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Thermal Insulation as Passive Fire Protection for Hydrocarbon Process Equipment?

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WESTERN NORWAY UNIVERSITY OF APPLIED SCIENCES

Master Thesis in Fire Safety Engineering

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Western Norway University of Applied Sciences

Thermal Insulation as Passive Fire Protection for Hydrocarbon Process Equipment?

Master thesis in Fire Safety Engineering

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Preface

This master thesis was written during the fall/spring semester at the department of Fire Safety and HSE at the Western Norway University of Applied Sciences (WNU). The thesis represents the final year of the master in Fire Safety and provides 60 (ING5002 Master thesis). The thesis is conducted as a cooperation between Q rådgivning and the WNU.

Selection of the topic for the thesis was determined after contact with Professor Torgrim Log, spring 2017. The thesis immediately caught my attention as it opened for the possibility to look an interesting and highly relevant problem. In addition, it presented the possibility of conducting practical experiments and linking the results with calculations, requirements, theory and reality. It has been a challenging, interesting and not at least a rewarding year.

The present work is conducted as a part of the doctoral work of Joachim S. Bjørge, fire and safety advisor in Q rådgivning, co-supervisor. All of the laboratory work executed at the fire lab at HVL have been performed in cooperation with Joachim S. Bjørge.

Haugesund 31.05.18

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RÅDGIVNING

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Finally, I would like to thank my family and friends for discussions and support throughout the year.

Abstract

The use of thermal insulation and passive fire protection (PFP) raises concerns in the process industry due to potential corrosion under insulation (CUI). Corrosion related incidents is one of the costliest problems facing the oil and gas industry today, especially in aging facilities. To limit corrosion related to CUI, an improved insulation methodology has been developed. An air gap of 25 mm is introduced to prevent direct contact with potentially soaked insulation. This improved method requires more space and may therefore not allow for the previously added 50 mm layer of PFP. To make space for the PFP extensive construction work is needed. To demonstrate that thermal insulation may provide sufficient fire protection without PFP would therefore be beneficial. This has recently been done for 16 mm thick steel column walls, representing a significant heat sink. The objective of the present work was to demonstrate the PFP performance of regular thermal insulation for thinner steel thicknesses and investigate the thermal insulation “breakdown” temperatures.

A small-scale mock-up simulating a part of a typical distillation column, with the recommended 25 mm air gap, was exposed to small-scale jet fires. The steel disks of diameter 320 mm were insulated radially and on the top surface to minimize external heat losses. The testing was done in a horizontal orientation to minimize internal convective heat losses, i.e. a conservative approach. A 28 kW cylindrical propane burner aligned vertically, exposed the downward facing mock-up cladding. Thermocouples were used to record the temperature development in the cladding, insulation and the internal steel plates. The test set-up was modified to give stable heat flux exposure levels. Results are presented for four different steel wall thicknesses; 3 mm, 6 mm, 12 mm and 16 mm, exposed to heat fluxes in the range 250 – 350 kW/m^2.

Requiring the highest recorded temperature in the steel plate not to exceed 400 °C during the first 30 minutes was used as the performance criterion in the present work. There was a clear relation between the steel plate thickness and the recorded temperature increase in the steel with exposure time. The thinner the steel plate was, the faster it reached temperatures above the set performance criterion. The temperature recordings during the tests with 16 mm steel plates did not reach temperatures exceeding 400 °C within the 40 minutes test period, while the 3 mm steel plate reached temperatures exceeding 400 °C within 25 minutes. This can be explained by more heat being required to heat thicker steel plates representing a larger heat sink.

To investigate how the thermal insulation behaves when heated, test samples of the insulation (5 cm · 5 cm · 5 cm) were treated in a muffle oven to 700 °C, 750 °C, 800 °C, 900 °C, 1000 °C and 1100 °C. The holding time at the referred maximum temperatures was 30 minutes. Thermocouples were placed in the insulation and in the upper part of the oven (to measure the oven temperature).

After testing, the insulation had shrunk i.e. lost height, the colour had changed, and the material had become firmer with a crumbly consistency. The temperature recordings inside the thermal insulation showed internal heat release at about 300 °C and 900 °C. The heat release at 300 °C may be explained by the combustion of anti-dusting materials (oil products). The heat release at about 900 °C was likely due to combustion of the binder material (Bakelite).

The thermal insulation showed surprisingly good fire resistance, even with a 3 mm steel plate thickness. The stainless-steel cladding protected the thermal insulation from direct fire exposure, hence preserved the thermal insulation for a longer period of time. The tests indicated that the thermal insulation collapsed when exposed to temperatures above 1200 °C. There were some variations between the different tests conducted with the same steel plate thickness. The tests did, however, show a clear connection between the steel plate thickness and the temperature development in the steel. The test set-up itself seemed to work well and gave a good indication of the temperature development in the steel.

More tests should be performed to determine the variability in the small-scale jet fire tests. It is also recommended to perform repeated oven testing at higher temperatures, as the insulation still was in good shape after heating up to 1100 °C. It may also be interesting to see how an additional layer of PFP, e.g. 10 mm, will prolong the time to collapse for the thermal insulation during fire testing.

Sammendrag

Det er knyttet flere bekymringer til bruk av termisk isolasjon og passiv brannbeskyttelse (PBB) i prosessindustrien på grunn av potensiell korrosjon under isolasjon (KUI). Korrosjonsrelaterte hendelser er en av de mest kostbare problemene olje- og gass industrien står overfor i dag, spesielt i aldrende anlegg. For å begrense KUI, har en forbedret isolasjonsløsning blitt utviklet. En 25 mm luftspalte er introdusert mellom metalloverflaten og den termiske isolasjonen for å forhindre direkte kontakt med en potensiell våt isolasjon. Denne løsningen gir naturlig et større byggeareal og det vil dermed ikke være rom for et tidligere 50 mm lag med PBB. Det kan derfor være fordelaktig om termisk isolasjon alene kan vise seg å være tilfredsstillende, uten bruk av PBB. Dette har nylig blitt vist for en 16 mm tykk tankvegg, der metallet representerer et betydelig termisk reservoar. Hensikten med masteroppgaven har vært å demonstrere industriell termisk isolasjon som PBB også for tynnere ståltykkelser, samt å undersøke nedbrytning av isolasjonen ved eleverte temperaturer.

En små-skala modell som fremstår som en del av en typisk destillasjonskolonne, med den anbefalte 25 mm luftspalten, ble eksponert mot en jet brann. Stålplatene med en 320 mm diameter var radielt isolert og på topp overflaten for å minimere eksterne varmetap. Testingen ble utført horisontalt for å minimere konvektive varmetap, dvs. en konservativ fremgangsmåte. En 28 kW sylindrisk propanbrenner ble plassert vertikalt og eksponerte den nedover vendte kledningen. Modellen var utstyrt med termoelementer for å registrere temperaturutviklingen i kapslingen, den termiske isolasjonen og stålplatene. Testoppsettet ble modifisert til å gi stabile varmefluksnivåer. Resultater er presentert for 3 mm, 6 mm, 12 mm og 16 mm ståltykkelse, der små- skala modellen ble eksponert for varmeflukser mellom 250 – 350 kW/m^2.

Den høyeste målte temperaturen i stålplatene skulle ikke overstige 400 °C i løpet av de første 30 minuttene, ble satt til å være ytelseskriteriet i det gjennomførte arbeidet. Det var en klar sammenheng mellom tykkelsen på stålplaten og temperaturutviklingen i stålet. Jo tynnere stålplate, desto raskere passerte temperaturene det gitte ytelseskriteriet. Testene utført med en 16 mm tykk stålplate oppnådde ikke temperaturer over 400 °C i løpet av de første 40 minuttene av branneksponeringen. Testingen utført med 3 mm stålplatetykkelse gav temperaturer over 400 °C innen 25 minutter. Dette kan forklares med at mer varme kreves for å varme opp tykkere stålplater, som representerer et større termisk reservoar.

For å studere egenskapene til den termiske isolasjonen ved eleverte temperaturer, ble prøvestykker (5 cm · 5 cm · 5 cm) varmet opp i en muffelovn til henholdsvis 700 °C, 750 °C, 800 °C, 900 °C, 1000 °C og 1100 °C. Holdetiden ved angitt maksimumstemperatur var 30 minutter. Et termoelement ble plassert i prøvestykket og et i den øvre delen av ovnen (for å måle ovnstemperaturen).

Etter testingen hadde prøvestykket krympet, dvs. mistet høyde, fargen hadde endret seg og materialet hadde blitt fastere med en smuldrende konsistens. Temperaturmålingene fra isolasjonen viste at varme ble avgitt ved ca. 300 °C og ved ca. 900 °C. Varmefrigjøringen ved ca. 300 °C skyldes forbrenning av støvdempingsprodukter (olje). Varmeproduksjonen ved ca. 900 °C skyldes mest sannsynlig forbrenning av isolasjonens binde materiale (Bakelitt).

Den termiske isolasjonen viste en overraskende god brannmotstand, selv med kun 3 mm stålplatetykkelse. Den beskyttende kledningen i rustfritt stål forhindret direkte branneksponering av den termiske isolasjonen og dermed forlenget tid til kollaps. Testene indikerte at den termiske isolasjonen kollapset når den ble utsatt for temperaturer over 1200 °C. Det var noe variasjon mellom de ulike testene utført med samme platetykkelse, men det var en klar sammenheng mellom stålplate tykkelsen og temperaturutviklingen i stålet. Selve testoppsettet fungerte bra og gav en god indikasjon på temperaturutviklingen i stålet.

Det anbefales at flere tester gjennomføres for å fastsette repeterbarheten til småskala jet brann-testene. Det anbefales også å gjennomføre flere tester i muffelovnen, fortrinnsvis på enda høyere temperaturer, da isolasjonen fortsatt var i relativt god stand etter 30 minutter holdetid på 1100 °C. Det kan også være interessant å se hvordan et ekstra lag med PBB, f.eks. 10 mm, vil forlenge tiden til kollaps av den termiske isolasjonen ved branntesting.

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Abbreviations

ALARP	As Low As Reasonable Practicable
CUI	Corrosion Under Insulation
PFP	Passive Fire Protection
PSA	Petroleum Safety Authority Norway
PSM	Pipe Section Mat
PSV	Pressure Safety Valve
PTFE	Polytetrafluoroethylene
PTHFM	Plate Thermocouple Heat Flux Meter
UTS	Ultimate tensile strength
WNU	Western Norway University of Applied Sciences

1 Introduction

1.1 Background

Hydrocarbons are of natural origin and can be found all over the world, in every continent and ocean. Hydrocarbons may occur as either liquid or gas and they play an important role in the world's energy production. About 53 % of the world's energy supply is produced by the oil and gas industry [1].

Hydrocarbons and chemical products can create severe damages when handled incorrectly. Fire and explosion protection therefore represents an important part in the risk management process at oil and gas processing plants. Fire protection and safety measures in the oil and gas industry are often based on methods to eliminate, prevent, mitigate or reduce the frequency of incidents, by identifying the possible hazard, evaluating their risk and recommending appropriate safeguards. The requirements depend on the organizational safety requirements, the identified risk and a cost-benefit analysis for major exposures. Typical safeguards are leak detection, ignition source control, passive fire protection, active fire protection, layout, the use of less/non-combustible materials, ventilation, spill control, overpressure protection, etc. [2].

Processing of hydrocarbons may include processes such as distillation and cracking. Thermal insulation is therefore often required for reducing unwanted thermal gains or losses. Insulation of process equipment and piping is therefore necessary to ensure a safe and efficient production in the oil and gas industry. Equipment and piping is often constructed in steel, which is vulnerable to fires, especially hydrocarbon fires, that quickly achieves high temperatures. To maintain the integrity of the equipment, if a fire occurs, an additional layer of passive fire protection has to be applied outside the thermal insulation, if the fire risk in the area is above acceptance criteria [2, 3].

The use of insulation rises several concerns, especially with respect to corrosion. Corrosion may occur for several reasons and can be external and internal. The total annual cost of corrosion in the oil and gas industry is estimated to be 11.2 billion NOK [4]. There is a huge need for reducing this number, as the oil and gas companies are striving for "zero failure" achievement [5].

August 6th 2012, a leak from a pipe in a crude oil distillation unit, in Richmond, California, resulted in a catastrophic release of flammable substances and produced a large vapour cloud, spreading over the surrounding areas. The ignition and the following combustion resulted in a black cloud of smoke spreading with the vapour cloud. The leak was hidden behind cladding and insulation. It was therefore difficult to establish the location and significance of the leak. It was not evaluated that corrosion could be the source of the leak, which resulted in some unfortunate decisions. Fortunately, nobody got seriously injured as a result of the accident, but it was reported over 15 000 treatments of breathing problems, chest pains, shortness of breath, sore throat and headaches in the following weeks after the accident [6].

At another refinery, Mongstad in Norway, the same year (8th November 2012), a powerful steam leak occurred, due to extreme corrosion under the insulation. Only 0.5 mm of the original 3.9 mm, of the pipe wall thickness was left. It was assumed that the reason for the extensive corrosion was due to contact with wet insulation for a long period of time. There were no serious injuries and the material damages were limited. However, the accident had major damage potential and could potentially have killed four people, had it occurred a few hours later [7]. The pipe rupture at the Richmond refinery is shown in Figure 1.1 a) and the pipe rupture at Mongstad is shown in Figure 1.1 b), both due to severe undetected corrosion under insulation (CUI).

a) b)

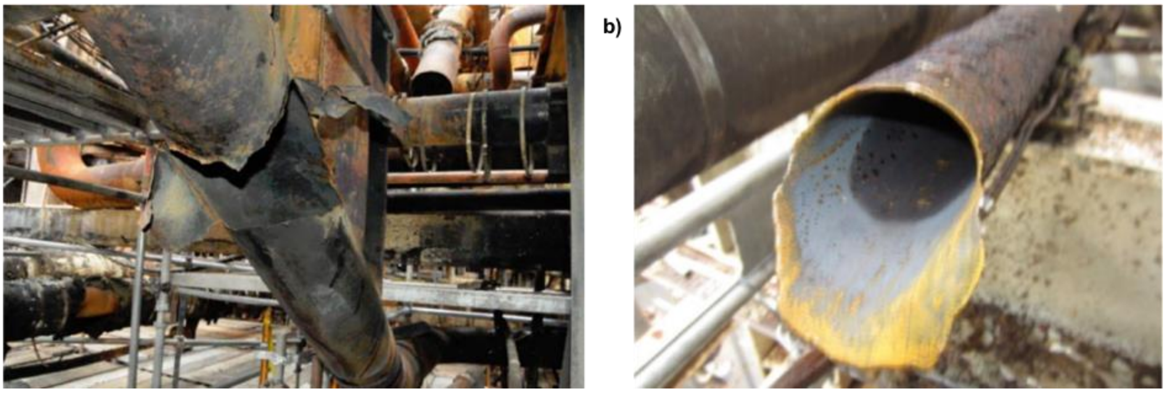

Figure 1.1 a) Ruptures of crude oil pipe at the Richmond refinery [6]. b) Rupture of pipe at Mongstad [7].

From 1999 to 2015, 131 corrosion related accidents were reported to the Petroleum safety authority Norway (PSA). 60 of these were due to CUI, which is one of the costliest problems facing the oil and gas industry today [8, 9]. If not detected, CUI may result in a sudden and hazardous leak, representing a threat to both employees, the general public as well as severe damages to the process equipment. To avoid accidents due to CUI, it is essential to have good routines for maintenance and continuous routines for systematic review of components that are highly corrosion exposed.

To limit problems related to CUI, an improved insulation methodology has been developed. An air gap of 25 mm is introduced between the metal surface and the thermal insulation, to prevent direct insulation contact with the metal surface. This improved method will give a larger structural dimension, i.e. requiring more space and restrict the possibility for keeping the previously required (usually) 50 mm passive protection (PFP) layer. In existing processing plants, this may present challenges regarding the structural elements surrounding the column/pipe/tank. To avoid extensive construction work in a live plant, an alternative solution may be beneficial [3], i.e. where the thermal insulation alone acts as the PFP.

1.2 Scope

The goal of this master thesis is to analyse and assess the fire resistance of industrial ("Rockwool") thermal insulation in combination with the recommended air gap for a typical distillation column. The thermal insulation protection potential will be evaluated for different wall thicknesses. Depending on the test results, the limit for fire resistance will be evaluated. The present study builds on the work recently carried out by Bjørge et al. [3]. Based on theory and test set-up developed by Professor Torgrim Log, Technical Safety Advisor in Statoil, a new insulation method has been developed. The new method introduces the recommended air gap (25 mm) and 50 mm thermal Rockwool insulation serving as PFP. The question is whether this solution will meet current requirements regarding fire resistance and time to rupture, also for protection of thinner steel walls.

PFP is more expensive than regular thermal insulation. Letting the thermal insulation act as PFP may therefore give a significant cost reduction. In addition, there will be a cost reduction regarding less construction work and less planning as well as a safety gain, with eliminating construction work in a live plant. There are therefore several reasons for investigating whether regular thermal insulation gives a sufficient fire protection.

The objectives of this MSc-thesis are to evaluate the fire resistance of regular thermal insulation. This is to be done through two different approaches:

1. Testing of a mock-up, representing a part of a typical distillation column, with distance thermal insulation. Four different steel wall thicknesses, representing a column wall, are evaluated; 3 mm, 6 mm, 12 mm and 16 mm. The evaluations done after the tests are based upon the temperature-time graphs, the condition of the thermal insulation, video recordings and photos.
2. Oven testing of the insulation, to examine properties of the insulation after exposure at elevated temperatures.

Comparison of the results shall be conducted and provide a basis for assessing the limit for fire resistance.

1.3 Previous work

During the fall 2016, fire protection performance of thermal insulation was studied at the Western Norway University of Applied Sciences (WNU), by Bjørge et al. [3]. The aim of that study was to develop a test concept for testing fire resistance of equipment protected with only air-gap and thermal insulation. The study demonstrated a conceptual methodology for small scale fire testing of a mock-up resembling a section of a distillation column, i.e. without the previously added 50 mm fire protection layer. The mock-up was exposed to a small-scale propane fire, with a test configuration giving heat flux levels in the range of 250 – 350 kW/m^2. The results from the testing, with steel of similar thickness as a real scale column wall (16 mm), indicated more than 30 minutes fire resistance given a 25 mm air gap, 50 mm thermal insulation and no passive fire protection (PFP). The results from that study, showed that the methodology has a good potential for low cost fire testing, also of other configurations.

Apart from the recent study by Bjørge et al., little research seemed to have been done within this area.

1.4 Limitations

The present testing is done with a scaled model and is not done according to any international standard. It does however simulate a full-scale fire test, exposed to more severe conditions than what could be expected in large pool fires.

2 Theory

2.1 Distillation column

The hydrocarbon basic refining process consists of several phases; separating, distillation, thermal cracking, purification, etc. The distillation unit is the basic refining equipment and obtains separation through evaporating the highly volatile components away from the low volatile components. The lighter the components are, the more volatile they are, and opposite for the heavy products, the heavier they are, the less volatile. A simple explanation of the separation process, is splitting the feed stream into two product steams. In a pure separation process, all the molecules in the feed stream appears unchanged, i.e. no molecules are created, rearranged or destroyed [10].

There is often a wide temperature span in the distillation unit, typically with a relative high temperature in the lower part and a relatively low temperature at the top, e.g. 107 °C in the bottom and -10 °C at the top. The temperature distribution depends on the product properties. Figure 2.1 shows two typical process plant distillation columns.

Figure 2.1 Distillation columns in a gas processing plant [11].

In some cases, the insulation is allowed to get wet. This is common in units that operates below the ambient dew point. Due to natural convection, humidity is supplied to the thermal insulation, leaving the insulation soaked in water [12].

A distillation column is typically 20 – 25 m high with a diameter of 4 m, with comparable thick column walls, e.g. 16 mm (carbon steel). Depending on the operating temperature, the distillation columns are usually insulated to prevent heat losses or heat gains. An additional layer of PFP is often added to the equipment for protection against fires [3].

The previous insulation method consisted of a layer off corrosion protection paint applied to the equipment surface, then a layer of thermal insulation in direct contact with this surface. For sufficient fire protection, an additional layer of PFP was added outside the thermal insulation, followed by cladding (stainless steel) for protection against rain, foul weather and direct flame exposure in fires. Recently, this method has resulted in severe corrosion due to the wet insulation-metal contact. To avoid this problem, an optimised insulation method has been developed. This method introduces a 25 mm airgap between the column wall and the thermal insulation preventing direct contact between the two. The insulation is kept at this distance by perforated stainless steel plates and electrically insulated from the steel wall by non-conducting 25 mm Polytetrafluoroethylene (PTFE) spacers [11]. A typical distillation column insulation system is shown in Figure 2.2.

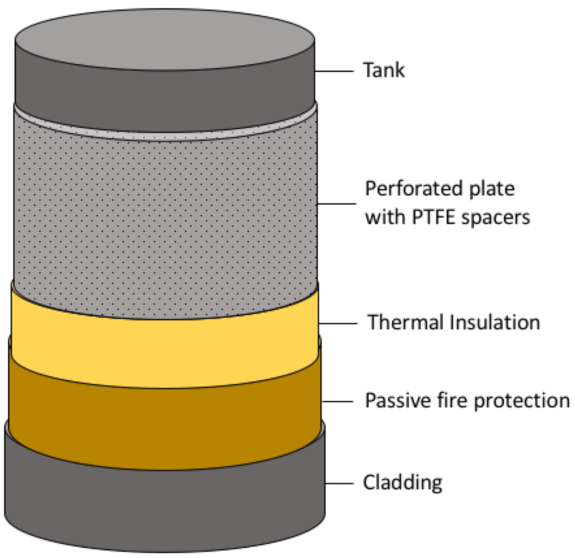

Figure 2.2 A typical distillation column insulation system.

2.2 Steel

Steel is a group L material, i.e. a material capable of carrying high stress, usually in tension or compression. The mechanical properties related to behaviour in tension and/or compression are of most interest. There are several types of steel, the most typical types, used for hydrocarbon process equipment, is carbon steel and stainless steel [13].

Carbon steel is an alloy of iron and up to 2.5 % carbon. Carbon steel is a widely used due to its availability and favourable cost [13].

Stainless steel is an alloy, normally containing at least 50 % iron and 10.5 % chromium. When exposed to air or water, it forms a thin film of chromium on the surface, making the material stainless. Due to the controlled adding of alloying elements, it is possible to make a wide range of material grades with different properties (strength, ability to resist atmospheric and chemical environments, operation at elevated temperatures, etc.) [14].

At elevated temperatures, the steel strength characteristics are reduced. This reduction will depend significantly on the material type and qualities. The relative strength as a function of temperature for different steel types is presented in Figure 2.3. The values are based on the Ultimate Tensile Strength (UTS) at given temperatures, given in [14]. As seen from Figure 2.3, carbon steel has lost 55 % of its strength at 600 °C, while stainless steel (AISI 316) only has lost 30% of its strength at the same temperature.

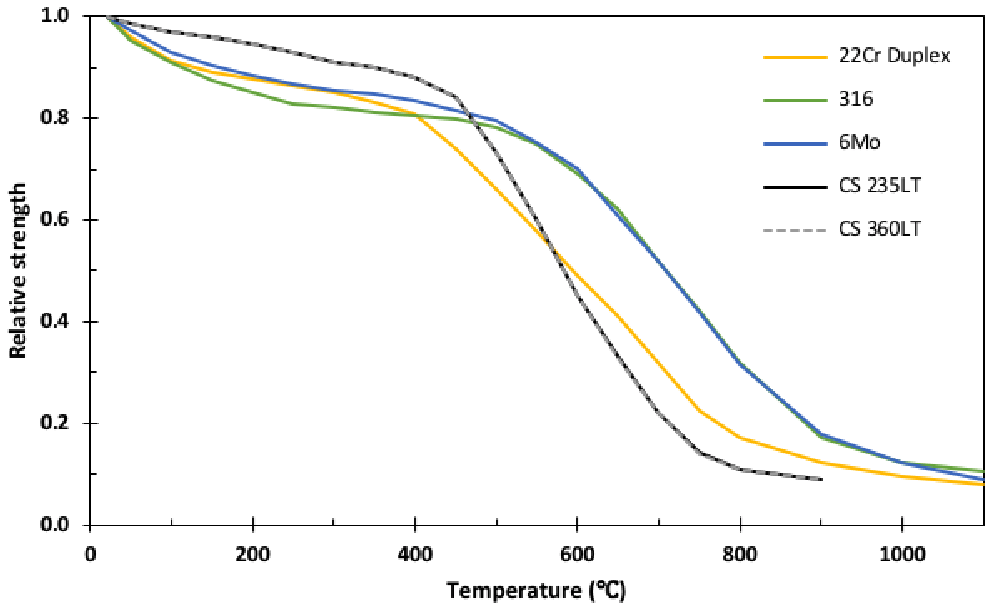

Figure 2.3 Relative strength as a function of temperature for different types of stainless steel and carbon steel materials. The graph is based on values from "Guidelines for the Protection of Pressurised Systems Exposed to Fire" [14].

2.2.1 Rupture criteria

Based on the pressure, temperature and the failure criterion for a specific equipment, it can be evaluated whether parts of the process equipment will rupture or not. In accordance with the ALARP principle (As Low As Reasonable Practicable) it is always a key issue to avoid any rupture, however a criterion for deciding whether it is an unacceptable rupture or not must be established. The main objective is to prevent a small fire from escalating.

Will the equipment rupture? If so, are the consequences of the rupture acceptable? To evaluate whether the equipment will rupture or, and if a rupture is acceptable or not, the following properties are normally evaluated; released quantity of flammable fluids, the composition of the released fluid (gas/liquid), and the pressure in the system at the time of the rupture. The type of equipment must also be considered, as well as the probability of impacting neighbour equipment, as all escalation to neighbour fire areas are unacceptable [14].

According to [14], based on the general acceptance criteria, exceedance of either of the following criteria is considered to make a rupture unacceptable: released quantity of hydrocarbons > 4 tons, released quantity of the sum of gas, initially flashed fraction of condensate or LPG > 1 ton, pressure at time of rupture of pressure vessels > 4.5 barg, pressure at time rupture of piping > 20 barg or rupture prior to 3 minutes after the onset of the fire.

2.2.2 Thermal conductivity

Pure iron is a good conductor of heat. Steel has a relatively high thermal conductivity compared to e.g. thermal insulation and air (see Table 2.1). The thermal conductivity of steel depends on the steel type and temperature, as shown in Figure 2.4.

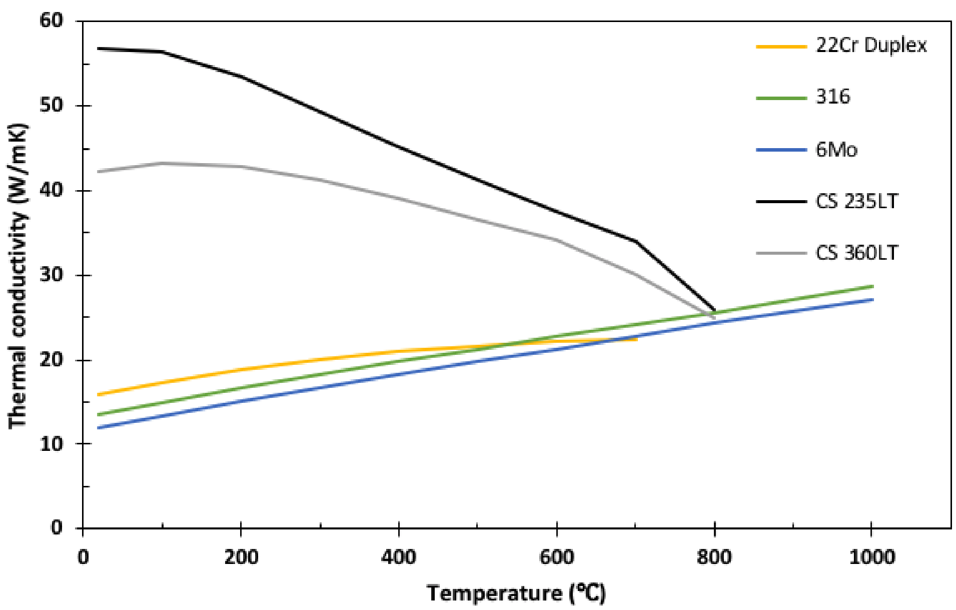

Figure 2.4 Thermal conductivity of various steel types as a function of temperature. The values are based on data from [14].

Carbon steel has a relative high thermal conductivity compared to stainless steel at ambient temperatures. As the temperature increases, the thermal conductivity of carbon steel decreases, while it increases for stainless steel.

2.2.3 Specific heat

The specific heat, c_a ($Jkg^{-1}K^{-1}$), for carbon steel is a function of temperature, and may be expressed by [15]:

$$c_a = 425 + 7.73 \cdot 10^{-1}\theta_a - 1.69 \cdot 10^{-3}\theta_a^2 + 2.22 \cdot 10^{-6}\theta_a^3 \tag{2.1}$$

where θ_a (°C) is the temperature. Equation 2.1 is only valid for temperatures between 20 °C $\leq \theta_a <$ 600 °C.

2.3 Thermal insulation/ Passive Fire Protection

Thermal insulation has several areas of application and may be applied for one or more functions; temperature control, personnel protection, humidity condensation prevention or sound attenuation. If thermal insulation is used for protecting equipment against fires, it is called passive fire protection (PFP). PFP may be used alone or in combination with thermal insulation, personnel protection or sound attenuating materials. The PFP then needs to withstand temperatures associated with fires. However, the use of PFP rises several concerns that may lead to an increased leak frequency and congestion. The main concerns are increased CUI, reduced possibility for inspection and maintenance, increased weight, space requirements, increased maintenance of PFP and increased cost. Still, the use of fire protection is important. The main reason for applying PFP, is to "buy time". By doing that allows the depressurisation system to reduce the pressure below the critical level or reduce the critical heat load until the fire is over. Depressurisation will either prevent a possible rupture or ensure less severe consequences. The main goal is to prevent an initial fire from escalating [14].

According to NORSOK S-001 [16], Technical Safety, the role of PFP is to ensure that relevant structures, piping and equipment components have adequate fire resistance with regard to load bearing properties, integrity and insulation properties during a dimensioning fire, and contribute in reducing the consequence in general.

2.3.1 Regulations and Standards

Onshore facilities in the petroleum industry in Norway is bounded by the technical and operational regulation, issued by the PSA. Chapter V: Fire and explosion protection in the design of onshore facilities, Section 30, states [17]:

"Where passive fire protection is used, this shall be designed such that it provides relevant structures and equipment with sufficient fire resistance as regards load capacity, integrity and isolation properties during a design fire load.

When designing passive fire protection, the cooling effect from fire-fighting equipment shall not be considered."

NORSOK S-001 [16], together with ISO 13702 [18], defines the required standard for implementation of technologies and emergency preparedness to establish and maintain an adequate level of safety for personnel, environment and material assets. Both standards describe different barriers; their role, interfaces, required utilities, functional and survivability requirements.

2.4 Protective barriers

In addition to PFP, pressurised equipment also has other protective barriers against fires and explosions, like e.g. depressurisation, fire relief and deluge/water spray. A depressurisation system is installed in order to reduce the pressure if the system experiences a leak , is exposed to a fire or other causes. Reducing the pressure, will minimize the material stress, hence reduce the risk for rupture of the equipment when heated in a fire. The reduced pressure will also reduce the leak rate and the duration of a potential leak. This will also limit the consequence of fire if the leak is ignited. Depressurisation can also be used to reduce the pressure when conducting maintenance. The depressurisation system is often designed in accordance with API Std 520, Part 1 [19] and API Std 521 [20], which implies that the depressurisation should be able to reduce the pressure to 6.9 barg or 50% of the design pressure, within 15 minutes. Normally depressurisation is therefore applied in combination with PFP, to avoid critical escalation of the fire, before the sufficient depressurisation is achieved. During a depressurization, flow of gas will cool the inside of the pipe/vessel due to expansion and gas transport. This effect may be accounted for in thermal calculations, but this effect will obviously not be present until the depressurization is activated [14].

Fire relief, pressure safety valve (PSV), is often provided to protect against overpressure in case of process upsets or fires. The PSV´s job is to relieve gas which is vaporising during a fire and/or relieve gas which is expanding due to heat input or relieve the expanding liquid for a 100 % liquid filled system [14].

Deluge/water spray is installed in order to cool equipment exposed to a fire, reduce the temperature development in the fire, hence the heat load applied to the system. Deluge/water spray can also be used to apply foam to extinguish hydrocarbon fires. Even though it can be argued that a deluge/water spray will have a positive effect in case of a fire, it cannot be given credit when designing a PFP system [16].

2.5 Heat transfer mechanisms

Heat transfer is transport, exchange and redistribution of thermal energy. A large amount of energy will be released in a fire. This energy will be transported away from the fire as a result of the three modes of heat transport, i.e. thermal conduction, convection and radiation. This chapter explains the basic physics for these heat transfer mechanisms.

2.5.1 Conduction

Conduction is described as heat transfer through a medium i.e. gas, liquid or solid. Conduction occurs by atoms and molecules with different kinetic energy, influencing each other [21]. For homogenous and isotropic objects, the steady state conduction, $\dot{q}''$ $(\mathrm{Wm^{-2}})$, in x-direction may be described by Fourier's law:

$$\dot{q}'' = -k\frac{dT}{dx} \tag{2.2}$$

where k ($\mathrm{Wm^{-1}K^{-1}}$) is the thermal conductivity and dT/dx ($\mathrm{Km^{-1}}$) is the temperature gradient. Materials with a high thermal conductivity conduct heat well while materials with low thermal conductivity are poor heat conductors. Some examples of the thermal conductivity for various materials at 20 °C is presented in Table 2.1.

Table 2.1 Thermal conductivity at 20 °C for selected materials [22].

Material	k ($\mathrm{Wm^{-1}K^{-1}}$)
Air	0.026
Steel (mild)	45.8
Thermal insulation	0.041
Water	0.591

The thermal conductivity of a material is a function of temperature. The extent to which the thermal conductivity changes, depends on the material and its aggregate state [13].

The thermal diffusivity of a material is the ratio of thermal conductivity to the volumetric heat capacity. The larger the diffusivity, the faster a temperature wave is distributed within the material [13]. The thermal diffusivity, α (m^2s^{-1}), is given by:

$$\alpha = \frac{k}{\rho c_p} \tag{2.3}$$

where ρ (kgm^{-3}) is the density and c_p ($Jkg^{-1}K^{-1}$) is the heat capacity.

2.5.2 Convection

Convection can be described as heat transfer by the motion of a fluid to or from a body. The convective heat transfer, $\dot{q}''$ (Wm^{-2}), can be calculated from Newton's law of cooling [13].

$$\dot{q}'' = h(T_s - T_\infty) \tag{2.4}$$

where h is the heat transfer coefficient ($Wm^{-2}K^{-1}$). T_s (K) and T_∞ (K) are the surface and fluid temperature, respectively.

2.5.3 Radiation

All objects, with a temperature above absolute zero, i.e. temperatures above 0 K, emit heat radiation. The radiation, $\dot{q}''$ (Wm^{-2}), can be calculated by:

$$\dot{q}'' = \varepsilon\sigma\phi T^4 \tag{2.5}$$

where $\varepsilon, \sigma, \phi$ and T are the emissivity (-), Stefan-Boltzmann constant ($5{,}67 \cdot 10^{-8}\ Wm^{-2}K^{-4}$), view factor (-) and the temperature (K), respectively. The emissivity for some common materials is given in Table 2.2.

Table 2.2 Material emissivity [13].

Material	Emissivity
Aluminium, crude	0.07 – 0.08 (0-200 °C)
Concrete, rough	0.94 (0-100 °C)
Steel, type AISI 303, oxidized	0.74 – 0.87 (300-1100 °C)

2.6 Industrial Fires

When considering industrial fires, it is common to distinguish between jet- and pool fires. The fire intensity depends on the degree of confinement as well as access to air supply [14]. Typical heat flux associated with pool and jet fires are shown in Table 2.3.

Table 2.3 Heat flux values for jet and pool fires [16].

	Jet fire		Pool fire
	For leak rates m > 2 kg/s kW/m^2	**For leak rates 0.1 kg/s < m < 2 kg/s** kW/m^2	kW/m^2
Local peak heat load	350	250	150
Global average heat load	100	0	100

Pool fires are described as a turbulent diffusion fire, burning above a horizontal pool of vaporizing hydrocarbon fuel under conditions where the fuel initially has zero or very low initial momentum, e.g. a fire resulting from liquid spills [23].

Jet fires are turbulent diffusion flames and are produced by the combustion of a continuous release, with some significant momentum in a fixed direction, e.g. rupture of a pipe containing pressurized gas. Because jet fires have very low thermal inertia, they reach full intensity almost instantaneously. In principle they can quickly be turned off. This is an important property, together with the change in heat release rate, fire size and the total duration, as it determines control and isolation strategies [23].

2.6.1 Heat loads from jet fires

When calculating heat loads from jet fires, it is necessary to understand the thermal load imposed by fires. This thermal load is a combination of convection and radiation to the object surface. Several issues must be evaluated, as this a very complex event: The relative proportions of radiative and convective load from a flame, i.e. the total heat load, vary depending on the fuel type, size and shape of the object and the location of the object within the flame. The heat load varies over the surface of the object and the heat absorbed by the object also varies with time [24]. The net heat flux, $\dot{Q}''_{net}$ (Wm^{-2}), exposed to an object fully engulfed in flames can be found by [3]:

$$\dot{Q}'' = Q_{CONV} + Q_{RAD}$$

$$\dot{Q}''_{net} = h(T_f - T_s) + \varepsilon_f \sigma (T_f^4 - T_s^4) \tag{2.6}$$

where ε_f (-) is the emissivity of the flame, T_f (K) is the flame temperature and T_S (K) is the object surface temperatures. The emissivity of the flame can be found from:

$$\varepsilon_f = 1 - e^{-KL} \tag{2.7}$$

where K (m^{-1}) is the extinction coefficient and L (m) is the optical flame thickness. When considering large hydrocarbon fires, the emissivity is often assumed to be optically thick, i.e., $\varepsilon_f = 1$.

Based on recorded temperatures in a thermally thin object exposed by a fire, the net heat flux to the object, $\dot{Q}''_{net,object}$ (Wm^{-2}), can be calculated by:

$$\dot{Q}''_{net,object} = m'' c_p \frac{dT}{dt} \tag{2.8}$$

where m'' (kgm^{-2}) is the mass divided by the area of the exposed object.

2.6.2 Jet fire testing – ISO 22899

The standardized jet fire test, ISO 22899-1 [25], describes a procedure for testing passive fire protection materials exposed to a jet fire. A rate of 0.3 kg/s propane gas, corresponding to approximately 14 MW, sonic release of gas is aimed at the test object, e.g. insulated pipe, wall configurations etc. The nozzle is aligned horizontally and aimed at the test specimen at a distance of 1 m where propane is the preferred fuel. The test specimen is exposed for various time periods. The most common test periods are 15 min, 30 min, 60 min, 90 min and 120 min. The result should be rounded down to the nearest 5 minutes.

The critical temperature rise is defined in advance of the test, according to the protection criteria for the evaluated equipment e.g. for load baring steel structures, 400 °C is used (according to ISO 13702, [18]). An example of the application of the rating, for load baring steel structures, is given below:

The maximum temperature rise observed after a jet fire duration of 60 minutes is 390 °C. The critical temperature rise is not exceeded in 60 minutes, hence the rating is: JF/Structural steel/400/60.

2.7 Temperature rise, insulated column

If the thermal conductivity of the thermal insulation is known, the time to failure of an insulated column can be found by an iterative procedure. Some assumptions/ simplifications must however be done. If the Biot number is large, i.e. the insulation has a low thermal conductivity, it may conservatively be assumed that the temperature of the exposed section of the insulation is equal to the temperature of the flame at all times during the fire exposure. It is also assumed that a quasi-steady state is achieved over the insulation for each time step Δt. The rate of heat going through the insulation can then be found by [22]:

$$\dot{q}" = \frac{k}{L}({T_F}^{j+1} - {T_S}^{j}) \tag{2.9}$$

where k is the thermal conductivity, L is the thickness of the insulation, T_F^{j+1} is flame temperature at the end of the $(j+1)$th time step and T_S^j is the steel temperature at the end of the jth time step.

The heat entering the steel per unit length of the column during the time interval, Δt, can now be found by:

$$Q_{in} = \frac{k}{L}\left({T_F}^{j+1} - {T_S}^{j}\right) \cdot A_i \cdot \Delta t \tag{2.10}$$

where A_i is the internal surface area of the insulation per unit length of the column through which heat is being transferred, conservatively assuming perfect thermal contact. The temperature raise in the steel during the time interval Δt, can now be found from:

$${T_F}^{j+1} - {T_S}^{j} = \frac{Q_{in}}{V_s \rho_s c_s} \tag{2.11}$$

where V_s, ρ_s and c_s is the volume, density and the thermal heat capacity of the steel.

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3 Small-scale jet fire testing

3.1 Test concept

The testing methodology is based on the previous research by Bjørge et.al. [3]. It is not sufficient to e.g. define 1100 °C as the target temperature recorded by a thermocouple, when considering the severity of the tests. The heat losses from the exposed steel cladding may reduce the heat exposure considerably. It is therefore essential to avoid radiative heat losses. This was solved by letting the exposed cladding only view hot surfaces. The optical flame thickness thereby becomes much less relevant for heat radiation as long as the exposed surfaces radiate sufficient heat at each other.

In order for the test set-up to work properly it was determined that the fire had to be sufficiently intense, and the dimensions had to be large enough to ensure a limited size influence. This was handled by using an axisymmetric test set-up with a cylindrical fire source aligned at the centre of the mock-up. The mock-up was constructed with a backside where the heat exposed steel lose heat by convection and radiation as in a real setting. A principle sketch of the test set-up including the mock-up, representing a section of a steel column, exposed to heat flux levels from 250 – 350 kW/m^2, is presented in Figure 3.1. The testing was done in a horizontal orientation, while in a real scenario the exposed wall would be vertical.

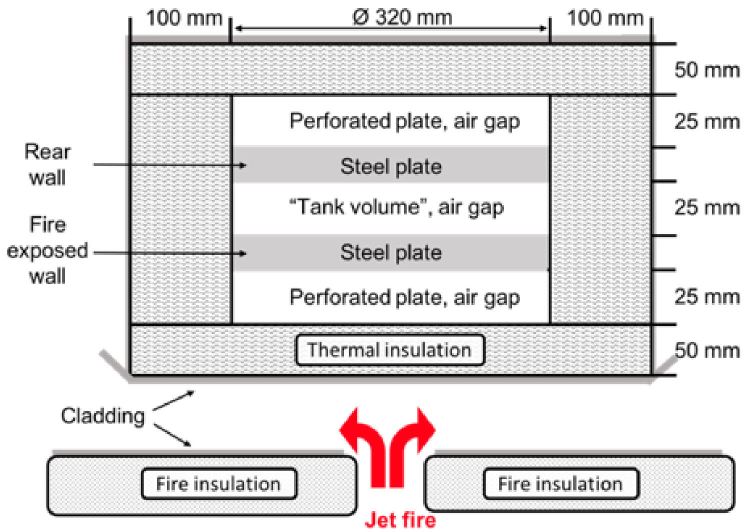

Figure 3.1 Principle sketch of the test set-up including the mock-up [3].

To avoid heat leak, the flame zone was "boxed" in with light concrete bricks. This was done to prevent ingress of ambient air cooling to the lower part of the flame zone and lower cladding. The bricks also radiated heat back to the flame zone as their exposed surface got heated.

Distillation columns are, as stated, large structures. In a fire scenario, only a fraction of the column diameter will be exposed. Comparing the 16 mm wall thickness to the 4000 mm diameter, the heat flow into the system may be considered one-dimensional. Arranging the cylindrical fire source vertically, exposing the horizontal mock-up, the heat flow will be one-dimensional through the thermal insulation if the size of the mock-up is not very large compared to the deflected flames. The heat exposure should be as independent of the radius as possible. It was therefore decided to use steel plate diameter of at least 20 times the plate thickness (16 mm), i.e. 320 mm [3].

3.2 Test set-up

The test concept described is further improved in the present work for more stable and more repeatable fire exposure. Due to the variation in wall thicknesses for different equipment/ distillation columns, four different steel plate thicknesses were tested in the present work; 3 mm, 6 mm, 12 mm and 16 mm. A 3 mm wall thickness is very thin, and rarely used in distillation columns, it is however important to investigate how the thermal insulation reacts with a thin backing, i.e. representing a limited heat sink.

A principle sketch of the mock-up including the location of the thermocouples, the plate thermometers (PT) and the fire source, is presented in Figure 3.2. The mock-up represents a section of a steel column, exposed to heat flux levels between 250 – 350 kW/m^2.

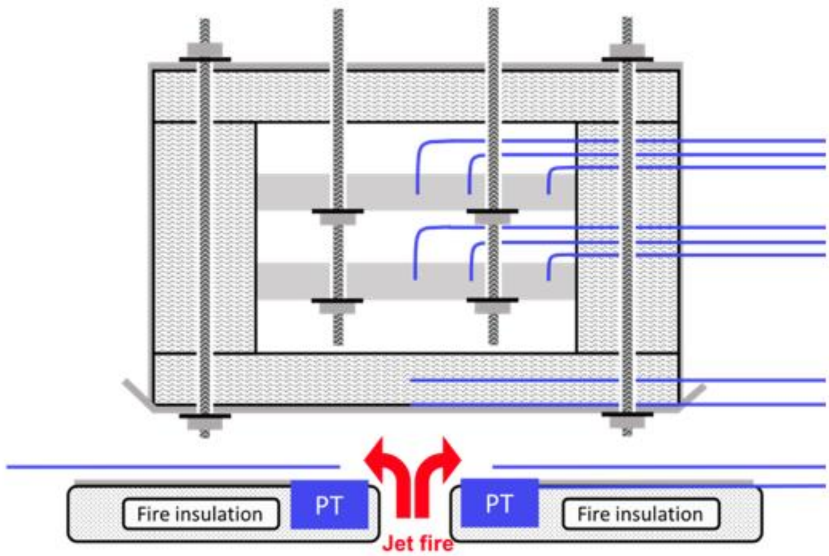

Figure 3.2 Principle sketch of the mock-up, including location of thermocouples (blue lines), Plate thermocouples (PT) and the fire source [3].

Twelve thermocouples (Type K, 1.6 mm diameter, stainless steel mantle, Pentronic AB) were used for temperature recordings during the experiment. The temperatures were recorded by a data logger (type Hewlett-Packard 34970A Data Acquisition/Data Logger Keysight switch unit). Eight of the thermocouples were placed inside the mock-up. The approximate location is shown in Figure 3.2. The remaining 4 thermocouples were placed in the flame zone (two), fire insulation (cladding box) and the suspension rig (for safety reasons). In addition to the thermocouples in the flame zone, two Plate Thermocouple Heat Flux Meters (PTHFM, article number 5928050-001, Pentronic AB), were placed under the mock-up, facing upwards. Placing the plate thermometers in this direction, allowed for reading the heat radiation it can view from the cladding in addition to convective heat that is received from the propane flame. Facing upwards and aligned with the cladding box surface it had virtually no influence on heat transfer within the flame zone. Photos of the composition of the mock-up are shown in Figure 3.3. A thorough description of how the mock-up is put together is presented in Appendix A.

Figure 3.3 Mounting of mock-up.

Information regarding the area, volume and the mass for the different steel plate thicknesses is presented in Table 3.1. Additional information about the steel plates is presented in Appendix F.

Table 3.1 Values for the area, volume and mass for the different steel plate thicknesses.

Steel plate thickness	A [m²]	V_s [m³]	m [kg]
3 mm	$0.779 \cdot 10^{-1}$	$0.241 \cdot 10^{-3}$	1.856
6 mm	$0.835 \cdot 10^{-1}$	$0.483 \cdot 10^{-3}$	3.957
12 mm	$0.789 \cdot 10^{-1}$	$0.965 \cdot 10^{-2}$	7.365
16 mm	$0.819 \cdot 10^{-1}$	$0.129 \cdot 10^{-2}$	9.725

3.3 Test set up

The mock-up was suspended from a frame (table frame), as shown in Figure 3.4. A 28 kW cylindrical propane burner (Sievert 346051 Turboroofer, 60 mm titanium power burner and a 500 mm neck tube) was used as the flame source and placed below the mock-up, as shown in Figure 3.5. To allow for a vertical upward orientated premixed propane jet, facing the mock-up cladding, the propane burner tube was carefully bent to about 90 ° at a local plumber´s workshop. The test set up was arranged symmetrically along the test unit axis, i.e. the centre of the jet flame was aligned with the centre of the test unit.

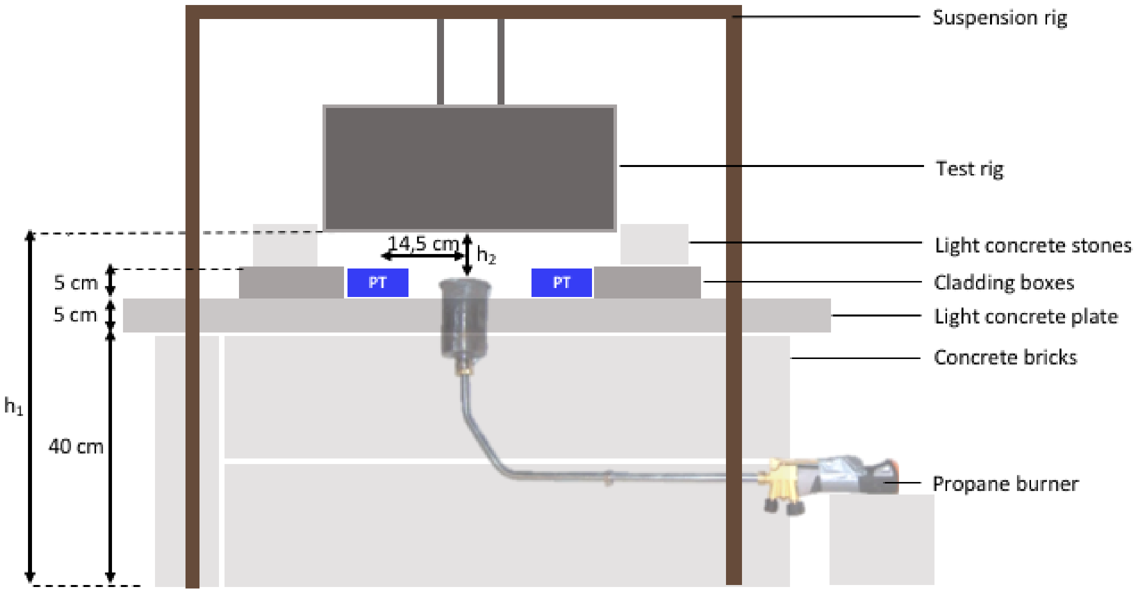

Figure 3.4 Principle sketch of the test set up side view, where h_1 and h_2 is presented in Table **3.2**. PT indicates the location of the plate thermocouples.

The arrangement of the burner, the two plate thermometers, as well the cladding boxes are shown in Figure 3.5. A thorough description of the test set-up and all the equipment needed is presented in Appendix B.

Figure 3.5 Burner (centre), plate thermometers and cladding boxes.

Light weight high temperature concrete bricks (Skamotec 225, Skamol A/S), 100 mm · 100 mm · 50 mm, were placed around the mock-up, 1 cm from the upper cladding edge, to limit cold air access to, and prevent radiative losses from the flame zone. Pictures of the test set-up and the arrangement of the light concrete stones, ready for fire exposure, are shown in Figure 3.6 and Figure 3.7. The horizontally suspended mock-up during fire exposure is shown in Figure 3.8.

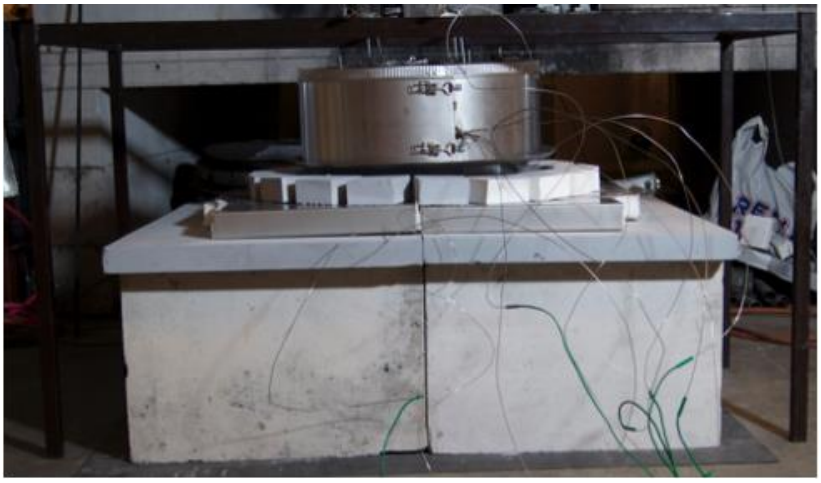

Figure 3.6 Horizontally suspended test unit ready for fire exposure, seen from the front.

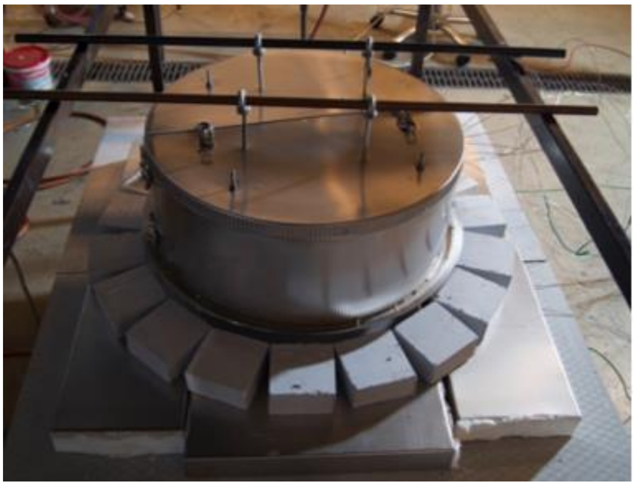

Figure 3.7 Horizontally suspended test unit ready for fire exposure, seen from the side.

Figure 3.8 Horizontally suspended test unit during fire exposure. The picture is taken during test 17.

3.4 Test details

Details about the test set-up is presented in Table 3.2. The test procedure is presented in Appendix D. Additional information about each test is presented in Appendix E.

Table 3.2 Experiment input.

Ref. number	Steel plate thickness	Mass flow propane [g/s]	Height from floor to cladding (h_1)	Height between burner and cladding (h_2)	Height of flame zone
1	16 mm	0.60	57.0 cm	9.5 cm	5.5 cm
2	16 mm	0.60	57.6 cm	8.2 cm	4.2 cm
3	16 mm	0.60	57.6 cm	8.2 cm	4.2 cm
4	16 mm	0.60	57.4 cm	7.1 cm	3.1 cm
5	16 mm	0.70	57.4 cm	7.8 cm	3.8 cm
6	12 mm	0.60	57.0 cm	8.5 cm	4.5 cm
7	12 mm	0.60	57.5 cm	8.9 cm	4.9 cm
8	12 mm	0.60	57.1 cm	7.6 cm	3.6 cm
9	12 mm	0.70	57.6 cm	8.4 cm	4.4 cm
10	12 mm	0.70	57.1 cm	7.5 cm	3.5 cm
11	6 mm	0.60	57.0 cm	7.8 cm	3.8 cm
12	6 mm	0.60	57.0 cm	7.8 cm	3.8 cm
13	6 mm	0.60	56.6 cm	7.2 cm	3.2 cm
14	6 mm	0.60	56.1 cm	6.7 cm	2.7 cm
15	6 mm	0.65	56.9 cm	7.1 cm	3.1 cm
16	6 mm	0.60	57.0 cm	8.5 cm	4.5 cm
17	3 mm	0.60	57.0 cm	7.8 cm	3.8 cm
18	3 mm	0.60	56.5 cm	7.3 cm	3.3 cm
19	3 mm	0.60	56.5 cm	7.9 cm	3.9 cm
20	3 mm	0.65	56.6 cm	6.8 cm	2.8 cm

Information about the tests, materials and instrumentation is presented in Appendix.

3.5 Performance criteria

The set performance criteria for each test is presented in Table 3.3.

Table 3.3 Performance criteria.

Description	Criteria
Temperature achievement in flame (plate thermometer)	> 1200 °C
Temperature in the exposed steel plate	< 400 °C after 30 minutes
Heat flux levels in flame zone	250 – 350 kW/m^2

4 Oven testing of insulation

4.1 Test set up

To investigate how the thermal insulation (Pipe section mat (PSM), Rockwool) behave when exposed to elevated temperatures (750 - 1100 °C), insulation test samples (5 cm · 5 cm · 5 cm) were tested in a muffle oven (Nabertherm L5, Program Controller S17). The test set up is shown in Figure 4.1. For safety reasons the oven was placed on a non-combustible surface and with a safety distance from walls/roof of 0.5 m to the sides and 1 m to the top. In case of hazardous gases released during the test, the oven was placed near an exhaust hood.

Figure 4.1 Picture of the test setup.

Two thermometers (Fluke 51 II) were used to measure temperatures. One thermocouple was placed in the centre of the insulation and one thermocouple was place in the upper part of the oven (to measure the oven temperature). Testing was done for six different maximum temperatures; 700 °C, 750 °C, 800 °C, 900 °C, 1000 °C and 1100 °C. The heating rate for each of the set temperatures is presented in Table 4.1. Each of the samples was exposed to the maximum (set) temperature for 30 minutes (holding time).

Table 4.1 Set temperature and the associated heating rate.

Set temperature	Rate [K/min]
700 °C	21.62
750 °C	20.46
800 °C	17.88
900 °C	19.55
1000 °C	16.97
1100 °C	15.26

The insulation test sample (50 mm · 50 mm · 50 mm) was placed on a ceramic plate (stable to temperatures up to 1200 °C), as shown in Figure 4.2. The test procedure is presented in Appendix N.

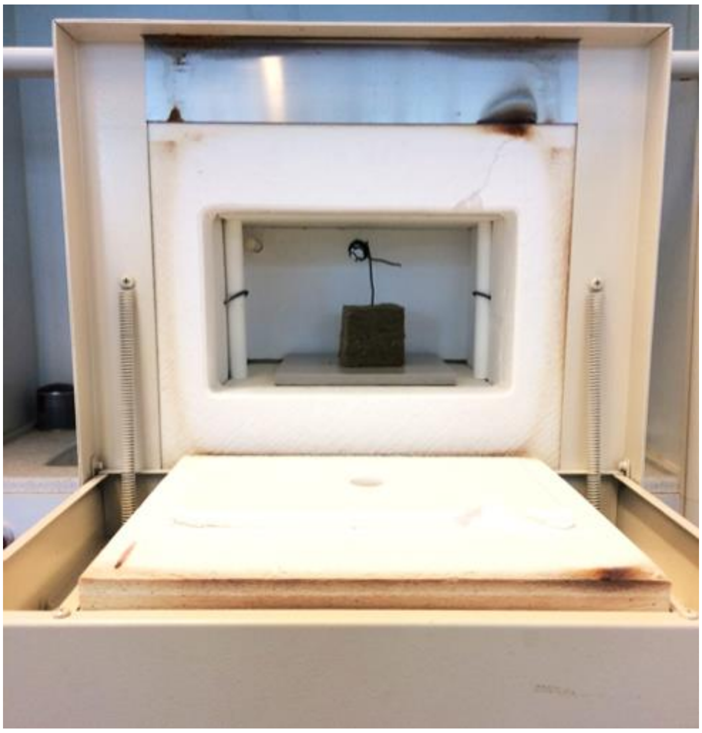

Figure 4.2 The insulation sample placed inside the muffle oven, with the thermocouple placed in the centre.

5 Results

5.1 Small scale jet fire test

5.1.1 16 mm steel plate

The temperature recordings as a function of time in the exposed steel plate (Exp), unexposed steel plate (Unexp) and in the flame zone (Flame, recorded by the plate thermometer) are shown in Figure 5.1. Three thermocouples were place in each steel plate. The temperature in Figure 5.1 represents the highest temperature recorded in the steel plate for each separate test. Results from test 1 and 3 are presented in Appendix H.

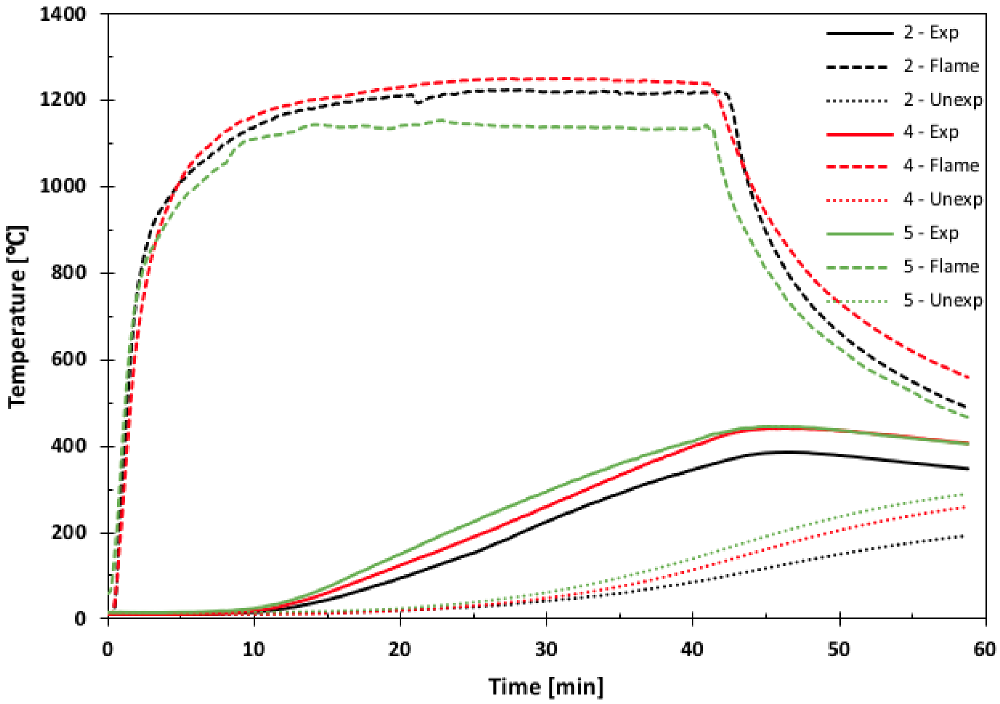

Figure 5.1 Temperature recordings as a function of time for the 16 mm steel plate. Exp, Unexp and Flame are the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time are shown in Figure 5.2. The heat flux level, $\dot{Q}"_{Flame}$, is calculated from Equation 2.11, where $h = 100\ kWm^{-2}K^{-1}$, T_F is the recorded temperature in the flame zone as a function of time (Plate TC), $T_s = 20\ °C$ and $\varepsilon_F = 0.85$. $\dot{Q}"_{PT}$ is based on the same calculation, but T_s is the temperature recorded in the cladding as a function of time (Inside Clad). As the temperature in the cladding increases, the convective contribution will disappear.

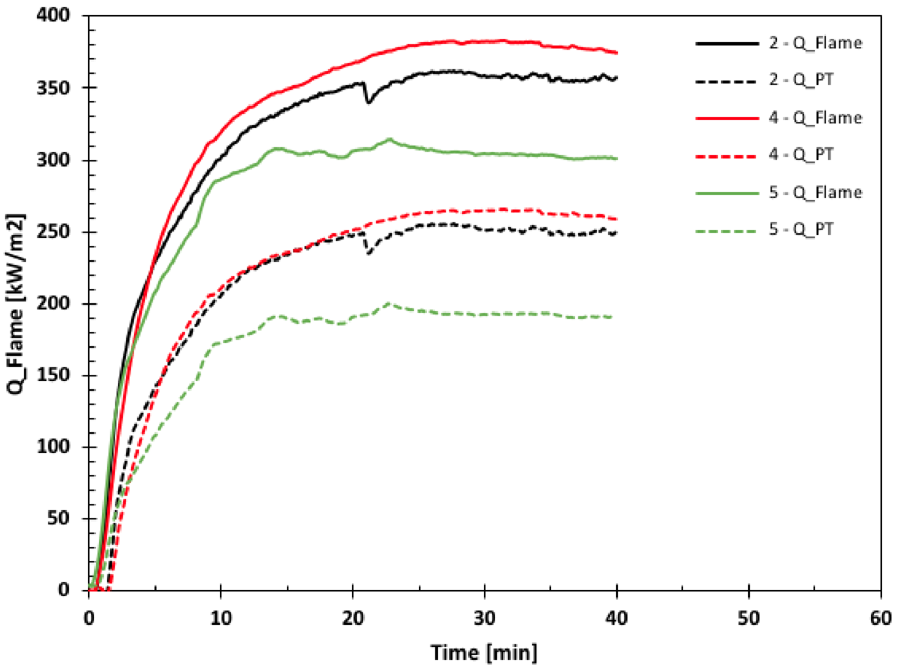

Figure 5.2 The calculated heat flux levels in the flame zone as a function of time. “Q_flame” represents the calculated heat flux level including the convective attribution, while “Q_PT” represents the calculated radiation measured by the plate thermometer (Plate TC), with a steel plate thickness of 16 mm. The test number is indicated in the label.

The total calculated heat flux to the exposed steel plate as a function of time are shown in Figure 5.3. The heat flux levels are calculated from Equation 2.8, where $c_{p,steel}$ is given by Equation 2.1. The calculation was done for the exposed and the unexposed steel plate, and by adding these two together the total heat flux level to the exposed steel plate was found.

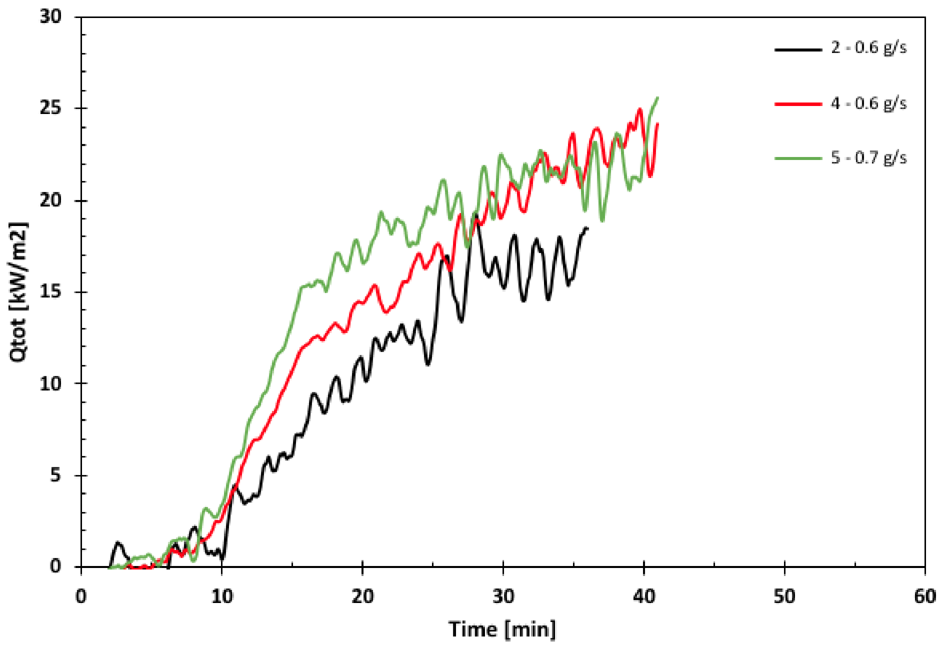

Figure 5.3 The total calculated heat flux to the exposed steel plate as a function of time, for test 2, 4 and 5, with a steel plate thickness of 16 mm.

The condition of the insulation after test 2, 4 and 5 are shown in Figure 5.4. Each row represents one test; the picture to the left shows the unexposed side of the insulation, the next picture shows the exposed side of the insulation, while the picture to the right shows the exposed cladding after testing.

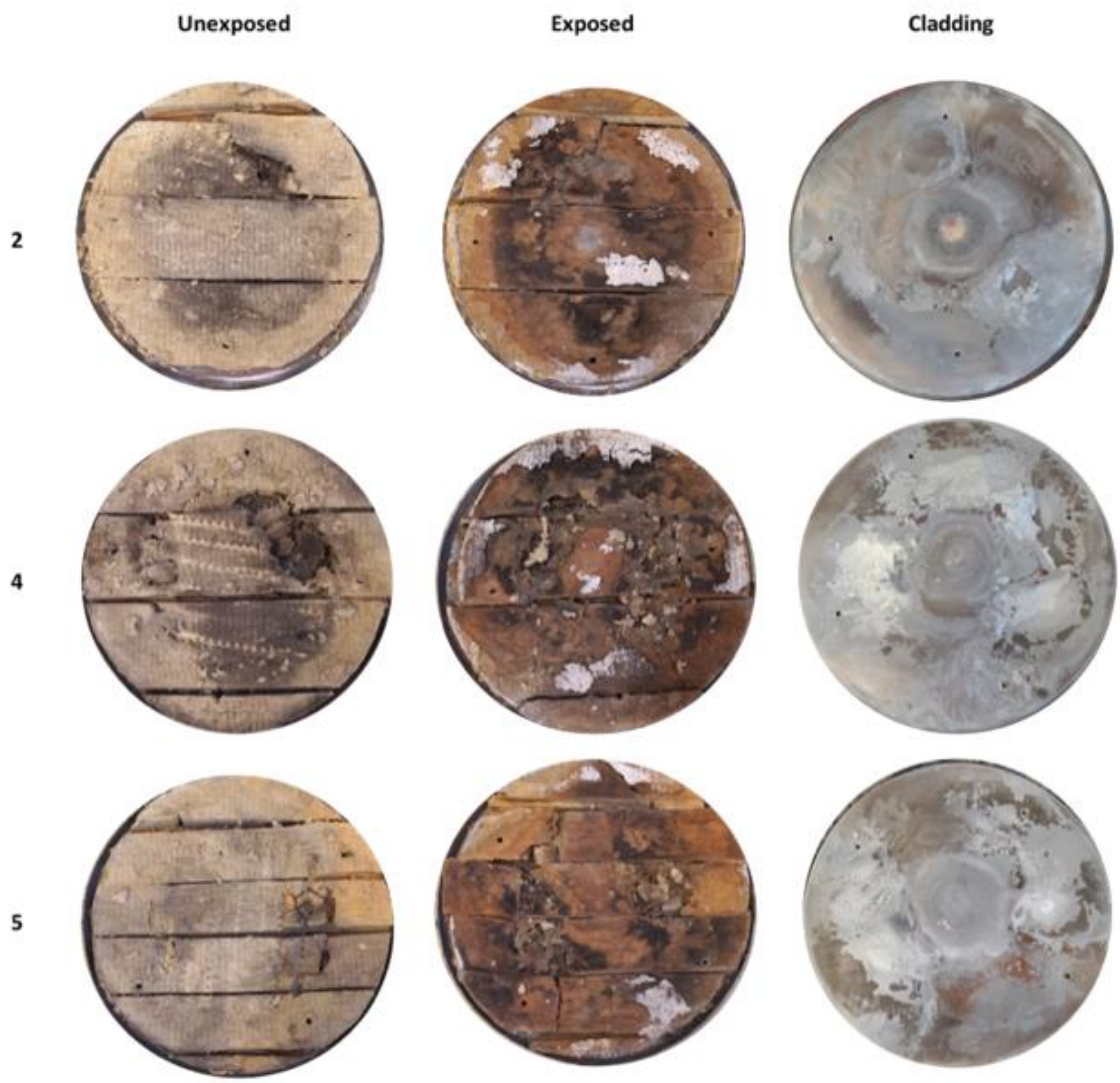

Figure 5.4 Insulation after the testing for test 2, 4 and 5, with a steel plate thickness of 16 mm. Each row represents one test, The unexposed side of the insulation, the exposed side of the insulation and the exposed side of the bottom cladding.

Pictures of the thermal insulation after testing are shown in Figure 5.5.

Figure 5.5 Close-up photos of the insulation after testing.

Additional results and pictures from the small-scale jet fire testing is presented in Appendix H and Appendix I.

5.1.2 12 mm steel plate

The temperature recordings as a function of time in the exposed steel plate (Exp), unexposed steel plate (Unexp) and in the flame zone (Flame, recorded by the plate thermometer) are shown in Figure 5.6. Three thermocouples were placed in each steel plate. The temperature in Figure 5.6 represents the highest temperature recorded in the steel plate for each separate test. Results from test 6 and 8 are presented in Appendix H.

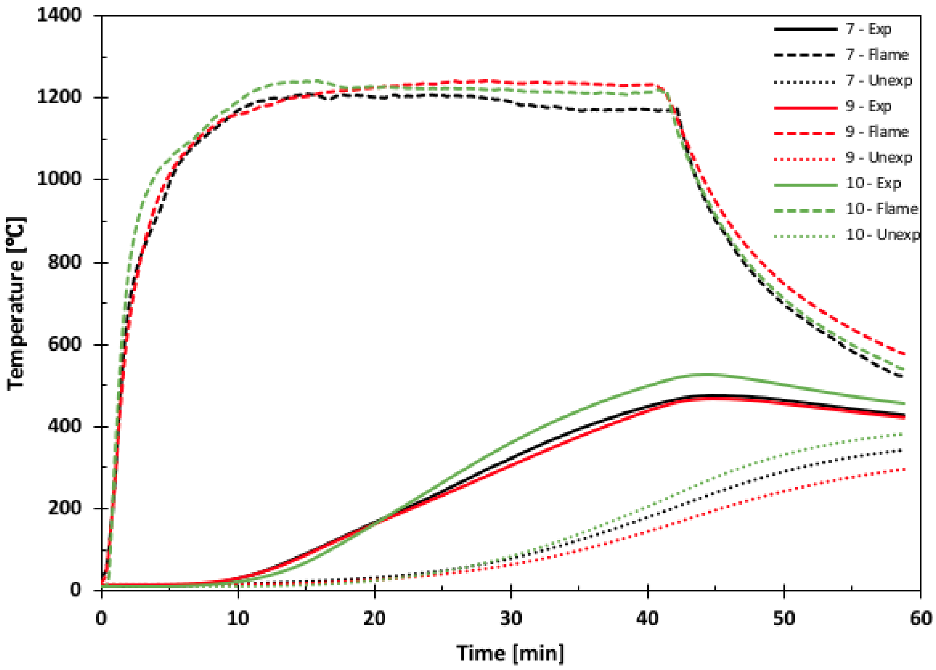

Figure 5.6 Temperature recordings as a function of time for the 12 mm steel plate. Exp, Unexp and Flame are the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time for test 7, 9 and 10 are shown in Figure 5.7.

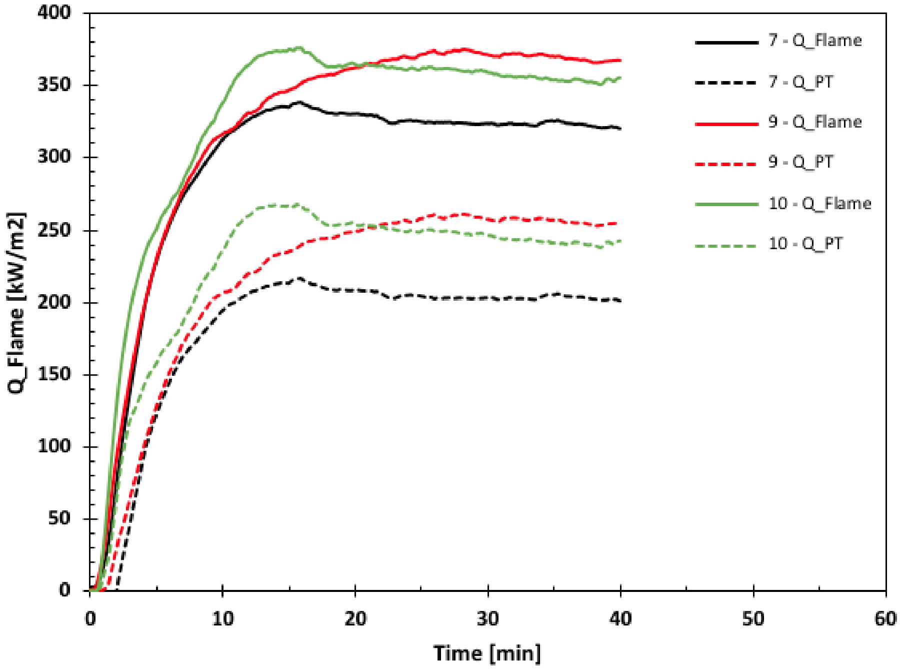

Figure 5.7 The calculated heat flux levels in the flame zone as a function of time. "Q_flame" represents the calculated heat flux level including the convective attribution, while "Q_PT" represents the calculated radiation measure by the plate thermometer (Plate TC), with a steel plate thickness of 12 mm. The test number is indicted in the label.

The total calculated heat flux to the exposed steel plate as a function of time for test 7, 9 and 10 are shown in Figure 5.8.

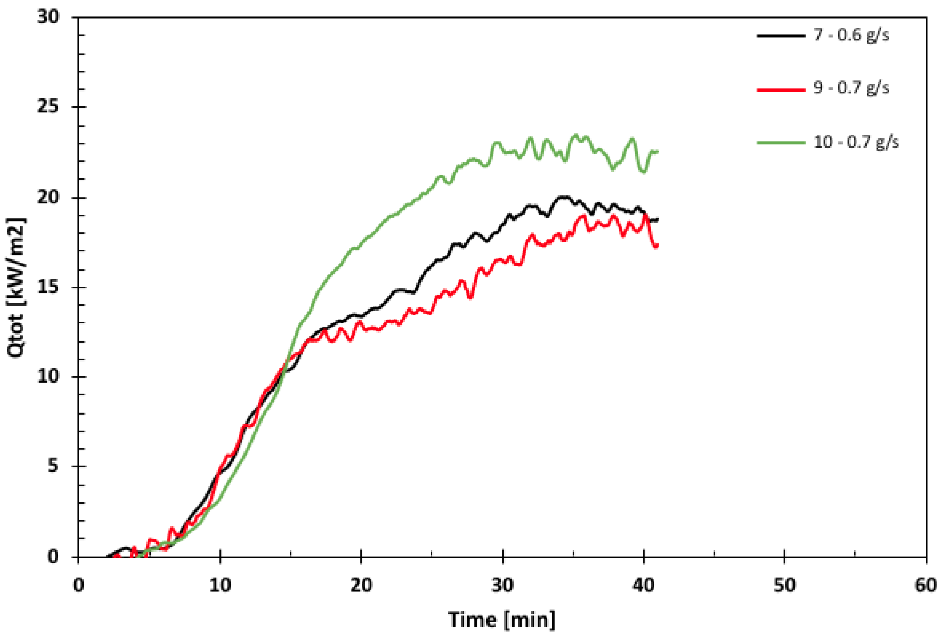

Figure 5.8 The total calculated heat flux to the exposed steel plate as a function of time, for test 7, 9 and 10, with a steel plate thickness of 12 mm.

The condition of the insulation after test 7, 9 and 10 are shown in Figure 5.9. Each row represents one test; the picture to the left shows the unexposed side of the insulation, the next picture shows the exposed side of the insulation, while the picture to the right shows the exposed cladding after testing. Additional pictures of the insulation after testing are presented in Appendix I.

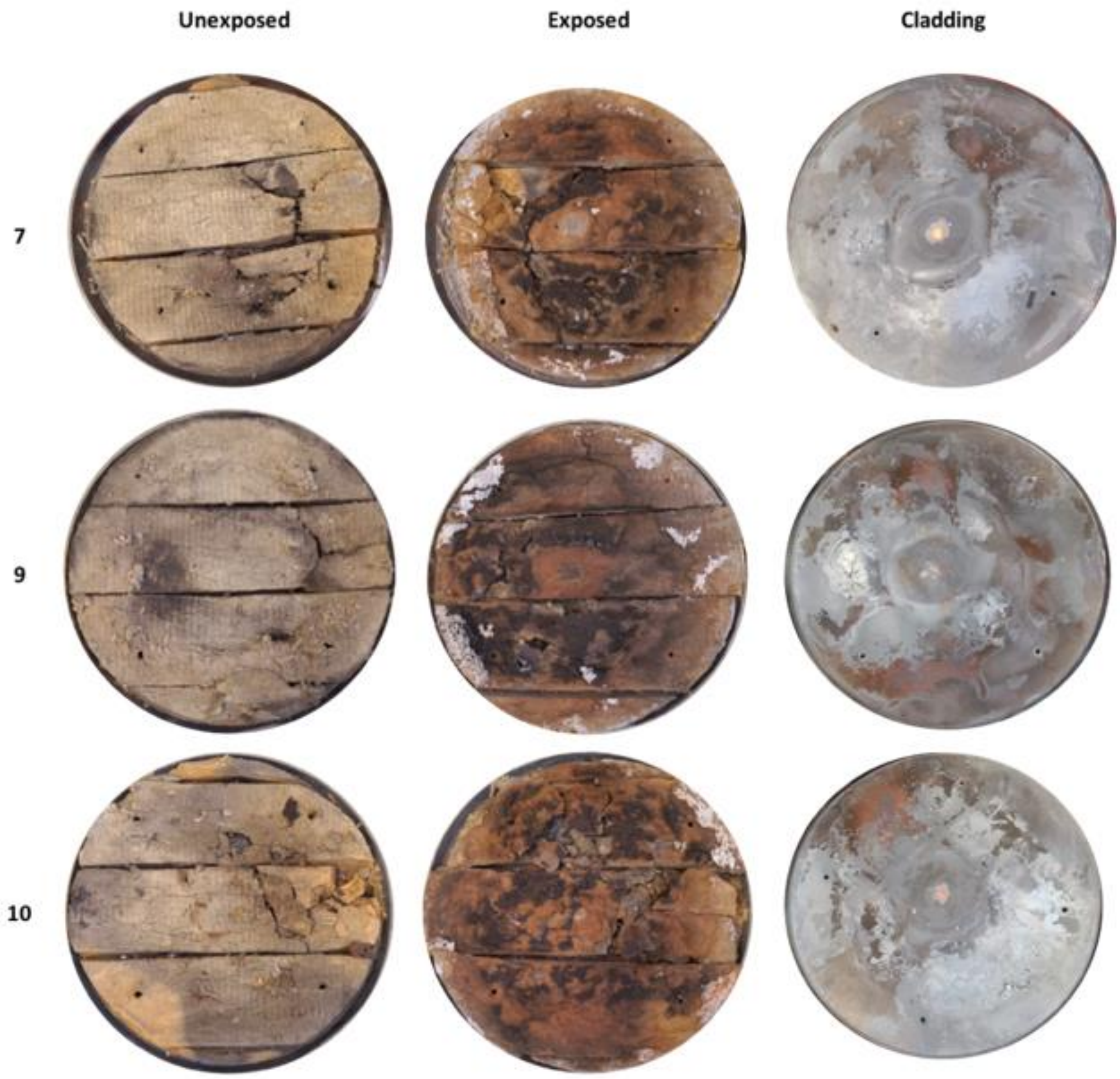

Figure 5.9 Insulation after the testing for test 7, 9 and 10, with a 12 mm steel plate thickness. Each row represents one test, The unexposed side of the insulation, the exposed side of the insulation and the exposed side of the bottom cladding.

5.1.3 6 mm steel plate

The temperature recordings as a function of time in the exposed steel plate (Exp), unexposed steel plate (Unexp) and in the flame zone (Flame) are shown in Figure 5.10 . Three thermocouples were placed in each steel plate. The temperature in Figure 5.10 represents the highest temperature recorded in the steel plate for each separate test. Results from test 11, 13 and 16 are presented in Appendix H.

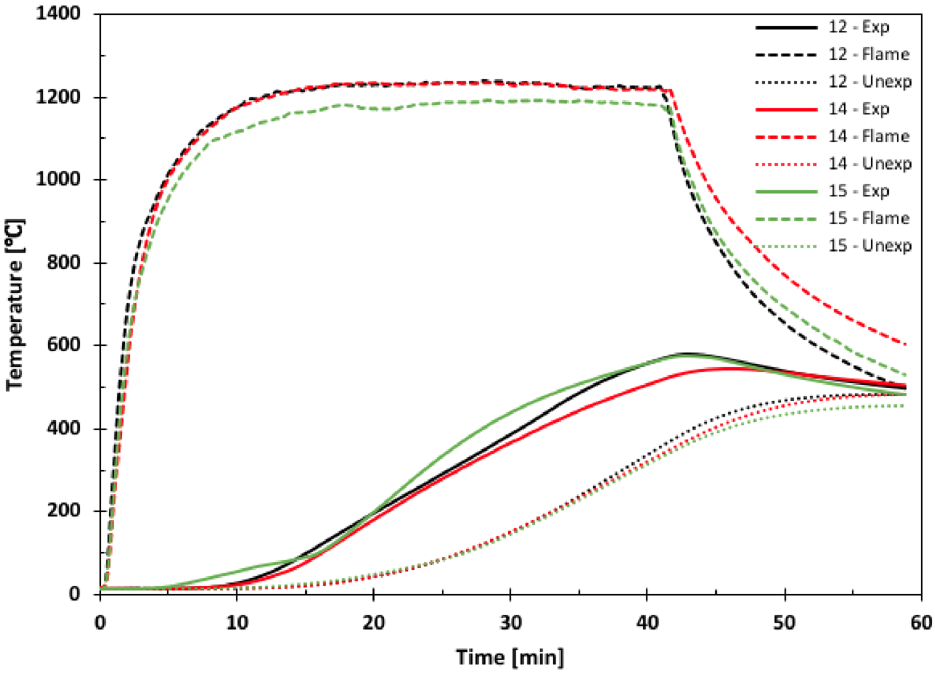

Figure 5.10 Temperature recordings as a function of time for the 6 mm steel plate. Exp, Unexp and Flame are the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time for test 12, 14 and 15 are shown in Figure 5.11.

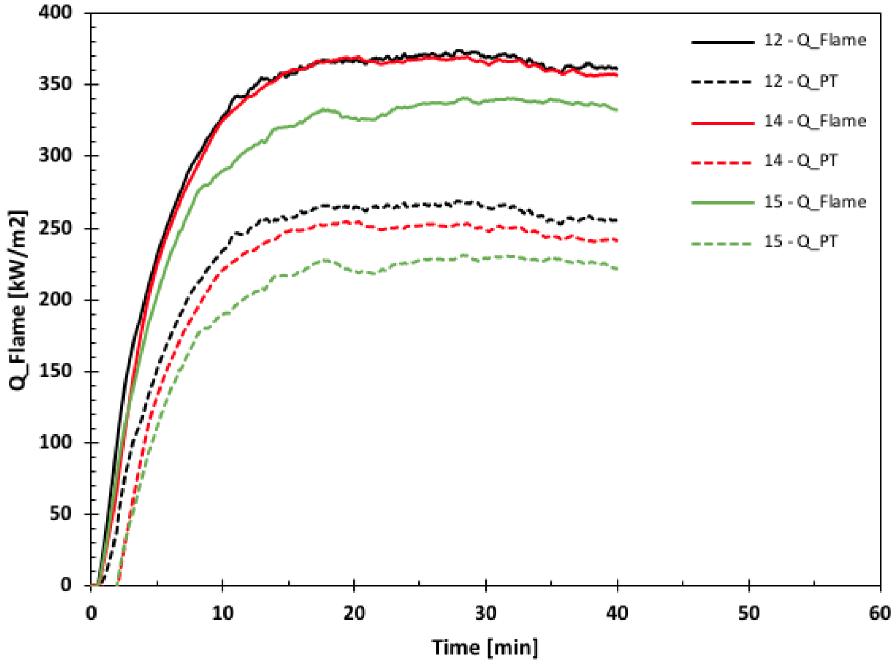

Figure 5.11 The calculated heat flux levels in the flame zone as a function of time. "Q_flame" represents the calculated heat flux level including the convective attribution, while "Q_PT" represents the calculated radiation measure by the plate thermometer (Plate TC), with a steel plate thickness of 6 mm. The test number is indicted in the label.

The total calculated heat flux to the exposed steel plate as a function of time for test 12, 14 and 15 are shown in Figure 5.12.

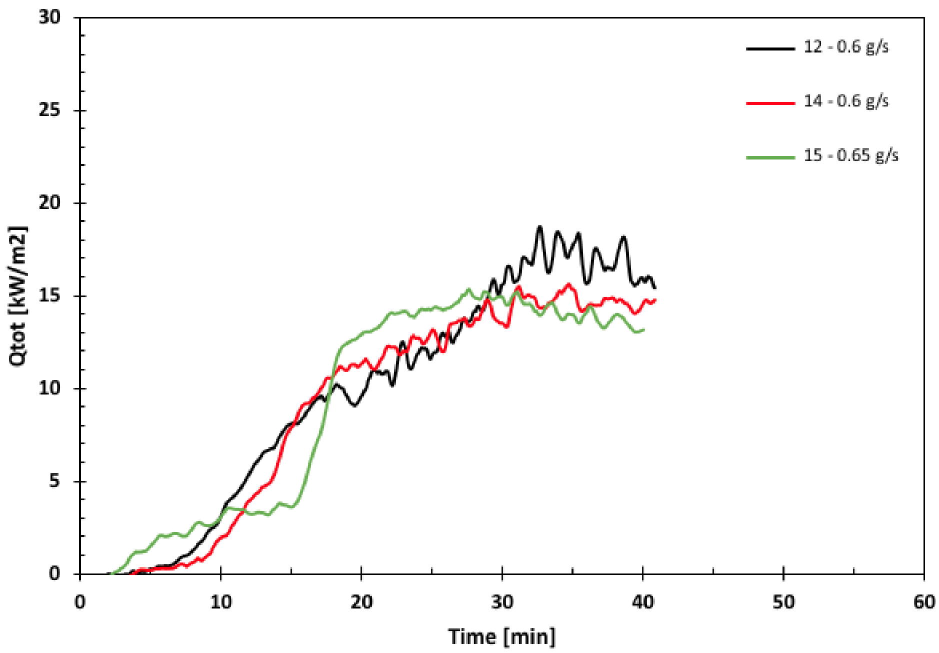

Figure 5.12 The total calculated heat flux to the exposed steel plate as a function of time, with a steel plate thickness of 6 mm. The test number is indicated by the label.

The condition of the insulation after test 12, 14 and 15 are shown in Figure 5.13. Each row represents one test; the picture to the left shows the unexposed side of the insulation, the next picture shows the exposed side of the insulation, while the picture to the right shows the exposed cladding after testing. Additional pictures of the insulation are presented in in Appendix I.

Figure 5.13 Insulation after the testing for test 12, 14 and 15, with a 6 mm steel plate thickness. Each row represents one test; the unexposed side of the insulation, the exposed side of the insulation and the exposed side of the bottom cladding.

5.1.4 3 mm steel plate

The temperature recordings as a function of time in the exposed steel plate (Exp), unexposed steel plate (Unexp) and in the flame zone (Flame) are shown in Figure 5.14. Three thermocouples were place in each steel plate. The temperature in Figure 5.14 represents the highest temperature recorded in the steel plate for each separate test. Results from test 17 are presented in Appendix H.

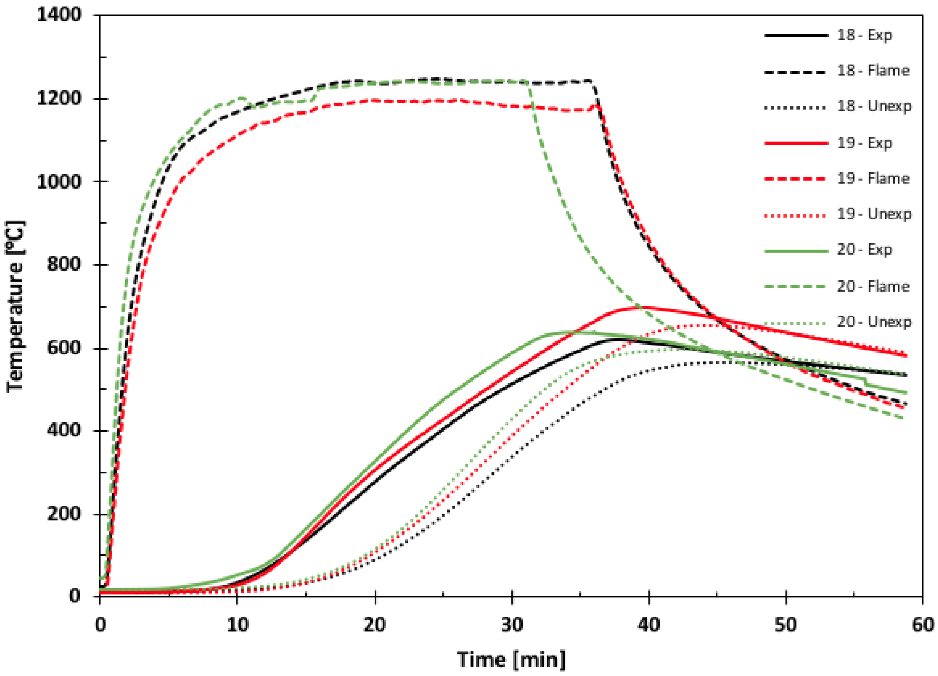

Figure 5.14 Temperature recordings as a function of time for the 3 mm steel plate. Exp, Unexp and Flame are the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time for test 18, 19 and 20 are shown in Figure 5.15.

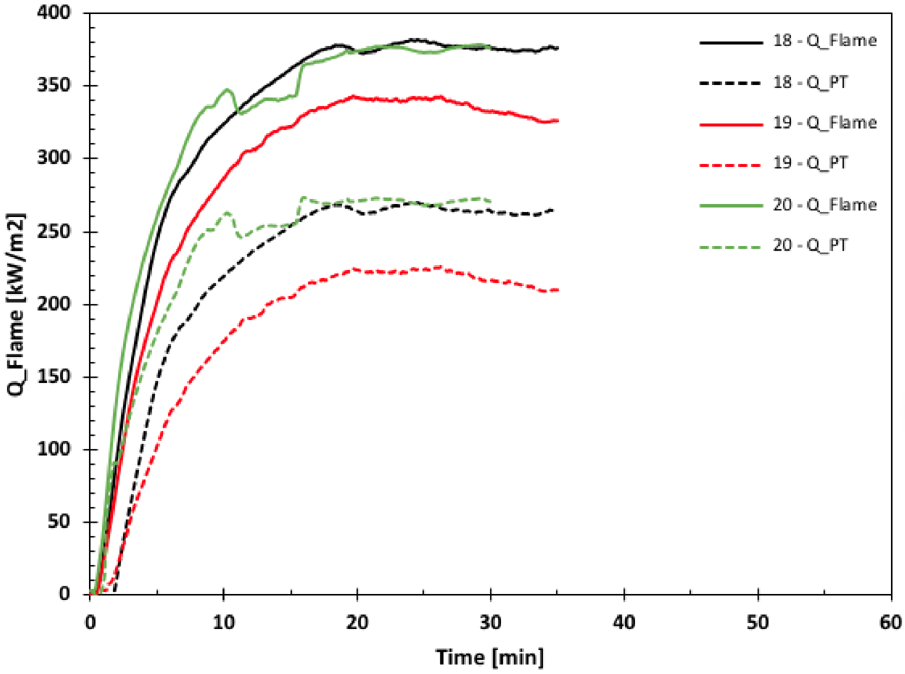

Figure 5.15 The calculated heat flux levels in the flame zone as a function of time. "Q_flame" represents the calculated heat flux level including the convective attribution, while "Q_PT" represents the calculated radiation measure by the plate thermometer (Plate TC). The test number is indicated by the label.

The total calculated heat flux to the exposed steel plate as a function of time for test 18, 19 and 20 are shown in Figure 5.16.

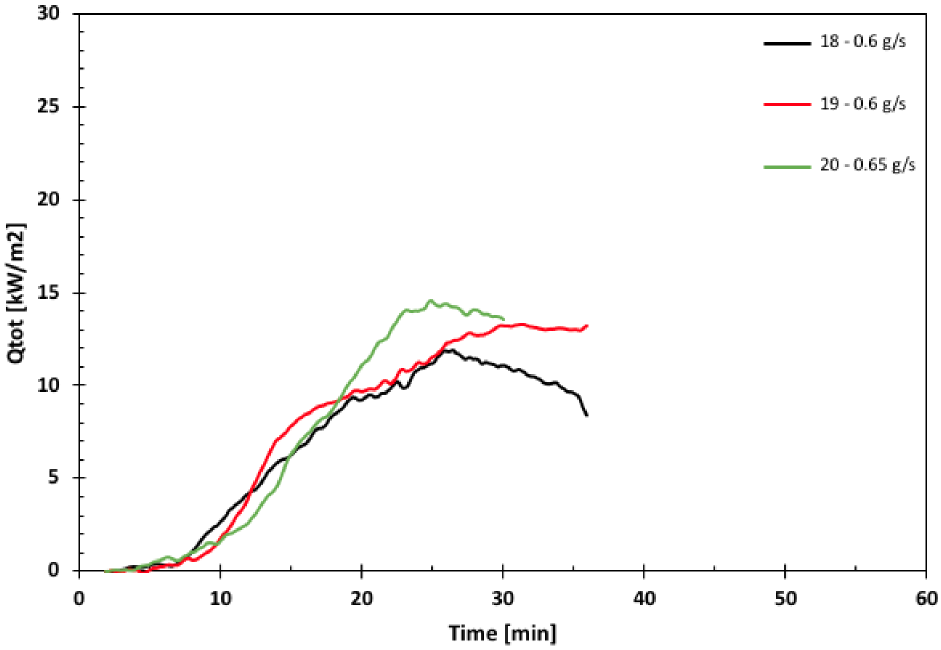

Figure 5.16 The total calculated heat flux to the exposed steel plate as a function of time, with a steel plate thickness of 3 mm. The test number is indicated by the label.

The condition of the insulation after test 18, 19 and 20 are shown in Figure 5.17. Each row represents one test; the picture to the right shows the unexposed side of the insulation, the middle picture shows the exposed side of the insulation, while the picture to the right shows the bottom cladding after testing. Additional pictures of the insulation are presented in Appendix I.

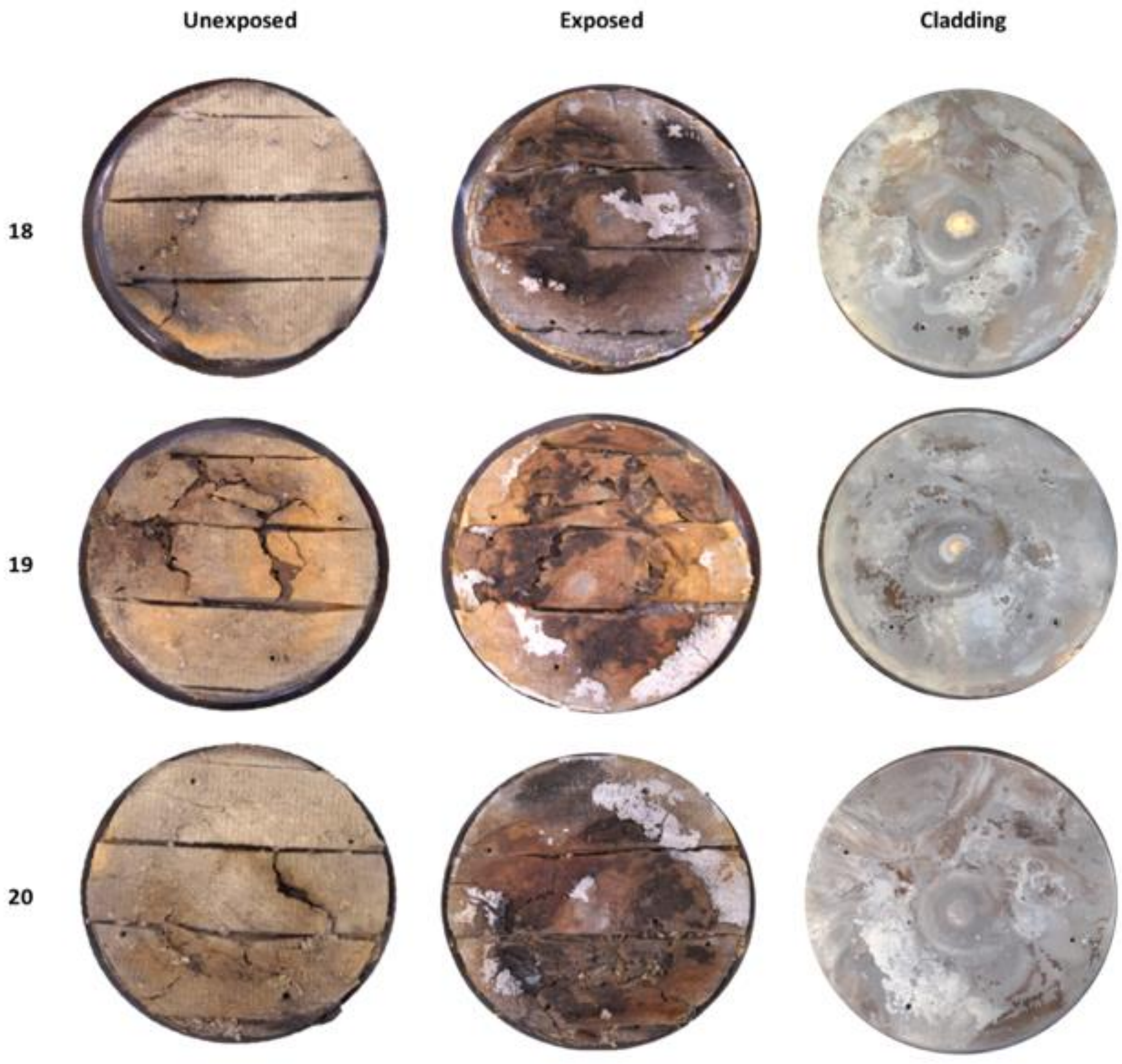

Figure 5.17 Insulation after the testing for test 18, 19 and 20, with a 3 mm steel plate thickness. Each row represents one test; the unexposed side of the insulation, the exposed side of the insulation and the exposed side of the bottom cladding.

5.1.5 Comparison

The average temperature recordings as a function of time are shown in Figure 5.18. The graph representing 16 mm is the average temperature recordings in the flame zone, the exposed steel plate and the unexposed steel plate, for test 2, 4 and 5. The same is done for the tests with 12 mm (test 7, 9 and 10), 6 mm (test 12, 14 and 15) and 3 mm (test 18, 19 and 20) steel plate thickness.

“Exp” is the temperature recordings in the exposed steel plate, “Unexp” is the temperature recordings in the unexposed steel plate and “Flame” is the temperature recordings in the flame zone.

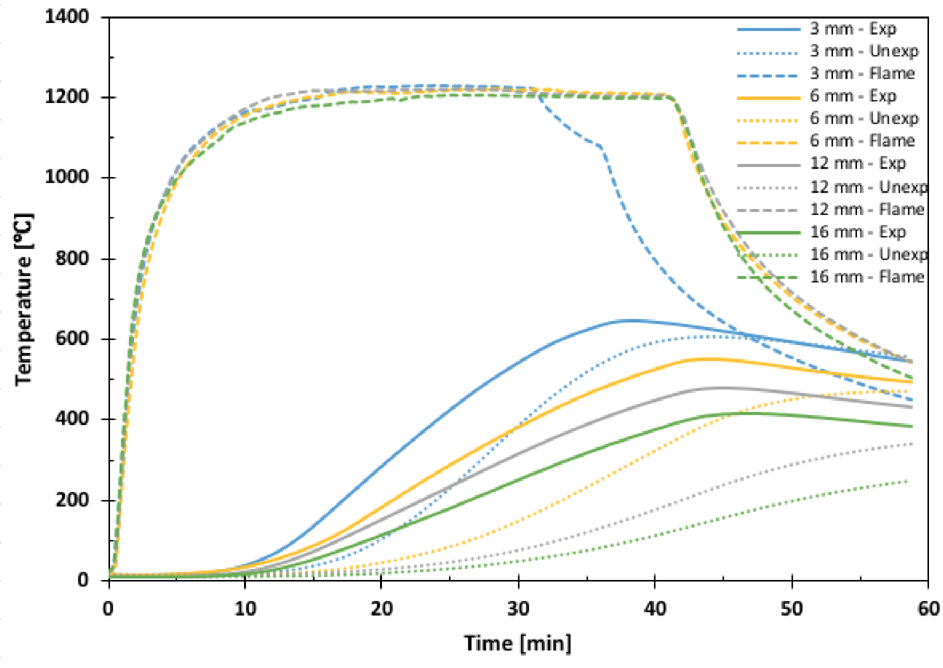

Figure 5.18 Average temperature recordings from each steel plate thickness; Exp, Unexp and Flame is the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively. The plate thickness is given in the label.

Each test has an approximately linear slope from 10 minutes until the test is executed. From this time span a first-degree expression, $y = ax + b$, can be found for each test, based on the recorded temperature in the exposed steel plate. The average values for *a* and *b* for each steel plate thickness is given in Table 5.1. The slope is based on the average recorded temperature in the exposed steel plate as a function of time, for each steel plate thickness as shown in Figure 5.19.

Table 5.1 Average slope, *a*, and intersection, *b*, for each steel plate thickness.

Steel plate thickness	*a*	*b*
3 mm	25.9	-248.3
6 mm	18.2	-175.0
12 mm	15.4	-152.3
16 mm	13.3	-148.2

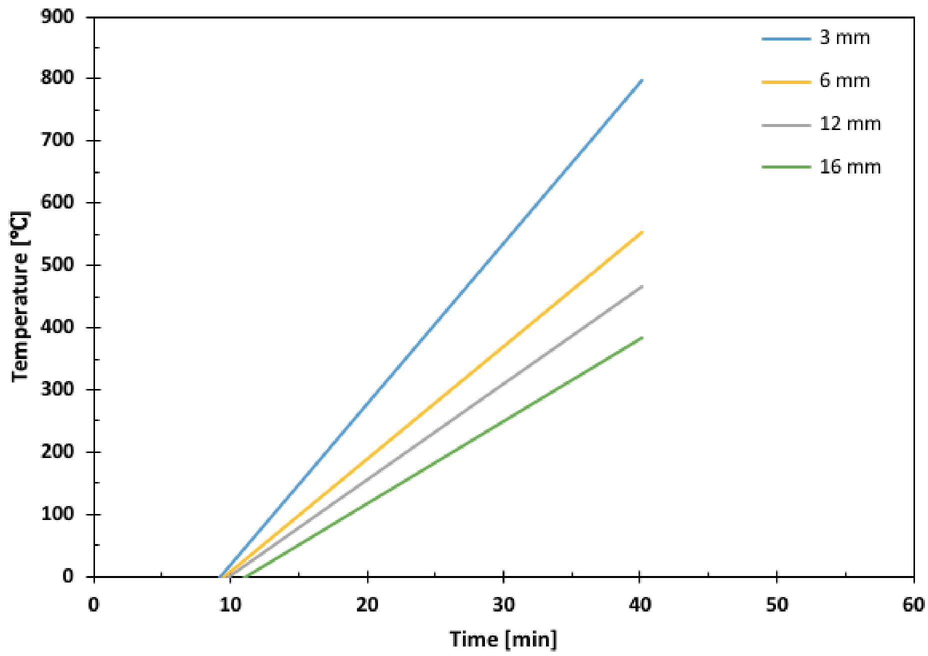

Figure 5.19 First degree expression based on the recorded exposed steel plate temperature as a function of time, from 10 – 40 minutes. The steel plate thickness is indicated by the label.

The average total calculated heat flux to the exposed steel plate as a function of time is shown in Figure 5.20. The average heat flux is calculated for each of the steel plate thicknesses; 16 mm (test 2, 4 and 5), 12 mm (test 7, 9 and 10), 6 mm (test 12, 14 and 15) and 3 mm (test 18, 19 and 20).

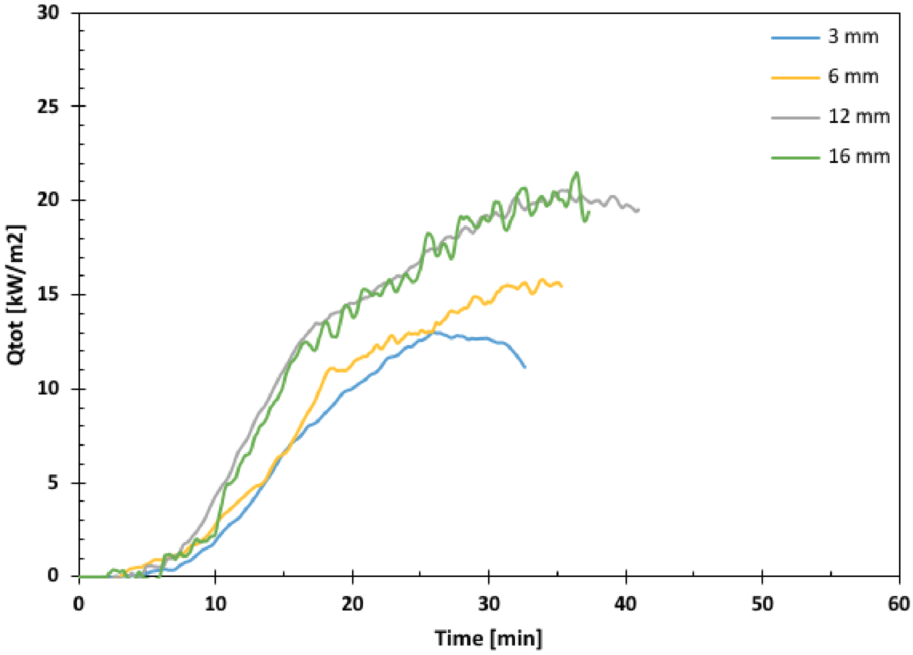

Figure 5.20 The average total calculated heat flux to the exposed steel plate as a function of time. The plate thickness is given in the label.

An estimate of the thermal conductivity is calculated by rearranging Equation 2.2, with respect to the thermal conductivity, k, where $\dot{q}"$ is the total calculated heat flux in to the exposed steel plate (Figure 5.20), dT is the temperature measured in the cladding as a function of time (Inside Cladd) minus the average temperature measured in the exposed steel plate as a function of time and dx is the thickness of the insulation. The airgap between the insulation ant the exposed steel plate is excluded. For simplicity, it was further assumed that the insulation thickness was 50 mm throughout the experiment. The average calculated effective thermal conductivity for the insulation as a function of time is shown in Figure 5.21. The results for the 16 mm, 12 mm, 6 mm and 3 mm plate thickness, i.e. average results from test 2, 4 and 5, test 7, 9 and 10, test 12, 14 and 15 and test 18, 19 and 20, respectively.

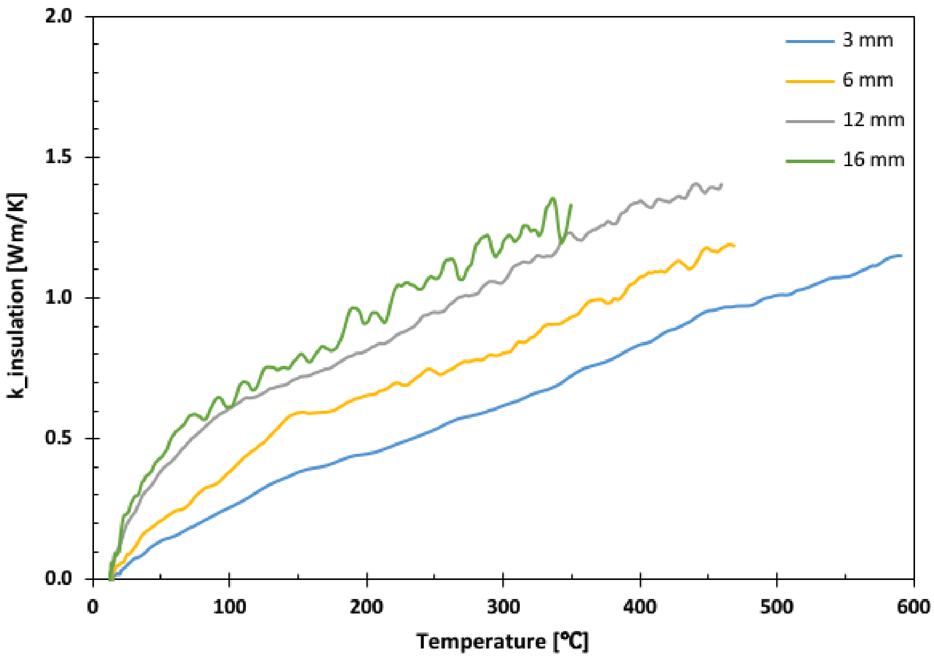

Figure 5.21 The average effective thermal conductivity as a function of time, for each steel plate thickness.

5.2 Calculated steel plate temperature

Based upon the recorded flame zone temperature (Plate TC), a calculated steel plate temperature can be found from Equation 2.11, where V_s and ρ_s are based on the values in Table 3.1 and c_s is calculated from Equation 2.1. From Equation 2.10, Q_{in} is calculated, where $L = 0.05$, $\Delta t = 5$, A_i is presented in Table 3.1 and k is the calculated thermal conductivity of the insulation, as shown in Figure 5.21. The calculated (Calc) and the average measured (Test) steel plate temperature as a function of time for each steel plate thickness are shown in Figure 5.22.

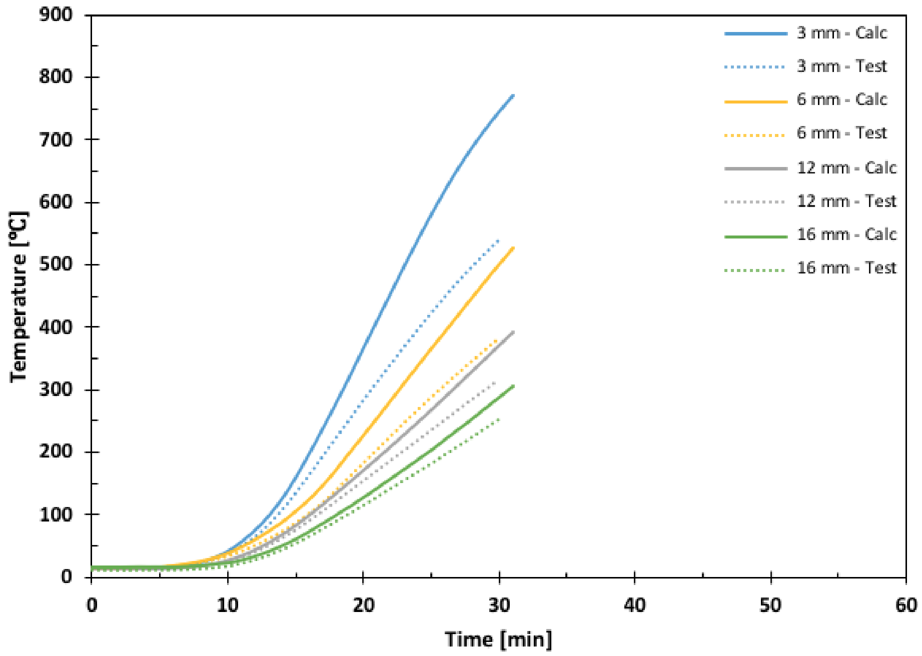

Figure 5.22 Calculated steel plate temperature (Calc) as a function of time, based on the thermal conductivity presented in Figure **5.21** and recorded temperature (Test) increase from Figure **5.18**.

5.3 Oven testing of insulation

5.3.1 Temperature recordings

The temperature recordings as a function of time, with a set temperature of 750 °C and 1100 °C, are shown in Figure 5.23 and Figure 5.24, respectively. The results from the other oven tests are presented in Appendix O.

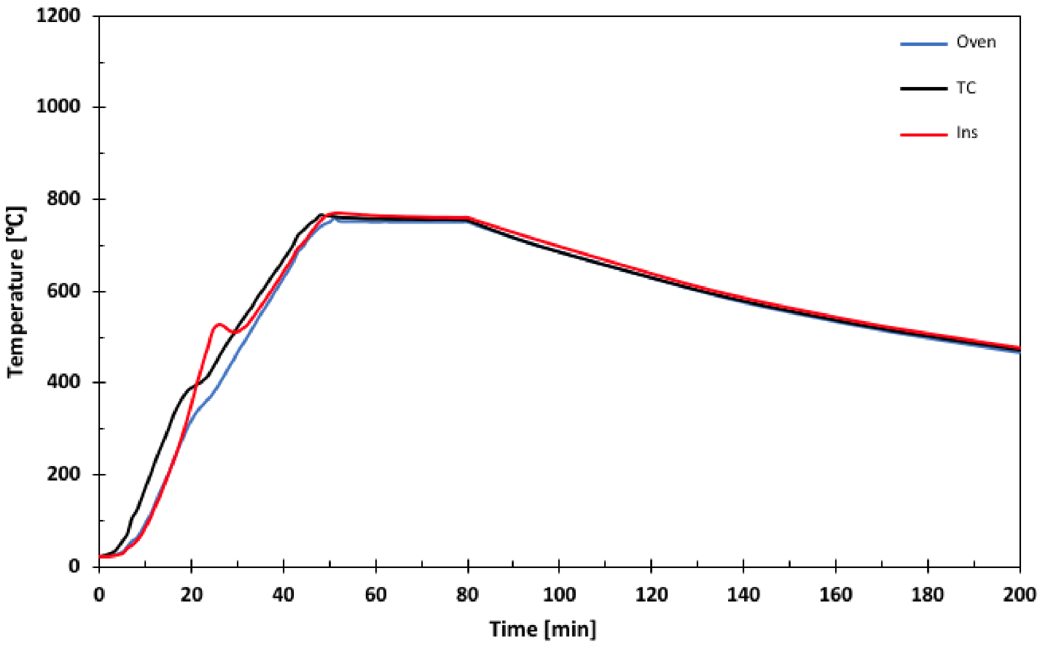

Figure 5.23 Temperature as a function of time, with a heating rate of 21 K/min and 30 minute holding time at 750 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

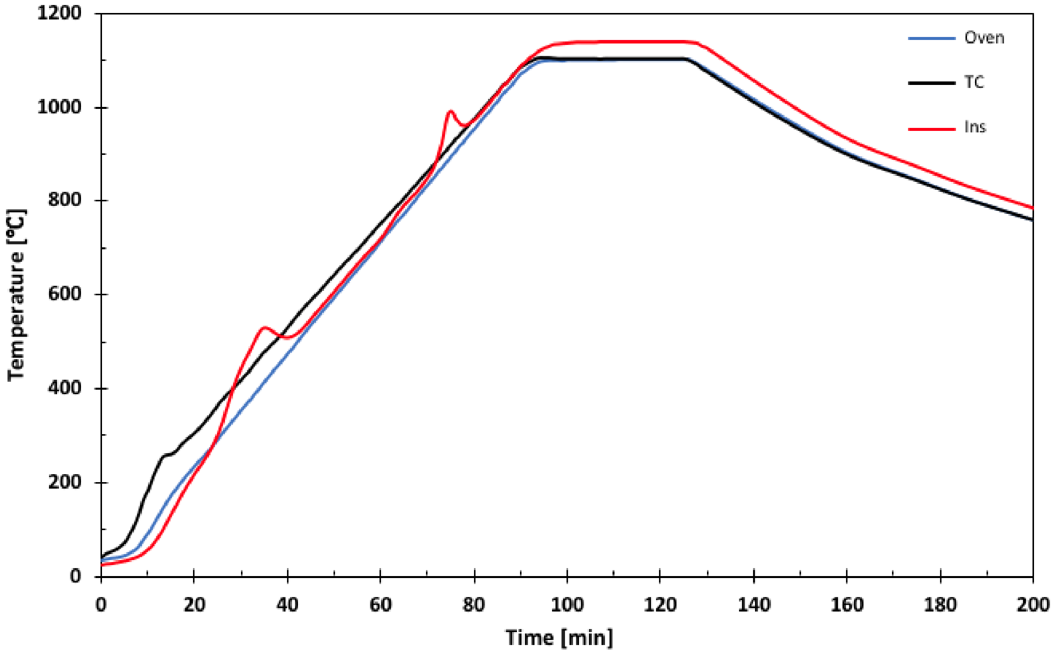

Figure 5.24 Temperature recordings as a function of time, with a heating rate of 15 K/min and 30 minutes hold time at 1100 °C. "Oven is the temperature recorded by the muffle oven, TC is temperature recorded by an external thermocouple and "Ins" is the temperature recorded in the centre of the thermal insulation.

The initial height of the insulation sample was 50 mm (H_b). After each test the height was measured centrally at each four vertical faces of the insulation sample, given in Table 5.2.

Table 5.2 Height measured at the middle of each side of the insulation sample after each test.

Test number - Set temperature [°C]	Height after testing [mm]				Average height after testing (H_a) [mm]
1 – 700	50	48	47	50	48.8
2 – 750	44	44	45	45	44.5
3 – 800	45	44	44	43	44
4 – 900	46	40	40	44	42.5
5 – 1000	43	41	41.5	41	41.6
6 – 1000	41	45	40	39	41.3
7 – 1100	40	35.5	37	41.5	41.0
8 – 1100	38.5	36	40	38.5	40.8

The height of the insulation slab after testing (H_a) as a function of the set temperature is shown in Figure 5.25. Two tests have been performed with a set temperature up to 1000 °C and 1100 °C, an average of these are presented.

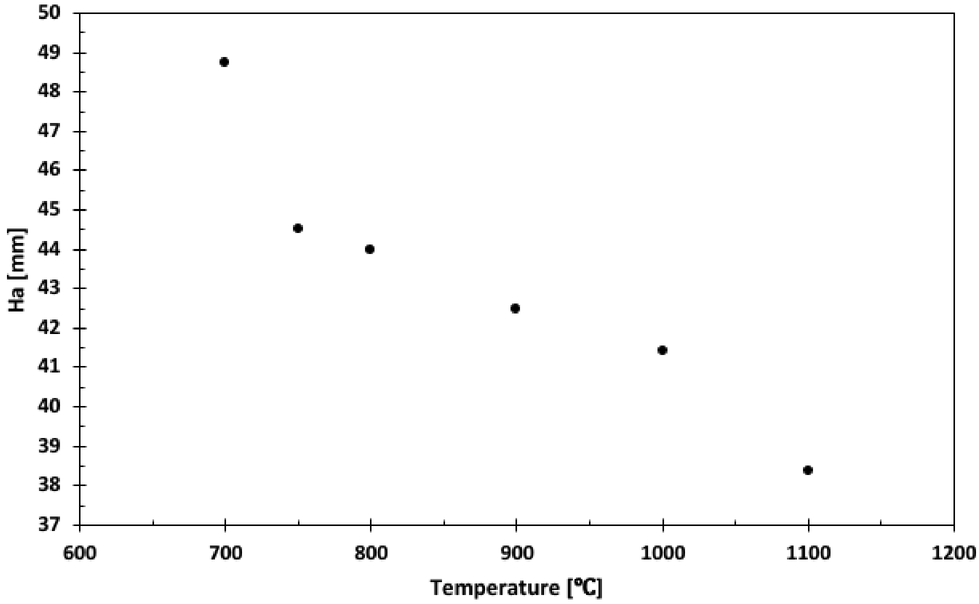

Figure 5.25 The height (H_a) of the insulation sample after heating as a function of the set temperature.

The thermal insulation test samples after each test, with the associated set temperature stated under each picture are shown in Figure 5.26 and Figure 5.27.

1 - 700 °C

2 - 750 °C

3 - 800 °C

4 - 900 °C

5 - 1000 °C

6 - 1000 °C

Figure 5.26 The insulation after testing with the associated set temperature under each picture.

7 - 1100 ℃

8 - 1100 ℃

Figure 5.27 The insulation after testing with the associated set temperature under each picture.

6 Discussion

6.1 Small scale jet fire test

6.1.1 16 mm steel plate

For the 16 mm steel plate, the temperature in the flame zone, recorded by the plate thermometer, was between 1140 °C and 1230 °C, corresponding to heat flux levels between 300 kW/m^2 and 380 kW/m^2 (200 kW/m^2 and 265 kW/m^2 excluding the convective contribution). All of the tests resulted in steel plate temperatures below 300 °C during the first 30 minutes of fire exposure.

The recorded flame zone temperature during test 5 was the lowest of the presented tests, however it recorded the highest temperature in the exposed steel plate. This might be explained by the condition of the insulation mat after test 5, which was clearly damaged. The relatively high recorded steel plate temperature in test 5 may be explained by the number of slabs in the tested thermal insulation mat, compared to test 2 and 4. More and smaller slabs, lead to more gaps where the heat could penetrate, hence a higher heat exposure to the steel plate without necessarily destroying the insulation first. In a real scale distillation column, the distance between the grooves is calculated to ensure that the insulation closely fits the pipe or vessel. Or it might be explained by the position of the thermocouple with regard to the destroyed part of the insulation mat. However, the thermal insulation mat after test 4, was the most damaged from the representative tests. This was also the test with the highest recorded flame zone temperature.

6.1.2 12 mm steel plate

For the 12 mm steel plate thickness, the temperature in the flame zone, recorded by the plate thermometer, was between 1160 °C and 1240 °C, corresponding to heat flux levels between 310 kW/m^2 and 379 kW/m^2 (200 kW/m^2 and 250 kW/m^2 excluding the convective contribution). The highest recorded temperature in the exposed steel plate after 30 minutes was 360 °C.

The recorded flame zone temperature during test 7 and 9 followed each other during the first 15 minutes, before the flame zone temperature slowly increased during test 9 and slowly decreased during test 7. However, the recorded steel plate temperature in the exposed steel plates was approximately the same throughout the tests. This might be explained by the condition of the insulation mat after testing; the insulation after test 7 had generally more extensive damages, while the insulation mat after test 9 had a more localised damage. The location of the thermocouples with respect to those damages might have had an impact on the recorded steel plate temperature. The temperature recordings in the unexposed steel plates also indicated that more heat had been transferred through the exposed steel plate during test 7, i.e. higher recorded temperatures. The insulation mat after test 10 was the most damaged of the presented tests. The insulation had almost completely disintegrated in large parts of the insulation, leaving only millimetres left of the insulation. This may be explained by the relatively high recorded temperatures in the steel plate and in the flame zone during this test.

6.1.3 6 mm steel plate

For the 6 mm steel plate thickness, the temperature in the flame zone, recorded by the plate thermometer, was between 1170 °C and 1230 °C, corresponding to heat flux levels between 320 kW/m^2 and 360 kW/m^2 (200 kW/m^2 and 260 kW/m^2 excluding the convective contribution). The highest recorded temperature in the exposed steel plate after 30 minutes was 440 °C.

The recorded flame zone temperature during test 15 was the lowest of the presented tests, but the recorded steel plate temperature was slightly higher, than in test 12 and 14. This might be explained by the large gaps observed between the insulation slabs, leading to more penetration of heat to the steel plate without necessarily destroying the insulation. This might also explain the increase in the exposed steel plate during the first 15 minutes in this test. In all three tests the insulation was clearly damaged, and it had almost completely vitrified in some locations.

6.1.4 3 mm steel plate thickness

For the 3 mm steel plate thickness, the temperature in the flame zone, recorded by the plate thermometer, was between 1190 °C and 1240 °C, corresponding to heat flux levels between 300 kW/m^2 and 380 kW/m^2 (200 kW/m^2 and 270 kW/m^2 excluding the convective contribution). The highest recorded temperature in the exposed steel plate after 30 minutes was 590 °C.

Extreme temperatures were recorded during test 18 and test 20. This reflected on condition of the insulation mat, hence the steel plate temperatures, both in the exposed and the unexposed steel plate. The condition of the insulation was very location based, i.e. in some locations the insulation had only lost 1 cm of the original height, while in other locations the insulation had completely vitrified. The flame zone temperature during test 19 was lower than in test 18 and 20, however the recorded temperature in the steel plate was within the same range. This might be explained by the condition of the insulation after the test 19, which had more severe damages. It can be seen from both the exposed and unexposed side of the insulation; the crack is clearly larger, hence more heat penetrated through the insulation. It can also be seen from the colour of the unexposed side of the insulation, which was more orange and heat exposed than in the two other tests. It should however be mentioned that test

19 was exposed for a longer period of time, allowing the steel plate to reach even higher temperatures than in test 18 and 20, hence a more damaged insulation.

6.1.5 Comparison between 16 mm, 12 mm, 6 mm and 3 mm

There was a clear connection between the steel plate thickness and the recorded steel plate temperatures. Requiring the highest recorded temperature in the steel plate not to exceed 400 °C during the first 30 minutes was used as the performance criterion in the present work. The thinner the steel plate, the faster it reached temperatures above the set performance criterion. The tests conducted with a 16 mm steel plate did not reach temperatures exceeding 400 °C within the 40 minutes of testing, while the 3 mm steel plate reached temperatures exceeding 400 °C within 25 minutes. The thicker the steel plate, the more heat was dissipated, i.e. the thicker steel plate worked as a larger heat sink. This will be even more prominent in a real scale column, also for thinner walls, as the heat will be dissipated into larger parts of the column, hence it will take longer time for the steel to reach 400 °C. In addition to the dissipation of heat, there will be internal convective cooling of the steel surface, i.e. conservative testing.

Each test had an approximately linear slope after 10 minutes exposure time until the fire source was turned off. From the presented average slope, it was shown that by decreasing the steel plate thickness from 16 mm to 12 mm, it gave a 16 % increase in the slope. Decreasing from 16 mm to 6 mm gave a 37 % increase, while decreasing from 16 mm to a 3 mm steel plate, resulted in an approximately 100 % increase in the slope, i.e. the temperature increased twice as fast. If the exposure time for the 3 mm steel plate had been carried out for 5 more minutes, and continued with the same slope, the steel plate would have reached 800 °C at 40 minutes.

The thinner the steel plate was, the more heat was transferred to the unexposed steel plate. This can be explained by the capacity of the thicker steel plates. This could also be seen from the calculated heat flux to the steel plates, where more heat was stored in the thicker steel plates, when exposed to the same heat flux levels. This can be explained by the thinner the steel plate, the less energy is required to heat up the e.g. 3 mm steel plate to the same temperature as the 16 mm steel plate.

Thermal insulation has a low thermal conductivity. The maximum recommended service temperature of the thermal insulation is 700 °C and the given melting point is >1100 °C. As the thermal insulation was exposed to temperatures above 1200 °C, disintegration of the insulation was initiated, i.e. the thermal conductivity of the insulation changed. The average effective thermal conductivity calculated for each steel plate thickness as a function of temperature, showed that the thicker the steel plate, the higher the thermal conductivity at the same temperature. Ideally the calculation should have resulted in an approximately equal effective thermal conductivity, however the calculation is based on the temperature recordings inside the cladding and in the steel plate. The measured temperature inside the cladding was dependent on the random buckling of the cladding, i.e. the temperature recordings varied depending on the location of the thermocouple. The calculation did not consider the air gap between the insulation and the exposed steel plate.

It is clear that the thermal insulation was seriously damaged after the testing. The insulation had shrunk in height and had become more porous, crumbly and some of the remains had a powder like structure. In the tests where the temperature in the flame zone was recorded to be above 1200 °C, the disintegration was clear in large parts of the insulation mat. In some locations the insulation had almost completely disintegrated leaving non/a few millimetres left. In the most extreme tests, recording temperatures up to 1250 °C, traces of a glass like material were observed.

There is no clear difference between the disintegration of the insulation and the steel plate thickness, but it can be seen from the temperature recordings and the exposure time, that the insulation holds better with a thicker backing. The thicker backing absorbed more of the heat, and the disintegration of the insulation was delayed. This could also be seen from the thinner steel plates, even when exposed to lower temperatures, the insulation was more destroyed, hence a higher steel plate temperature. With a thinner backing, the resistance of the thermal insulation was more important, as less of the heat was conducted by the steel. The stainless-steel cladding protected the thermal insulation from direct flame exposure, hence preserved the insulation for a longer period of time.

6.1.6 Performance criteria

The set performance criteria were based upon the standard criteria used in the oil and gas industry for carbon steel structures, where the steel temperature should not reach temperatures above 400 °C within the first 30 minutes of fire exposure. This is a relative conservative performance criterion, as carbon steel only starts to lose its integrity at 400 °C but is not likely to rupture before the steel has reached 600 °C to 700°C, depending on the steel grade and the pressure utilization. Additionally, the temperature criteria in the exposed steel plate in the present work were based on the highest recorded temperature with respect to the three measurement locations.

There are several conditions and factors that must be evaluated when considering the results, e.g. the tests was conducted with a start temperature around 15 – 20 °C in the steel plates, this is not always the case. The temperature distribution in a distillation column may vary from 0 to 100 °C. If the start temperature is e.g. 100 °C, this must be considered with regard to the time to reach 400 °C.

As stated by Bjørge et. al. [3], the time to reach the set temperature criteria in the steel is only one of several parameters in risk evaluation regarding process equipment. Safety for people is always the first priority. Time to collapse of pressurized equipment containing hydrocarbons exposed to a fire and potentially a sudden fire escalation should be evaluated against several factors, e.g. such as the time it takes for people to evacuate, loss of economic values and environmental factors. Operation pressure versus design pressure, PSV set-points, i.e. pressure utilization, as well as blow down capacity, are also factors that must be considered in the final risk evaluation. The fire frequency in the area of interest should also be considered, as well as the problem related to tall structures and equipment that represents a threat to neighboring equipment and structures late in a fire scenario.

For comparing the performed test with heat exposure simulating a jet fire, the temperature performance criteria in the flame zone was set to be >1200 °C, corresponding to heat flux levels above 345 kW/m^2. The temperature achievement is based on the recordings done by the plate thermometer, mainly measuring the radiation from the heated cladding, hence not the highest recorded temperature in the flame zone.

6.1.7 Repeatability, reproducibility and uncertainties

The mock-up worked well and could easily be put together/taken apart before and after each test. Between each test the cladding bottom and the exposed thermal insulation mat was replaced. After repeatedly severe testing the test equipment was clearly damaged, and equipment was replaced when required.

The aim of the testing was to expose the mock-up to heat flux levels between 250 kW/m^2 and 350 kW/m^2, simulating a jet fire, with a target temperature >1200 °C. To reach these temperatures there were a balance between preventing air entrainment to the flame zone, i.e. cooling, and getting enough air to the burner to sustain a premixed flame. Buckling of the cladding boxes and the exposed cladding also seemed to be an issue regarding the flame zone temperature. The buckling of the cladding boxes also lead to displacement of the light weight concrete bricks placed around the mock-up, allowing more air entrainment to the flame zone. It was therefore necessary to adjust these during the experiments.

From the temperature recordings, seen in the recordings both from the plate thermometers and the thermocouples, there were a difference between the two recording locations in some of the tests. The temperature recordings done by the plate thermometer and the thermocouple on one side slowly increased in temperature, while the recordings on the other side slowly decreased. This might be explained by that the buckling of the mock-up cladding lead more air to one side of the flame zone, where the temperature increased and less air to the other side where the temperature decreased. Or it might be explained by that one side was supplied with air, hence cooling of the flame zone. There were therefore some difficulties with upholding a uniform flame zone temperature during the whole experiment.

A temperature difference from 30 °C up to 80 °C in the flame zone seemed to have a small impact on the temperature development in the steel plates, given that the flame zone had reached the insulation break down temperature. The temperature in the flame zone seemed to be at the borderline between the breakdown temperature of the insulation, explaining the variations in the condition of the insulation mat after testing.

In some of the tests, a slowly decreasing temperature was experienced in the flame zone, i.e. it seemed like it struggled to uphold the high heat flux levels. This might be due to the disintegration of the insulation, leading to more heat loss to the steel plate, hence a decreasing flame zone temperature. There were also variations in ventilation or wind driven air currents in the fire lab, which might explain the temperature drops in some of the tests. In at least one test, an abrupt increase in air currents was clearly felt by the experimenters. A drop in recorded flame and plate thermometer temperatures were nearly simultaneously observed. This lead to improved shielding of the whole test setup. Based on observation, it was decided to always report the highest steel plate temperature recorded in the respective tests.

The buckling of the cladding bottom also seemed to affect the disintegration of the insulation mat. In the locations were buckling had occurred, there were clear burns in the insulation mat. The random buckling of the cladding also resulted in difficulties with regard to the temperature recordings between the insulation mat and the cladding. There were a large temperature difference between the different tests, depending on the location of the thermocouple with respect to the buckling of the cladding.

Further, there were some difficulties with dislocation of the mock-up during the experiment. Observations from the video recordings showed that the mock-up slowly moved downwards during the test, in some of the cases the mock-up got a sudden and significant drop (approximately 2 to 3 cm). This affected the flame zone temperature and the distance between the burner and the exposed cladding. There were also some height differences between the burner and the bottom cladding with respect to the different tests. It was preferred that the start distance between the burner and cladding was the same. The height difference might have affected disintegration of the insulation. In some cases, it was also observed from the cladding after the testing, that the burner had not been in centre. This could be due to the movement during the test.

The same outer cladding box was used for all the different steel plate thicknesses, originally made for the 16 mm steel plate. When the thinner steel plates were tested, there were therefore more room for movement of the mock-up, i.e. when the mock-up dropped, the distance between the exposed steel plate and the thermal insulation might have been larger than 25 mm, depending on the drop.

The recorded steel plate temperature might have been affected by the random disintegration of the insulation, e.g. in some locations the insulation had almost completely disintegrated, while in other locations in the same insulation mat was almost completely intact. Even if steel is a good conductor of heat, there might have been a temperature difference depending on the location in the steel plate, especially in the thicker steel plates.

The thermocouple placed at the edge of the steel plate (r = Ro) experienced the highest temperature in the majority of the tests. This was the thermocouple placed nearest the opening were all of the thermocouples was lead out from the mock-up. This might therefore be explained by flames penetrating in. The temperature difference between the different thermocouple positions might also be explained by the contact between the thermocouple and the steel. But in general, there were small variations between the different positions.

It turned out different insulation mats were used. The insulating material itself was the same, but the number of slabs and the material holding the insulation slabs together were different in some of the test (aluminium or a fabric material). These differences may have affected the results, as there seemed to be some difference between the insulation with the fabric material and the ones with aluminium. However, all of the tests presented in chapter 5 were with the same material, a layer of aluminium. Generally, there are always some variations in the different components, voids, moisture etc. in the insulation.

The insulation mats used are divided into slabs for fitting perfect around a circular pipe/vessel. In the present testing this was not the case, and there might have been some variations between how close the slabs were in the different tests. There are some uncertainties to how the disintegrated insulation (the powder like structure) will behave in a vertical orientation as it may fall downwards.

For some tests, dismantling was done a couple of hours after the test was executed, others after 24 hours. Even after 24 hours the steel plates had a temperature of up to 100°C. This might have affected the condition of the thermal insulation.

As an attempt to achieve even higher temperatures in the flame zone, the flow rate was adjusted from 0.60 g/s up to 0.65 g/s (corresponding to 30 kW) and 0.70 g/s (corresponding to 33 kW). However, this had little/no effect on the recorded temperature in the flame zone.

6.1.8 Limitations

The experiments where conducted horizontally, while the insulation will be installed on a vertical column. In a real scenario, there will be convective cooling between the cladding and the thermal insulation, as well as to the heated steel walls, due to movement of air. As the thermal insulation starts to disintegrate, there will be increased room for convective cooling. The large dimensions of a full-scale distillation column, will also dissipate heat to external parts of the column, hence a prolonged time to hazardous temperatures. In the small-scale mock-up there were some dissipation of heat between the exposed and the unexposed steel plate, but not near to the same extent as in a full-scale distillation column.

The testing was done with the thermal insulation (Rockwool pipe section mat) normally used and stainless-steel cladding. The perforated plate between the thermal insulation and the air gap was in stainless-steel and the steel plates (column wall) in carbon steel. The testing is only valid for the specified materials.

Radial heat loss was prevented by the geometry and the dimensions of the exposed steel plate diameter to the thickness ratio, the design of the test unit including 50 mm thickness radial insulation and the box closing the test unit.

6.2 Numerical calculations

The calculated steel temperature was highly dependent on the thickness of the thermal insulation and the thermal conductivity of the insulating material. Using a constant thermal conductivity in the calculation gave almost no increase in the exposed steel plate. The thermal conductivity of the insulation changed as the insulation started to disintegrate, the calculated effective thermal conductivity as a function of time was used in the calculation. The calculated thermal conductivity was based on the measured steel plate temperature and was not iterated as a function of the calculated steel temperature as would be a more correct procedure.

The calculated steel temperature was higher than the recorded steel temperature. This is due the assumption that the temperature of the exposed surface is equal to that of the fire at all times during the test, hence the heat flux in to the thermal insulation is overestimated and thereby the steel plate temperature. It was observed from the calculations that the thinner the steel plate thickness was, the larger difference between the calculated and the measured steel temperature.

Adding an additional layer of passive fire protection or e.g. increasing the thickness of the thermal insulation would extend the time to reach 400 °C significantly, for all the steel plate thicknesses. Adding e.g. a 10 mm layer of PFP would protect the thermal insulation from the highest temperature exposure. Thereby a longer time before the thermal insulation start to disintegrate, hence a longer time before the steel reaches unacceptable temperatures.

6.3 Oven testing of insulation

Observations of the insulation after oven testing showed that the insulation shrunk, i.e. loss of height, the colour of the insulation had changed, and the material had become firmer with a crumbly consistency. The compressive strength of the insulation changed significantly as it was heated. Originally the insulation was airy and could easily be pulled apart and pressed together. As the holding temperature increased the insulation sample became firmer. When pushing down the material, it did not return to its original form.

The temperature recordings from the centre of the thermal insulation showed that heat was released from the insulation at low temperatures during the heating. There was a sudden temperature increase that started at approximately 300 °C and another at 900 °C, before the temperature dropped down and followed the oven temperature again. The height and duration of the temperature increase did however vary, i.e. some of the tests had more significant peaks. This might be due to the variation in the different components in the thermal insulation samples.

The sudden heat production that started at approximately 300 °C could be explained by the combustion of the anti-dusting materials (oil products) in the Rockwool insulation. The heat released just below 900 °C, i.e. only observed in the heating up to 900 °C, 1000 °C and 1100 °C, could be explained by the combustion of the binder (Bakelite) in the thermal insulation.

The specified maximum operating temperature for the thermal insulation is 700 °C. Heating up to this temperature showed almost no loss in height of the insulation sample and no colour change was observed in this test. However, heating the insulation up to 750 °C, showed a more significant reduction in height, the colour had changed, and the material had become firmer.

The height of the insulation sample shrunk as a function of temperature, i.e. as the set temperature increased, the height of the insulation sample after the 30-minute holding time, shrunk. Heating up to 1100 °C did in addition show melting/vitrifying at the bottom of the insulation sample. It was also observed some heat production in the insulation after the oven had reached 1100 °C, i.e. the recorded temperature at the centre of the insulation sample was higher than that of the oven after the set temperature was reached and during the cooling. However, the insulation sample was still in relatively good shape, even after heating up to 1100 °C, with a 30-minute holding time. The breakdown temperature of the insulation can therefore not be determined by the conducted oven tests.

The measured height of the insulation was based on an average value, measured centrally at each four vertical faces of the insulation sample. There were some variations between the different sides as the test samples had a tendency to lose more height on one side than the other sides.

Small black soot particles were observed on the ceramic plate and inside the oven. These black spots particles were only observed in the tests with holding temperatures at 900 °C and higher. It should also be mentioned that the soot particles appeared during the cooling of the oven. During each test a small peek was done into the oven during the cooling time, approximately between 400 °C and 500 °C. This revealed that there were no soot particles at this time, i.e. the soot particles appeared in late stage of the cooling process.

6.3.1 Repeatability, reproducibility and uncertainties

The heating elements in the oven were placed on two of the sides, but the majority were placed at the bottom of the oven. This may have affected the temperature at the bottom, i.e. a higher temperature. The insulation slab was placed in direct contact with the ceramic plate. Even when the oven cooled down, it may have taken longer time for the ceramic plate to cool down, especially if this in addition had a higher temperature than what was recorded in the oven itself. This might also explain why the vitrifying at the bottom of the insulation was present in the tests done up to 1100 °C.

The integrated thermocouple in the oven was place in the upper left corner and had a ceramic cover. This explains why the oven temperature recorded a lower temperature than the additional thermocouple (used to measure the oven temperature).

Two tests were conducted at 1000 °C and two tests at 1100 °C. They seemed to show approximately the same results, however there were some variations in the loss in height. More tests should be performed to determine the repeatability/variations. The test setup itself can easily be reproduced.

6.3.2 Limitations

The oven, simulating a fire, was slowly heated up to the holding temperature, with the insulation sample inside the oven. This will not be the case in a real fire scenario, where the fire will reach full intensity almost immediately. The insulation sample was not taken out of the oven before it had completely cooled down. However, this was the same for all the tests conducted.

6.4 Equipment

The thermocouples are only verified for measuring temperatures up to 1200 °C with a ±5 °C error of margin. This had no major effect on the present work.

The plate thermometer (PTHFM) is only verified for temperatures up to 800 °C and for a short period of time up to 1200 °C and was not intended for use in situations as tested in the present work. However, the plate thermometer worked well and represented the best source of the surface temperature recordings.

All of the equipment was highly damaged by the extensive heat exposure. Several thermocouples were destroyed and melted into the disintegrated and partly glass-like insulation. The upper layer of the plate thermometer started spalling thin chips. After repeated testing it cracked open. The titanium burner was also affected by the repeated extreme testing and finally had to be replaced with a new burner. The tests performed in the present work may, however, be considered low cost testing compared to full scale jet fire testing.

7 Conclusion

The aim of the present work was to determine the fire resistance of thermal insulation for protection of process equipment against fires. Requiring the highest recorded temperature in the steel plate not to exceed 400 °C during the first 30 minutes of testing was used as the performance criterion in the present work. This was a relatively conservative performance criterion, as the steel is not expected to rupture before it has reached 600 °C to 700 °C, depending on the steel grade.

For the tests conducted with 16 mm and 12 mm steel plate thicknesses, the recorded steel plate temperature did not exceed temperatures above the set performance criteria within 30 minutes of testing. The tests conducted with 6 mm and 3 mm steel plate thicknesses, did however exceed temperatures above the set performance criteria within 28 minutes and 22 minutes, respectively. The results are conservative, as convective cooling will extend the time to reach 400 °C even further in a real scale distillation column. The thermal insulation showed a promising fire resistance, especially in combination with a thick backing, i.e. 16 mm and 12 mm. This can be explained by more heat being required to heat thicker steel plates representing larger heat sinks.

The test set-up itself work well and gave a good indication of the temperature development in the steel. There were some variations between the different tests conducted with the same steel plate thickness, however the tests showed a clear connection between the steel plate thickness and the temperature development in the steel.

After the oven testing, the insulation had shrunk i.e. lost height, the colour had changed, the material had become firmer with a crumbly consistency. However, the insulation was in relatively good shape, even after heating up to 1100 °C, with a 30-minute holding time. It is therefore recommended preform further testing at even higher temperatures to determine the breakdown temperature of the insulation.

Both the small-scale jet fire tests and the oven tests showed that the thermal insulation maintained well when exposed to temperatures below 1200 °C. The small-scale jet fire tests indicated that when the insulation was exposed to temperatures above 1200 °C, disintegration of the insulation was present, and, in some locations, sintering was observed. The stainless-steel cladding did however protect the thermal insulation from direct flame exposure, hence preserved the insulation for a longer period of time.

The thermal insulation showed surprisingly good fire resistance, even with a 3 mm backing. It should be mentioned that thermal insulation will give a lower degree of fire protection than PFP. However, the distance thermal insulation solution may be preferred to avoid the risks and costs associated with extensive construction work when modifying existing equipment. More tests should be performed to determine the variability in the small-scale jet fire tests. The previous testing is only valid for the tested configuration and steel wall thickness.

8 Further work

8.1 Small scale jet fire testing

More tests should be performed at each steel plate thickness to determine the repeatability of the testing. It should also be evaluated if thicker steel plates are to be tested. If more tests are to be performed, it is recommended to use the same insulation mats in all the tests. In addition, it is recommended to do some adjustments in the test set-up, to avoid the movement of the mock-up during the experiments. This can easily be done by e.g. placing a screw nut just below the cladding top.

It may also be interesting to test with PFP to provide a better foundation of the use of thermal insulation as passive fire protection. What happens if e.g. a 5 mm or 10 mm layer of a fire insulating material is applied in addition to the thermal insulation? The thermal insulation will then be exposed to lower temperatures, maybe below the breakdown temperature? Or replacing 10 mm of the thermal insulation with PFP, i.e. 40 mm of thermal insulation and 10 mm of PFP? There are several interesting aspects that can be investigated.

CFD modelling may be interesting to conduct and compare with the small-scale jet fire tests.

8.2 Oven testing of insulation

More repeated testing should be performed to determine the variability in the testing. Also testing at higher temperatures should be conducted to determine the breakdown temperature of the insulation. Use of a data logger for the temperature recordings may be beneficial as it will be time consuming and more accurate.

Tests with PFP may also be interesting to determine a basis for comparison between the two.

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Appendix A: Composition of mock-up

The mock-up is produced by KAFEER at Statoil Kårstø. It comes in several parts, and before the execution of the test can start, some preparations must be done. This appendix will show how the mock-up is prepared and put together. All the parts of the mock-up are presented in Figure A. In addition to this equipment, 7 thermocouples are to be placed inside the mock-up before testing.

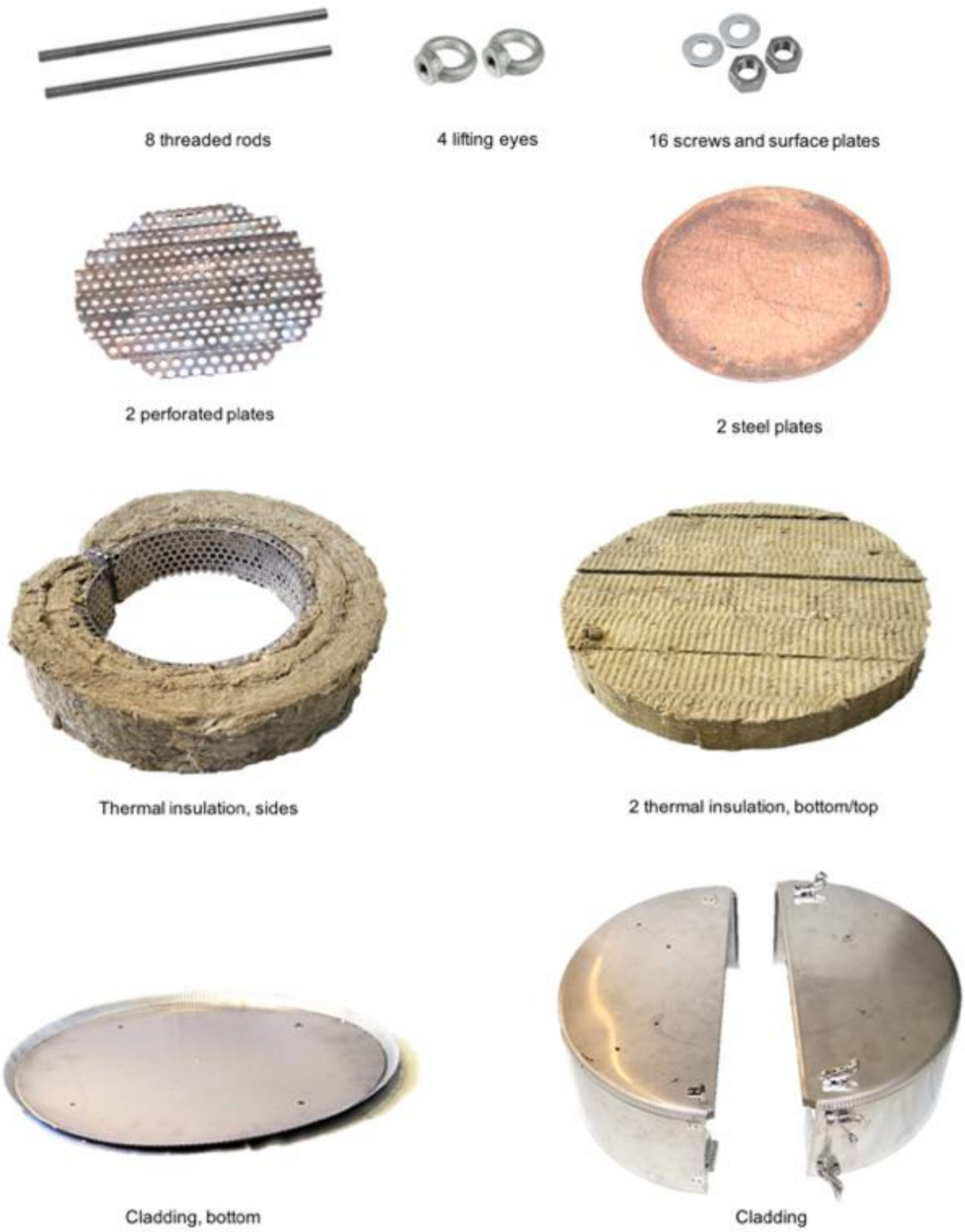


Figure A. 1 All the parts needed for putting the mock-up together.

Procedure:

1. 8 threaded rods and 16 screws are used to combine the mock-up. Start with taking 4 of the screws and screw them on one threaded rod each. Make sure they are placed in the same distance from the end, 2.5 cm.

2. Place the threaded rods through the steel plate, so that the 2.5 cm end is at the bottom, where the perforated plate is to be placed.
3. In each of the steel plates, a hole was made with a 1.6 mm drill; at the centre, at the edge and one at half the radius. Place one thermocouple in each hole.
4. Take 4 screws and screw one on each threaded rod. The distance from the top of the steel plate to the top of the screw must be 2.5 cm.
5. It is now ready for the second plate to be placed. Similar to the other plate, there are 3 small holes, this must point in the same direction as the plate below. Place the thermocouples on the second plate and put the second perforated plate on the top. The mock-up should now look like Figure A.2.

Figure A. 2 The mock-up after step 1. – 5. are completed.

6. Find the 4 remaining threaded rods and tread them through the holes in the bottom cladding.
7. Place the bottom, thermal insulation on the cladding. Make sure the "protected" side of the insulation points down.
8. Place one thermocouple in the middle of the bottom thermal insulation and one thermocouple between the thermal insulation and the bottom cladding.
9. Place the mock-up, from step 1 – 5 on top of the thermal insulation.
10. Take the side of the thermal insulation and place it on top/around the steel plates. The mock-up should now look like Figure A.3. PS! The perforated plate inside the insulation ring, was removed.

Figure A. 3 The mock-up after combining part 1 and 2.

11. Place the second thermal insulation mat on the top. Make sure that the "protected" side, points upwards.
12. The mock-up is now ready for the final cladding to be applied. Be careful, so that the thermocouples don't fall out of place.

13. Fasten the 4 remaining screws on the 4 outer threaded rods and a fishing eye on the 4 inner threaded rods.
14. The mock-up should now look like Figure A.5 and are now ready for testing.

Figure A. 4 Mock-up ready for testing.

Appendix B: Test set up

This appendix will show how the test set-up is prepared after the mock-up is put together. All the necessary equipment for execution of the test is presented in Figure B.1 and Figure B.2. In addition, a table bottom and 2 computers (one for controlling the propane flow and one for the temperature logger).

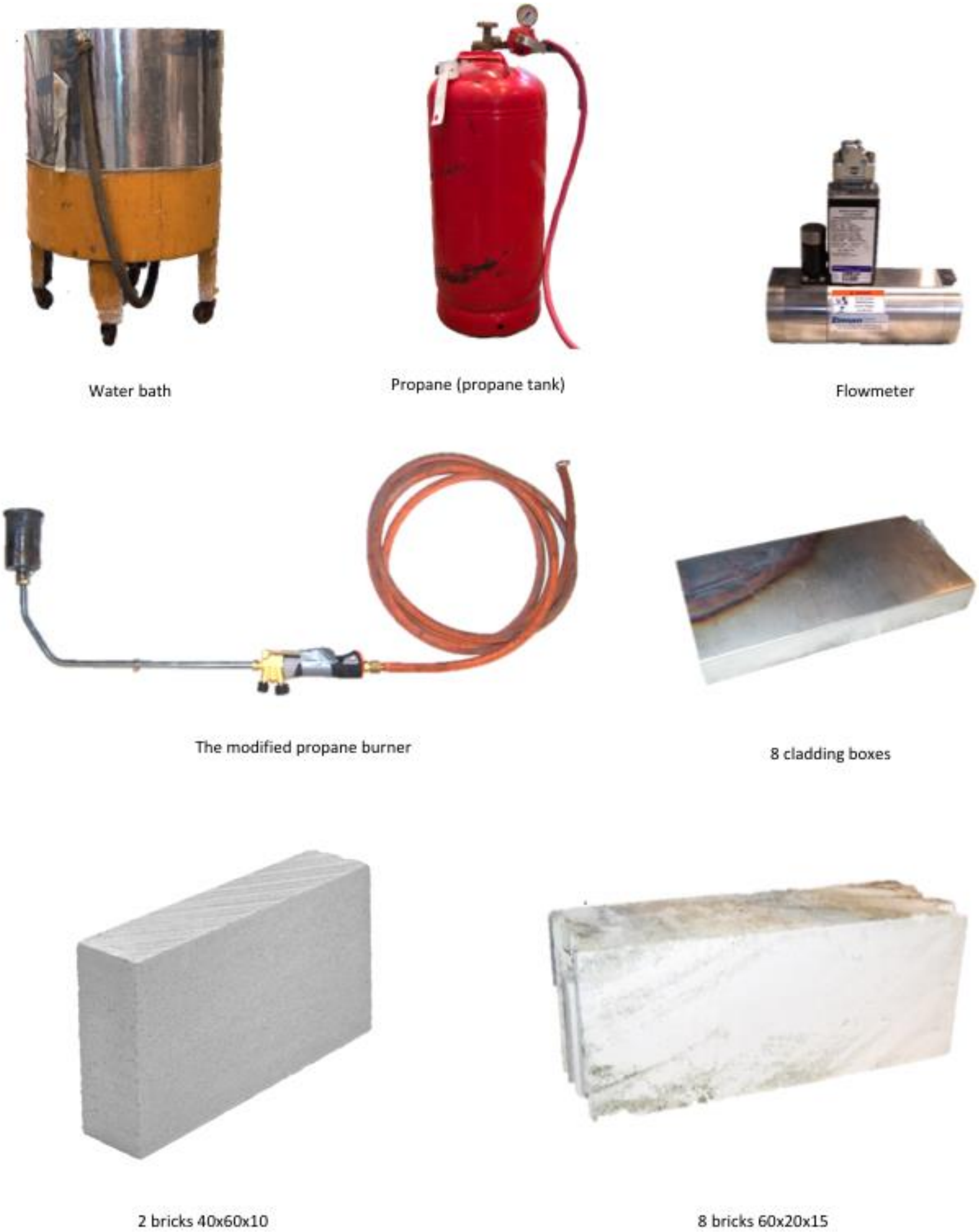


Figure B. 1 Equipment needed for test set-up.

10 Thermocouples
Type K (1.5 mm)

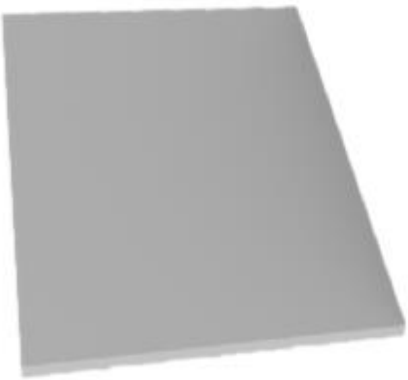
Datalogger
HP34970A

2 Plate thermometers
(PTHFM)

19 Stones of Skamotec
10 cm x 10 cm x 5 cm

2 Steel plates
20 cm x 10 cm x 0.5

2 Cobber rods



Skamotec plate
122 cm x 100 cm x 5 cm

Test rig

Figure B. 2 Equipment needed for test set-up.

Procedure:

1. Before the preparation for the first test can start the Skamotec plate must be prepared. Cut the plate in to similar part, so that each plate follows the measure 61 cm x 100 cm x 5 cm. In the center of each plate make a half circle, so the two plates can be pushed together around the burner.
2. Start with the 8 bricks with the measure 60 cm x 20 cm x 15 cm. Build them together on top of each other 2 and 2, in 4 rows. They should be built on top of each other so that the distance from the floor to the top of the second brick is 40 cm. They should be grouped in two, 4 and 4, so that there is a small gap in the middle (the burner is to be placed here in step 4).
3. Place the bricks with the measure 40 cm x 60 cm x 10 cm, in front of each group, with the 60 cm length down.
4. Take the two Skamotec plates and place them on top of each group and place the burner in the center of the plates. The distance from the top of the Skamotec plates to the top of the burner should be 3 cm. The test set up should now look like Figure B.3
5. Place the table bottom over the test set up, as shown in Figure B.3.

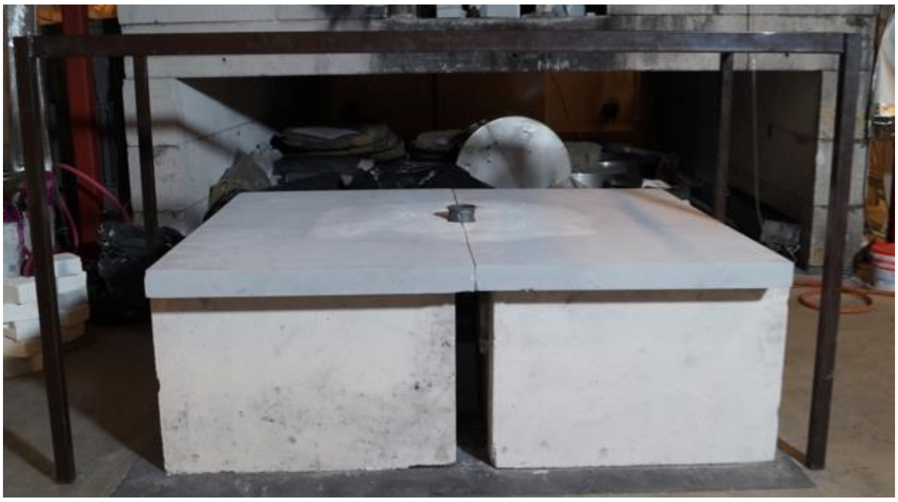


Figure B. 3 The test setup after step 1. – 5.

6. Place a steel plate on each side of the burner as shown in Figure B.4.

Figure B. 4 Location of the steel plates around the burner.

7. Take the two plate thermometers and two thermocouples. Place the plate thermometer 14.5 cm from the center of the burner to the center of the plate thermometer on each side of the burner. Place the thermocouple in the center of the plate thermometer, approximately 3 cm above the PT. Together with the 8 thermocouples placed inside the mock-up and the two in the flame zone, all 12 thermocouples are placed.
8. Make sure that all the thermocouples and plate thermometers are connected to the logger and working.
9. Place the 8 cladding boxes around the burner and the plate thermometer, as shown in Figure B.5.

Figure B. 5 Location of cladding boxes, burner and plate thermometers, seen from above.

10. Now the mock-up can be placed above the test set up and the Skamotec stones can be placed around the mock-up, as shown in Figure B.6.

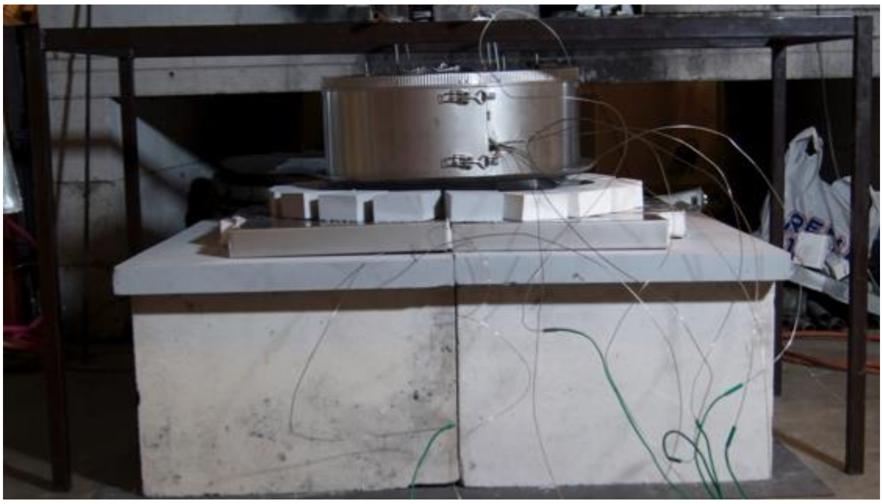


Figure B. 6 Test setup ready for testing. It should be noted that there should be a gap in the front between the two bricks, as shown in Figure B.3.

11. Place the propane tank in the water bath and connect the propane tank to the flow meter and the flow meter to the burner.
12. The test set up is now complete and ready for testing.

Appendix C: Safety review

Before the tests are executed make sure that all the steps in Table C.1 is cleared.

Table C. 1 Checklist before the test procedure can start.

Questions	OK?
Assessment of the largest fire that the test may cause and other risks the test may cause.	☐
Which extinguishing method can be used?	☐
Are you known with the safety procedures applying for work in the lab?	☐
Do you know where the emergency shower, fire extinguisher and main supply for gas is?	☐
Do you have a phone available in case of emergency?	☐
Have the risk related to the chemicals used during the test been verified?	☐
Do you know how to handle any residue?	☐

If the fire alarm goes off:

- If the fire alarm goes off due to the ongoing test and the situation is under control, call 110 immediately and let them know it is a false alarm.
- If the fire alarm goes off in other cases, make a controlled shutdown of the test and leave the fire lab through the exit door. Go to town hall square.

Table C. 2 Contact information.

Contact	Phone
Arjen Kraaijeveld (lab responsible)	+47 52 70 26 57
Emergency services	110/ 112/ 113

Appendix D: Test procedure – Small scale jet fire testing

Before the test can start it is important that all the test participants have read and understood all the points in Appendix C: Safety review, and that all the checkpoints are OK. If so, the following steps are to be followed:

- Put on protective gear
- Clean the area and verify escape routes
- Place the mock-up at a safe location under the exhaust hood
- Test the reading of the thermocouples
- Verify the suspension and the mock-up
- <u>Before</u> the gas is initiated:
    - Turn off the fire alarm
    - Turn on the exhaust hood
    - Start the logger
    - Start the video camera
- The gas container must be heated in the “washing machine”. This must be done with extreme caution. Check the water temperature frequently during the test and don’t forget to turn of the heater (this can create major problems).
- Open the gas supply, set the flow to 0.2 g/s and light the burner.
- Adjust to wanted mass flow: 0.6 g/s
- During the whole test one person must stay near the propane tank and be ready to turn of the supply in case of emergency.
- The burner is lit through the whole experiment (about 40-30 minutes where the temperature should/must > 1208 °C)
- When the test is to be completed:
    - Turn off the gas supply and let the remaining gas in the pipes burn out
    - Switch off the burner
- Let the logger continue for about 30 minutes after the burner is turned off.
- The mock-up is given sufficient time for cooling, approximately 12 hours
- After the mock-up has cooled down, it will be taken apart
    - Be careful, the carbon steel plates can still have temperatures around 100 °C, even after 12 hours. They must be handled with extreme care.
- Documentation of the test results

NB! Watch out for toxic gases during the tests and when the rig is to be taken apart.

Appendix E: Test information

Information about the conducted tests, in the order they have been carried out, are presented in Table E.1.

Table E. 1 Relevant information about the conducted tests.

Test Number	Steel plate thickness	Date	Gas flow	Test duration	Ref. number in report
1	16 mm	23.11.16	0.40 g/s	40 min	*,**
2	16 mm	24.11.16	0.50 g/s	38 min	*,**
3	16 mm	25. 11 16	0.75 g/s	38 min	*,**
4	16 mm	07.09.17	0.40 g/s	20 min	**
5	16 mm	16.10.17	0.60 g/s	41 min	1
6	6 mm	17.10.17	0.60 g/s	41 min	**
7	6 mm	18.10.17	0.60 g/s	32 min	16
8	8 mm	18.10.17	0.60 g/s	35 min	***
9	12 mm	20.10.17	0.60 g/s	40 min	6
10	3 mm	08.01.18	0.60 g/s	35 min	**
11	3 mm	09.01.18	0.60 g/s	41 min	**
12	3 mm	10.01.18	0.60 g/s	37 min	17
13	6 mm	10.01.18	0.60 g/s	41 min	11
14	6 mm	11.01.18	0.60 g/s	41 min	12
15	3 mm	11.01.18	0.60 g/s	36 min	18
16	3 mm	12.01.18	0.60 g/s	36 min	19
17	12 mm	12.01.18	0.60 g/s	42 min	7
18	16 mm	22.01.18	0.60 g/s	42 min	2
19	16 mm	23.01.18	0.60 g/s	41 min	3
20	6 mm	23.01.18	0.60 g/s	42 min	13
21	12 mm	24.01.18	0.60 g/s	44 min	8
22	6 mm	25.01.18	0.60 g/s	41 min	14
23	16 mm	26.01.18	0.60 g/s	41 min	4
24	12 mm	26.01.18	0.60 g/s	41 min	9
25	12 mm	28.01.18	0.70 g/s	41 min	10
26	16 mm	28.01.18	0.70 g/s	41 min	5
27	6 mm	29.01.18	0.65 g/s	42 min	15

*Tests conducted fall 2016 by Professor Torgrim Log and Joachim Bjørge [3].

**Introducer tests conducted to find the ultimate test set up. These are not presented.

***Only one test was conducted with 8 mm steel thickness, the results from this test is therefore not presented.

Information about the placement of the thermocouples can be found in Table E.2.

Table E. 2 Information about the placement of the thermocouples.

Thermocouple number	Placement	Name in graph
1	In the Fire insulation block, under the mock-up	Under cladd
2	Inside of the cladding	Inside cladd
3	Center of the thermal insulation	Cent insu.
4	Center of front column wall (first plate)	r = 0
5	½ radius of front column wall (first plate)	r = 0.5Ro
6	Edge of front column wall (first plate)	r = Ro
7	Center of back wall (second plate)	Upper r = 0
8	½ radius of back wall (second plate)	Upper r = 0.5Ro
9	Edge of back wall (second plate)	Upper r = Ro
10	Placed inside the suspension (for safety reasons)	-
11	In the flame zone	Flame
12	Below the flame (PT)	Plate TC
13	Below the flame (PT)	Plate TC 2

Appendix F: Steel plates specifications

The weight and diameter for the different steel plate thicknesses and the perforated plates are presented in Table F.1.

Table F. 1 Steel plate specifications.

Plate	Weight [g]	Diameter [cm]
3 mm		
Exposed	1855.7	31.5
Unexposed	1862.0	31.8
6 mm		
Exposed	3956.9	32.6
Unexposed	3958.6	32.7
8 mm		
Exposed	5145.8	32.2
Unexposed	5124.4	32.0
12 mm		
Exposed	7364.5	31.7
Unexposed	7467.9	31.7
16 mm		
Exposed	9725.4	32.3
Unexposed	9611.5	32.4
Perforate plates		
Exposed	387.4	32.5
Unexposed	426.7	32.5

Appendix G: Propane

The amount of propane used during each test is presented in Table J.1. The tests marked with "-", is not noted, as the weight of the tank was above 30 kg (maximum load of the available weight was 30 kg).

Table G. 1 Amount of propane used during the test.

Test	Weight before test [g]	Weight after test [g]	Amount used [g]	Duration of test [s]	Calculated flow [g/s]
5 – 16 mm	28098	26580	1518	2400	0.633
6 – 6 mm	26580	25060	1520	2400	0.633
7 – 6 mm	25060	23900	1160	1800	0.644
8 – 8 mm	23900	22564	1336	2160	0.619
9 - 12 mm	22564	21120	1444	2400	0.602
10 – 3 mm	28934	27588	1346	2100	0.641
11 – 3 mm	25690	23230	1510	2460	0.612
12 – 3 mm	23230	21811	1419	2220	0.639
13 – 6 mm	21811	20302	1509	2460	0.613
14 – 6 mm	-	-	-	-	-
15 – 3 mm	-	-	-	-	-
16 – 3 mm	-	-	-	-	-
17 – 12 mm	-	-	-	-	-
18 – 16 mm	-	-	-	-	-
19 – 16 mm	-	-	-	-	-
20 – 6 mm	-	-	-	-	-
21 – 12 mm	26820	25310	1510	2640	0.572
22 – 6 mm	25310	23650	1660	2460	0.675
23 – 16 mm	23650	22110	1540	2460	0.626
24 – 12 mm	-	-	-	-	-
25 – 12 mm	-	-	-	-	-
26 – 16 mm	-	-	-	-	-
27 – 6 mm	-	-	-	-	-
28 – 3 mm	-	-	-	-	-

Appendix H: Results from small-scale jet fire testing

This appendix represents additional results from all the conducted tests.

H.1 16 mm steel plate

The temperature recordings as a function of time in the exposed steel plate (Exp), unexposed steel plate (Unexp) and in the flame zone (Flame) are shown in Figure H.1. Three thermocouples were placed in each steel plate. The temperature in Figure H.1 represents the highest temperature recorded in the steel plate for each separate test.

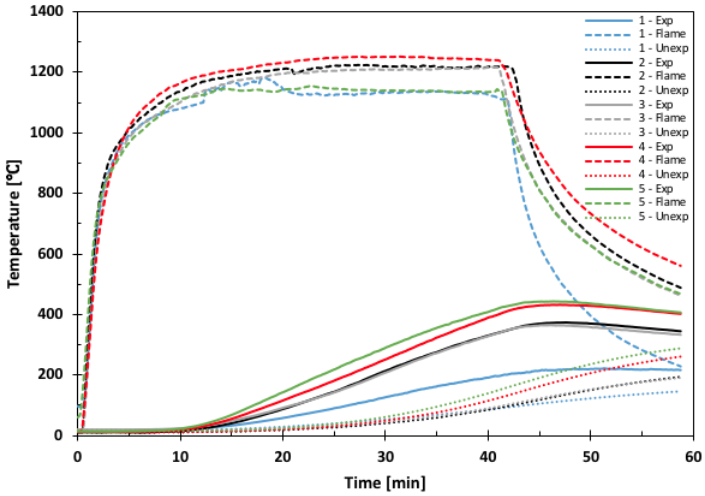


Figure H.1 Temperature recordings as a function of time for the 16 mm steel plate. Exp, Unexp and Flame are the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time are shown in Figure H.2. The heat flux level, $\dot{Q}"_{Flame}$, is calculated from Equation 2.11, where $h = 100\ kWm^{-2}K^{-1}$, T_F is the recorded temperature in the flame zone as a function of time (Plate TC), $T_s = 20\ °C$ and $\varepsilon_F = 0.85$. $\dot{Q}"_{PT}$ is based on the same calculation, but T_s is the temperature recorded in the cladding as a function of time (Inside Clad). As the temperature in the cladding increases, the convective contribution will disappear.

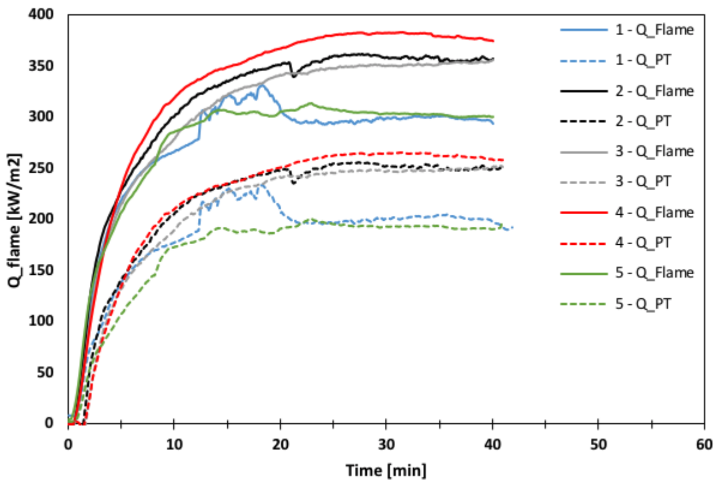


Figure H. 2 The calculated heat flux levels in the flame zone as a function of time. “Q_flame” represents the calculated heat flux level including the convective attribution, while “Q_PT” represents the calculated radiation measured by the plate thermometer (Plate TC), with a steel plate thickness of 16 mm. The test number is indicated in the label.

The total calculated heat flux to the exposed steel plate as a function of time are shown in Figure H.3. The heat flux levels are calculated from Equation 2.8, where $c_{p,steel}$ is given by Equation 2.1. The calculation was done for the exposed and the unexposed steel plate, and by adding these two together the total heat flux level to the exposed steel plate was found.

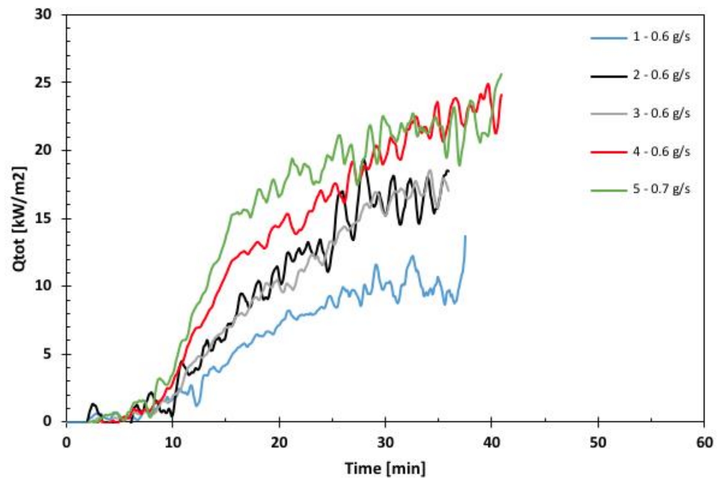


Figure H. 3 The total calculated heat flux to the exposed steel plate as a function of time, for test 2, 4 and 5, with a steel plate thickness of 16 mm.

The calculated effective thermal conductivity of the insulation as a function of the steel plate temperature is presented in Figure H.4. The effective thermal conductivity is calculated by solving Equation 2.2 with respect to k, where $\dot{q}"$ is the total calculated heat flux in to the exposed steel plate, dT is the temperature measured in the cladding as a function of time (Inside Cladd) minus the average temperature measured in the exposed steel plate as a function of time (r = 0, r = 0.5Ro and r = Ro) and dx is the thickness of the insulation.

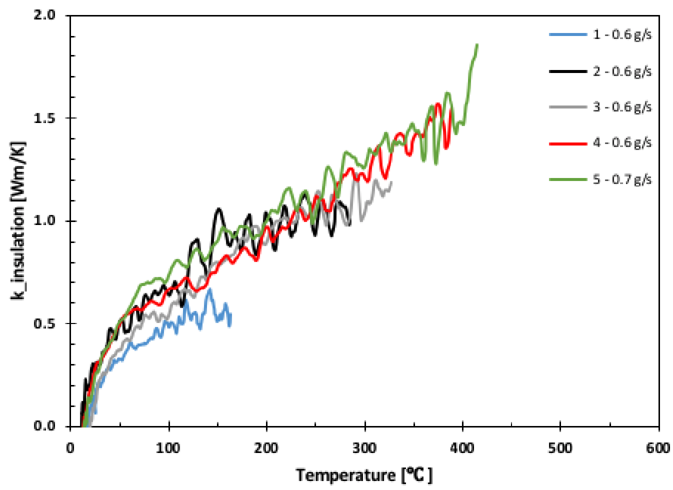


Figure H. 4 The calculated effective thermal conductivity as a function of the steel plate temperature.

H.2 12 mm steel plate

The temperature recordings as a function of time in the exposed steel plate (Exp), unexposed steel plate (Unexp) and in the flame zone (Flame), is presented in Figure H.5.

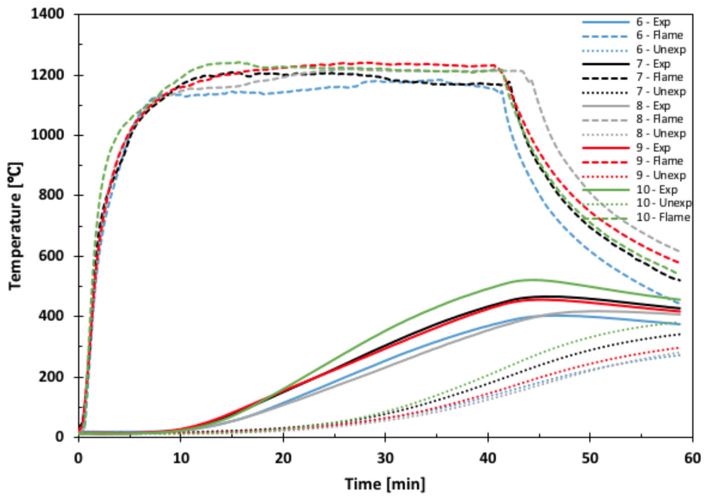


Figure H. 5 Temperature recordings as a function of time. Exp, Unexp and Flame is the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively, with a steel plate thickness of 16 mm. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time are shown in Figure H.6.

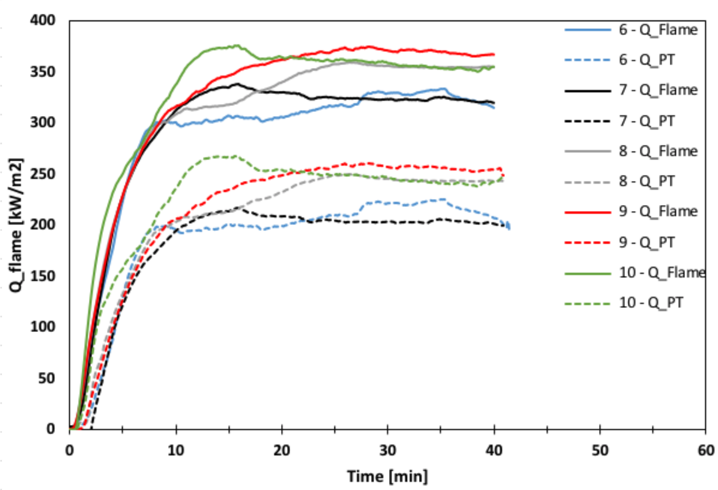


Figure H. 6 The calculated heat flux levels in the flame zone as a function of time. "Q_flame" represents the calculated heat flux level including the convective attribution, while "Q_PT" represents the calculated radiation measure by the plate thermometer (Plate TC), with a steel plate thickness of 12 mm. The test number is indicted in the label.

The total calculated heat flux level in to the steel plates as a function of time is presented in Figure H.7.

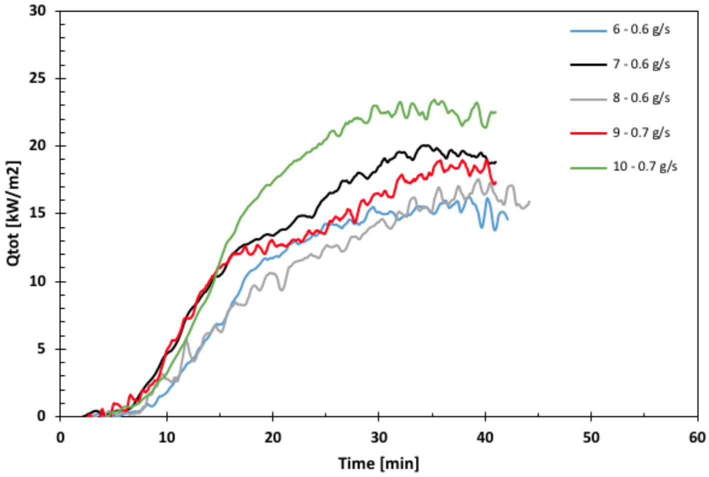


Figure H. 7 The total calculated net heat flux levels to the exposed steel plate as a function of time.

The effective calculated thermal conductivity of the insulation as a function of the steel plate temperature is presented in Figure H.8.

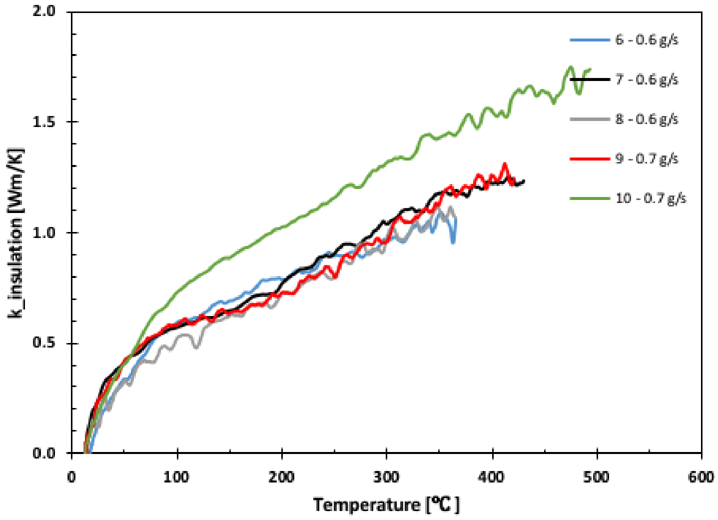


Figure H. 8 The calculated effective thermal conductivity as a function of the steel plate temperature.

H.3 6 mm steel plate

The temperature recordings as a function of time in the exposed steel plate (Exp), unexposed steel plate (Unexp) and in the flame zone (Flame) are presented in Figure H.9

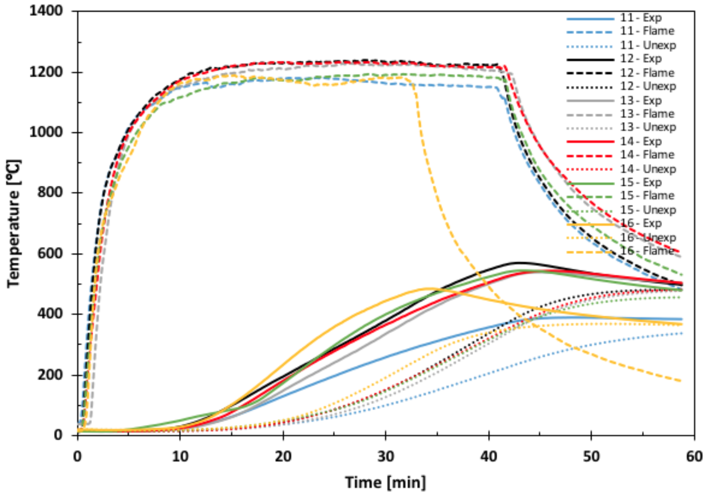


Figure H. 9 Temperature recordings as a function of time. Exp, Unexp and Flame is the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively, with a steel plate thickness of 16 mm. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time for test 11, 12, 13, 14 and 15 are shown in Figure H.10.

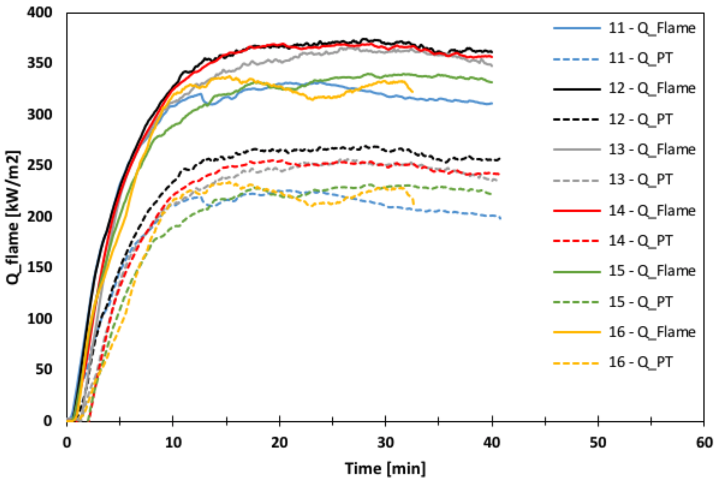


Figure H. 10 The calculated heat flux levels in the flame zone as a function of time. "Q_flame" represents the calculated heat flux level including the convective attribution, while "Q_PT" represents the calculated radiation measure by the plate thermometer (Plate TC), with a steel plate thickness of 6 mm. The test number is indicted in the label.

The total calculated heat flux level in to the steel plates as a function of time is presented in Figure H.11.

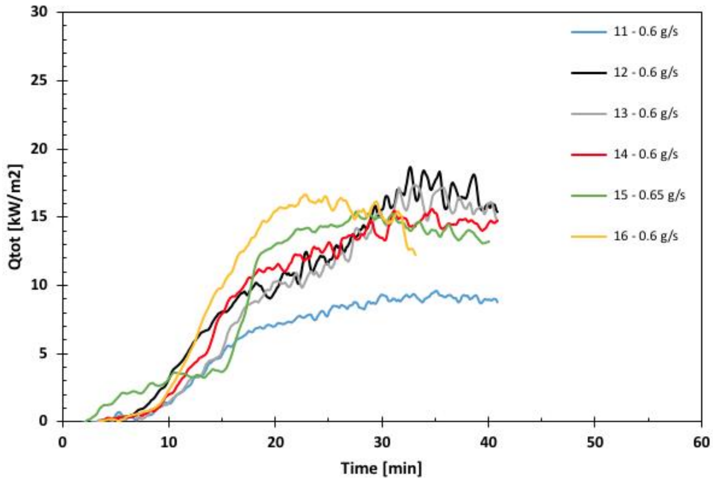


Figure H. 11 The total calculated heat flux levels going through the steel plates as a function of time.

The effective calculated thermal conductivity of the insulation as a function of the steel plate temperature is presented in Figure H.12.

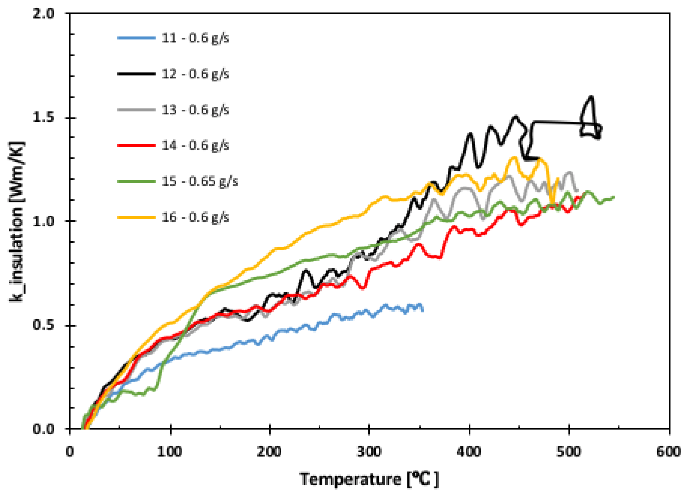


Figure H. 12 The total calculated heat flux to the exposed steel plate as a function of time, with a steel plate thickness of 6 mm. The test number is indicated by the label.

H.4 3 mm steel plate

The temperature recordings in the flame zone and in the steel plates as a function of time for test 11, 12, 13, 14, 15 and 16, is presented in Figure H.13.

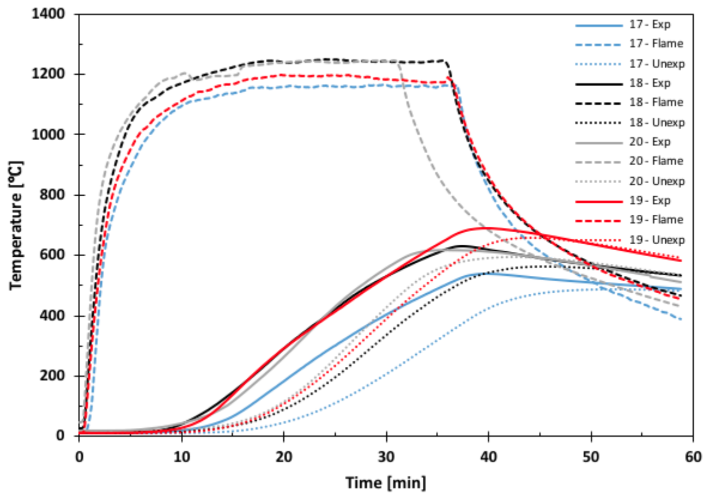


Figure H. 13 Temperature recordings as a function of time for the 3 mm steel plate. Exp, Unexp and Flame are the temperature recordings in the exposed steel plate, unexposed steel plate and in the flame zone, respectively. The test number is indicated in the label.

The total calculated heat flux levels in the flame zone as a function of time for test 17, 18, 19 and 20 are shown in Figure H.14.

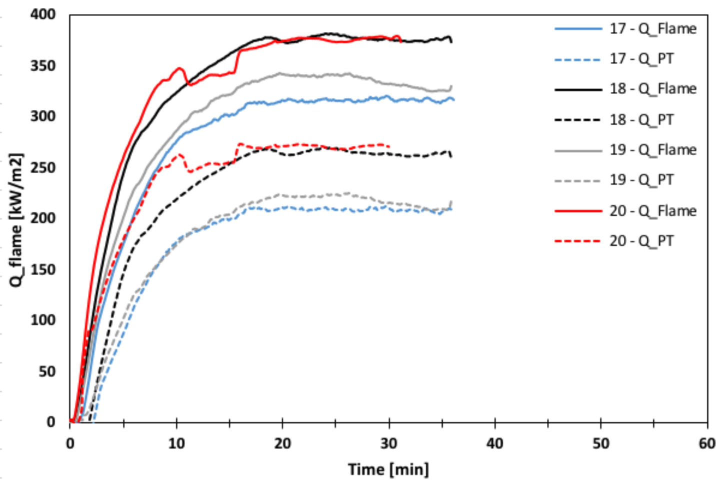


Figure H. 14 The calculated heat flux levels in the flame zone as a function of time. "Q_flame" represents the calculated heat flux level including the convective attribution, while "Q_PT" represents the calculated radiation measure by the plate thermometer (Plate TC), with a steel plate thickness of 3 mm. The test number is indicted in the label

The total calculated heat flux to the exposed steel plate as a function of time for test 17, 18, 19 and 20 are shown in Figure H.15.

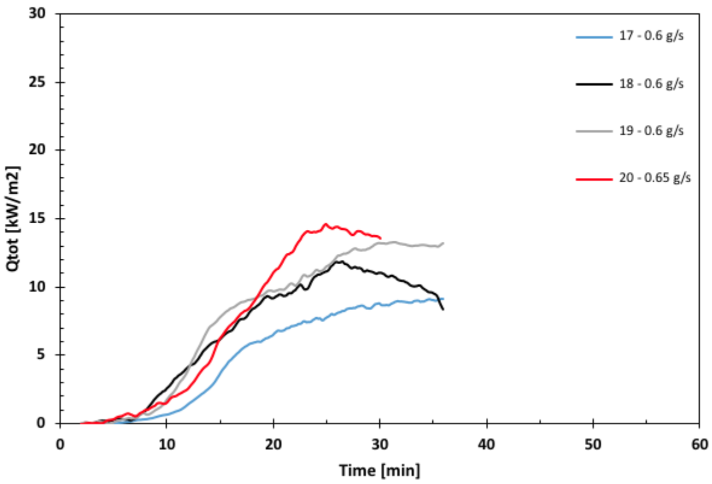


Figure H. 15 The total calculated heat flux to the exposed steel plate as a function of time, with a steel plate thickness of 3 mm. The test number is indicated by the label.

The effective calculated thermal conductivity of the insulation as a function of the steel plate temperature is shown in Figure H.16.

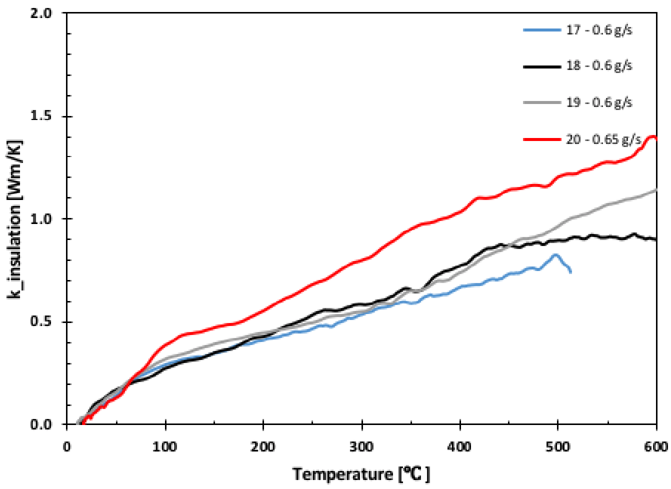


Figure H. 16 The calculated effective thermal conductivity as a function of the steel plate temperature.

Appendix I: Insulation after testing

I.1 16 mm steel plate

The condition of the insulation after test 1, 2, 3, 4 and 5 are shown in Figure I.1 and Figure I.2. Each row represents one test; the picture to the left shows the unexposed side of the insulation, the next picture shows the exposed side of the insulation, while the picture to the right shows the exposed cladding after testing.

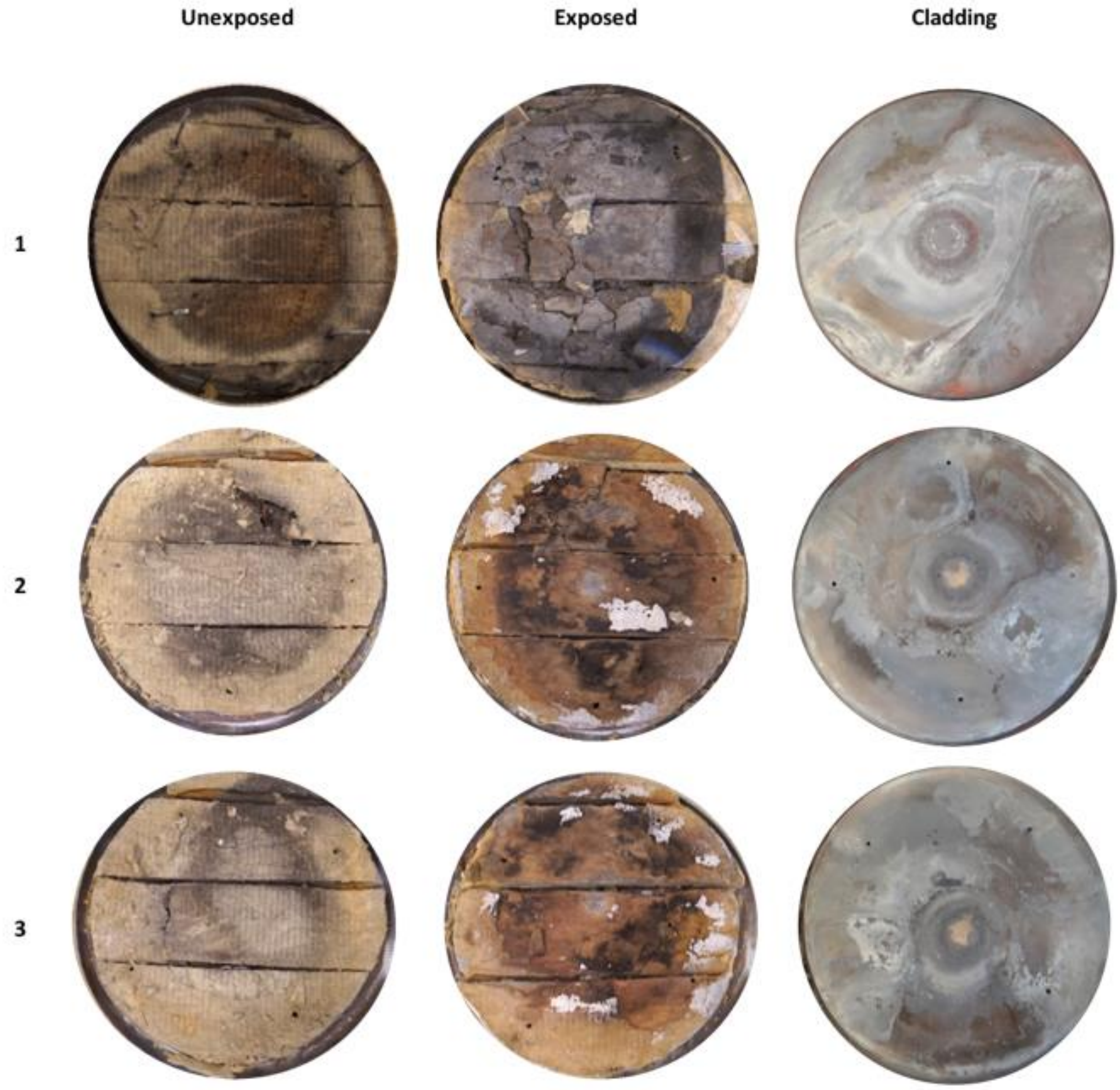


Figure I. 1 Insulation after testing for test 1, 2 and 3. The column to the left shows the unexposed side of the insulation after testing, the middle column shows the exposed side of the insulation after testing, and the column to the right shows the exposed cladding. Each row represents one test.

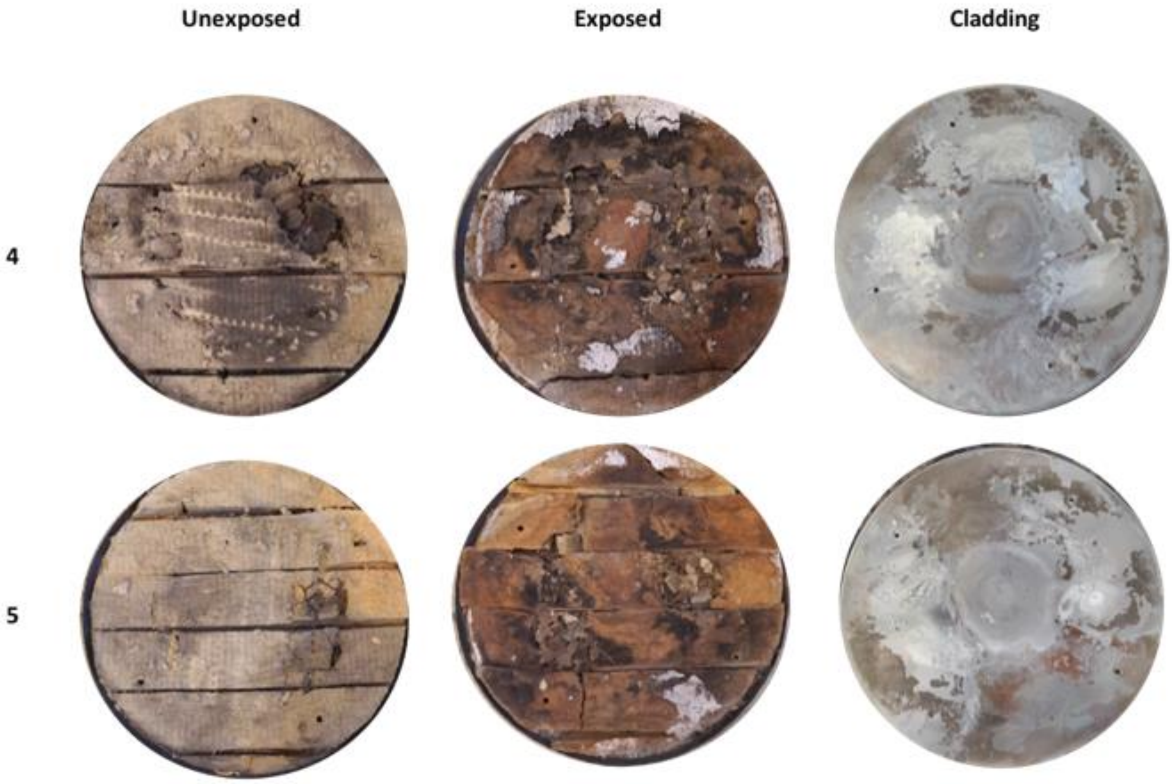


Figure I. 2 Insulation after testing for test 4 and 5. The column to the left shows the unexposed side of the insulation after testing, the middle column shows the exposed side of the insulation after testing, and the column to the right shows the exposed cladding. Each row represents one test.

Measures of the height at different locations of the insulation after test 1, 2, 3, 4 and 5 is presented in Figure I.3 and Figure I.4.

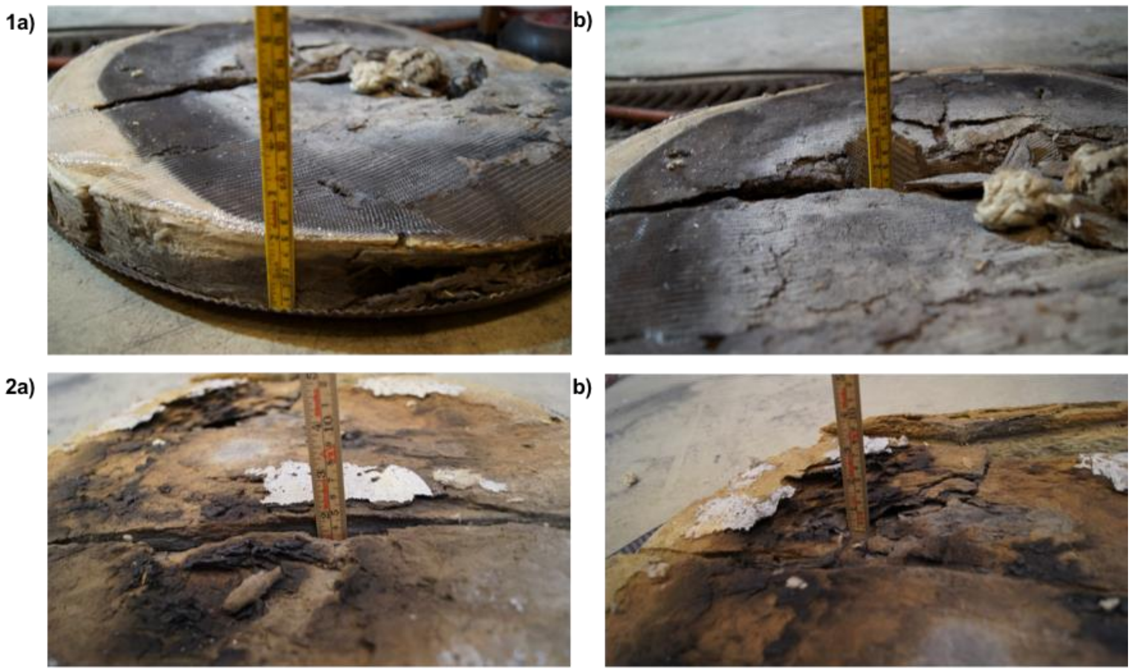


Figure I. 3 1a and b) Height of the insulation after test 1. 2a and b) Height of the insulation after test 2.

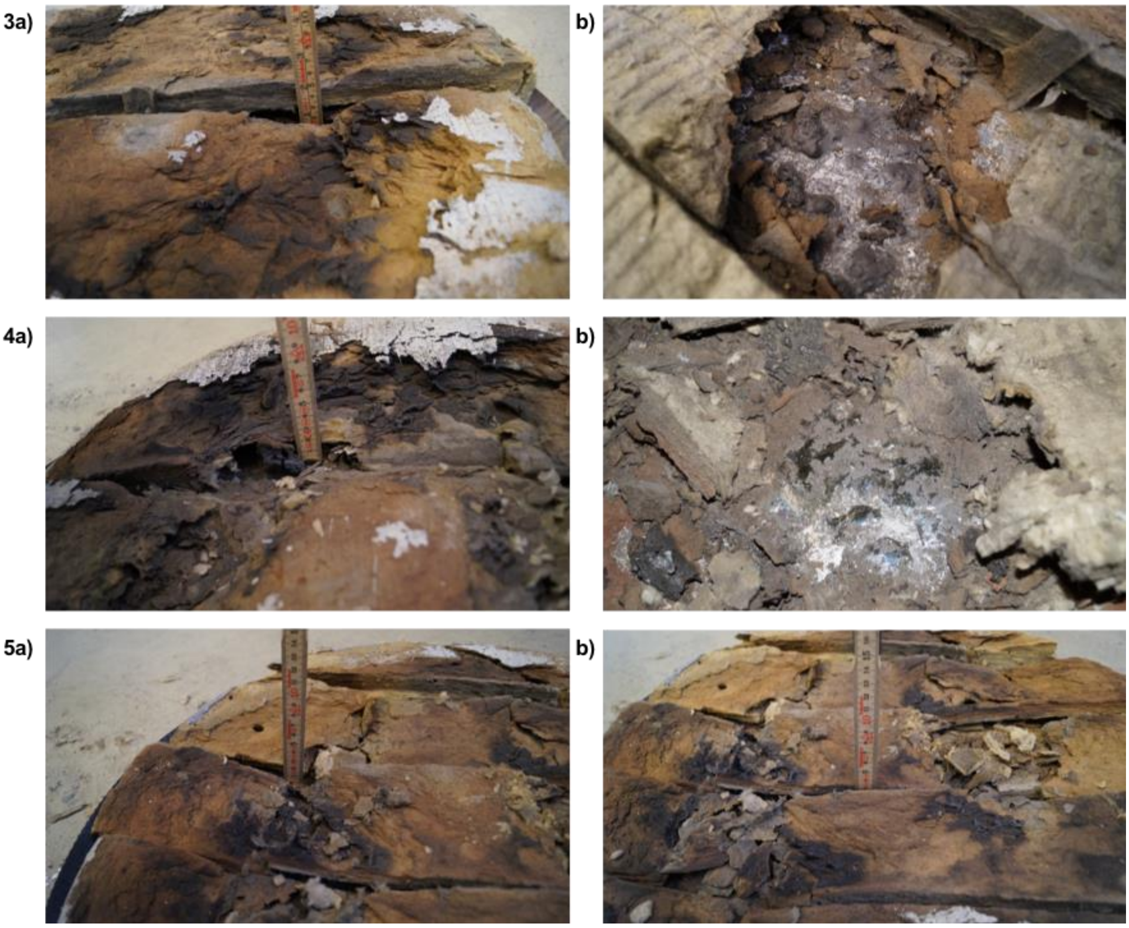


Figure I. 4 3a and b) Insulation after test 3. 4a and b) insulation after test 4. 5a and b) Insulation after test 5.

I.2 12 mm steel plate

The condition of the insulation after test 6, 7, 8, 9 and 10 are shown in Figure I.5 and Figure I.6. Each row represents one test; the picture to the left shows the unexposed side of the insulation, the next picture shows the exposed side of the insulation, while the picture to the right shows the exposed cladding after testing.

Figure I. 5 Insulation after testing for test 6, 7 and 8. The column to the left shows the unexposed side of the insulation after testing, the middle column shows the exposed side of the insulation after testing, and the column to the right shows the exposed cladding. Each row represents one test.

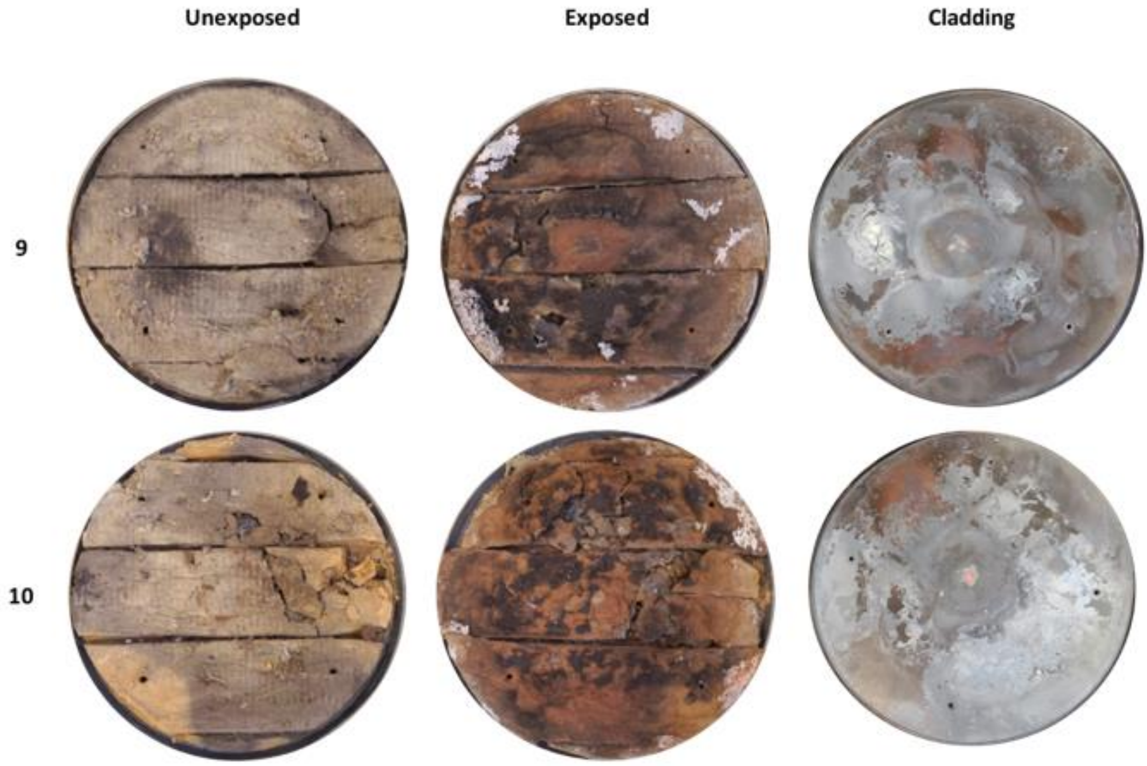


Figure I. 6 Insulation after testing for test 9 and 10. The column to the left shows the unexposed side of the insulation after testing, the middle column shows the exposed side of the insulation after testing, and the column to the right shows the exposed cladding. Each row represents one test.

Measures of the insulation after test 6, 7, 8, 9 and 10 are presented in Figure I.7 and Figure I.8.

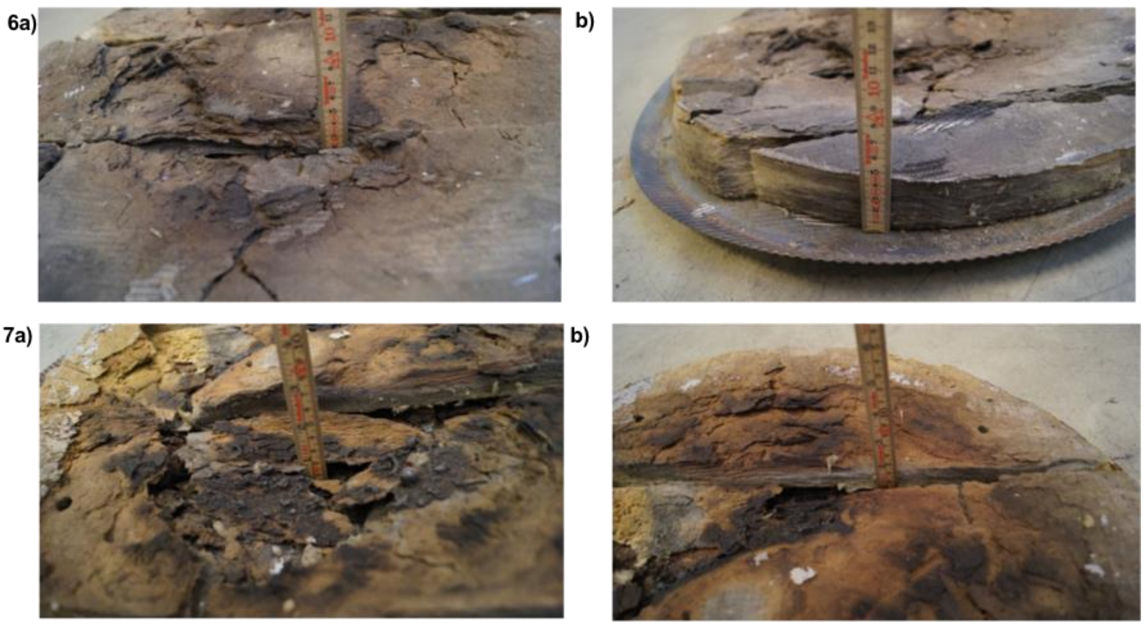


Figure I. 7 6a and b) Insulation after test 6. 7a and b) Insulation after test 7.

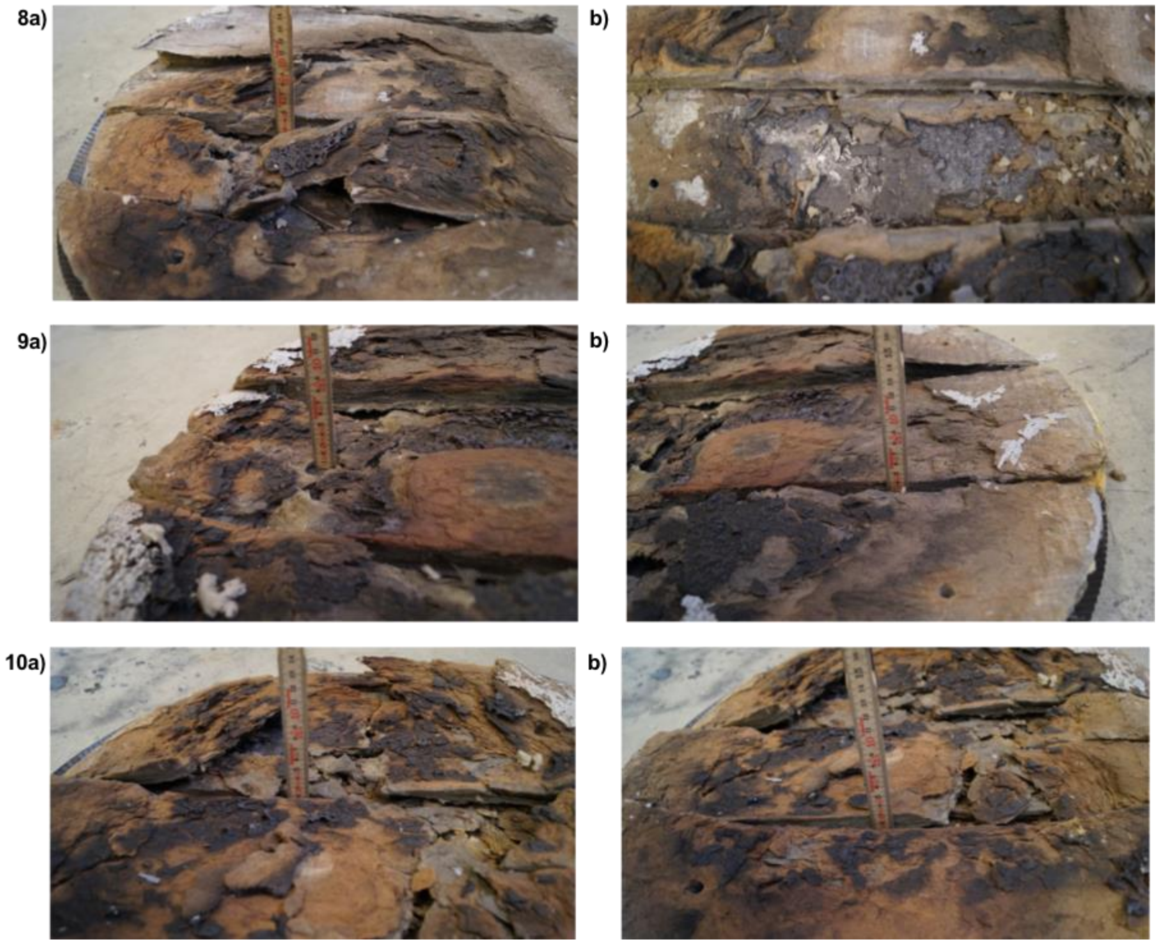


Figure I. 8 8a and b) Insulation after test 8. 9a and b) Insulation after test 9. 10a and b) Insulation after test 10.

I.3 6 mm steel plate

The condition of the insulation after test 11, 12, 13, 14 and 15 are shown in Figure I.9 and Figure I.10. Each row represents one test; the picture to the left shows the unexposed side of the insulation, the next picture shows the exposed side of the insulation, while the picture to the right shows the exposed cladding after testing.

Figure I. 9 Insulation after testing for test 11, 12, and 13. The column to the left shows the unexposed side of the insulation after testing, the middle column shows the exposed side of the insulation after testing, and the column to the right shows the exposed cladding. Each row represents one test.

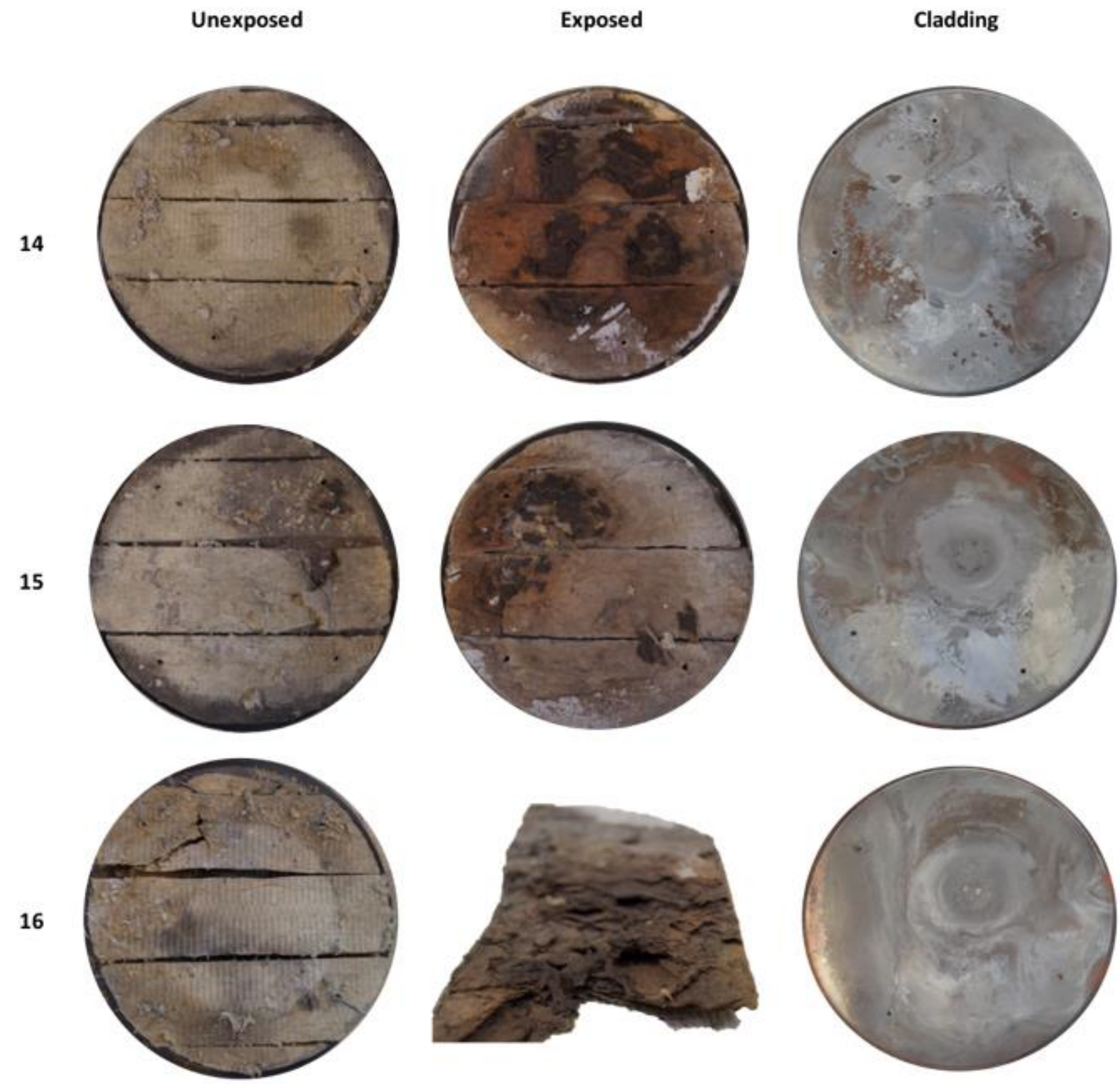


Figure I. 10 Insulation after testing for test 14, 15 and 16. The column to the left shows the unexposed side of the insulation after testing, the middle column shows the exposed side of the insulation after testing, and the column to the right shows the exposed cladding. Each row represents one test.

Measures of the insulation after test 11, 12, 13, 14 and 15 are presented in Figure I.11 and Figure I.12.

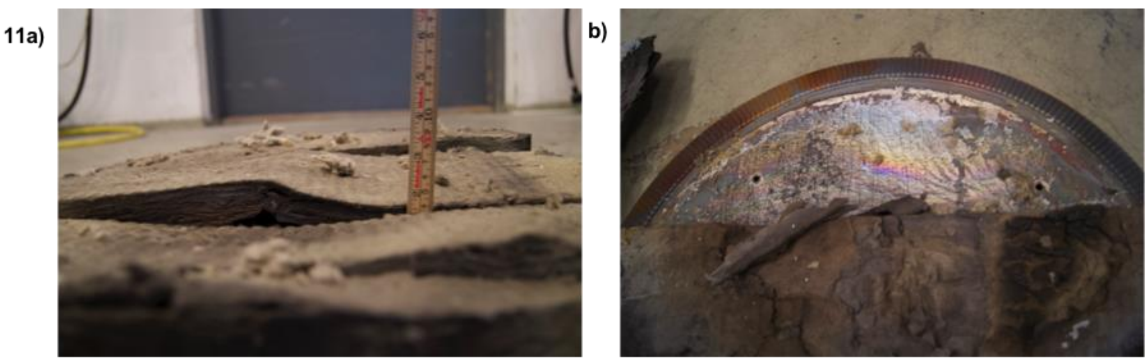


Figure I. 11 a) Height of the insulation after test 11. b) insulation after test 11.

Figure I. 12 12 a and b) Insulation after test 12. 13a and b) insulation after test 13. 14a and b) Insulation after test 14. 15a and b) Insulation after test 15.

I.4 3 mm steel plate

The condition of the insulation after test 17, 18, 19 and 20 are shown in Figure I.13. Each row represents one test; the picture to the right shows the unexposed side of the insulation, the middle picture shows the exposed side of the insulation, while the picture to the right shows the bottom cladding after testing.

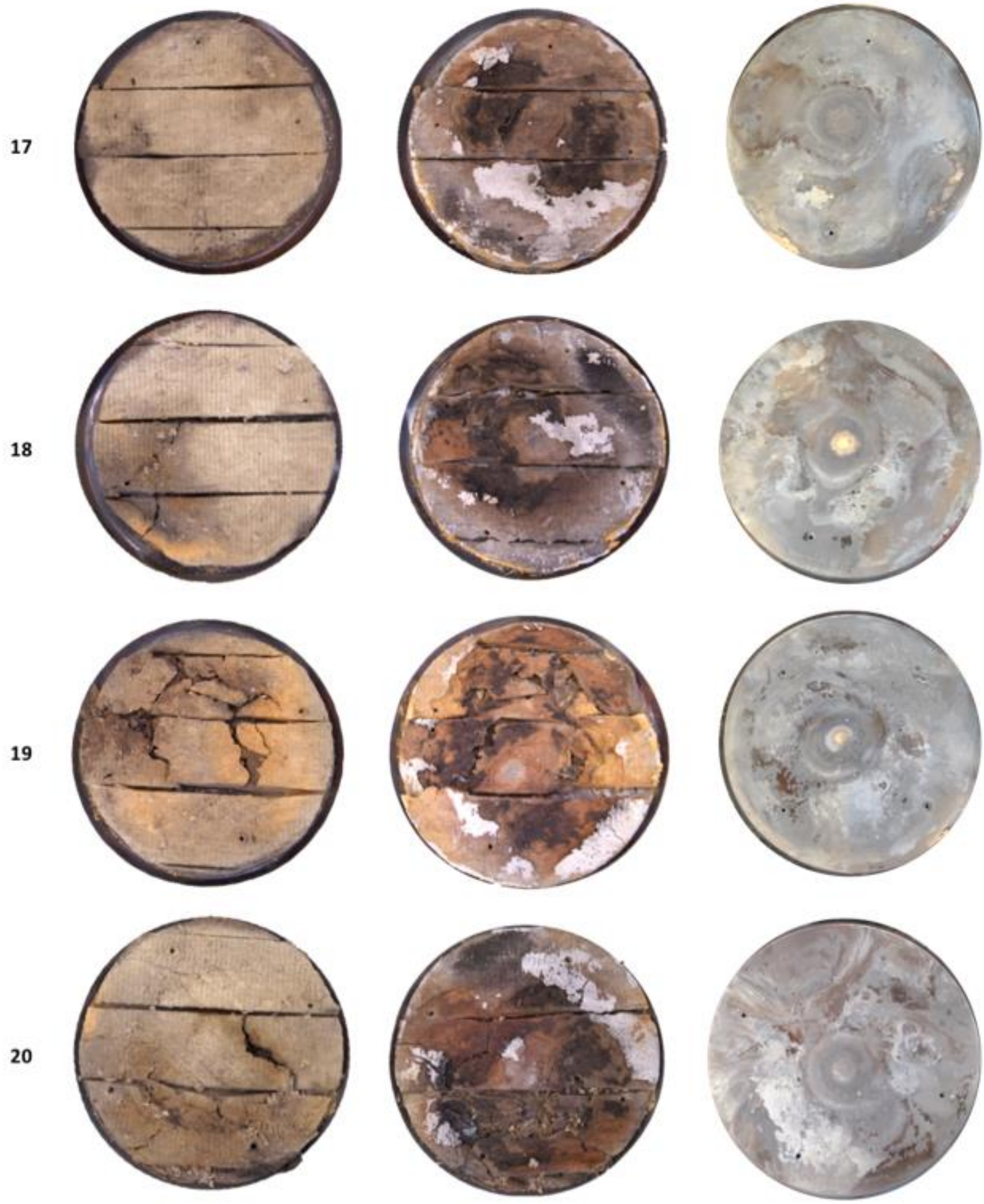


Figure I. 13 Insulation after testing for test 17, 18, 19 and 20. The column to the left shows the unexposed side of the insulation after testing, the middle column shows the exposed side of the insulation after testing, and the column to the right shows the exposed cladding. Each row represents one test.

Measures of the insulation after test 17, 18, 19 and 20 are presented in Figure I.14.

17a)

b)


18a)

b)


19a)

b)


20a)

b)


Figure I. 14 17a and b) Insulation after test 17. 18a and b) Insulation after test 18. 19a and b) Insulation after test 19. 20a and b) Insulation after test 20.

Appendix J: Pictures from small scale jet fire testing

Pictures of the exposed mock-up are shown in Figure J.1. Pictures of the equipment after testing are shown in Figure J.2 and Figure J.3.

Figure J. 1 Pictures of mock-up during testing.

Figure J. 2 Pictures of test equipment after testing.

Figure J. 3 Pictures of test equipment after testing. The upper right pictures show shards from the insulation after testing.

Appendix K: Rockwool Pipe Section Mat (Thermal insulation)

Rockwool Pipe Section Mat (PSM) consists of a rigid foil faced slab with factory machined grooves on the inside face to specifically suit large pipe diameters. The distance between the grooves is calculated to ensure that PSM closely fits the pipe wall with all grooves tightly butted together [26]. The product properties in accordance with EN 14303 are presented in Table K.1.

Table K. 1 Product properties of Rockwool Pipe Section Mat (PSM) [26].

Name	Description								
Material	Stone wool								
Operating range	-40 to 700 °C								
Name	Performance								Norms
Thermal conductivity	Tm°C	50	100	150	200	250	300	350	EN ISO 8497
	W/mK	0.041	0.046	0.054	0.064	0.075	0.088	0.106	
Maximum service temperature	700 °C								EN 14706
Melting temperature	> 1000 °C								
Reaction to fire	Euroclass A1								EN 13501-1
Nominal density	140 kg/m^3								EN 1602
Water absorption	$\leq$ 1 kg/m^2								EN 1609
	$\leq$ 20 kg/m^2								BP 172
Water vapor diffusion resistance	S_d > 200 m								EN 12086
Air flow resistivity	$\geq$ 60 kPa.s/m^2								
Designation code	MW EN 14303-T4-ST(+)700-WS1-MV2								EN 12086

The chemical composition of Rockwool is presented in Table K.2.

Table K. 2 Chemical composition of Rockwool [27].

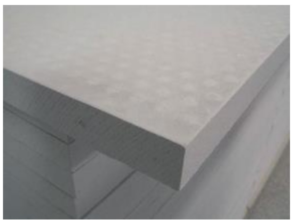
Material	Weight [%]
Mineral wool*	95 - 99
Bakelite (binder)	0 - 5
Mineral oil (dust absorbing)	0 - 1

*MMVF: Man made vitreous (silicate) fiber containing random orientation of oxides from alkaline metals and alkaline earth metals ($Na_2O + K_2O + CaO + MgO$) larger than 18 weight%.

NB! First time heating above 175 °C results in releasing of formaldehyde- and ammonia gasses which may be detrimental to health.

Appendix L: Instrumentation

Thermocouples		
	Producer	Pentronic AB
	Size	1.6 mm
	Type	K
	Material	Stainless steel mantle
	Max temperature	1200 °C
	Tolerance	±1.5 °C (0.4 % of reading > 375 °C)
Propane burner		
	Name	Turboroofer 346051
	Producer	Sievert
	Type	Titan Pro 60
	Hose connection	R3/8"V
	Neck tube	500 mm
	Effect	114 kW
	Diameter	60 mm
Plate thermometer		
	Name	Plate thermometer heat flux meter (PTHFM)
	Producer	Pentronic AB
	Model	5928050
	Type	K
	Size	106 mm x 106 mm x 31 mm
	Max temperature	850 °C (short time 1100 °C)
	Tolerance	±1.5 °C (0.4 % of reading > 375 °C)

Flux meter		
	Name	Propane flow meter
	Producer	Brooks Instrument
	Supplier	Zimsen Prosec Instrumenting
	Gas	C3H8/0 – 225 ln/min/0.343
	Inlet pressure	3 Bar
	Outlet pressure	0 Bar
Data logger		
	Producer	Keysight Technologies
	Name	Data Acquisition/ Data Logger Switch Unit
	Type	HEWLETT-PACKARD 34970A
Scamotek plate		
	Name	Skamotec 225
	Producer	Skamol
	Thermal conductivity	0.061 W/mK (10 °C) 0.07 w/mK (200 °C)
	Class	A1

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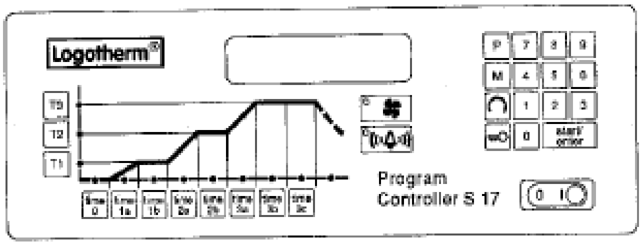
Appendix M: Instructions Nabertherm oven – Program controller S17

Nabertherm®	Program Controller S 17	Operating Instructions



Features

The program controller *S* 17:

- is an electronic temperature program controller
- has 9 memory locations for one program each (maximum 3 ramps and 3 holding times)
- can combine 2 or 3 programs together, so that a maximum of 9 ramps and 9 holding times are available for one program cycle
- can switch on/off an acoustic signal
- can switch socket outlet at the rear wall of the furnace on/off (max. 600 W, e.g. for fan)
- can control sequences of higher and lower temperatures
- can be swiched on with a pre-selection time

Safety

The S 17 switches:

- to the next time section only when the temperature set has been reached (temperature priority)
- the furnace on again (having been switched off manually or due to power failure) during a program cycle only:
  - if the interruption took place at time 0 (time 0 stops running during the power interruption)
  - if the temperature is higher than 100°C and has dropped by less than 20°C.

Fault indication

F3: Thermocouple defect (measuring circuit interrupted)*
F4: Thermocouple reversed*
F5: Temperature or time value entered incorrect**
F6: Controller defect*
Fb: Controller defect*
Fb-: Furnace does not heat*

Fault clearance:

* Call service technician
** Enter correct value

	Press button	Response	Remark
Entering a program 1. Switch on controller	0 I	Furnace temperature appears on display	If a holding time of 99 hours is entered, the holding time is then infinite. At temperature T3 an additional time 3c is available to switch on the acoustic signal, for instance, shortly before the end of the program (see" Switching on peripheral equipment").
2. Enter the time required within the next temperature shall be reached (in this case, 30 minutes)	time 1a, 3, 0	Relevant diode flashes 00:30 appears on display	A program entered in this way can be: - started immediately (Starting the program) - stored (Storing the program) - started with the automatic start-up (Switching on the furnace automatically)
3. Enter temperature (in this case 500°C)	T1, 5, 0, 0	Relevant diode flashes 500°C appears on display	
4. Enter time throughout T1 shall be held (in this case 2 hours and 15 minutes)	time 1b, 2, 1, 5	Relevant diode flashes 02:15 appears on display	
5. Continue as under point 2			
Switching on the peripheral equipment Switch on acoustic signal (in this case during time 3c)	time 3c	Diode time 3c flashes Diode lights up	Switching on of the socket-outlet at the rear wall of the furnace or of the acoustic signal can be assigned to each time section.
Switch on fan - here this means switch on socket-outlet at rear wall of furnace - (in this case during time 2b)	time 2b	Diode time 2b flashes Diode lights up	The fan can also be switched on and off independently of the program by pressing the symbol button.
Starting the program	start/ enter	Furnace switches on. Temperature appears on display	The LED of the time axis indicates the program section. On completion, the furnace switches off automatically. The last LED remains alight until the furnace is switched off. Temperature of the heating chamber is indicated. A black point in the left corner of display indicates that the furnace is heating.

Details without guaranty, subject to alteration.
Text and design: TECH INFO KÖSLER

Nabertherm, Bahnhofstr. 20, D-2804 Lilienthal/Bremen
Telefon 49 (4298) 2709-0, Telex 246 881 nabe d; Fax 49 (4298) 8309

Made in Germany
Reg.-Nr. B 3.14/05.92

Nabertherm® | **Program Controller S 17** | **Operating Instructions**

	Press button	Response	Remark
Storing a program (in this case in memory location 7)	M 7 start/enter	S=7 appears on display	Time for automatic start-up cannot be stored.
Calling up a stored program (in this case from memory location 5)	P 5 start/enter	P=5 appears on display	By pressing start/enter again the program will be started
Checking entered values Check temperature value (in this case T3)	T3	Relevant diode flashes. Temp. value appears on display.	The value called up is indicated for a period of 10 secs.
Check time value (in this case time 4)	time 3c	Relevant diode flashes. Before start: programmed value is indicated / After start: remaining time is indicated	The program is not interrupted by the checking procedure.
Altering values in stored program Call up program (in this case program 4) Alter value (in this case T2 into 950°C) Store program	P 4 start/enter T2 9 5 0 M 4 start/enter	Old value T2 is indicated, then 950°C appears on display	All values entered can be altered. If an alteration is made whilst a program cycle is running, the button start/enter must be pressed afterwards.
Switching on the furnace automatically Enter waiting time (in this case the furnace will switch on automatically after 1 hour and 20 minutes)	time 0 1 2 0 start/enter	01:20 appears on display Waiting time remaining appears on display	time 0 must be pressed before starting a program. The time remaining until the furnace switches on automatically is indicated.
Locking a program which has started	⊸●		To cancel locking: switch off controller.
Combining programs together (in this case programs 5,7 and 4)	P 5 ∩ 7 ∩ 4 start/enter	P 5-7-4 appears on display	It is possible to link 2 or 3 programs in freely selectable order.
Start the program	start/enter	Respective program and furnace temperature appear on display	
Deleting a program	P 0 start/enter	PO and max. permissible furnace temperature appears on display.	A running program will be immediately terminated.
Deleting a stored program (in this case program 6)	P 0 start/enter M 6 start/enter	PO and max. permissible furnace temperature appears on display.	A running program will be immediately terminated. If the program has been stored all values of this program are set at zero.

Details without guaranty, subject to alteration
Text and design: TECH INFO KÖSLER
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Made in Germany
Reg.-Nr. 8 2 14/05 92

Appendix N: Test procedure – Oven testing of insulation

When the oven is placed in a safe location, near an exhaust hood, the following procedure is to be followed:

1. Start with cutting an insulation sample with the measure 5 cm x 5 cm x 5 cm. If the insulation has a layer of aluminium in the bottom, this should be removed.
2. Place the sample on the ceramic plate and place it in the centre of the oven.
3. Place one thermocouple in the centre of the insulation and one thermocouple in the upper part of the oven.
4. Connect the two thermocouples to each of the thermometers.
5. Close the oven and press the On/Off switch. The oven is now to be programed, depending on the target temperature as show in Table N.1.

Table N. 1 Set time and hold time for each set temperature.

Set temperature	Set time	Hold time
700 °C	45 minutes	30 minutes
750 °C	50 minutes	30 minutes
800 °C	55 minutes	30 minutes
900 °C	60 minutes	30 minutes
1000 °C	75 minutes	30 minutes
1100 °C	90 minutes	30 minutes

6. To program the oven, start by pressing T1 and set the wanted set temperature, end with pressing the Start/ Enter button, see Figure N.1.
7. Time 0 should be equal to 0.
8. Time 1a should be set to the wanted set time, end with pressing the start/enter button.
9. Time 1b should be set to be the wanted hold time, end with pressing the start/enter button.

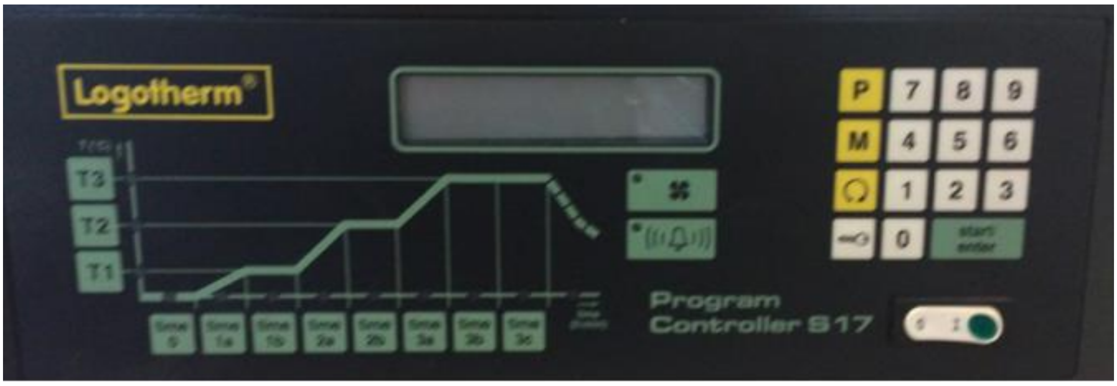

Figure N. 1 Nabertherm Logotherm Program Controller S17.

10. Use a stopwatch to control the time. Read of and not the temperature each minute until the hold time is finished. The temperature should be noted each 15 minutes, during the cooling time.
11. Let the oven completely cool down before opening its to be opened.
12. When the oven has cooled down, take out the insulation sample and measure the height.

Appendix O: Results from Oven testing of insulation

O.1 Heating up to 750 °C

Temperature recordings as a function of time, with a set temperature of 700 °C and a hold time of 30 minutes, are presented in Figure O.1 The temperature was recorded each minute. “Oven” represents the measured temperature by the oven thermostat, and “Insulation” represents the temperature recordings in the centre of the insulation.

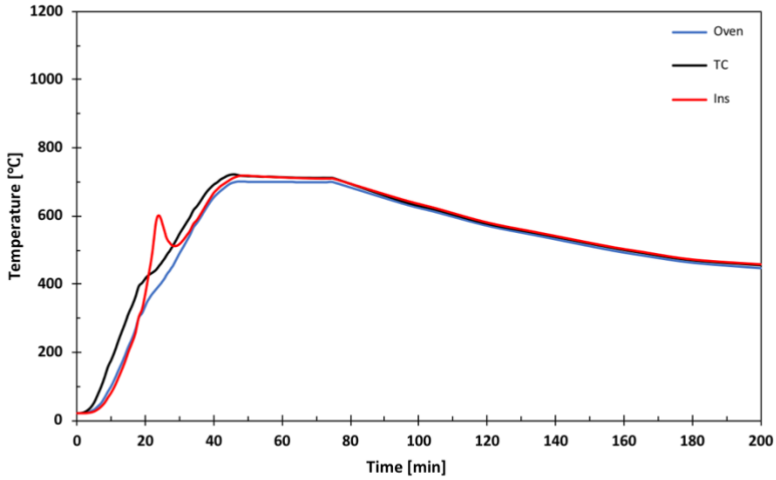

Figure O. 1 Temperature as a function of time, with a heating rate of 22 K/min and 30 minute holding time at 700 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

O.2 Heating up to 750 °C

Figure O. 2 shows the temperature recordings as a function of time, with a set temperature of 750 °C and a hold time of 30 minutes. The temperature was recorded each minute. “Oven” represents the measured temperature by the oven thermostat, and “Insulation” represents the temperature recordings in the centre of the insulation.

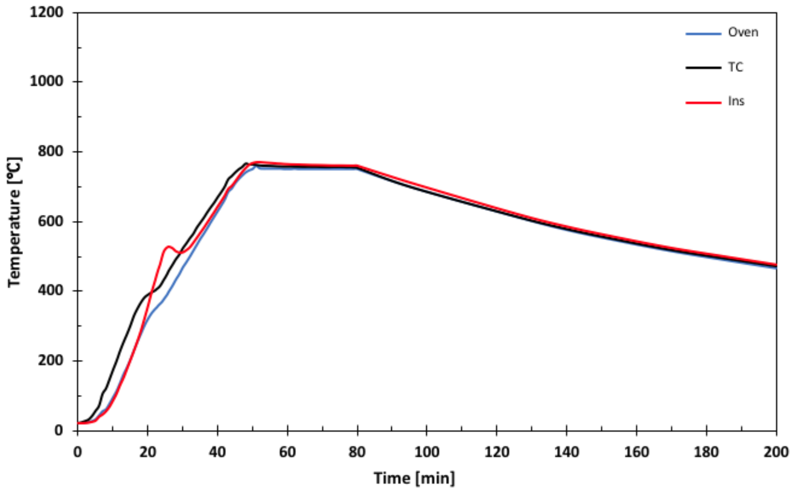

Figure O. 2 Temperature as a function of time, with a heating rate of 21 K/min and 30 minute holding time at 750 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

O.3 Heating up to 800 °C

Figure O. 3 shows the temperature recordings as a function of time, with a set temperature of 800 °C and a hold time of 30 minutes. The temperature was recorded each minute. “Oven” represents the measured temperature by the oven thermostat, and “Insulation” represents the temperature recordings in the centre of the insulation.

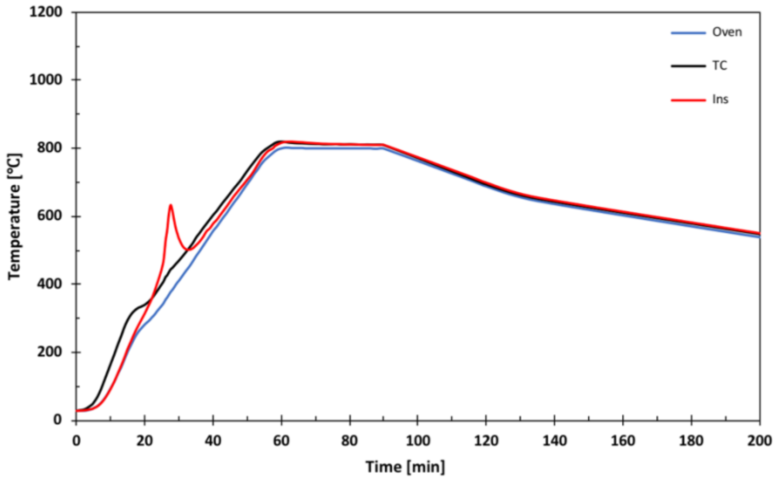

Figure O. 3 Temperature as a function of time, with a heating rate of 18 K/min and 30 minute holding time at 800 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

O.2 Heating up to 900 °C

Figure O. 4 shows the temperature recordings as a function of time, with a set temperature of 900 °C and a hold time of 30 minutes. The temperature is plot for each minute. “Oven” represents the measured temperature by the oven thermostat, and “Insulation” represents the temperature recordings in the centre of the insulation.

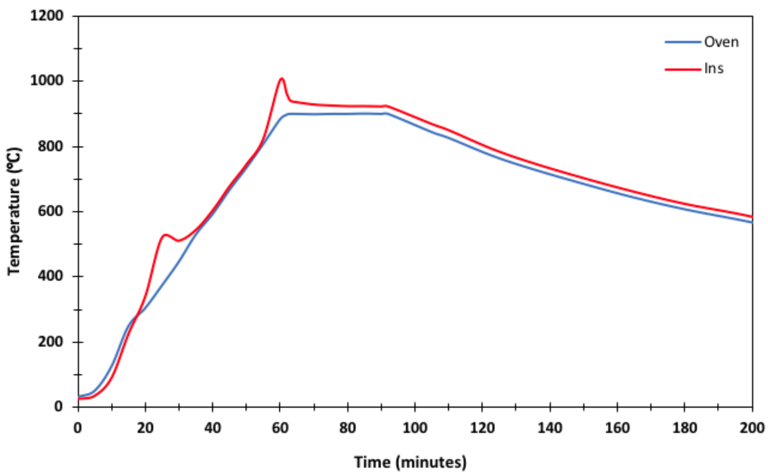

Figure O. 4 Temperature as a function of time, with a heating rate of 20 K/min and 30 minute holding time at 900 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

O.3 Heating up to 1000 °C

Figure O. 5 and Figure O. 6 shows the temperature recordings as a function of time. The oven is heated up to 1000 °C, with a set time of 75 minutes. The temperature is plot for each minute. "Oven" represents the measured temperature by the oven thermostat, and "Insulation" represents the temperature recordings in the centre of the insulation.

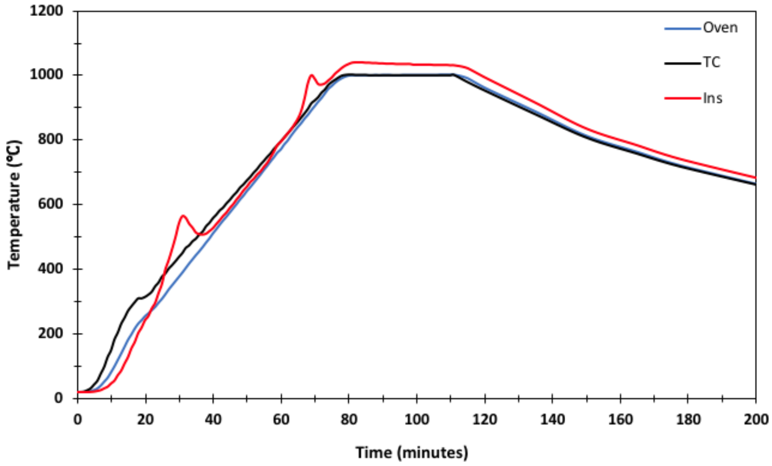

Figure O. 5 Temperature as a function of time, with a heating rate of 17 K/min and 30 minute holding time at 1000 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

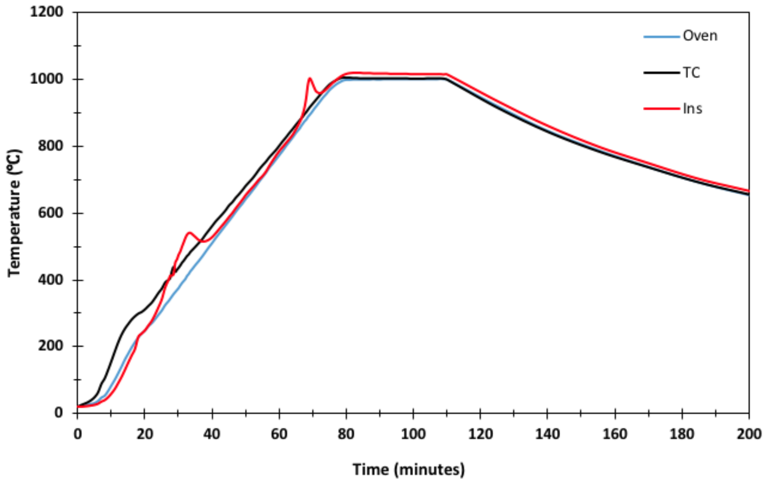

Figure O. 6 Temperature as a function of time, with a heating rate of 17 K/min and 30 minute holding time at 1000 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

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O.4 Heating up to 1100 °C

Figure O. 7 and Figure O. 8 shows the temperature recordings as a function of time. The oven is heated up to 1100 °C, with a set time of 90 minutes. The temperature is plot for each minute. "Oven" represents the measured temperature by the oven thermostat, and "Insulation" represents the temperature recordings in the centre of the insulation.

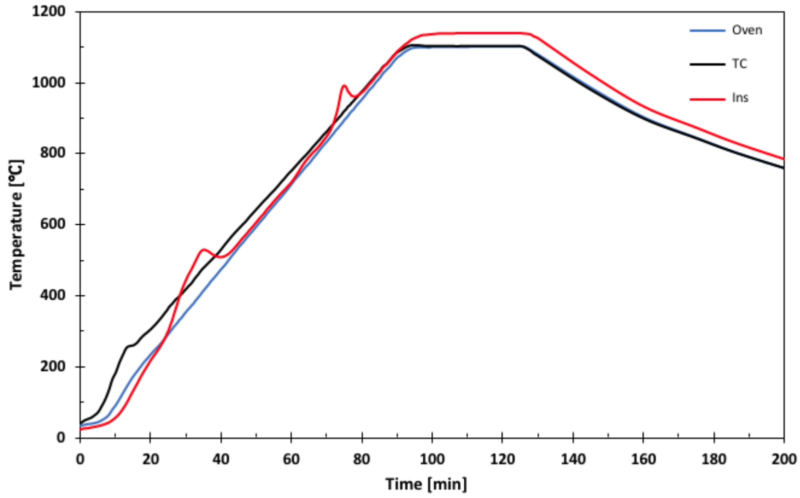

Figure O. 7 Temperature as a function of time, with a heating rate of 15 K/min and 30 minute holding time at 1100 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

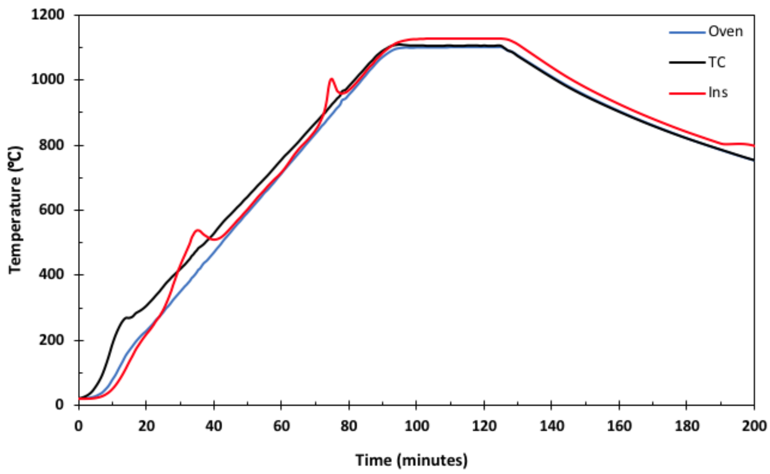

Figure O. 8 Temperature as a function of time, with a heating rate of 15 K/min and 30 minute holding time at 1100 °C. Oven, TC and Ins represent the temperatures recorded in the muffle oven, by an external thermocouple and inside the thermal insulation, respectively.

Appendix P: Pictures from Oven testing of insulation

Two insulation samples, before (to the left) and after the test with a set temperature of 900 °C (to the right), are shown in Figure P.1.

Figure P. 1 Insulation specimen before (to the left) and after (to the right) the oven testing. The picture to the right is the insulation specimen after the test with a set temperature of 900 °C.

Pictures of the insulation samples after test 4 and 5 at 1100 °C are shown in Figure P.2.

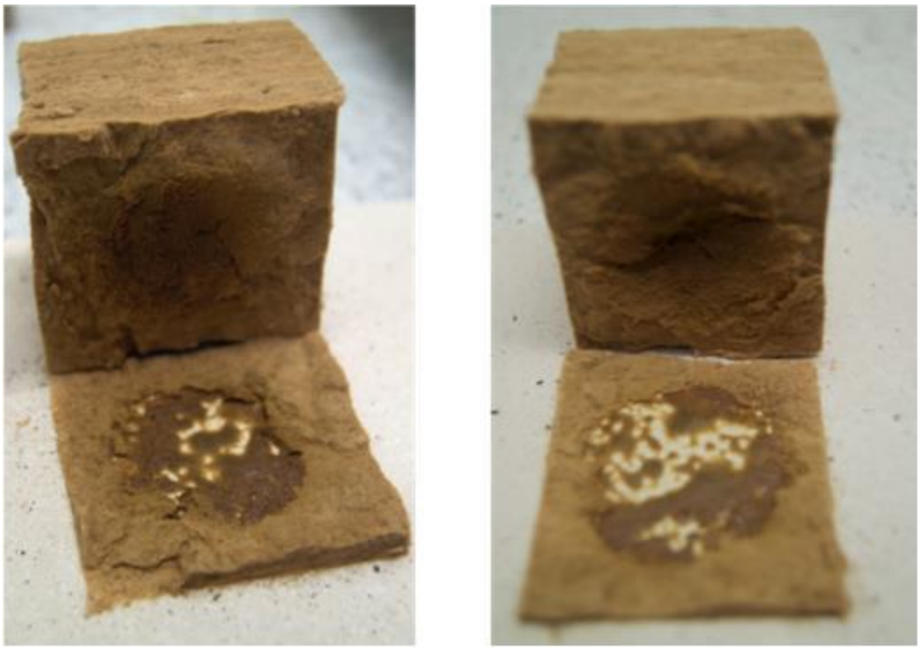

Figure P. 2 Insulation specimen after test 4 (to the left) and 5 (to the right), were the oven is heated to 1100 °C.

After the tests were the oven was heated up to 900 °C, 1000 °C and 1100 °C, small soot particles were observed inside the oven, as shown in Figure P. 3. These were not observed after the test were the oven was heated up to 750 °C.

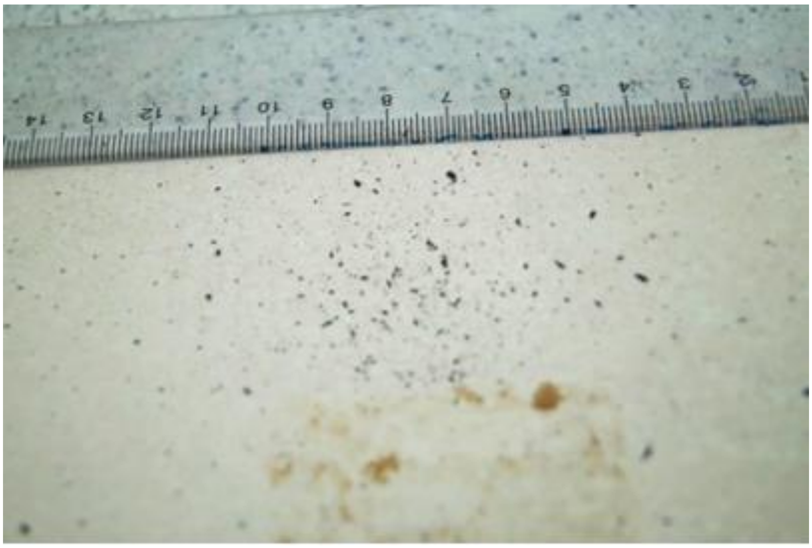

Figure P. 3 Soot particles observed after testing up to 900 °C, 1000 °C and 1100 °C

Picture of the insulation after heating up to 750 °C, is shown in Figure P.4.

Figure P. 4 Insulation specimen after heating up to 750 °C.