- Fire plume scenario where the specimens were exposed to a vertical flow as in a fire plume with a free flow velocity of around 10 m/s, thermal exposure less severe than the standard fire curve
- Furnace tests with three side exposure hanging in the roof of the furnace exposed to a standard fire scenario

The test campaign shows that system A was far from functioning as intended. During the standardized furnace test the design temperature 550 °C was reached already after 33 minutes by the first thermocouple in one of the test specimens, and after 40 minutes of exposure the average temperature was higher than the design temperature for this specimen designed for 60 minutes of protection. When doing the tests with exposure in a ceiling jet scenario the test time was only 30 minutes with no temperatures above the design temperature but the spread in temperatures indicated that some adhesion problems probably occurred also during this tests. In the fire plume tests the adhesion of the system was lost which resulted in the first thermocouple rising over the design temperature in one of the test specimens already after approximately 22 minutes and the average temperature reached over the design temperature after 30 minutes. Contradictory to these results system A was shown to be the best insulator during the cone calorimeter tests. In this test the specimens are exposed to thermal radiation from above, i.e. the demand on adhesion between intumescent paint, primer and steel is minimal as gravity cannot make the system fall off. It was noted when performing cone calorimeter tests at the highest level of incident radiation, 50 kW/m^2,that system A expanded much more than the other systems with system B having the second largest expansion. This high expansion may be a factor leading to the instability of the system. This illustrates clearly the importance of adhesion on the function of intumescent paint systems. During the study it was discovered that the documentation regarding system A was not complete as the primer provided by the supplier was not the one that the certification was based on, but according to the supplier it was equivalent. If the adhesion problem of system A depends on wrong choice of primer is not possible to know.

During the furnace test also system B lost the adhesion with a reduced fire resistance as a result. This loss of adhesion was indicated by a sudden rise in temperatures after around 45 minutes where the first thermocouple was showing a temperature over the design temperature 550 °C. During the tests with the ceiling jet and fire plume scenario no indication of loss of adhesion was seen and the design temperature was not exceeded. System B was the system having the second largest expansion during the cone calorimeter tests which may indicate, together with the results of system A, that high expansion can lead to adhesion problems.

System C and D behaved as expected in all tests giving the fire resistance they were designed for. During the furnace test of system D a bump in temperature development indicated opening of a crack or delamination but it was recovered.

4.1 Recommendations and further research

When buying an intumescent system from a supplier the documentation needs to be carefully assessed as all components, primer, intumescent paint and top coat needs to be properly documented. In a user's perspective it is vital that the component lists are followed thoroughly so that the fire resistance properties are upheld. This study shows that there is a system available on the Nordic market that is not properly documented.

The European Standard EN 13381-8 is based on the general furnace testing method used in fire resistance testing. During furnace testing the thermal exposure is prescribed but nothing is stated regarding the level of convective flows around the test specimens. In this study the system with the best insulating properties during heat exposure in the cone lost its adhesion during the furnace test where gravity and convective flows are factors influencing adhesion. Despite that these systems potentially can be influenced by convective flows this factor is not included in the test standard in a proper way. The development of a test method including a controllable flow scenario, a fire plume test or a ceiling jet test representing real fires, similar to the once used in this study is therefore recommended.

Another area for development is to quantify the gas velocities in furnaces during standardized testing and compare this with flows estimated for real fires in different geometrical configurations.

The question of variance of performance of intumescent systems depending on the oxygen content and heating scenario needs also attention as this seems to be important influences in the degradation process of the foamed material.

During the test of system D in the furnace a type of healing process appeared to happen when the temperature after an initial rise went down for a while. This is an interesting aspect that needs further investigation as this indicates that a certain amount recovery of lost protection can happened during the expansion process of the system.

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Appendix A, additional measurement results

Cone calorimeter tests

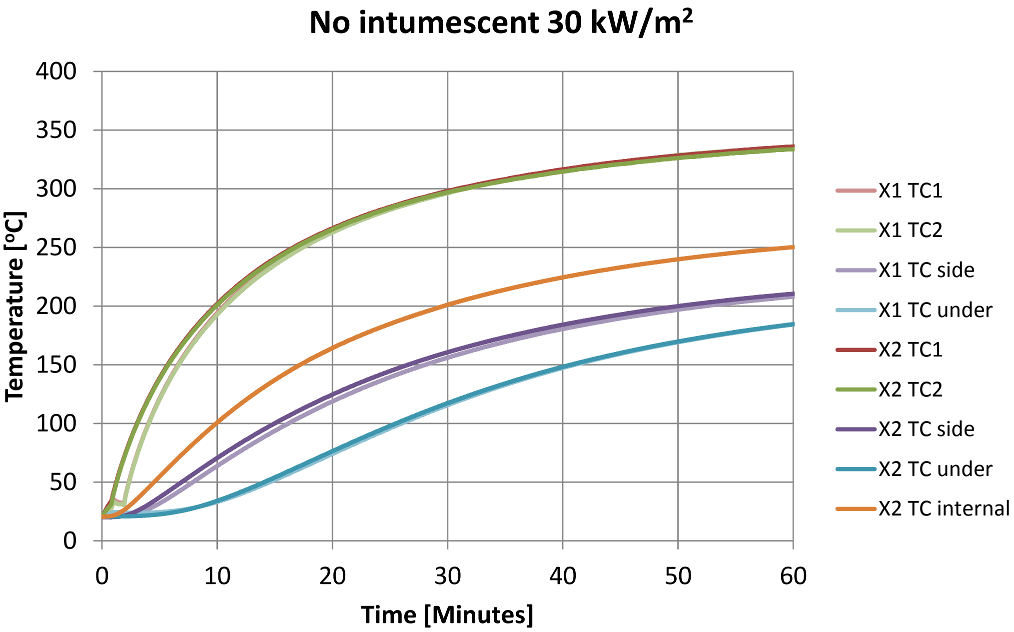

Figure 44 Cone calorimeter tests on steel without intumescent paint, 30 kW/m^2 exposure.

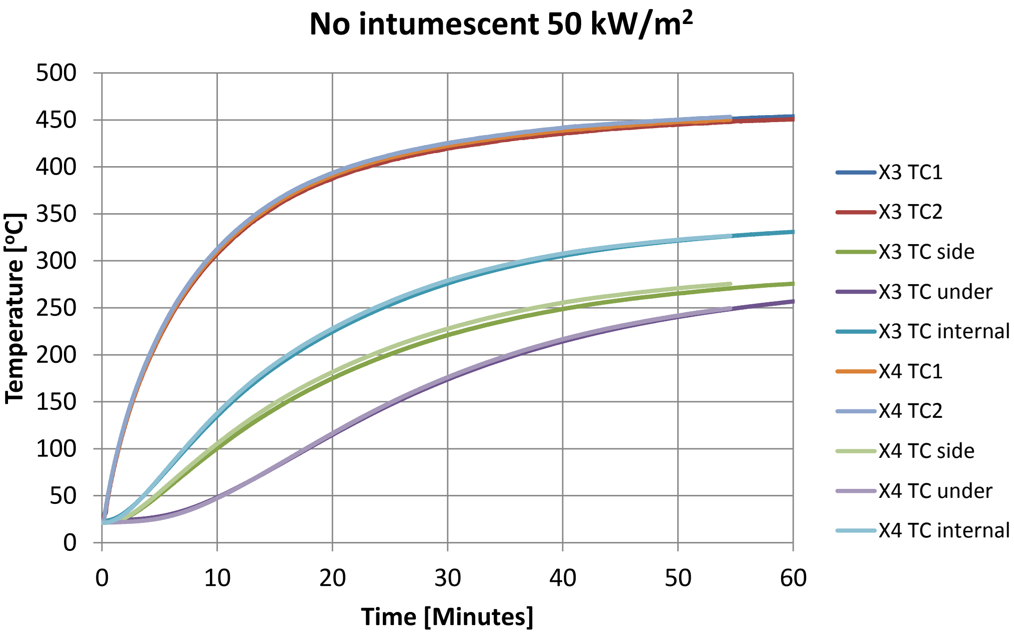

Figure 45 Cone calorimeter tests on steel without intumescent paint, 50 kW/m^2 exposure.

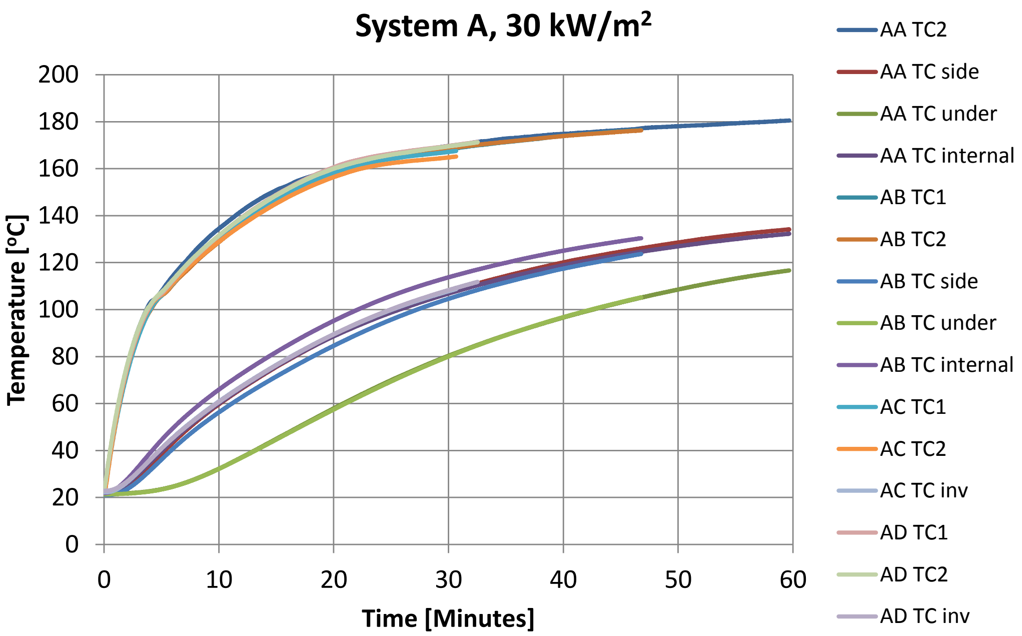

Figure 46 Cone calorimeter tests on steel with intumescent paint system A, 30 kW/m^2 exposure.

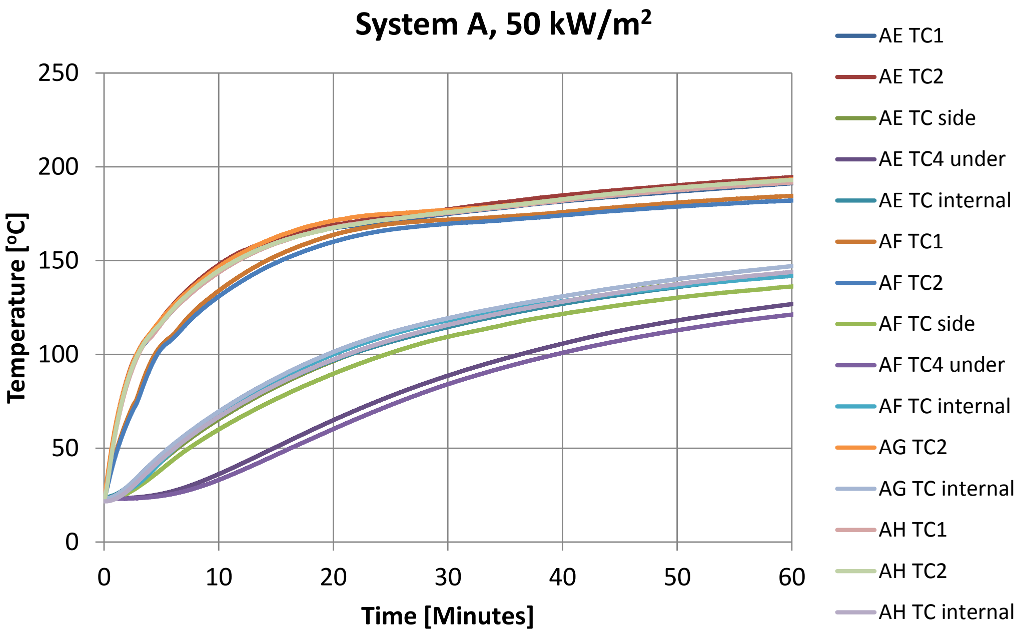

Figure 47 Cone calorimeter tests on steel with intumescent paint system A, 50 kW/m^2 exposure.

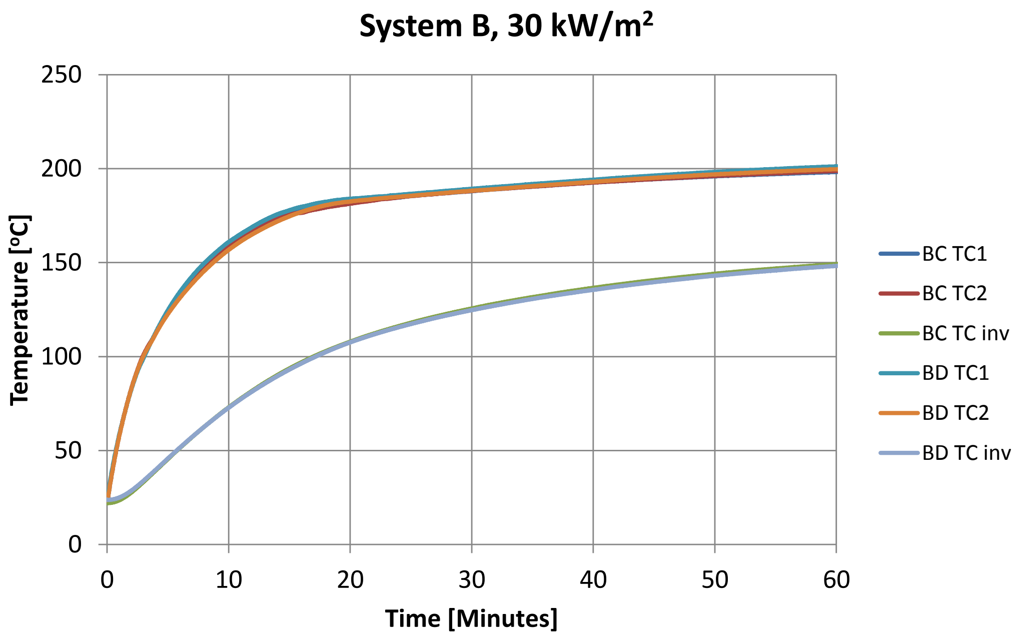

Figure 48 Cone calorimeter tests on steel with intumescent paint system B, 30 kW/m^2 exposure.

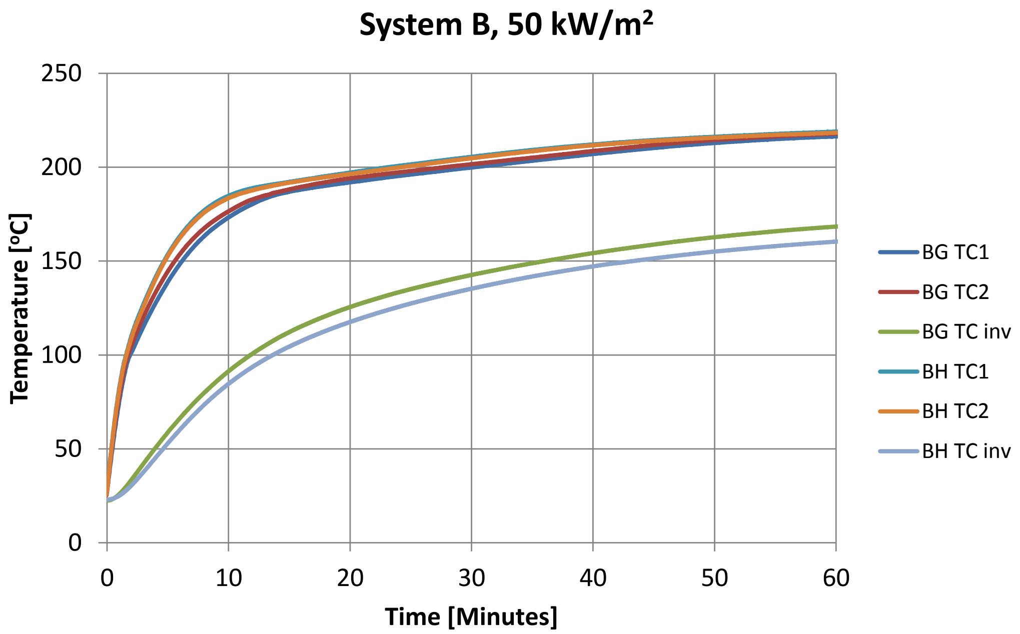

Figure 49 Cone calorimeter tests on steel with intumescent paint system B, 50 kW/m^2 exposure.

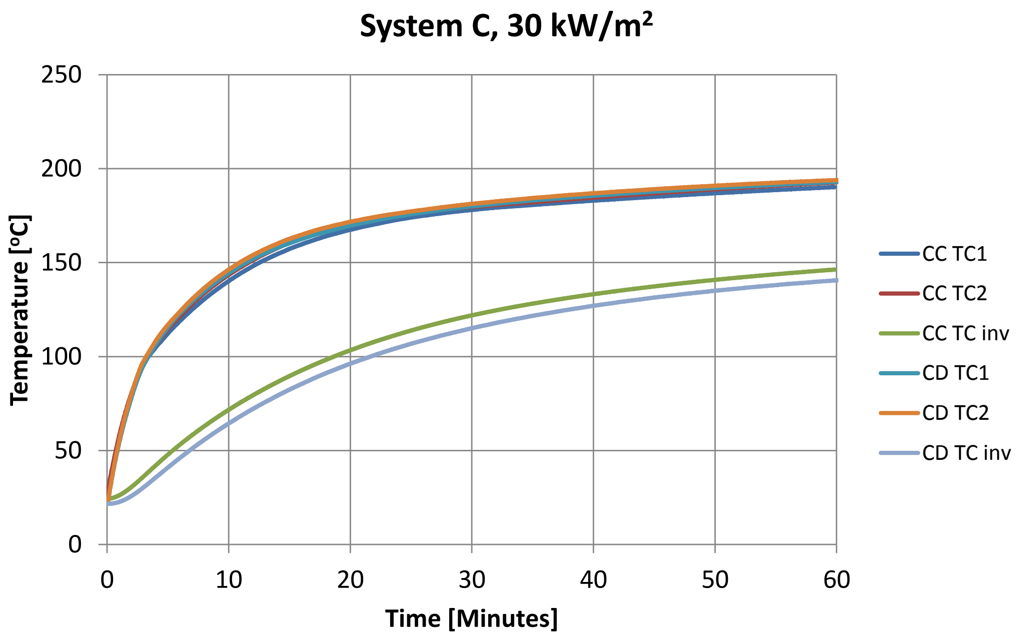

Figure 50 Cone calorimeter tests on steel with intumescent paint system C, 30 kW/m^2 exposure.

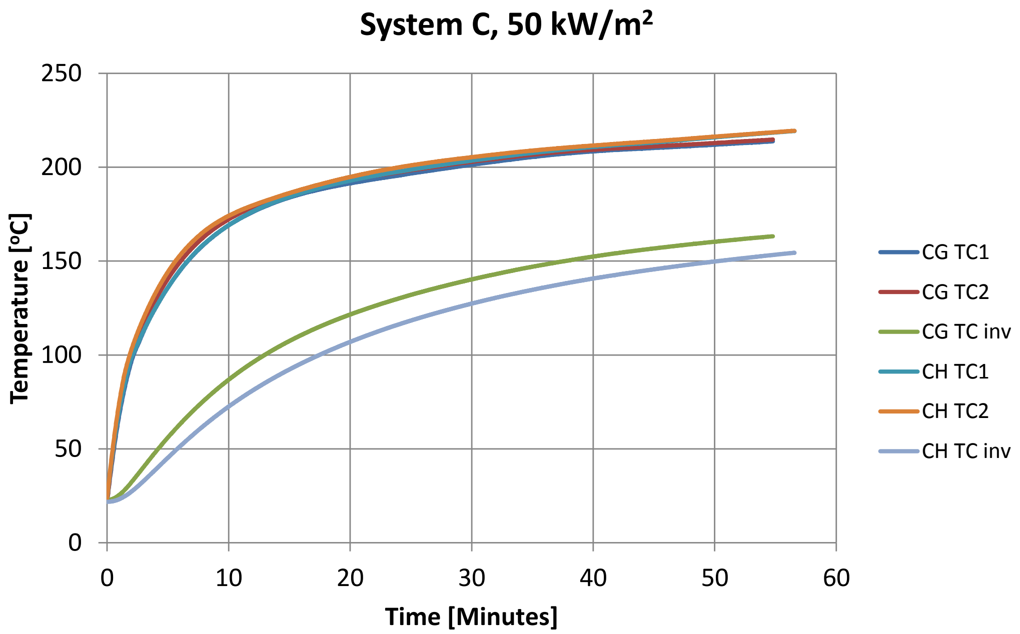

Figure 51 Cone calorimeter tests on steel with intumescent paint system C, 50 kW/m^2 exposure.

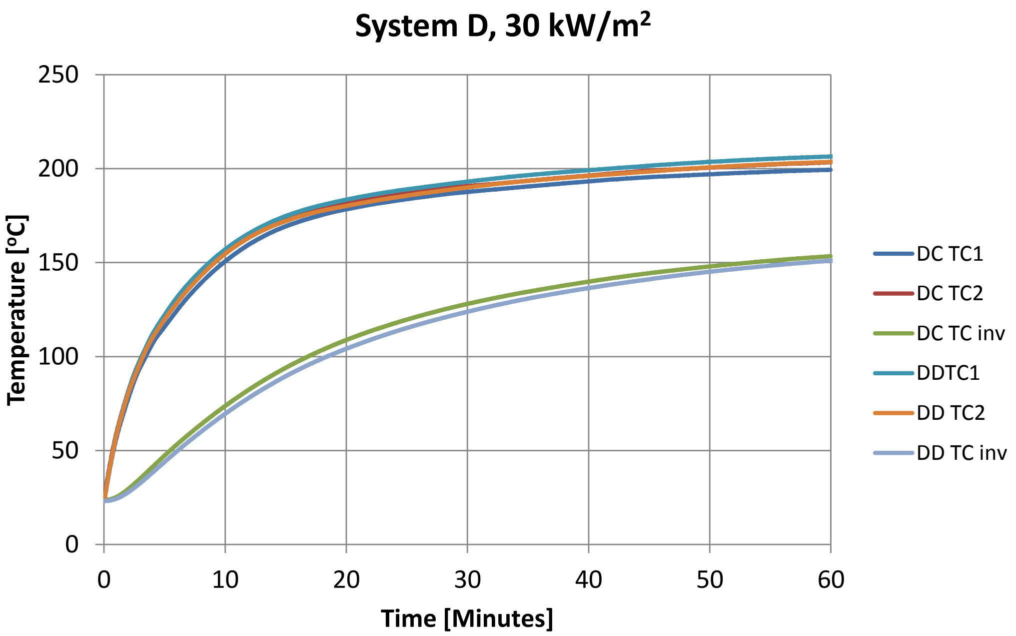

Figure 52 Cone calorimeter tests on steel with intumescent paint system D, 30 kW/m^2 exposure.

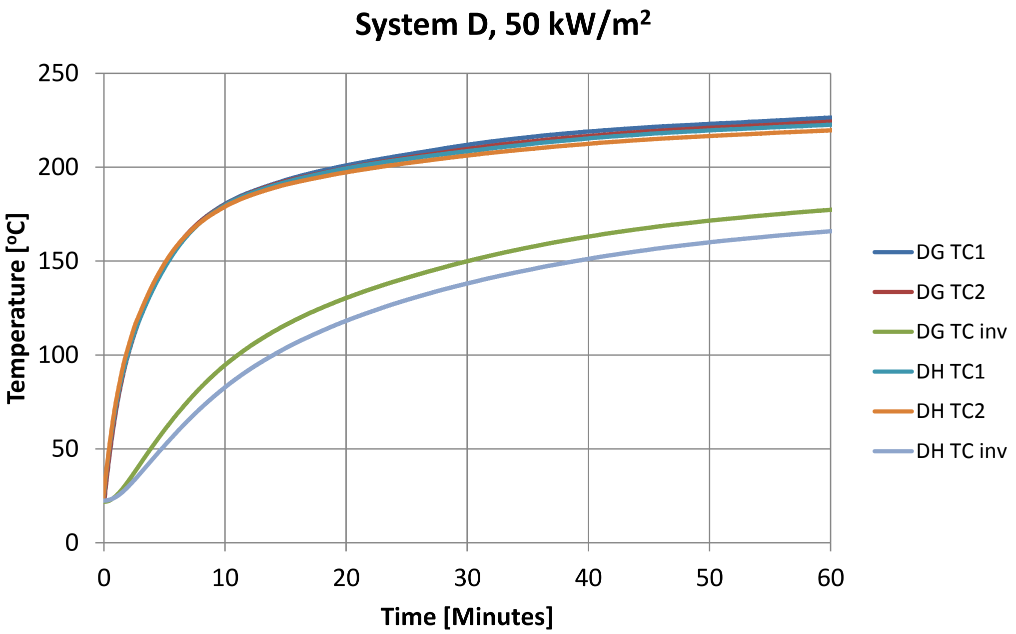

Figure 53 Cone calorimeter tests on steel with intumescent paint system D, 50 kW/m^2 exposure.

Ceiling jet tests

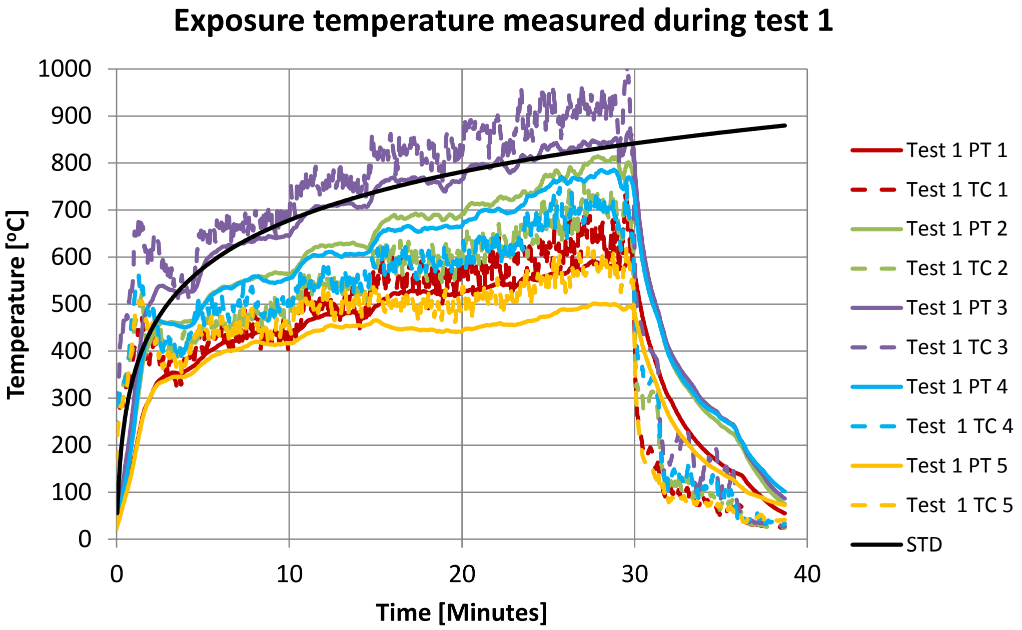

Figure 54 Exposure temperatures during test 1. Plate thermometers and 1 mm shielded thermocouples.

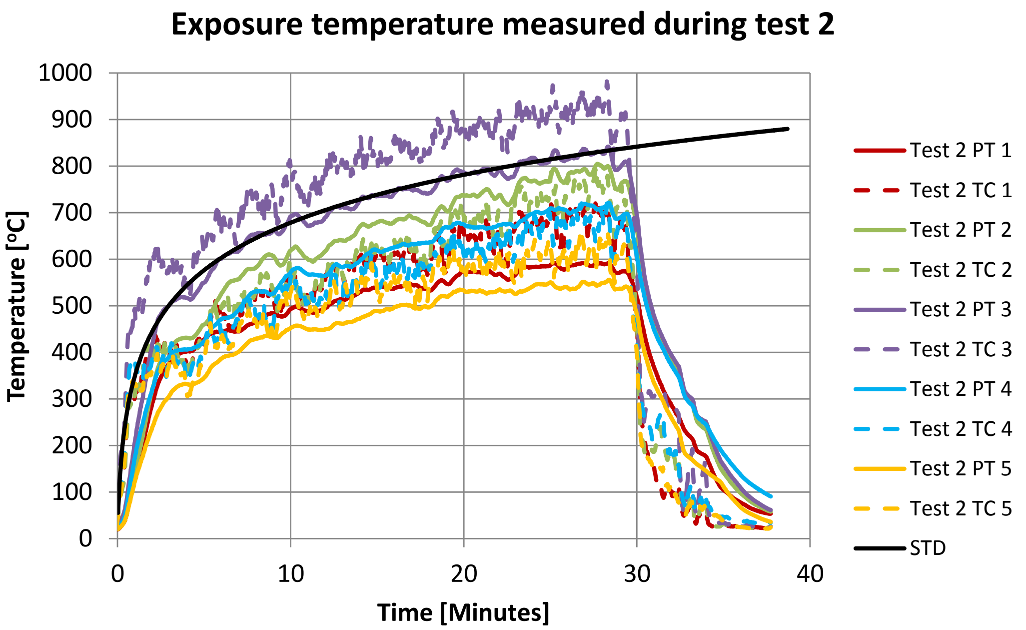

Figure 55 Exposure temperatures during test 2. Plate thermometers and 1 mm shielded thermocouples.

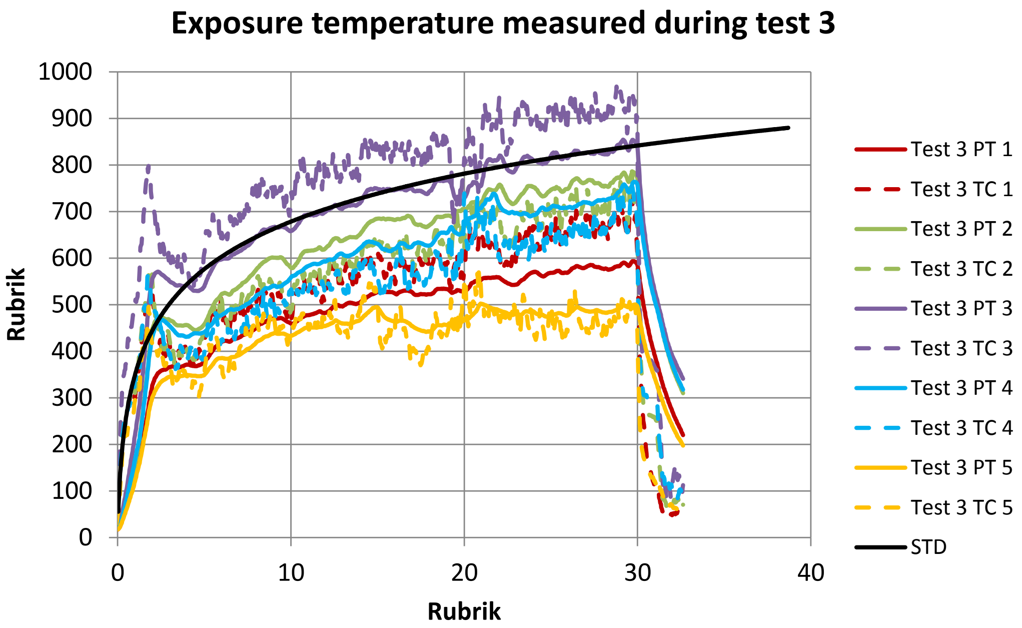

Figure 56 Exposure temperatures during test 3. Plate thermometers and 1 mm shielded thermocouples.

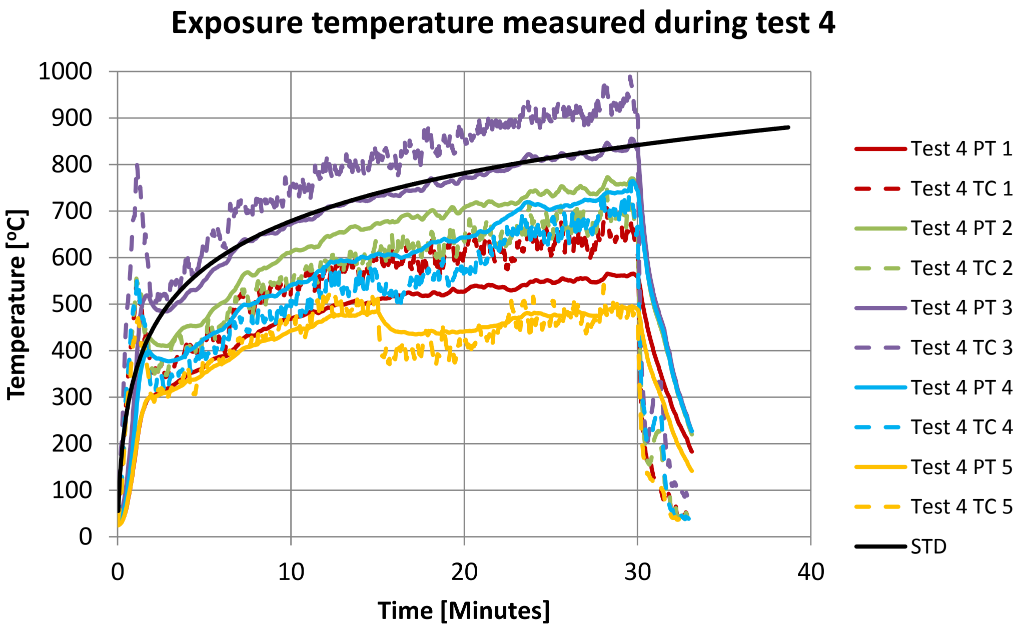

Figure 57 Exposure temperatures during test 4. Plate thermometers and 1 mm shielded thermocouples.

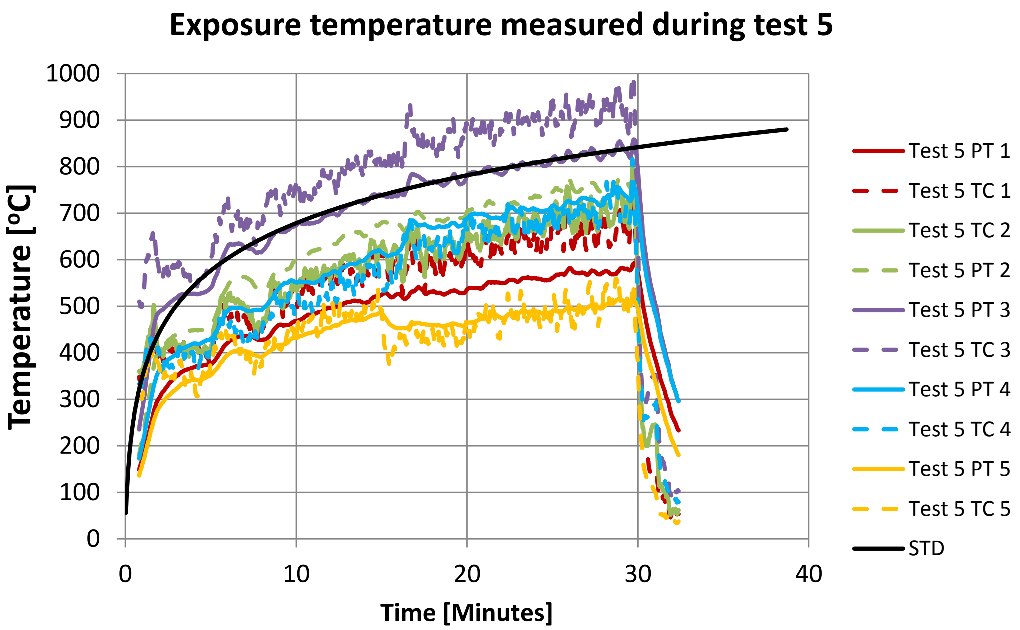

Figure 58 Exposure temperatures during test 5. Plate thermometers and 1 mm shielded thermocouples.

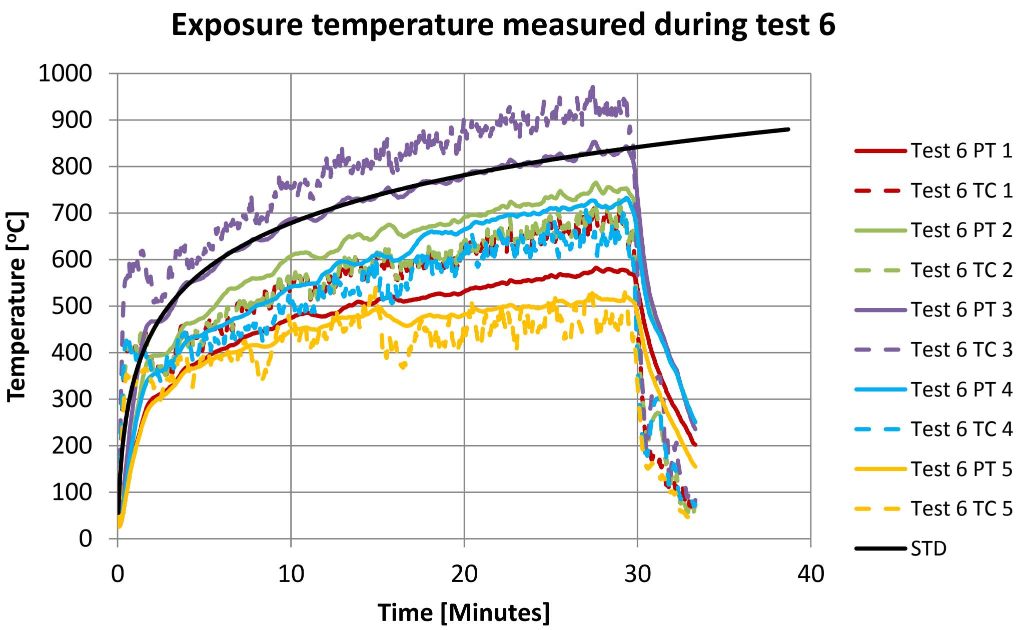

Figure 59 Exposure temperatures during test 6. Plate thermometers and 1 mm shielded thermocouples.

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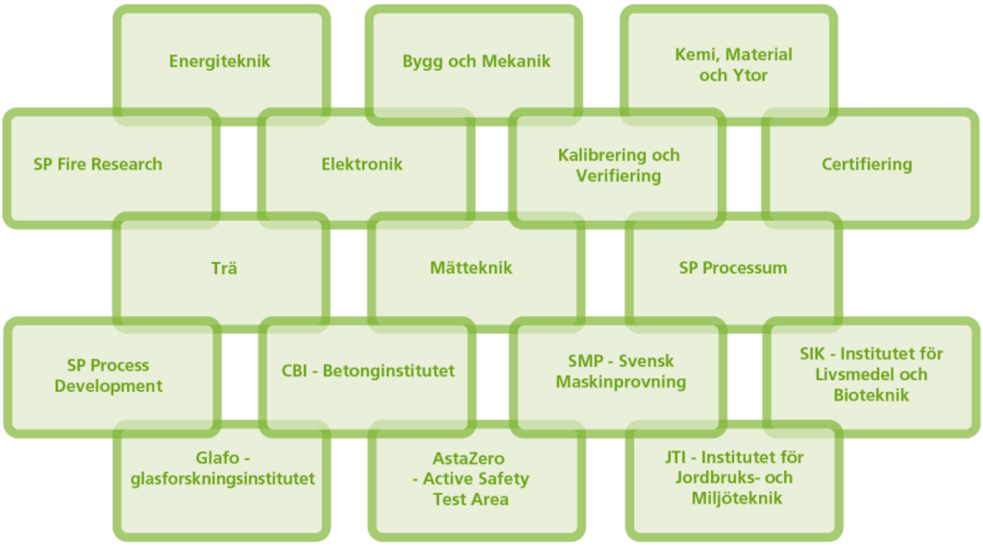

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www.sp.se

SP Rapport 2016:43

ISBN 978-91-88349-47-7

ISSN 0284-5172

Mer information om SP:s publikationer: **www.sp.se/publ**

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