Fire resistance in a sunshading element

as an alternative design solution for fire retardant glazing

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Colophon

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Picture of glass shards from the measurements (Goldbach, 2016)

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“Fragments bring hapiness”

Abstract

This master thesis of the Building Technology track concerning fire resistance in a sun shading element as an alternative for fire retardant glazing was produced by the idea of Wiebe Schotanus from the Safety Region Haaglanden, who proposed the idea of combining sunshading and fire retardant properties as an alternative design solution for fire retardant glazing.

The subject fire safety has grown in the past years into a major field of study, which is becoming more important in the building industry. This growth can also be seen in changes in the Dutch Building Decree the past years and in the built environment. Also in architecture there is an increasing demand for glass. Because of these factors also the demand for fire retardant glazing has increased as well as the demand for other fire retardant products and sunshading.

In order to meet the increasing demand for glass in architecture, coupled with the increasing demand for sunshading elements and the growth of fire retardant products, in this thesis a concept design is developed for a fire retardant sun shading element as a design alternative for fire retardant glazing in public buildings. Herewith the chance on the development of fire by flash-over via the outside of a building should decrease and a cheaper design alternative for fire retardant glazing is proposed.

To develop this concept research studies has been done to fire development, rules regarding fire safety in public buildings in Holland according to the Dutch Building Decree, fire retardant and sunshading products and materials in order to set a program of requirements. This is followed by simulations in the computer programs TRA and TRISCO in order to simulate the heat transfer during a fire in a room, especially in the glass and the façade and in order to determine the optimal distance between the window and the sunshading element on the inside. Also simulations are made with the same distances (75 and 100 mm) between the window and the element as the distances used in the measurements in order to compare them. With the use of prototypes made out of playing cards, wood and steel a couple of problems were solved and the mechanism to open and close the sunshading were tested. The mechanism of the fire retardant shading element closes automatically in case of fire, without the use of human effort or electricity. This is done by a wire which melts at high temperatures, with the result that the lamellae close automatically.

At last measurements are performed in an oven of 700 degrees Celsius in order to test this self-closing mechanism and to measure the temperature rise in the glass in different situations, with the use of the fire retardant shading element and with two different glass thicknesses of 4 and 6 mm. The fire retardant shading element is tested at a distance of 75 and 100 mm from the window, in opened and closed situation and at last also a closed element with a fire retardant coating at a distance of 75 mm is tested. The system closed itself, because of the high temperatures and the melted wire, in around 10 seconds. One of the most important conclusions for as well the simulations as well as for the measurements is that how further away the element is from the heat source (fire), the less radiation it receives and how longer it takes for the glass pane to break. Also it takes longer for the glass to break when the 6 mm glass pane is used, because of the bigger mass. The fire retardant coating expanded because of the high temperatures from 1 mm to 20-30 mm, but did not have a remarkable effect on the time in which the glass pane broke. This probably because of the higher temperature in the oven in comparison to the other measurements and because of the conducted heat from the steel frame to the glass, because the frame was not coated or insulated and heat transfer from the steel to the glass was possible. But the fire retardant coating prevented the flames from raging to the outside of the element and the window when it was broken. So the element does prevent flash-over via the outside.

Hereby a concept design is developed for a design alternative for fire retardant glazing. Naturally, this concept needs further study and more testing before it will become a definitive alternative design solution for fire retardant glazing.

Acknowledgement & Preface

This master thesis is the end of a 5 year study period at the Faculty of Architecture of the TU Delft. The subject fire safety for this master thesis is born while doing the bachelor and as well the master at the Faculty of Architecture & the built environment at the Delft University. After all the theory and projects I barely learned anything about fire safety, although it has been become more important in the building industry. To fill this gap of knowledge before graduating the decision had been made to do my final thesis about the subject of fire safety. With the integration of the subjects sunshading, fire safety and design a concept design of a fire retardant shading element is developed.

Although it was not their specialism, I want to thank my mentor team for all their help and their support during the graduation period. I want to thank my first mentor Fred Veer for his ability to put things into perspective when I could not and for all his knowledge about glass. My second tutor Regina Bokel I like to thank for her help with the simulations, the research and building physics part of this thesis. Because of them I had the opportunity to learn more about fire safety before graduating. Also I want to thank Kees Baardolf for teaching me the principles of working with steel and his endless willingness to help me with building the prototypes, the model and his help during the tests in the oven. And at last I want to thank my parents for their moral and financial support during my bachelor and master, so I was able to finish this study properly within five years.

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List of abbreviations

WBD	Resistance against fire penetration
WBO	Resistance against flash-over
WBDBO	Resistance against fire penetration and flash-over

Glossary

Fire penetration	Fire expansion from one space to another space, through the construction. This will occur when the construction is burning, when the construction loses its cohesion or when in an intact structure the temperature on the non-fire side will increase high enough so that ignition occurs.
Fire propagation	This will occur in the same room, mostly by the interior. This may also occur because of internal flash-over.
Fire resistance	The time that these constructions can be resistive to fire, without the occurrence of flash-over.
Flash-over	The expansion of fire from one building to another building or via the outside from one room to another room in the same building, because of (raging) flames, embers or heat flux. Flash-over can also occur inside the room, for example between furniture, but when this is the case it will be explicitly mentioned.

1. Introduction

Introduction & research questions

The subject fire safety for this master thesis is born while doing the bachelor and as well the master at the Faculty of Architecture & the built environment at the Delft University. After all the theory and projects I barely learned anything about fire safety, although it has been become more important in the building industry. To fill this gap of knowledge before graduating the decision had been made to do this final thesis about the subject of fire safety.

Relevance

To get to know the current problems on fire safety in buildings the research has to begin at the people who know most of fire safety and fire prevention, namely the fire department, the people who give training for fire-fighters and also the fire consultancies. Therefore the Dutch Institute of Physical Safety (de Witte, L) and the fire department of The Hague (Schotanus, W.) were contacted to get to know the current problems of fire safety in buildings. The result was an unequivocal answer; the difference between what is said on paper and thus in the theory of fire safety, and what is happening in reality during a fire. Also the smoke expansion through the construction and, in particular for architects, the lack of integration of fire safety and design are current big problems in fire safety in buildings. That is where the question about fire safety in sunshading had arisen. Architects are designing more with glass (façades) and because of all the glass sunshading is, besides the specifications of the glass, becoming more important to keep the indoor environment comfortable. With glass surfaces also the risk of flashover of fire via the outside will be higher. That is where the fire retardant glazing is playing an important role. The government also wants more fire safety glass in public buildings like schools, day-cares, hospitals and governmental buildings. Architects are looking for an alternative design solution for fire resistant glass, because this glass is relatively expensive in comparison to normal double or HR++ glass and not always wanted, especially in monuments where it will not always fit into the existing frames.

Aim & research question

The aim of the research is to get insight in fire retardant glazing and other fire retardant products, sunshading products, how they work and from which materials they are made and from this conclude which materials and methods are best to use for the fire retardant shading element. It is also important to master the current rules regarding fire safety in public buildings. Therefore the following research question is made:

In which way is it possible to use sunshading as a fire retardant element, such that it will be an alternative design solution for fire retardant glazing in public buildings in Holland?

What are the criteria and specifications of the fire retardant element?

- What are the current rules in Holland regarding fire resistance of windows?
- What are the current criteria for fire retardant glazing and how does it work?
- What criteria should the fire retardant sunshading element meet?
- What is the influence of the distance between the element and the window?
- What is the critical time in which the system has to close in order to prevent the window from breaking?
- How to ensure that the system will close automatically in case of fire?
- How to ensure natural ventilation via the window and what will be the influence during fire?

Which materials will be used?

- What kind of materials is best to use for the sunshading?
- What kind of materials is best to use for the fire resistance?
- What will be the influence of UV over time?
- What is the sustainability of the materials?

What will be the durability of the element?

- How is the price in relation to current fire retardant glazing and sunshading?
- How to prevent malfunction, possible damage and wearing?
- What will be the performance of the sunshading element in relation to thermal comfort?

What will be the influence of a fire retardant sunshading element on a fire and what will be the consequence for the fire fighters?

Project location

The location of the problem is public buildings in Holland in general. This because the rules and criteria regarding fire safety which are used are rules which are set in the Dutch Building Decree. For every common type of building different rules are set. To limit the rules only the ones that apply to public buildings are used, because the problems mostly occurs in these types of buildings.

The posed problem
The posed problem is the lack of integration between fire safety and design in architecture and the high costs of fire retardant glazing. Also the problems which occur when fire retardant glazing needs to be placed into the older frames of monumental buildings are a problem.

Design assignment
The design assignment will be a concept for a design for a sunshading element, which also functions as a substitute for fire retardant glass.

Method

To get to know the current relevant fire safety problems the Dutch Institute of Physical Safety and the fire department of The Hague were contacted to get insight in the current fire safety problems. Then a literature study is be done in order to get the basic knowledge about fire, fire development, fire safety and the current rules and regulations regarding fire safety in public buildings in Holland. Then a research was done concerning current fire retardant glazing and other fire retardant products. For sunshading products also this study is done. In these studies the materials, properties, the mechanism and the advantages and disadvantages are being discussed and used as reference. Also the lectures of the Civil Engineering course Fire Safety Design (CIE5131) were studied and with this course a visit was made to the Efectis Fire Laboratory in Bleiswijk and an official fire test was attended.

After the research fire simulations in a small room (3.6 x 3.6 x 3.6 meters) and a large room (7.2 x 7.2 x 3.6 meters) were made in order to determine the optimal distance between the fire retardant shading element and the window. This optimal distance is important for the functionality of the element, to determine the heat transfer from the fire to the element and from the element to the window and to reduce the loss of space in the room. For this simulation the program Thermal Radiation Analysis (TRA) is used for simulating the heat flux. The conduction and convection of the heat is simulated in the program TRISCO. Also a variation on the 4-16-4 millimetre glass is simulated in order to determine the effect of the thicker glass panes (6-16-6 millimetre) and to determine the criteria of the glass for the program of requirements. The results of these simulations were used in order to supplement the program of requirements. At last also simulations were done with the same distances between the window and the element as the distances used in the measurements, in order to compare the results of the measurements with the simulations.

When this was done the design of the fire retardant shading element was further developed, in combination with a material study for the element and the mechanism. This mechanism for the shading element was also developed and made into a prototype to see if it was working properly. After a test measurement the real measurements were done. These tests were done with the prototype in an oven and the element at different distances from the window in order to determine the temperature rise in the element and in the glass over time, with the use of an infrared thermometer. These measurements were performed until the glass pane broke. Also the time in which the mechanism of the element closes itself was tested with these measurements. At last a measurement was done with a fire retardant coating on the element. When all the measurements were done extra attention was paid to the complete design.

2. Theoretical framework

Fire

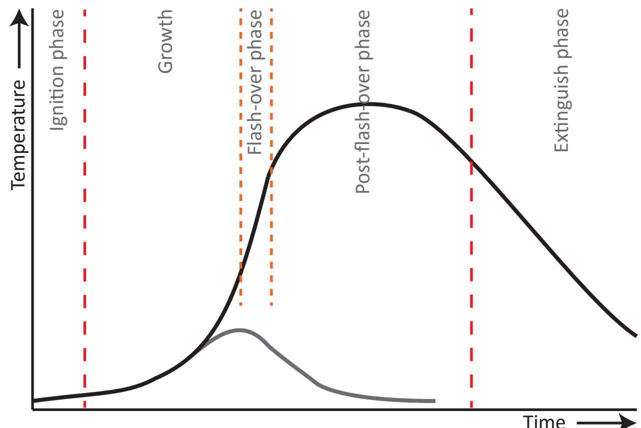
To get to know the behaviour of fire and the behaviour of materials in a fire in the theoretical framework the theory of fire, rules and regulations and specifications for the fire retardant shading element are explained as well as for the fire retardant glazing and other fire retardant products.

Development of fire

A fire in a compartment consists of three phases, namely the ignition, the fully developed fire and the decay of the fire. The phase of ignition and the increase of temperature and smoke will occur from 0 degrees to around 300 degrees Celsius. In the second phase the fire is fully developed and the temperature will rise from 500 degrees to 1000-1200 degrees Celsius. Then the fire will reach the third phase, namely the decay of the fire. At this moment most of the materials is burnt and the temperature will also decrease [Van der Veek & Janse, 2005].

A two-zone fire model is a model where the fire is located in the cold zone and the products of combustion in the hot zone. This is the pre-flash-over phase. In this phase the fire will spread in all directions with an equal speed. In the post-flash-over phase everything in the room is on fire. If all the 'fuel' for the fire is burnt the fire will extinguish. In the graph you see the graph of fire development in a space. Here five phases are shown [Herpen, 2012]:

- The smoulder phase (ignition phase): here the fire starts.
- Pre-flash-over phase (growth): the development of fire until flash-over occurs.
- Flash-over phase: in case of flash over the temperature is that high that gasses will burn or the heat flux will be so high that the fire load will ignite.
- Post-flash-over phase: the phase of a fully developed fire.
- The extinguish phase: decay of the fire because all the fuel is consumed or extinguishing of the fire by fire fighters.



Graph 1: five phases of fire development (Lamont, 2001)

A very important thing to keep in mind while studying fire physics is that everything is assumed and calculated into models and however these models will be an approximation of real life, in real life the behaviour of fire will always be different because it is very unpredictable [Herpen, 2012].

Heat transfer in fires

To measure or simulate a fire there are two important kinds of heat transfer that have to be kept in mind, namely radiation and convection. These two factors represent the total heat transfer during a fire.

When radiation is occurring there is a heat transfer from one place to another place, in the form of electromagnetic waves, without a transfer medium. When this incident radiation reaches an object, a part of the heat is absorbed, another part is reflected and the rest is transmitted.

$$a+\rho+\tau=1$$

With
a = absorption of the incident radiation
ρ = reflection of the incident radiation
τ = transmission of the incident radiation

The heat transfer through radiation can be calculated with the use of the Stefan-Boltzmann law:

$$q_s = \varepsilon * \sigma * T^4$$

With
q_s = heat flow density of the emitted radiation
ε = emission coefficient of the materials surface
$\sigma = 56.7*10^{-9}$ (Stefan Bolzmann constant)
T = absolute temperature in Kelvin

Convection is the other way of heat transfer during a fire. In this case the heat is transferred through a transfer medium. This can be for example air or fluid. The gradient of heat transfer is then dependent on the velocity of the transfer medium and the temperature difference between the transfer medium and the object. This can be shown in the next formula:

$$q = h*A*(T_s-T_f)$$

With q = heat transfer per time unit
h = heat transfer coefficient
T_s = temperature of the surface
T_f = temperature of the fluid

So the total heat transfer is a combination of the heat transfer by radiation and the heat transfer by convection:

$$q_{total} = q_{radiation} + q_{convection} = \varepsilon*\sigma*T^4+h*A*(T_s-T_f) \text{ in W/m}^2$$

The relation between the incident heat flux, the temperature rise in the glass and the time can be found in the next formula:

$$Power*time = \rho*c*volume *\Delta T$$

With power in Watt
time in seconds
ρ in kg/m^3
C in J/kg*K
volume in m^3
ΔT in Kelvin

At last there is a formula for the heat intensity. The amount of energy will decrease when the distance to the heat source increases. The energy decreases with the squared distance, this is also called the inverse square-law:

$$Intensity = radiation / (4*\pi*radius^2)$$

With intensity is energy per m^2 per second
radiation in Watt

This law only applies for a point source. In case of the measurements a line source applies. In case of a line source the source of the radiation will have the form of a cylinder. The intensity will then be:

$$Intensity = radiation / (2*\pi*radius)$$

With intensity is energy per m^2 per second
radiation in Watt

So with the line source as heat source (as used in the measurements with the bricks in the oven) the decrease of the energy happens less rapid than in comparison to a point source [Waldron, 1989]. To get the optimal distance between the window and the element consideration should be given to the fact that when the distance between the window and the element increases, the distance to the fire decreases and thus also the heat intensity.

Fire development and rules and regulations concerning public buildings in Holland
In the Dutch Building Decree rules are set concerning building, using and demolishing of a building. Here an overview is given of the rules concerning fire penetration and flash-over.

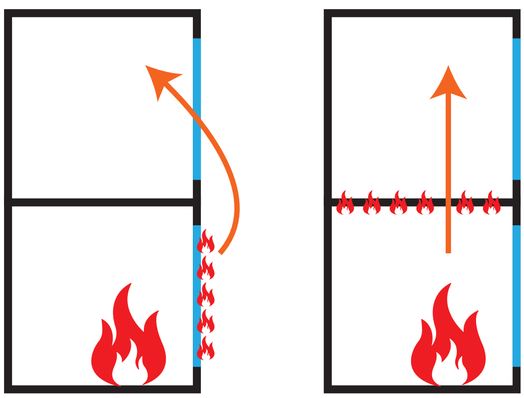


Figure 1: flash-over & fire penetration

In order to reduce the spread of fire a building is often divided into fire compartments. In general a fire compartment cannot exceed the area of 1000 m^2. To this compartment rules are set regarding the fire safety. These rules mostly concern the resistance against fire penetration (WBD) and flash-over (WBO), the WBDBO. This is the Dutch abbreviation of 'weerstand tegen branddoorslag (WBD) en brandoverslag (WBO)'. Fire penetration is the spread of fire via the inside of the building. The WBD is the degree to which this expansion of fire via the inside of the building is prevented. Flash-over is the spread of fire via the outside of the building to another part of the building. The WBO is the degree to which this expansion of fire via the outside of the building is prevented. For flash-over the heat flux becomes important. When the heat flux on the threated space becomes more than 15 kW/m^2 radiant flux, preventive fire safety measures must be taken in order to prevent flash over. [Van der Veek et al., 2005] This heat flux consists of two factors, namely the radiation through the openings in the fire compartment and the radiation of the raging flames. The radiation through the openings in the fire compartment is the radiation of the heat because of the fire in the compartment. The radiation of the raging flames is the radiation caused by the raging flames out of the window. This combination is the heat flux which reaches the window of the threated space. The 15 kW/m^2 is a fixed average based on possible combustibles and scenarios, where a fire will rise. [Van der Veek et al., 2005]

In case of flash-over glazing in the façade will be the weakest link, because windows will break in the first minutes of a fire and the openings will become a source for the expansion of fire, smoke and heat and a source for oxygen, which is one of the elements needed for a fire. [Tupker, 1961]

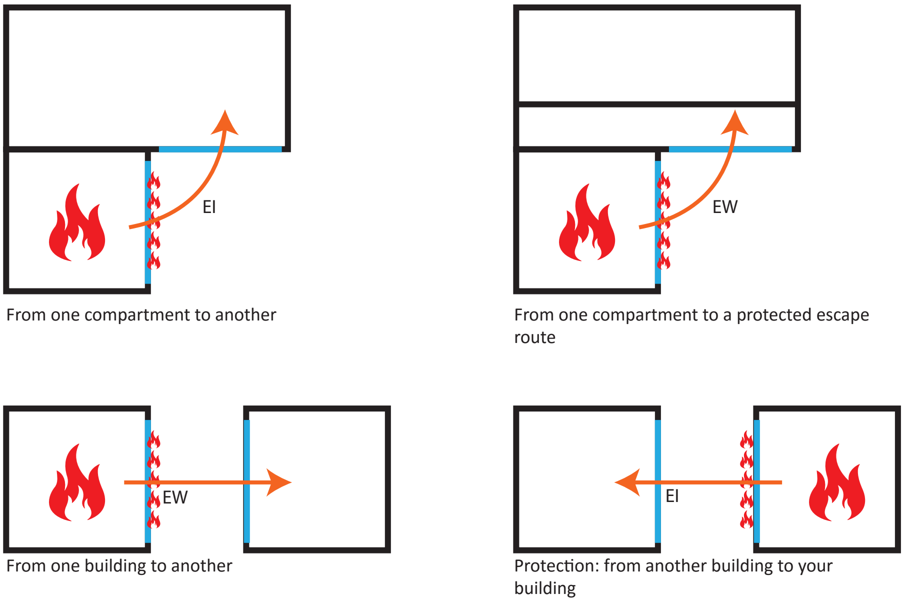


Figure 2: cases of flash-over and the Dutch Building Decree

In the Dutch Building Decree cases are described to prevent the spread of fire. Fire safety measures in the façade are needed when there is a risk of spread of fire between one fire compartment to another fire compartment, or from one compartment to a protected escape route, to an elevator shaft of a fire fighters elevator and to a not-closed protected escape route (see Figure 2). The resistance against fire penetration and flash-over has to be at least 60 minutes, according to NEN6068 [BRIS Bouwbesluit online, 2015]. The requirement of 30 minutes only applies for fire compartments in a utility building where the highest floor is at a height of 5 meters or less (7 meters for residential functions) and it also applies for low buildings on the same plot and for a fire compartment where the maximum fire load is 500 MJ/m^2 [Bris Bouwbesluit online, 2015]. Also fire safety measurements are needed when there is a risk of spread of fire from one building on one lot to another building on the adjacent plot. In this case symmetry of an identical building on the adjacent plot is in order (see Figure 3), which façade is the same distance from the property boundary as the face of the respective building. In case there is no construction zoning on the adjacent plot and it is not intended as a playground, campground or storage of flammable substances, symmetry can take place as if the field is situated adjacent to public green. If a deviation of these rules is necessary, equivalence to these rules must be demonstrated. [BRIS Bouwbesluit online, 2015]

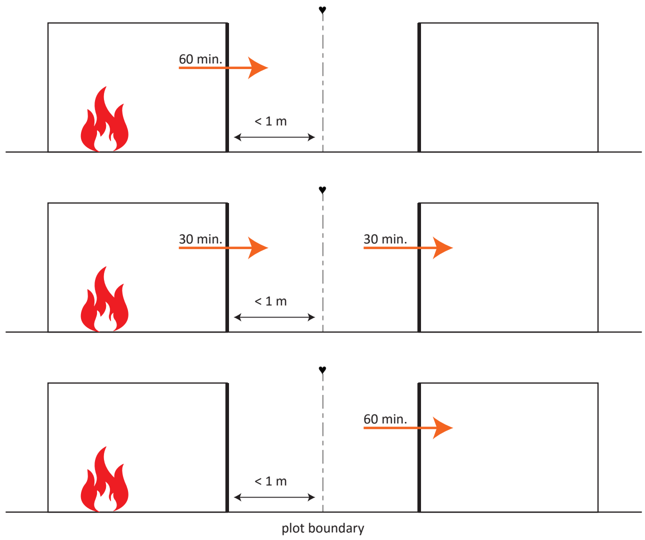


Figure 3: symmetry and the risk of fire spread

Fire safety glass

Here the classification of fire safety glass and the different types of fire safety glass are explained, in combination with how they work and the specifications of the glazing.

A single pane of float glass will crack during the first two minutes of a fire. A double pane of float glass will crack between 2 and 5 minutes of fire. This is not enough to be considered fire safe, therefore fire safety glass is produced. There are three different kinds of classifications for fire safety glazing, namely E, EW and EI [NEN-EN 1999-1-2:2007 & NEN-EN 12101-9:2004]. The criteria are explained below:

- E (integrity): Fire-protective rated glass: this glass stops the spread of fire and smoke from the fire side to the non-fire side; integrity without radiation control.
- EW (integrity plus heat flux control): this glass stops the spread of fire and smoke from the fire side to the non-fire side and has very high heat insulation. The heat flux at the non-fire side at 1 meter distance will not exceed 15 KW/m^2 during a certain period of time. [Van der Veek et al., 2005]
- EI (integrity and insulation): Fire-resistive rated glass: this glass stops the spread of fire and smoke from the fire side to the non-fire side and has a partial heat reduction up to <15KW at 1 meter distance. The average temperature on the not-heated side will not rise above 140 degrees Celsius and the local maximum temperature on the not-heated side will not

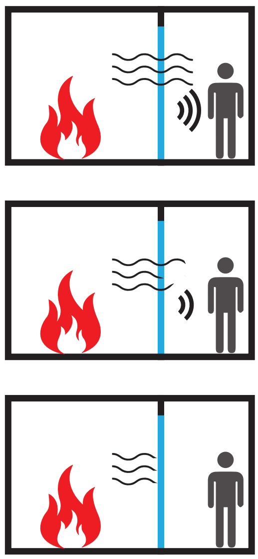


Figure 4: E, EW & EI

rise above 180 degrees Celsius. [Van der Veek et a., 2005] There is also a DH classification, but this classification is not applied on glass, because this classification is only for products which function as a smoke barrier, to prevent smoke expansion.

In general there are more than sixteen different fire retardant techniques for fire safety glass. These techniques can be globally classified into five classifications, namely safety wired glass, full tempered glass, full tempered glass with coating, full tempered glass with an epoxy resin interlayer and fire-resistant glass with intumescent interlayers. These classifications are explained below.

Safety wired glass (E)

There are different kinds of wired glass, but in general wired glass is glass with within the glass metal wires of 0,5 mm, mostly in a square grid pattern, used as a reinforcement of the glass. When a fire reaches the temperature of around 400 degrees Celsius, the glass will break but the metal wires will hold the glass together. In case of fire there is not a big vent, because the glass area is held together by the wires, so the fire and smoke are mostly stopped. [Vree, 2015] Cracks may partially melt close, when the temperature reaches the melting temperature of glass between 520 and 600 degrees Celsius, but the smoke still can go through [Devent & Dumont, 2013]. Also the heat flux of the fire is not stopped by normal wired glass. Materials on the non-fire side of the glass may ignite because of the heat.

Normal wired glass can be used only to reach the E classification. Safety wired glass can be provided with an extra film on the surface of the glass which is fire-rated, to reach an EW classification. Normal safety wired glass may be applied as fire separation, but the fire resistance is dependent on the duration of the fire resistance and the surface area of the wires. [Boot-Dijkhuis, 2012] This is shown in table 1.

Fire resistance	m^2 wires	Per segment of
20 minutes	3,0	2,5 x 2,5 meters
30 minutes	1,7	2,5 x 2,5 meters
60 minutes	0,9	2,5 x 2,5 meters

Table 1: safety wired glass (Boot-Dijkhuis, 2012)

Full tempered glass (E)

The temperature differences in full tempered glass can be accommodated in the glass until 250-300 degrees Celsius. With normal glass this can only be accommodated till a temperature difference between the glass and the edges of the glass is more than between 30 and 40 degrees Celsius. When full tempered glass breaks, it will break into small non-cutting glass beads. Therefore the risk of personal injury at breakage is considerably reduced. In the first 10 minutes of a ‘regular’ fire the temperature difference in the glass may rise till 250 – 300 degrees Celsius, dependent on the depth of the rebates. When the depth is higher the temperature difference in the glass will be higher. After these first 10 minutes the temperature difference will decrease and the glass will not break because of thermal stresses. However at a temperature of around 520 degrees Celsius the glass will become plastic and it will soften. [Brandveilig met staal, 2015]

Full tempered glass with coating (EW)

This is full tempered glass with a coating, whereby it will reach the EW classification. The coating will delay the ignition and limit the heat flux from the fire side to the non-fire side. [Devent & Dumont, 2013] There are different kinds of coating which are explained on the next page [Kandare et al., 2013]:

- Reflective coating: this type of coating, which is mostly applied on single pane glazing, reflects the heat flux, whereby the temperature of the glass will increases less rapidly.
- Char forming coating: This coating becomes active in the condensed phase and is based on phosphorus [Kandola et al., 2012]. The coating is preventing oxygen supply, which is needed for the fire. Hereby the temperature rise of the glass will delay.
- Flame-inhibiting coating: This coating becomes active in the gaseous phase and is based on halogenated paraffin [Kandola et al., 2012].
- Intumescent coating: At a certain temperature the coating will melt, bubbles occur and a multi-cellular carbonaceous char layer is formed. This layer is physically preventing the glass from a rapid temperature increase. [Kandola et al., 2012] This delay in temperature rise will also slow down the build-up of thermal strain in the glass, so the glass will crack less soon. [Veer et al., 2001] The barrier will not only slow down the heat transfer, but also between the gaseous phase and the condensed phase it slows down the mass transfer. Damage or scratches in the coating can influence the working of the coating and thus the fire resistance. [Duquesne et al., 2000]

Full tempered glass with an epoxy resin interlayer (EW)

This type of glass is the full tempered glass where there is an interlayer in between two or more tempered glass layers. This glass is provided with a high quality, moisture resistant spacer. In case of a fire the glass will break and the interlayer will carbonize and form a heat insulating shield. Hereby the heat flux and the heat transfer are decreased. When this glazing is used in facades the outside glass layer has a low-emissivity coating in the direction of the radiation, so the interlayer will be protected against UV. [Brandveilig met staal, 2015] The biggest disadvantage of this type of glass during a fire is the development of smoke, as well on the fire side as on the non-fire side. [Hendrix, 2011]

Fire resistant glass with intumescent interlayers (EW/EI)
This (multi-)laminated glass is provided with an intumescent interlayer. In case of fire the glass will break when a temperature of 550 degrees Celsius is reached. Then the silicate interlayer will expand within a couple of minutes and the opaque foam will isolate at high temperatures. This way the radiation and the temperature are reduced, because the heat transfer by convection is limited and the heat flux is absorbed. The interlayers will also hold the broken glass in its position. With more interlayers the fire resistance is higher. Also here the outside glass layer will be provided with a low-emissivity coating. [Devent & Dumont, 2013]

When the interlayer is made of silicate the total glass construction is also UV stable. But this type of glass cannot be placed on locations where the temperature of the glass is beneath -40 and may rise above 60 degrees Celsius for double glazing and beneath -10 and above 45 degrees Celsius for single pane glazing, because then the interlayer will react on the temperature. This glass may also contain deviations like small inclusions, bubbles, small optical imperfection of slight haze. These deviations will not affect the fire resistance if they fall within the quality standards. [Devent & Dumont, 2013]

Influence of the breaking of the glass of a window during a fire
Fire safety glass is just a part of the whole fire retardant element. The framing, profiles, details and seals must also qualify to get certain classifications, because the element is as strong as its weakest link. During a fire the centre of the glass is heated mostly by radiation. When the glass is heated in the middle, there will be a temperature difference between the middle and the edges of the glass, because glass is a poor conductor. This temperature difference will cause thermal expansion and this thermal expansion will be eventually the reason why the glass will break. This will already happen during the first 2 till 5 minutes of a fire for normal glazing. When the glass breaks the window is then just a big vent in the wall. [Emmons, 1986] This vent will provide fresh air for the fire to fire and the gasses are released, so the fire is spreading. [Keksi-Rahkonen, 1988]

Price of glazing
Where for regular double glazing the prize varies around 65 euro/m^2, exclusive assembly, for HR+++ it is already around 120 euro/m^2 [LeadFactor, 2015]. But for fire retardant glazing, exclusive assembly, the prices vary between 250 till 550 euro/m^2. Here also the transport, framework, assembly and finishing is more expensive than with regular glazing, because damaging the coating will affect the working of the product.

Other fire retardant products
Fire resistive roller blinds (max. 120 minutes)
The cloth of fire resistive roller blinds is made of non-flammable cloth based on glass fibre, reinforced with stainless steel yarns or ribs and finished with a coating of polyurethane. The stainless steel yarns or ribs will provide reinforcement at overpressure because of the fire. The cloth is fire resistant against temperatures above 1000 degrees Celsius and the heat flux will be relatively low. The guides of the system are made of galvanized steel with baffles to keep the fire out. [Firetexx, 2015]

Because of the good heat resistance of polyurethane it is often used as coating to make products more fire safe and to protect the fire retardant coating underneath from UV and weathering. To make the coating more fire retardant, two other materials are added. Polyhedral oligomeric silsesquioxanes and montmorillonite clay are added for the processing of polyurethane nanocomposites. These nanoadditives have a reducing effect on the damaging effects of a fire. The PU nanocomposites can be melted and yarns can be made of it. These yarns can be knitted or woven and used as textile where fire resistance is desirable. Also textiles can be coated with this PU nanocomposites to make it more fire retardant. [Deveaux, Rochery & Bourbigot, 2002]

There are also roller blinds made of textile which is provided with a fire intumescent coating. In case of fire the coating will bulge and the foam will prevent the heat flow of hot gases along the steel and also the radiation will incident on the foam instead of on the steel. The roller blinds can be opened with a key switch, smoke or temperature detectors or units connected to the fire alarm system. The system is provided with special drives (230 V), which will close automatically in case of a (possible) fire. It is also possible to connect the system to an emergency battery in case of power failure. [Boot-Dijkhuis, 2012] The roller blinds are a pending construction element and not made for daily use, in comparison to the roller shutters which are described below. This non-flammable textile has a coating, which will wear of when it is used on daily basis. [Verloo, 2015]

Fire resistive roller shutters
The principle of the roller shutters is the same as the principle of the roller blinds. In case of fire the shutters will come down to prevent the spread of fire, smoke and heat for a maximum duration of 96 minutes. These roller shutters are also available with a fire resistance of 30 or 60 minutes. The roller shutters are made of galvanized steel with a mineral wool filling. In case of fire the profiles are provided with a fire intumescent layer. [Boot-Dijkhuis, 2012] For both the roller shutters as well the roller blinds it is important that both constructions can be closed anytime and are not hindered by the inventory. These constructions are tested by the regulations which apply to doors and windows and thus not as a wall. [Veek, Janse & Stichting Bouwresearch, 2005]

Coatings on cloth & fire retardant shade cloth
There are also fire retardant coatings available for cloth. When this coating, like the Finivlam Combi, is applied on cloth and when the fire reaches a temperature of 120 degrees Celsius the coating becomes active. The coating will cool the surface and will prevent the spread of fire. Also the oxygen is exhausted from the direct area, so the fire will extinguish. [Finivlam, 2015] In America and Australia there is also a fire retardant shade cloth on the market for domestic use. This is cloth is mostly used

as cover for example for pools or BBQ areas. There are also fire retardant roller shades made of fibre glass with a vinyl coating and provided with a spring mechanism. These shades are made to darken the room and are fire retardant. In such products UV stabilizers are used to prevent degradation of the flame resistance by UV radiation.

Similar products
There are already some products on the market which function as a combination of glass, fire protection and sunshading, but this is mostly fire safety glass with in between the glass panes solar shading, like the Inblindz which is explained in the theoretical framework of sunshading. With these kinds of products the problem of the thick and expensive fire safety glass is still there, only the sunshading is integrated into this product. From tests is concluded that with this product a fire resistance of EW30 is reached and a flame density of E30. [Bruin, 2015]

Defined fire classifications for materials
For materials in the Netherlands fire classes are defined. These classes reach from 1 (the best) to 5 (the worse) and show the resistance against fire. There is also a Euroclass, this represents a classification method used in whole Europe. These classes reach from A1 to F, here also forming of smoke and droplets are taken into account. This classification is often combined with the letter ‘s’ for smoke and ‘d’ for droplets. The number behind the letter represents the grade of the classification. In table 2 these classifications are shown [RockPro, 2015].

Euro classification	Behaviour of the material		Smoke production		Droplet forming	
A1	no contribution	non-flammable	S0	none	D0	none
A2	barely contribution	practically incombustible	S1	barely	D1	<10 seconds
B	limited contribution	very hard combustible	S2	average	D2	>10 seconds
C	big contribution	combustible	S3	big		
D	high contribution	good combustible				
E	very high contribution	very good combustible				
F	dangerous contribution	excellent combustible				

Table 2: Euro-classification for materials [RockPro, 2015]

Sunshading

In almost every building with glass sunshading is used to prevent the sun from heating up the building and to prevent glare on the inside of the building. To get to know which type of sunshading may work best for the fire protection different kinds of shading are researched and later compared in relation to fire protection. For a fire retardant sunshading element especially the resistance against flash-over will become important, because then the fire will flash-over via the outside of the façade to another building (part) or to the next floor.

The effectiveness of sunshading is not only dependent on the physical properties of the fabric, but also the type of shading, the distance from the distance from the window, the edges of the shading and the surface. With more fabric layers the insulation will be higher and the heat flow will be reduced by 15 – 20 %. [Dubois, 1997]

Type of shading

There are many different kinds of sunshading in the façade, but globally they can be specified into five categories:

- Awnings: this is the most common used sunshading. Awnings are sun screens which have two fixed arms. With a manual or electric action the arms come down and the screen is expanded. To fold the sunshading the arms are put up and the fabric is coiled into the box which is placed above the window against the façade. The sun screen will have an angle of between 10 and 90 degrees in relation to the façade. A markies (figure 5) is an old traditional awning with more sides. With this shading not only the front, but also the sides are provided with fabric. The fabric for the awnings is mostly made of acrylic canvas or polyester. The disadvantage of an awning is that, because of the fixed arms, there is no free passage along the window when the shading is expanded. Also with normal awnings the sides are not covered with cloth, so it is possible that sun will shine into the space through the sides. The maximum width is around 4 meters. [Zonwering-weetjes, 2015]
- Folding arm awnings (figure 6): the awning is mounted to the wall above the window and with using 2 arms, which are nodding forward, the sunscreen can be expanded. In comparison to the normal awning there is a free passage underneath the screen when it is expanded. The maximum width is 10 meters. [Zonwering-weetjes, 2015]
- Screens: this type of sunshading is moving parallel to the window, with using the same principle as a roller shutter (figure 7) which is often used as a sunshading element on the inside. The fabric is sliding vertically downwards in between two guides. The fabric is made out of glass fibre or polyester with a PVC coating, so there is still a view from the inside to the outside. From the outside however, it will not be possible to look to the inside of the building, so this screen also provides a bit of privacy. Because the screen is close to the window it has better insulating properties. [Dubois, 1997] The big advantage of this type of shading is that it is does not take extra space and there is a free passage in front of the windows. This sunscreen is also available as a zip screen. Then the screen is zipped into the guides. These zippers run by a special plastic insert into the guides. This way the fabric is held in place and is more resistant against wind. Also insects cannot go along the side to the back side of the screen.
- There is also a combination of screen and awning, namely the markisolette (figure 8). This shading system has the same principles as the screen, so the screen rolls down parallel to the window. At a chosen moment the screen is tilted forward, like a normal awning. [Zonwering-weetjes, 2015]
- Inside sunshading: the main difference of this type of sunshading is that this one is placed on the inside of the window. Examples of this type of sunshading are blinds, lamellae and shades. The biggest disadvantage of this kind of sunshading is that the glass of the windows is heated as well as the space between the window and the shading. This will prevent the sun from shining into the space, but there is still a bit of heat coming into the space, because the shading is inside instead of outside. The amount of heat is also dependent on the properties of the glass. The biggest advantage is that the screen will not suffer from wind, vandalism and also less from UV radiation because of the window. [Zonwering-weetjes, 2015]
- Sunshading in between glass panes (figure 9): because the sunshading is in between two glass panes the shading is protected from wind, dirt and risk on damage. The light, heat and privacy can be adjusted with this system. In contrast to the other sunshading systems (except the screens) this will not take as much space as the others do. [Pilkington, 2015] This product is also available with fire retardant glazing instead of normal glazing, like the Inblindz.
- Overhang (figure 10): this is not a direct type of sunshading, because it is more a

Figure 5: markies (Interdrape, 2016)

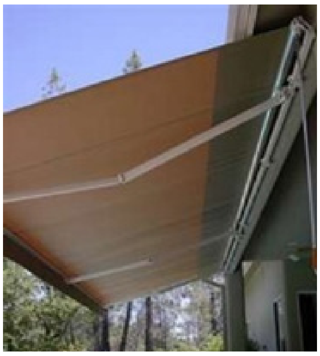


Figure 6: folding arm awnings (Sneyder, 2011)

Figure 7: roller shutter (Raambekleindg Nederland.nl, 2016)

Figure 8: markisolette (Markant, 2011)

building element. An overhang is an element perpendicularly fixed to the façade. In summer this will keep the direct sunlight from shining into the space and in the winter, because of the lower position of the sun the sun will be shining into the space and will heat the room. [Zonwering-weetjes, 2015]

Figure 9: sunshading between fire retardant glazing (Inblindz, 2016)

Figure 10: overhang (Hollada, 2014)

3. Design research

Design research

In this chapter the design research including the design of the element and the mechanism are elaborated. This starts with the criteria for the sunshading and fire retardant element in the program of requirements, followed by a design and material study, prototypes made out of different materials, the principle of the lamellae and an explanation of the design and the durability of the element.

The design of the system which will function as well as sunshading as well as a fire retardant product and as an alternative design solution for fire retardant glazing, has to meet different criteria. Here the most important criteria are shown in the following program of requirements for the fire retardant sunshading element:

- Integrity: To meet criteria E for fire retardant glazing, the system has to stop the spread of fire and smoke from the fire side to the non-fire side.
- Heat flux: Besides integrity the system also has to stop heat flux from the fire side to the non-fire side to meet the criteria of EW fire retardant glazing. This only applies when the heat flux at the non-fire side at 1 meter distance will not exceed 15 KW/m^2 during a certain period of time [Van der Veek et al., 2005].
- Temperature: The system also has to stop heat from the fire side to the non-fire side. When the average temperature on the not-heated side will not rise above 140 degrees Celsius and the local maximum temperature on the not-heated side will not rise above 180 degrees Celsius and the radiation at the non-fire side at 1 meter distance will not exceed 15 kW/m^2 it will meet the EI criteria of fire retardant glazing [Van der Veek et al., 2005].
- Costs: The cost of the new system has to be lower than the average costs of 250 till 550 euro per square meter for fire retardant glazing plus the price of a normal sunshading element.
- Sunshading: The system has to function as sunshading, which is manually adjustable from almost transparent and fully opened to fully closed and be fully pulled up.
- Esthetical: From an architectural viewpoint the shading/fire retardant system has to make an esthetical contribution to the design and possibly be integrated into the wall.
- Self-closing: In case of fire the system has to close automatically, without the use of electricity or human effort. This way the chance of failure during a fire is lowered.
- Material: The material has to be UV resistant and at the same time fire retardant and non-flammable. Also it has to be UV proof. These properties can be divided over different places of the element.
- Glass: 4 mm and 6 mm glass panes are used for the measurements and for the simulations 4/16/4 and 6/16/6 mm glass panes are used.
- Distance: The optimal distance between the window and the fire retardant shading element has to be determined by heat transfer simulations of the fire. For the prototype the distances of 75 and 100 mm are used in order to lose as less space as possible.

Placing of the element on the inside or on the outside of the window?

One of the biggest questions for this system is if it is better to place it on the inside of a building or on the outside. From the sunshading point of view it is better to keep the shading on the outside, because sunshading on the outside of a building is more effective in reflecting heat than shading on the inside. When the shading is placed on the inside of a building, the heat from the window is already inside the building. On the other hand, the sunshading on the outside is better because it keeps the heat outside, but it is also associated with higher requirements for the construction, weather resistance, vandalism and it is more expensive, as well in purchase as well as in maintenance. [Stichting Bouwresearch, 1980]

When the fire retardant system is placed on the inside of a building and inside the room a fire occurs, the windows are protected from the heat and radiation and will not break as fast as normally would happen, as long as the fire retardant product is working properly. With regard to the shading properties, the distance between the shading device and the window will have a negligible influence on the indoor room temperature. Only the air flow between the element and the window will have an influence, but this air flow is so small in comparison to the rest of the room that the difference in temperature in the room, caused by a different distance between the window and the element, will be negligible. So this distance will be determined by the fire retardant specification of the element. When the fire retardant system is placed on the outside, during a fire the glass will break already after 2 to 5 minutes, dependent on the type of glass. The breaking of the glass and the shards may damage the fire retardant system or coating, which will influence the time that the system is fire and flame resistant and prevent flash-over. For the fire retardant properties it is better to place the fire retardant shading element on the inside of the window. The distance from the window has to be determined from the simulation and theoretical relation between distance and radiation.

Design study

To get insight in the different places and different types of the element which functions as sunshading and as fire retardant element a design study is done with the most common shading types and fire retardant products. An overview is given on the next pages with the different places of the shading, the advantages and disadvantages and their principle. The result of this study you find below.

Horizontal blinds on the inside
This principle is based on basic horizontal venetian blinds on the inside of the building. The blinds have to cover not only the whole window but also the framework, because of the chance on breaking the glass caused by thermal expansion because of temperature differences in the glass [Joshi & Pagni, 2004] .

The horizontal lamellae are on the top side provided with a UV coating and on the bottom the lamellae are provided with a fire retardant coating. This way the coating is not directly exposed to UV light. The horizontal blinds can be connected to the guides on the side, to keep the lamellae in place. These guides could also be provided with a fire retardant coating. The side of the lamellae which is the closest to the window will be heavier. In case of fire the lamellae will close automatically, because the stress is released from the system and the heavier part of the lamellae will fall down, because of the extra weight and gravity. The biggest disadvantage of this system is a bigger chance on dust and thus cleaning it often is necessary, because the lamellae are placed horizontally.
With this system also questions are raised about how the system will fall down automatically in case of fire, when it is fully pulled up. Then also a wire has to melt, which causes the system to automatically fall down and close.

Horizontal blinds on the outside
Horizontal lamellae are placed on the outside of a window. In this case the lamellae are well connected to guides on the side, to keep the lamellae in its place in case of wind. The system works the same as the system for lamellae on the inside of the window. Only now the part of the lamellae which is the furthest away from the window is made heavier. On the outside the chance on damaging and wearing is bigger, because of the weather (wind, rain, sun, temperature differences) and the chance on possible vandalism.

Vertical blinds on the inside
The tops of the lamellae are connected to a rotating pin. The bottoms of the lamellae are connected to a spring. When the lamellae are fully closed tension is released from the spring. In every other position of the lamellae the spring is under tension. A small wire connects every lamellae and causes the lamellae to stay in place or to rotate parallel. In case of fire this wire is burned. Because the wire is then not holding the lamellae in place, the lamellae will rotate because of the released of tension in the spring. This way the lamellae will close automatically in case of fire.

Vertical blinds on the outside
The vertical blinds on the outside will work following the same principle as the blinds on the inside. Only here the working and wearing of the spring has to be checked every now and then, because of the weather conditions.

Roller blinds on the inside
In this case the principle of normal roller blinds is used. Only then the inside of the cloth is provided with a fire retardant coating and the side of the cloth which is the closest to the window is provided with an UV coating. The biggest disadvantage is the possible wearing of the cloth and coating by often opening and closing the system, because then the cloth is rolled up. To keep the cloth in place, use is made of zip screens. These screens are on the side provided with half zippers, so the screen is fixed into the profile. The cloth has to be a bit transparent, so when the system is fully down as sunshading, there is still a bit of view to the outside.

Roller blinds on the outside
This system has the same principle as the roller blinds on the inside. On the outside it has to be kept in mind that the chance on wearing and damaging is bigger than on the inside of a building, because of the weather and possible vandalism.

Awnings on the outside
This is one of the most traditional sunshading systems. When this principle is used also as a fire retardant system, the top of the cloth is provided with an UV coating, while the down side of the cloth is provided with a fire retardant coating. The vertical arms of the awnings are connected to the wall. The horizontal awnings are locked, so they won't exceed the angle of 90 degrees in relation to the vertical awnings. In case of fire there has to be a mechanism to ensure that the lock falls away and the arms of the awning fall down and the window is covered with fire retardant cloth. But the window will still break and possibly damage the cloth.

Analysis of different types of sunshading

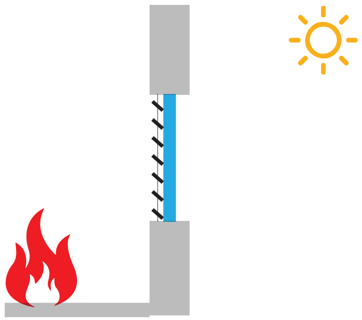
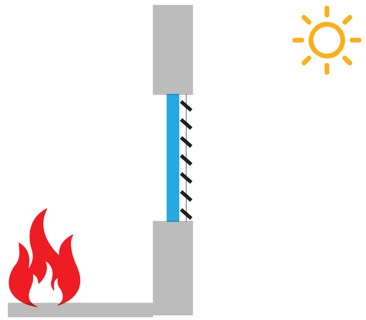
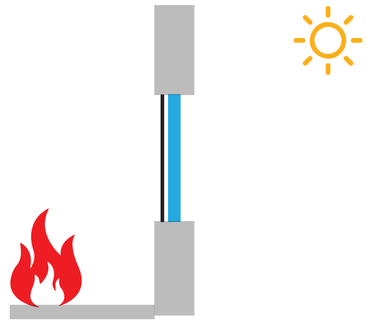
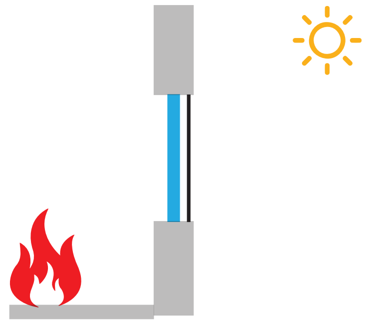
Horizontal blinds on the inside	Horizontal blinds on the outside	Vertical blinds on the inside	Vertical blinds on the outside
			
+ 1 side of the lamel UV coating 1 side of the lamel fire retardant coating + Window is not breaking + Different positions of the shading + Maintainance is easier	+ 1 side of the lamel UV coating 1 side of the lamel fire retardant coating + Different positions of the shading + Sun shading on the outside	+ 1 side of the lamel UV coating 1 side of the lamel fire retardant coating + Less sight disturbance + Window is not breaking + Differnt positions of the shading + Less dust / cleaning + Maintainance is easier	+ 1 side of the lamel UV coating 1 side of the lamel fire retardant coating + Window is not breaking in case of fire + Different positions of the shading
- Sun shading on the inside - Dust and cleaning - Fully opened?	- Wind - Cleaning? - Window is breaking - Possible damage by breaking the glass, preventing with safety layer	- Sun shading on the inside	- Wind? - Cleaning? - Window is breaking - Possible damage by breaking the glass, preventing with safety layer
Principle Heavier weight on the right side. During a fire a wire will burn and loosen the shading out of its position and it will fall, because of the weight, and closes. It has to cover also the framework.	Principle Heavier weight on the right side. During a fire a wire on the inside will burn and loosen the shading out of its position and it will fall, because of the weight, and closes.	Principle At the bottom the lamellae are connected to a spring. A wire causes the lamellae to move parallel. In case of fire this wire breaks and because of the spring the lamellae closes.	Principle At the bottom the lamellae are connected to a spring. A wire causes the lamellae to move parallel. In case of fire this wire breaks and because of the spring the lamellae closes.

Table 3a: analasys of different types of sunshading (1/2)

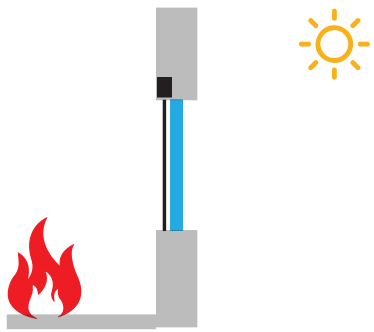
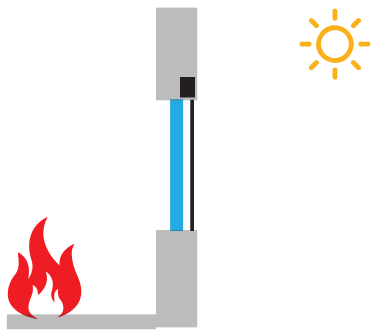
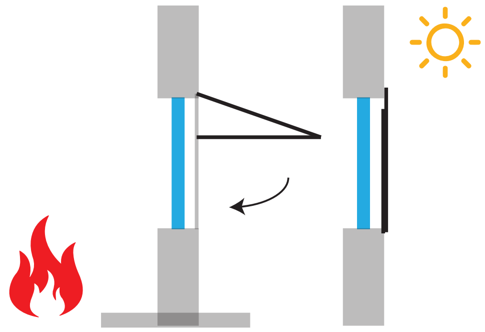
Roller cloth on the inside	Roller cloth on the outside	Awnings on the outside
		
+ Window is not breaking + Maintainance is easier	+ Different positions of the shading + Sun shading on the outside	+ 1 side UV coating 1 side fire retardant coating + Less sight disturbance + Differnt positions of the shading + Cleaning
- UV & fire retardant in 1 cloth - Sun shading on the inside - Cleaning? - No positions possible - Wear of the coating? - View or fully closed?	- UV & fire retardant in 1 cloth - Cleaning? - Window is breaking - Possible damage by breaking the glass, preventing with safety layer - No positions possible - Wear of the coating?	- Wind - Window is breaking - No free walking space along the window
Principle Heavier weight on the bottom During a fire a wire will burn and loosen the shading and it will fall, because of the weight, and closes. It has to cover also the framework.	Principle Heavier weight on the bottom. During a fire a wire on the inside will burn and loosen the shading and it will fall, because of the weight, and closes. The cloth is windproof through the zipper.	Principle When the window breaks the horizontal bar of the shading will fall and the shading will close the gap of the window

Table 3b: analasys of different types of sunshading (2/2)

Design of the mechanism

One of the most important specifications for the design of the mechanism is that is has to close automatically in case of fire, preferably without the use of electricity or human effort. So the mechanism has to react to the fire. One of the first ideas of this mechanism is sort of wire which will burn at low temperatures. Because the breakage of the wire the tension on the system is released and because of gravity the system will close automatically. Therefore the wire of the lamellae in front of the window is made out of nylon. This way in case of higher temperatures the wire will melt easily, because of the low melting point. This is also shown at the page of the steel prototype.

One of the first ideas was to let the system stay closed with the use of magnets, however at high temperatures magnets will lose their working. When magnets are used based on alnico alloys it may work at higher temperatures of 450 degrees Celsius. This is further explained in the material study. When one part of the lamellae are made heavier the system will also stay closed, because of gravity. Also another mechanism is developed where, because of the melting wire and falling away of the bridge that keeps the lamellae in place, the system closes and stays closed automatically (shown in Figure 12). This without the use of electricity or human effort. This design is further explained in the chapter of the prototype and the chapter of how to keep the lamellae in place?

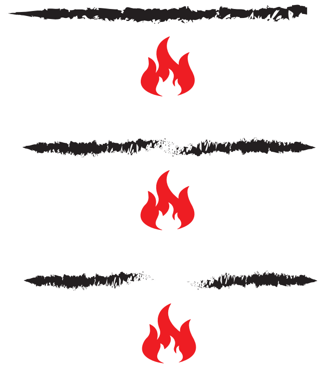


Figure 11: concept of the burning wire

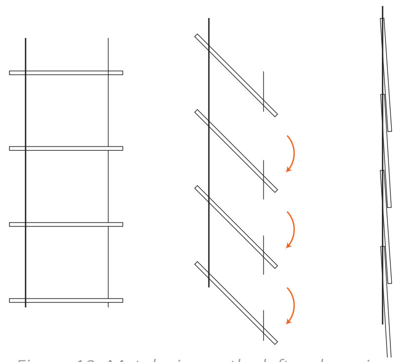


Figure 12: Metal wire on the left, nylon wire on the right

Material study

In this material study an overview is given of the used materials and their properties.

Magnets
At higher temperatures magnets will lose their magnetism. This will happen at the Curie temperature (named after Pierre Curie). At this temperature induces magnetism takes the place of the permanent magnetic field. Dependent on the materials of the magnet this will occur at a different temperature. For alnico magnets the Curie temperature will lie around 800 degrees Celsius. For neodymium magnets this temperature is a lot lower between 300 and 400 degrees Celsius.

Nylon wire
The wire has to burn or melt in order to close the automatically in case of fire. If this happens at a relatively low temperature the glass pane is shorter exposed to high temperatures and the fire retardant sunshading close and prevent flash-over. Nylon wires will melt at a relatively low temperature of around 200 and 270 degrees Celsius, dependant on the specifics of the nylon [Aspas, 2016]. One of the specifications of nylon is that it is not UV resistant. For the shading element UV resistance is an important specification, because the wire will be exposed to a lot of UV. But when the thread is provided with an UV coating the thread will function well in the fire retardant shading element.

Glass
When the glass is heated slowly there is less tension within the glass because the heat can diffuse slowly in the glass. When the glass is heated quickly there is a bigger chance on thermal breakage caused by the tension which occurs because of the temperature differences in the glass pane. In comparison with thinner glass the thicker glass is stronger and has more capacity and mass to accumulate heat, so it will break less easy.

Sunshading & material for the lamellae
For sunshading the best type of material is dependent on the type of the sunshading. In the case of fire retardant sunshading on the inside of the building where lamellae are used a lightweight material which has an excellent performance while exposed to UV, is best for this use. The material should also be stiff enough to be used over larger widths without bending much. Materials such as steel and aluminium have an excellent UV resistance and can withstand high temperatures (aluminium around 600 degrees Celsius and steel around 1500 degrees Celsius). Also both materials are non-flammable. For the fire resistance it is best to use a material which can withstand the higher temperatures and is non-flammable, like steel. Therefor the prototype will be made out of steel. Steel is also a material which is used but is not consumed, because it is well recyclable and re-usable. [CES Edupack, 2015]

Concept design

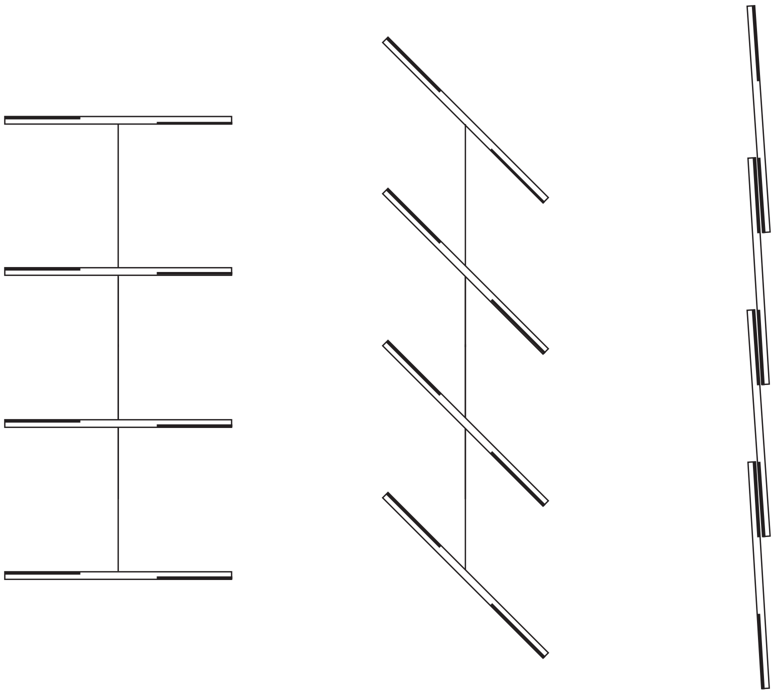


Figure 13: different positions of the sunshading system

Three different positions of the system. Fully opened, half opened and fully closed.
Scale 1:1

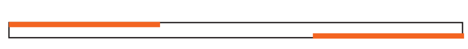


Figure 14: magnetic aggravation at the ends of the element

In orange: aggravation at both ends of the element, which will also function as a magnetic element, to ensure automatically closing of the system due to gravity and to ensure the system to stay closed because of the magnetic attraction.
Scale 1:0,5

Note: magnets will lose their magnetism in high temperatures

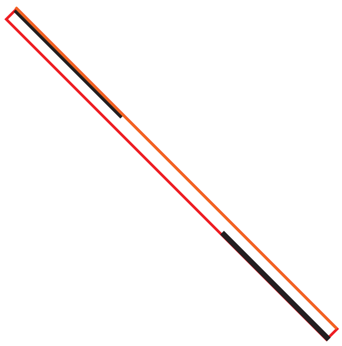


Figure 15: UV-coating and fire retardant coating

In orange: UV coating on the side which is the closest to the window (top)

In red: fire retardant coating (bottom)
Scale 1:0,5

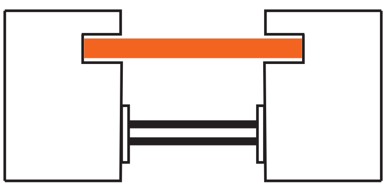


Figure 16: fully sealing of the window

Sketch of the horizontal section of hiding the element in the wall to ensure fully sealing of the window in case of fire.
Scale 1:10

First design

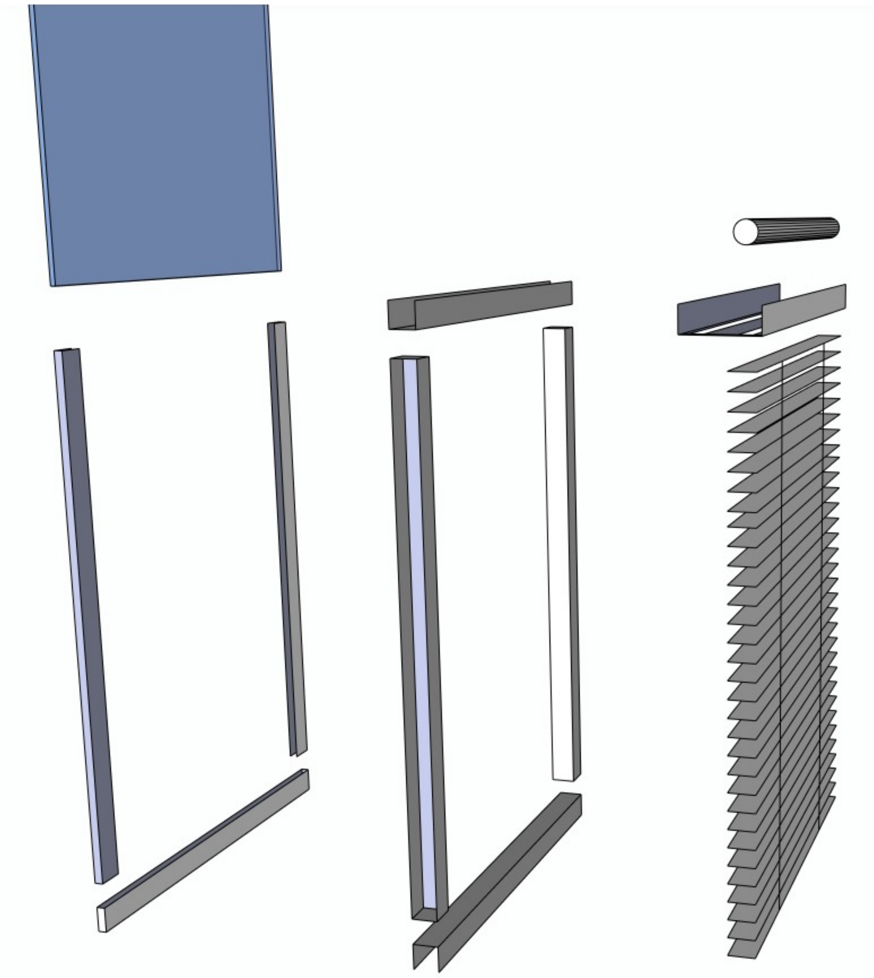


Figure 17: first design of the sunshading element with the frame and the window

Exploded view of the design and prototype. Left the U-shaped profile for the glass. In the middle the frame and on the right the mounting principle for the lamellae.

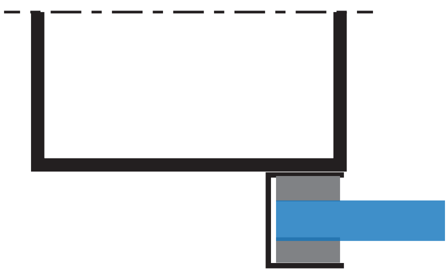


Figure 18: first design of the profile for the glass

Horizontal section of the connection of the glass and the frame, with the use of a U-shaped profile. Between the glass and the U-profile there is a rubber for the insulation.
Scale 1:1

Figure 19: first design of the mounting element

Vertical section of the mounting element with the pipe which hangs the lamellae at two different distances from the window (75 mm and 100 mm)
Scale 1:1

Second design

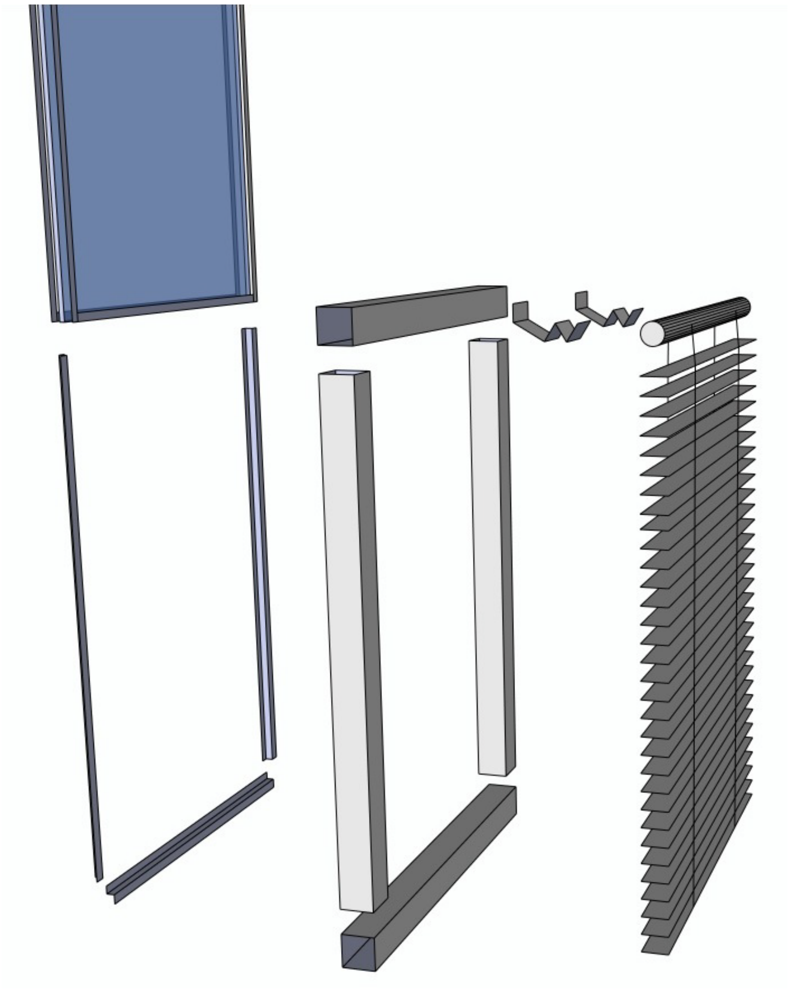


Figure 20: second design of the sunshading element with the frame and the window

Exploded view of the design and prototype. Left the Z-shaped profile for the glass. In the middle the frame and on the right the easier mounting principle for the lamellae.

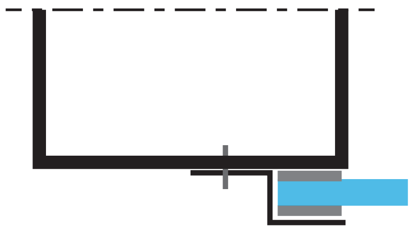


Figure 21: second design of the profile for the glass

To make the profile easier to connect to the frame one leg of the U-shape is bend the other way.
Scale 1:1

Figure 22: second design of the mounting element

Two simple mounting points to lay the pipes in is enough to hang the lamellae at two different distances from the window (75 mm and 100 mm)
Scale 1:2

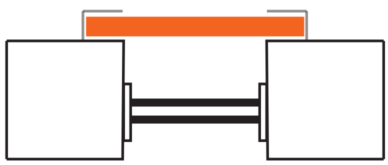
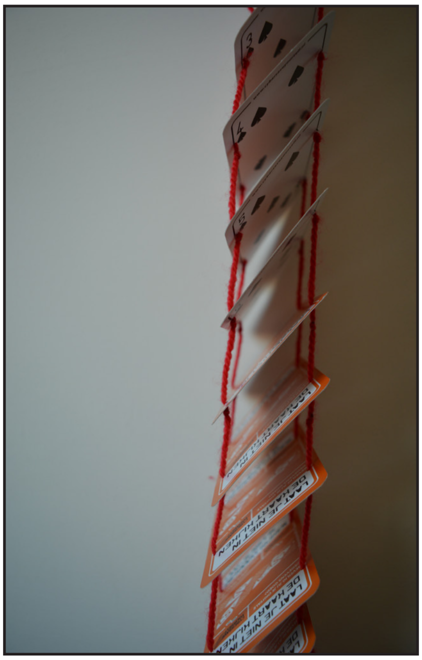


Figure 23: new principle for sealing the window

The element covers the whole window and a part of the frame in order to fully seal the window in case of fire. A U-shaped profile can be added to keep the lamellae in place.
Scale 1:10

Prototype playing cards



This is the first prototype of the lamellae made out of playing cards. This prototype was very useful in order to determine one of the problems. On the photo top left the 'lamellae' are open and in the picture in the middle the lamellae are as closed as possible. Here the first problem occurred. In the right picture the problem is shown. Because the holes through the cards are made perpendicular to the cards, the wire is bended in a strange way. This problem is also schematically shown in figure 24. However, when the holes are made at an angle, this problem is solved and the lamellae will close better because then the wire is in a straight line (figure 25). When the lamellae are open the wire will not be in a straight line, but this will help to keep the lamellae in place and to prevent the lamellae from sliding down the wire (photo top right).

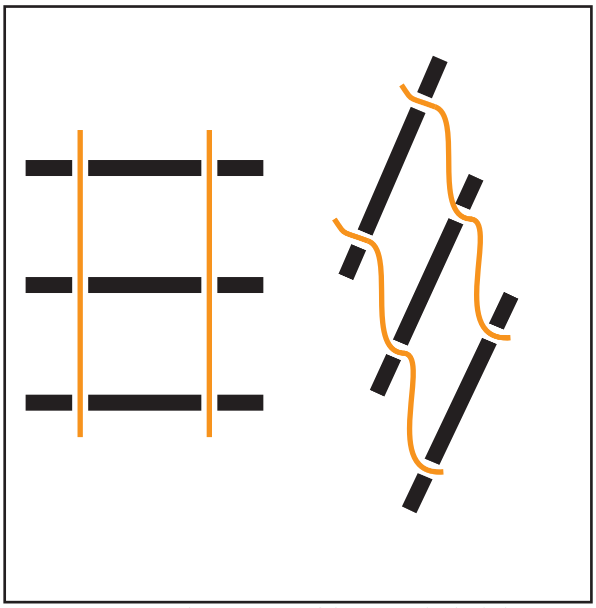


Figure 24: schematic view of the perpendicular holes

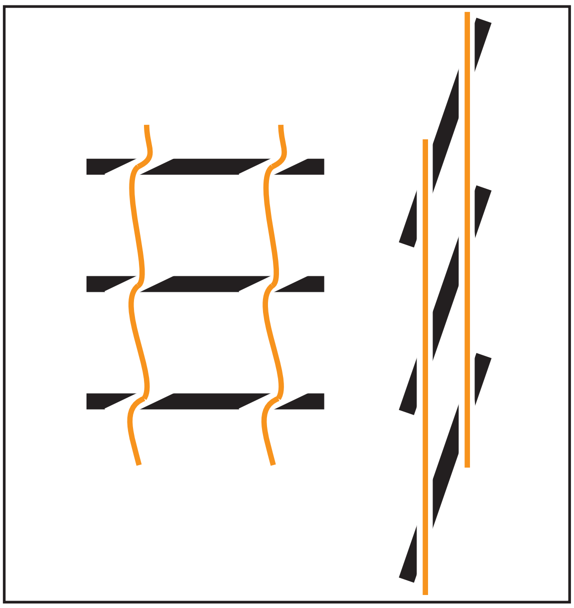
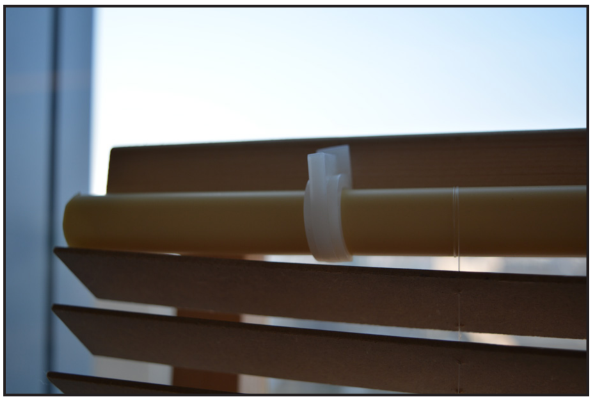


Figure 25: schematic view of the holes at an angle

Prototype wood



The pictures show the wooden prototype. This prototype was just the first on scale, to get to know the right measurements to place it perfectly into the opening of the oven and to get to know the most common problems while making this prototype. It functions as a learning model before making a prototype out of steel.

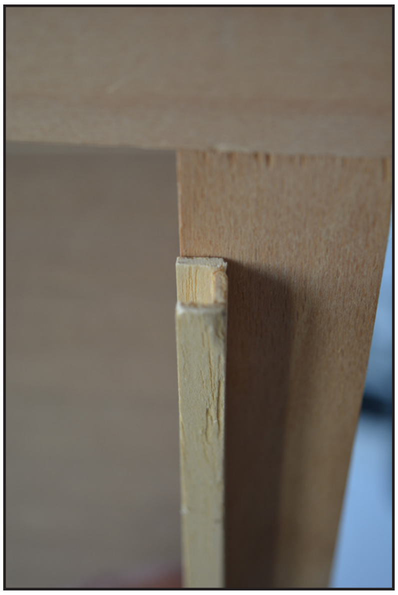
Left the mounting mechanism of this prototype is shown. This was just an easy connection with a clip in which the pipe could be clamped in and still be turned. This prototype was just made for one distance between the element and the window. The steel prototype will have a mounting mechanism to hang the lamellae at two different distances from the window (75 mm and 100 mm)

With the use of a cord the lamellae can be opened and closed. In this prototype the lamellae are connected by a nylon fishing wire which is knitted to keep the lamellae in place.

The lamellae will cover the whole frame in order to protect the framework as shown in the picture at the left bottom.

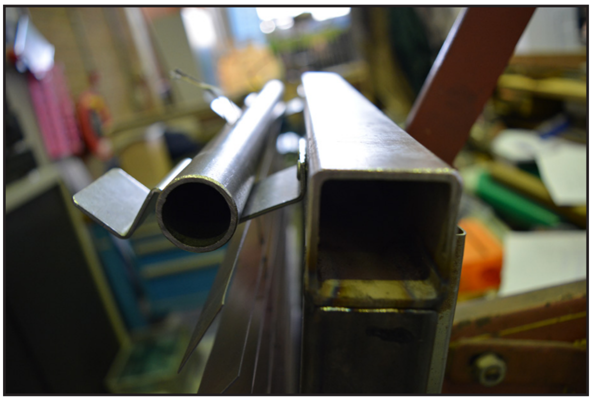
As shown in the picture at the bottom the window will be held in place by the U-profile. The glass pane can be slided in from the top.

At the right bottom the lamellae in closed (top) and open (bottom) situation are shown.

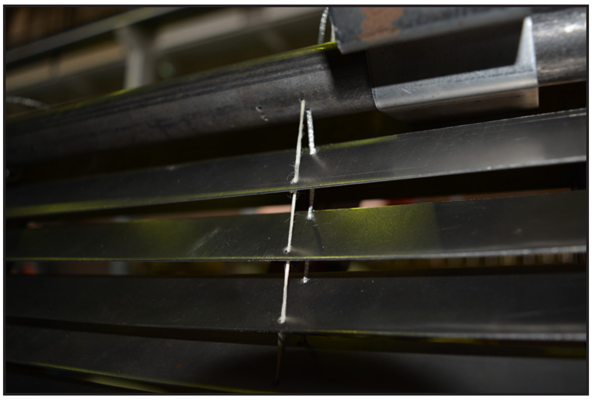


Prototype steel

The prototype made out of steel is based on the wooden prototype, only little adjustments are made in order to make it easier to build.
The frame is made out of 4 steel beams welded together. With two mounting points where the steel pipe can be layed in, the lamellae can hang at two different distances.



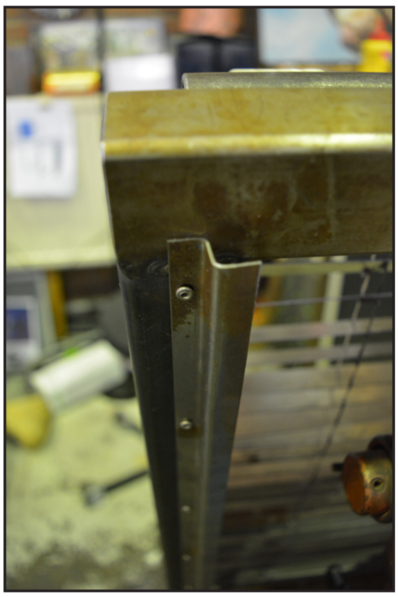
The pictures show the vertical view of the mounting principle of the steel prototype. It is a bended steel plate, which allows you to place the pipe with the lamellae at two different distances from the window, namely 75 mm and 100 mm. It also allows the pipe to turn in order to change the lamellae from open to fully closed.



The lamellae are connected with two kinds of wires. In front a nylon wire which will melt at higher temperatures in order to close the system automatically. The wires in the back are made out of steel and will keep the lamellae in place. There is also a small steel wire in between the plastic wire and the steel wire, in order to keep the lamellae in place. This is shown at photo 4 on page 41.

The front of the steel prototype is shown on the left, with all the lamellae and the mounting principle.

At the back a profile is made in order to slide the glass pane in. It will also hold the pane in place. The ends of the glass pane are provided with a rubber to protect the glass while it is in the frame. This rubber is also there in a normal window frame.



How to keep the lamellae in place?

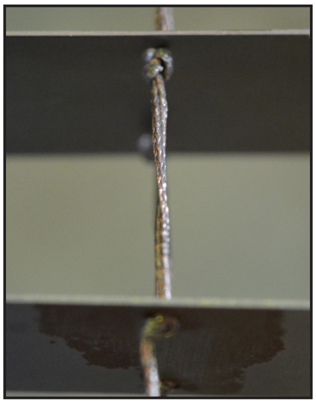


Photo 1: keeping the lamellae in place by knots

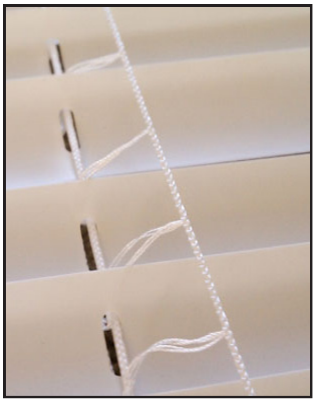


Figure 26: ladder cord [Christine, 2012]

Photo 4: keeping the lamellae in place by making a metal ladder cord

In the prototypes of playing cards and wood the lamellae are kept in place by knots in the wire. Also in the first steel prototype this was tried, however the steel wire is not that easy to knot, because the steel wire frays.

So the second idea to keep the lamellae in place was by folding the wire around the gap in the lamellae. But this way the lamellae would not close very well so this was also not the solution.

Another option that was tried to keep the lamellae in place was with the use of little tubes. When the wire, in between the two lamellae, is going through a tube, the length of the tube would define the distance between the lamellae. However, this would also cause the lamellae to not close perfectly.

In normal horizontal venetian blinds use is made of a so called 'ladder cord', which is shown in the picture on the left. In between the double wire the lamellae are placed. This way all the lamellae have the same distance in between. So that was the new starting point for the steel prototype. Between the nylon thread and the steel wire a same kind of bridging is made out of steel wire. This way the lamellae also close perfectly in case of fire (when the nylon wire is melted).

At photo 5 is shown the new laddercord for the fire retardant shading element. One vertical wire (left one) and the bridge has to be made of a flexible steel rope. The other vertical wire (right one) will be made of nylon. In case of fire the nylon wire melts away and the lamellae will be held by the metal rope and the system will close.

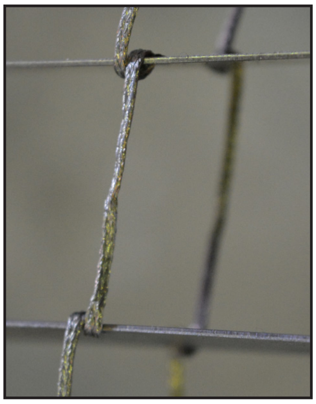


Photo 2: keeping the lamellae in place by folding the wire

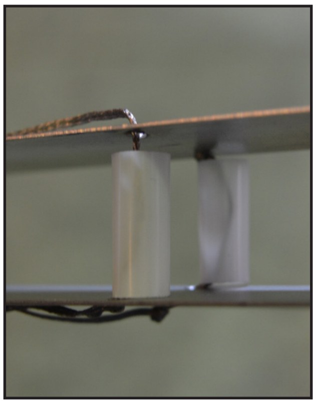


Photo 3: keeping the lamellae in place by tubes

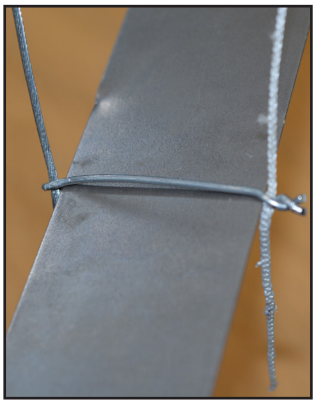


Photo 5: new laddercord design

Design

The design of the fire retardant shading element will look the same as normal sunshading. With a steel cover with fire retardant coating the mounting principle is out of sight (figure 27). The shading can be changed from fully opened to fully closed (figure 28, with the mounting principle in sight). The whole element can also be completely integrated into the wall (figure 29) or can be completely taken of for maintenance, cleaning (figure 30), or be stored when it is just not necessary anymore.

Also less lamellae could be used in order to get a clearer view to the outside (figure 31), but then the depth of the lamellae has to be larger, in order to still cover the whole window when fully closed.

To provide better sliding of the lamellae and to ensure they will stay fully closed in case of fire an extra profile can be added (figure 32). Also the element with this profile can be integrated into the wall (figure 33).

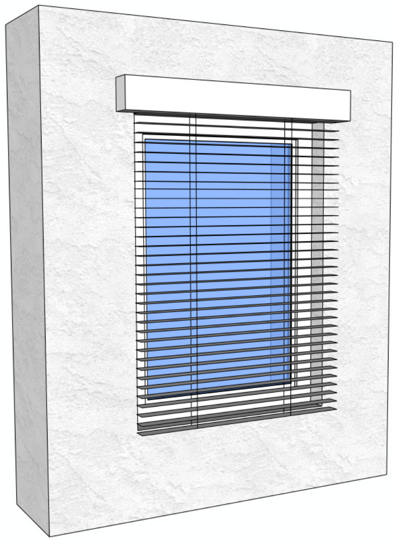


Figure 27: fire retardant shading element as a normal sunshading

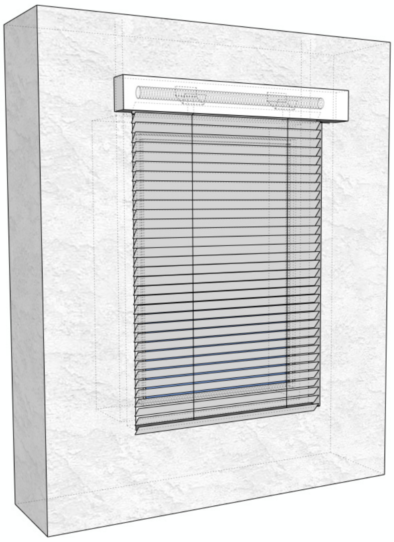


Figure 28: closed shading element with the mounting principle shown

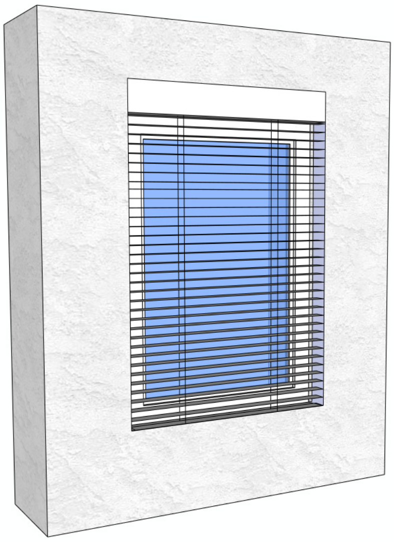


Figure 29: the element integrated in the wall

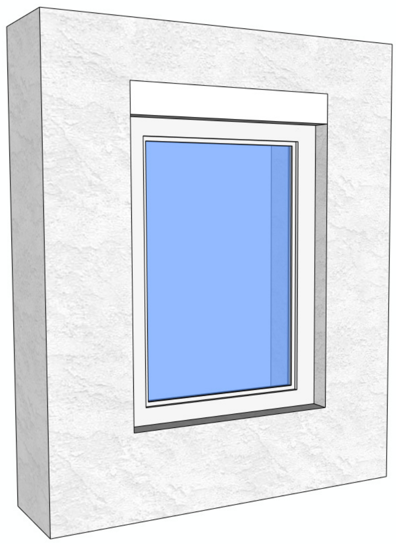


Figure 30: the element is taken out

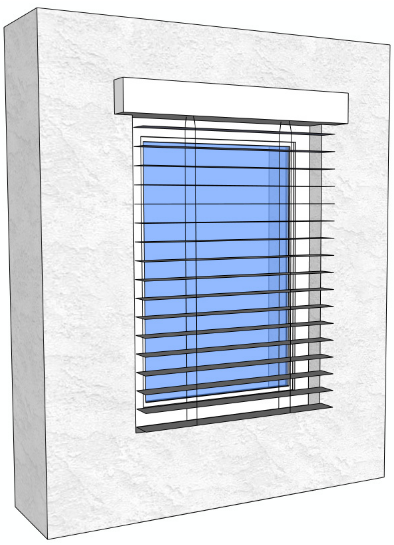


Figure 31: less lamellae used

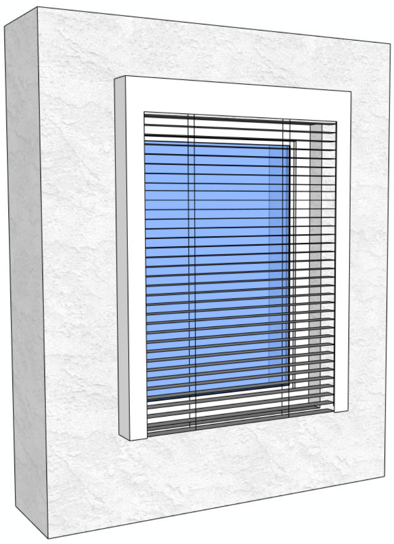


Figure 32: the element with sliding profile

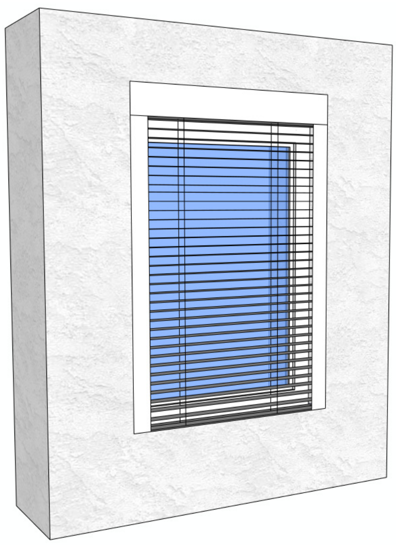


Figure 33: integrated sliding profile

Explanation of the design

The prototypes are made as simply as possible. Not only because adjusting steel is not that easy but also because the design has to be as simple as possible.

Cleaning & maintenance
The pipe with lamellae lies loose on the bended profiles. This way the distance between the window and the element can be easily adjusted, for example to open the window. Also when after the fire the nylon wire has to be replaced the whole element can be easily taken of the system and be replaced. Because the system is that easy to take off also maintenance and cleaning of the lamellae becomes a lot easier.

Prototype vs. reality
The dimensions of the prototype are based on the dimensions of the oven. In reality the dimensions of the element and the frame are dependent on the dimensions of the window. Because the tests in the oven are done in order to test the concept of the fire retardant shading elements the scale will not have a big influence. However, when the perimeter of the glass is less, the chance of thermal stresses caused by temperature differences also will be less.

Influence of the concept fire retardant sunshading element on a fire and the consequence for the fire fighters
If the whole concept of the fire retardant sunshading element is working properly a couple of things happen:

- The produced smoke will not have a way out through the window, because it is still a whole, so it will find its way through the cracks and other openings while the temperature in the room still rises.
- Because the window will not break there is no extra ventilation through the broken window. When there is less oxygen supply to the fire, the fire will extinguish quicker.
- Because of the window and the sunshading element the fire will not spread to other buildings or other building parts via the outside and the fire fighters will still be able to enter the building through the window if they want, because the sunshading element is not totally fixed to the wall.
- When the glass breaks, the fire retardant shading element will still prevent the spread of fire via the outside by flash-over. After the fire the glass and the element can be easily replaced.

Durability

In this chapter the durability and sustainability of the element are discussed and answers are given to the research questions regarding these topics.

Price

The cost of the new system has to be lower than the average costs of 250 till 550 euro per square meter for fire retardant glazing plus the costs of a shading element. For normal horizontal venetian blinds the prices varies between 20 and 150 euros, dependent on the material and the size. So the total costs will be between 250 and 700 euros, for the fire retardant glazing with a shading element on the inside. HR+++ glass costs around 120 euro per square meter and adding fire retardant properties to the shading will cost around 50 euro. So with the fire retardant shading element the total costs will lie between 190 and 320 euros, which still cheaper than the fire retardant glazing with a sunshading element.

Malfunction, possible damage and wearing

The shading element is placed on the inside of the window. This will reduce the chance of wearing in relation to shading on the outside of a building. Wearage of the wires because of changing the position of the shading elements should be checked. Also the fire retardant coating should be checked regularly. Another important thing is to provide the nylon wire with a UV resistant coating and to regularly check the nylon wire.

In case of damage the lamellae can be easily taken of the system, because of the easy mounting principle. This way it is easy to replace the lamellae with new ones.

Performance & ventilation

For now the fire retardant shading element will be on the inside of the window. Sunshading elements on the inside of a building are not as effective as on the outside of the building, because the glass of the windows is heated as well as the space between the window and the shading. So there is still a bit of heat coming into the space, because the shading is inside instead of outside, however the shading element will still prevent the sun from directly shining into the space and the change on wearing and damage is less when the shading element is on the inside.

The biggest advantage is that the screen will not suffer from wind, vandalism and also less from UV radiation because of the glass. The current disadvantage is that the system cannot be completely pulled up yet. But because of the easy mounting principle the system can be completely taken of in case of cleaning the windows or in periods in the season that the shading is not necessary.

Windows behind the system can be opened through the lamellae or in case of automatic windows, which are applied more often nowadays, the window is able to open. The distance of the opening is however dependent on the distance between the window and the shading element. In a lot of public buildings there are not many manually openable windows, because the buildings are provided with an advanced climate control system. In case of fire these windows have to close automatically or otherwise they will be a big oxygen source for the fire and the fire will increase and the smoke will have a way out. Another important thing is that the inventory cannot be place under or right next to the lamellae, because it has to able to close to completely.

4. Simulations

Simulation of the fire

The simulation of the fire is divided into two simulations, namely one for the heat flux from the fire onto the element and a simulation of the conduction in the element and convection of the heat from the element to the window. The radiation simulation will be done in the simulation program TRA (Thermal Radiation Analysis). The simulation of the conduction and convection will be done in the computer program Trisco. From the radiation simulation the temperature and heat flux on the element and on the window are determined for variable distances between the element and the window. These numeric results are used as specifications of the element in the conduction and convection simulation in TRISCO. With this simulation the temperature on the window with variable distances of the element are determined. So both simulations take place in order to determine the optimal distance between the window and the fire retardant element on the inside of the building and to compare the results of the simulations to the results of the measurements. To determine this optimal distance it is important to get to know the following variables on forehand:

- Start temperature of the glass in degrees Celsius = 298 K (24,9 degrees Celsius)
- Start temperature of the room in degrees Celsius = 298 K (24,9 degrees Celsius)
- Start temperature of the element in degrees Celsius = 298 K (24,9 degrees Celsius)
- Start temperature of the space between the element and the window = 298 K (24,9 degrees Celsius)
- Configuration of the fire retardant element: as explained under assumptions
- The type of glass: as explained under assumptions

The results of the simulations should determine the following variables:

- Incident radiation on the glass during the simulation
- Incident radiation on the element during the simulation
- Temperature of the glass during the simulation
- Temperature of the element during the simulation

Assumptions for the simulation in TRA

Because the distance between the window and the shading element will have a negligible effect on the indoor room temperature, this distance will be determined by the fire retardant specification of the element and the relation between heat radiation and distance to the heat source, as explained in the theory. Therefore simulations will be done in order to determine the optimal distance between the window and the fire retardant shading element and to compare the results of the simulations with the results of the measurements. In the program Thermal Radiation Analysis (TRA) the heat transfer by radiation is simulated.

For the simulation the following assumptions are made:

Glass and framework
For the simulation HR++ glazing is used with a filling of air. This type of glass is currently (December 2015) one of the most common used glazing types in Dutch public buildings. HR++ glazing is glazing with on the inner glass pane a heat reflective coating on the side of the cavity. This will reflect the long wave heat flux back into the room. For the simulation SGG Climaplus 4-16-4 millimetre glass is used[1]. Later on also a variant simulation with 6-16-6 millimetre glass is used. For the framework wood is chosen, because this will set higher limits to the fire resistance of the fire retardant shading element. [Saint-Gobain Glass, 2015]

Configuration of the element
For the simulation horizontal lamellae with the dimension of 3 cm depth and 1 mm thickness are chosen. The lamellae are made of steel. When they are fully closed, in case of fire, this will result in a steel wall with on average a thickness of 1.67 mm, because of the overlap. The simulations are done with the element in three positions, namely opened (fully horizontal), half opened (45 degrees slope) and fully closed. In order to determine the optimal distance between the window and the element simulations are done with a varying distance of 10 millimetres.

Space
The dimensions of the space which is designed to do the simulations in are 7.2 meters large, 7.2 meters width and 3.6 meters high. This is just a representative large space in public buildings. Also a simulation will be done with a space with the dimensions of 3.6 meters large, by 3.6 meters width and 3.6 meters height. This will be a representative small space in public buildings.

Distances
As shown in the schematic section on the next page, the distance

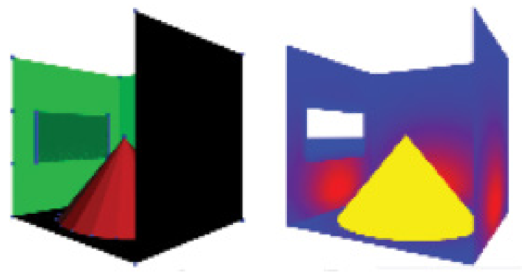


Figure 34: simulations in a small space in TRA

[1] Another type of glass with the same specifications will reach comparable results.

X is the distance between the window and the element. This is the optimal distance which is be determined with the use of the simulations. However an important thing to keep in mind is when distance X becomes bigger, the element will be closer to the fire (distance Y will become less).

Fire
The fire, with a cone shape, will take place in the middle of the room (at 3.6 : 3.6 : 0 meter for the large space and at 1.8 : 1.8: 0 meter for the small space), will have a diameter of 3 and a height of 1.8 meters. The temperature of the fire will be 1223.15 Kelvin (950.00 degrees Celsius).

Smoke
In the simulations the smoke produced by the fire is not taken into account. The temperature of the smoke must be so high before it will radiate heat, that in these simulations this is negligible.

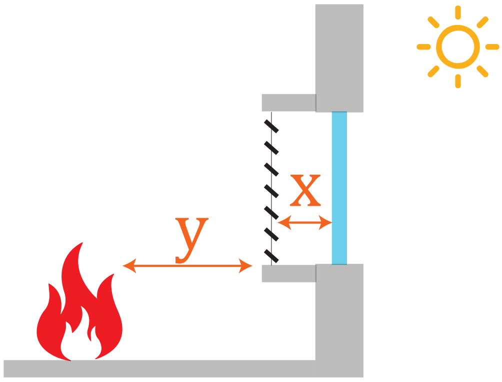


Figure 35: optimal distance between window and the element

Assumptions for the simulation in TRISCO

In the program TRISCO the heat transfer by conduction and convection is simulated. The assumptions which are made for the simulation in TRA are also applied to the simulation in TRISCO. In the next table the used materials and their specifications are showed.

Used materials and starting temperatures in TRISCO:

	Material	λ [W/mK]	Temperature [°C]	H [W/m²K]
Wall	Stony 2300 kg/m²	0.700	-	-
Window	Glass 4-16-4 and 6-16-6 mm	0.800	-	-
Cavity window	Air 16 mm	0.030	-	-
Interior air	Air	-	24.9	7.70
Exterior air	Air	-	4.9	25.00
Element	Steel 1 mmm	16	*	-
Space between element and window start temp.	Air	-	24.9	7.70

Table 4: materials and starting temperatures used for the simulation in TRISCO

The temperature of the element is the temperature which follows from the maximum incident heat flux on the element from the TRA simulations.

For the simulation with the shading element half open (rotated under 45 degrees), the shading elements are not oblique simulated, but every shading element of 3 cm with and 1 millimetre height is split into three blocks of 7 millimetre by 7 millimetre, which is shown in figure 37. This is done because the program cannot simulate sloped elements because they do not occur in the rules on which this program is based. Now a problem may occur in the corners of the blocks, so the next time a bit of overlap will be better. This is also explained in the discussion.

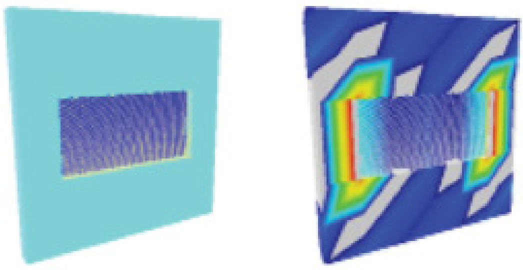


Figure 36: simulations in TRISCO - wall element

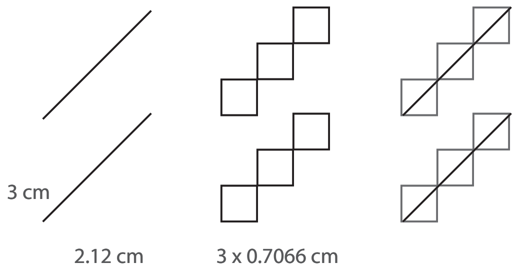


Figure 37: assumptions for the sloped elements in TRISCO

Two kinds of simulations
There are two kinds of simulations made in TRISCO. The old ones, which you will find in the appendix, were made in order to determine the optimal distance was not reliable because of the temperature drop. Therefore the distances of 75 and 100 mm were taken for the measurements. In order to compare these measurements to also new simulations were done with the distances of 75, 100, 125 and 150 mm. These results are shown in the following pages.

Maximum incident heat flux and temperature of the element from TRA - small space

	Element fully opened				Element half opened				Element closed			
Distance between window and element	Average incident radiation [kW/m²]	Temperature [°C]	Maximum incident radiation [kW/m²]	Temperature [°C]	Average incident radiation [kW/m²]	Temperature [°C]	Maximum incident radiation [kW/m²]	Temperature [°C]	Average incident radiation [kW/m²]	Temperature [°C]	Maximum incident radiation [kW/m²]	Temperature [°C]
100 mm	6.09	309.56	30.38	585.54	1.87	176.47	18.57	487.86	24.33	539.90	41.22	652.73
110 mm	6.28	313.75	31.53	593.44	2.12	188.13	20.22	503.86	24.39	540.39	41.42	653.83
120 mm	6.54	319.34	32.62	600.73	2.33	197.29	21.26	513.45	24.44	540.80	41.62	654.94
130 mm	6.64	321.45	33.09	603.82	2.58	207.54	22.63	525.58	24.49	541.21	41.82	656.04
135 mm	6.87	326.21	33.86	608.81	2.69	211.85	22.91	527.99	24.51	541.37	41.92	656.54
140 mm	6.89	326.62	33.97	609.52	2.81	216.42	23.58	533.68	24.54	541.62	42.02	657.14
150 mm	7.11	331.07	34.60	613.53	3.05	225,20	24.57	541,86	24.59	542.02	42.22	658.23
200 mm	8.21	351.95	36.19	623.24	4.23	262.77	27.88	567.58	24.81	543.81	43.19	663.48
300 mm	10.39	388.05	37.66	632.28	6.53	319.13	31.03	590.03	25.16	546.62	45.07	673.42
400 mm	12.11	412.85	38.00	634.29	8.68	360.26	32.76	601.66	25.39	548.46	46.88	682.68
500 mm	14.00	437.33	38.60	637.81	10.61	391.38	33.64	607.40	25.54	549.65	48.82	692.33

Table 5: maximum incident heat flux and temperature of the element from TRA - small space

Note: these temperatures are used for the temperature of the element in the TRISCO simulations.

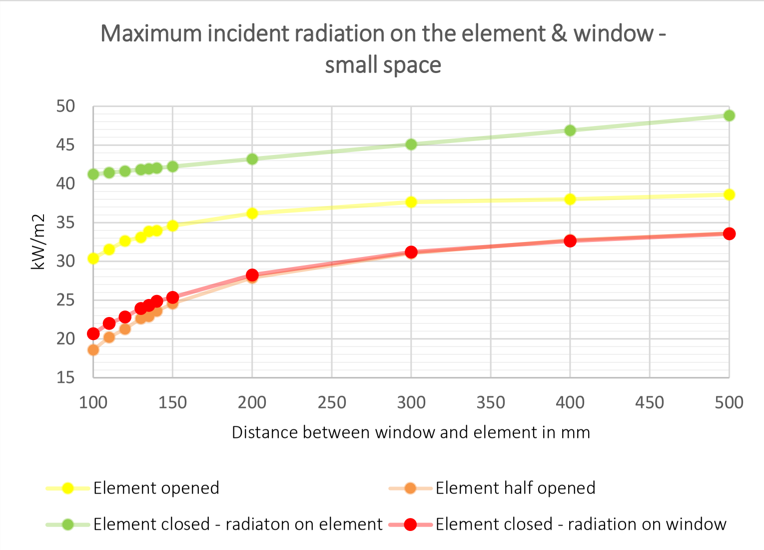
Maximum incident heat flux and temperature of the element from TRA - large space

	Element fully opened				Element half opened				Element closed			
Distance between window and element	Average incident radiation [kW/m²]	Temperature [°C]	Maximum incident radiation [kW/m²]	Temperature [°C]	Average incident radiation [kW/m²]	Temperature [°C]	Maximum incident radiation [kW/m²]	Temperature [°C]	Average incident radiation [kW/m²]	Temperature [°C]	Maximum incident radiation [kW/m²]	Temperature [°C]
100 mm	3.53	241.48	6.33	314.83	0.00	24.85	0.00	24.85	9.79	378.7	12.74	421.3
110 mm	3.39	236.89	6.47	317.85	0.00	24.85	0.00	24.85	9.83	379.34	12.82	422.35
120 mm	3.44	238.55	6.98	328.45	0.01	26.5	0.06	34.38	9.88	380.13	12.89	423.27
130 mm	3.49	240.18	7.17	332.26	0.05	32.85	0.38	74.39	9.92	380.76	12.97	424.31
135 mm	3.57	242.77	7.62	341.01	0.12	43.1	0.81	112.73	9.96	381.39	13.05	425.35
140 mm	3.67	245.95	7.72	342.91	0.20	53.70	1.31	146.42	10.01	382.18	13.13	426.38
150 mm	3.86	251.84	8.46	356.41	0.47	83.48	2.82	216.79	10.23	385.60	13.54	431.6
200 mm	3.96	254.86	9.05	366.59	0.70	104.00	4.13	259.88	10.70	392.73	14.41	442.31
300 mm	4.17	261.04	10.30	386.67	1.04	129.28	6.19	311.77	11.18	399.78	15.35	453.37
400 mm	4.34	265.89	11.00	397.16	1.37	149.96	7.64	341.39	11.57	405.36	16.33	464.39
500 mm	14.00	437.33	38.60	637.81	10.61	391.38	33.64	607.40	25.54	549.65	48.82	692.33

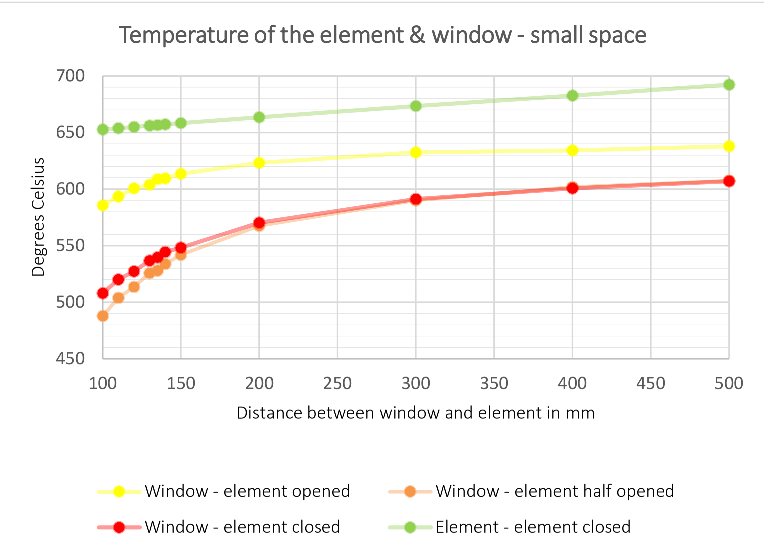
Table 6: maximum incident heat flux and temperature of the element from TRA - large space

Note: these temperatures are used for the temperature of the element in the TRISCO simulations.

Results of the simulations in TRA



Graph 2: maximum incident radiation on the element & window - small spcae



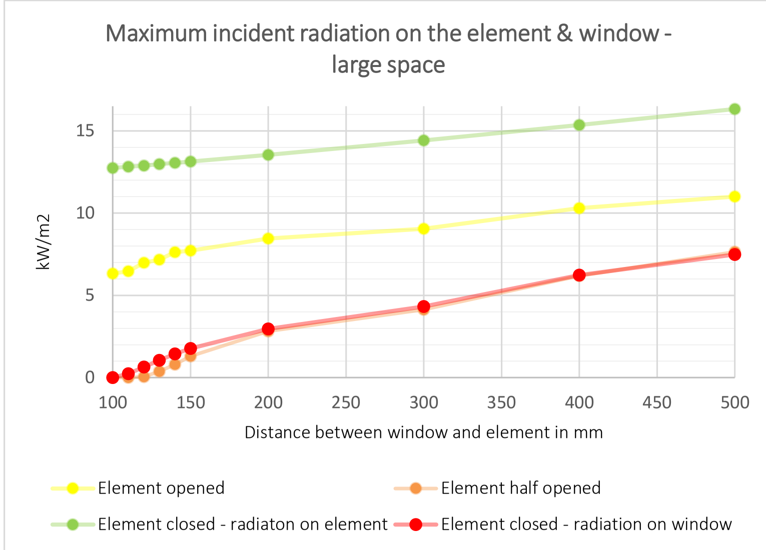
Graph 3: temperature of the element & window- small space

In the graphs you see the maximum incident heat radiation on the window and the element and also the temperature of the window and the element. The distance between the element and the fire is the distance between the window and the fire (1,8 meters) minus the distance between the window and the element. So when the distance between the window and the element 100 mm is, than the distance between the element and the fire is 1,7 meters.

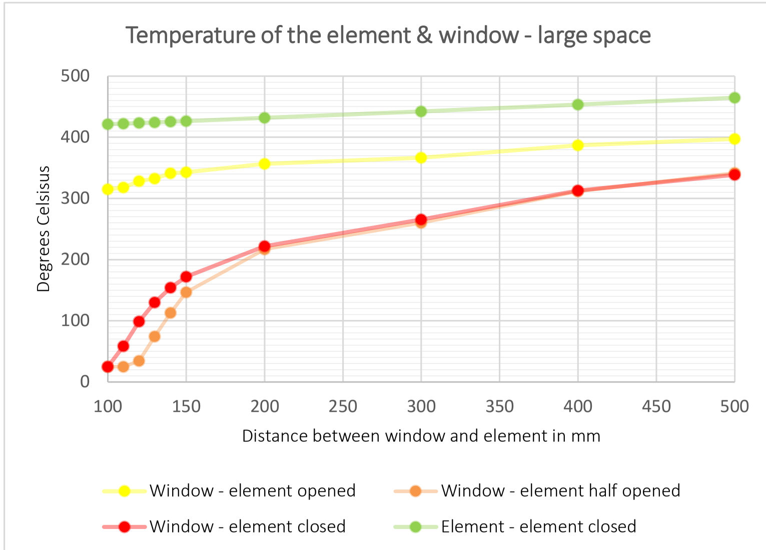
The radiation on the element and is the highest when the distance between the window and the element is higher. Also the radiation on only the element (green line) is the highest because the element is also closer to the heat source in comparison to the window. The radiation on the window is the lowest when the element is half opened.

The graphs of the radiation correspond with the ones of the temperature, because when the incident heat radiation is higher, also the temperature will be higher.

The complete results are shown in tables you can find in the appendix.



Graph 4: maximum incident radiation on the element & window - large space



Graph 5: temperature of the element & window - large space

Results of the simulation in TRSICO

Here the results of the TRISCO simulations are shown for a fire in a small space, with two different glass thicknesses, namely 4/16/4 mm and 6/16/6 mm. There are three different distances measured, namely 75, 100, 125 and 150 mm in order to compare the simulations to the results of the measurements. In the measurements also the distances of 75 and 100 mm are taken, because of the strange temperature drop in the first simulations of TRISCO. The results of these measurements are shown in the appendix.

The maximum incident heat flux and corresponding temperature of the element from the TRA simulations are used in this simulation as the temperature of element. In the graph only the temperature of the inside glass pane is shown, because this pane is the first to be exposed to the heat and in the simulation program TRA was double glazing not possible. As shown in the graph there is a relation between the distance of the element and the radiation and heat. When the element is closer to the window, and thus further away from the heat source, the incident radiation and the temperature on the window are lower.

The results show temperatures in the end situation, after a very long time. So, unfortunately, no temperature rise in the glass is shown with these simulations, so it was easier to compare these simulations to the measurements. Because of these temperatures in the end situation, there is also not much of a difference between the different types of glass. However the temperatures of the outside air and the outside glass pane and the air cavity of the glass are lower with the 6-16-6 mm glass, because of the mass.

Small space		**Element closed**				**Temperature [°C]**			
		4/16/4 mm glass				**6/16/6 mm glass**			
Specifications		**75 mm**	**100 mm**	**125 mm**	**150 mm**	**75 mm**	**100 mm**	**125 mm**	**150 mm**
Outside air	4.9 °C	211.96	217.77	222.39	224.73	199.88	205.06	209.24	211.28
Concrete	300 mm	649.88	652.73	655.49	635.29	649.88	652.73	655.49	635.42
Glass outside pane	4 or 6 mm	236.81	243.23	248.38	251.05	235.41	241.43	246.34	248.82
Air cavity glass	16 mm	624.09	623.82	626.32	628.44	616.68	621.40	623.89	626.00
Glass inside pane	**4 or 6 mm**	**626.42**	**629.17**	**631.69**	**633.84**	**626.61**	**629.36**	**631.88**	**634.03**
Steel plate	1 mm*	649.88	652.73	655.49	658.23	649.88	652.73	655.49	658.23
Inside air	24.9 °C	649.88	652.73	655.49	658.23	649.88	652.73	655.49	658.23

Table 7: result of the TRISCO simulation with the distances of the measurements

Graph 6: result of the TRISCO simulation with the different types of glass

Time versus heat flux

Glass is a poor conductor and that is why normal float glass will break when a temperature differences between 30 and 40 degrees occurs between the glass and the edges of the glass in the frame. From the formula beneath the relation between the incident heat flux is calculated. The temperature rise in the glass and the time can be found with the next formula [Van der Linden, 2013]:

$$\text{Power} * \text{Time} = \rho\ (kg/m^3) * c\ (J/(kg*K)) * \text{Volume}\ (m^3) * \Delta T\ (K)$$

With Power in Watt
Time in seconds
ρ in kg/m^3 – for glass this is 2600
c in J/kgK – for glass this is 840
Volume in m^3 – with 4 mm glass for the small space it is 0.01152 and for the large space 0.02304
ΔT is 35 degrees

With this formula and the maximum incident heat flux (see also table 7 & 8) the maximum time is calculated in which this element may be half or fully opened and exposed to this maximum radiation in order not to break the window because of a temperature difference of 35 degrees. This shows also the time in which the nylon wire has to melt in order not to break the window.

4-16-4 mm glass	**Time in seconds**							
	Small space				Large space			
	Element open		Element half open		Element open		Element half open	
Distance between window and element	Maximum incident radiation window *[kW/m²]	Time [s]	Maximum incident radiation window *[kW/m²]	Time [s]	Maximum incident radiation window *[kW/m²]	Time [s]	Maximum incident radiation window *[kW/m²]	Time [s]
100 mm	30.38	10.1	18.57	16.5	6.33	48.3	0.00	305760.0
110 mm	31.53	9.7	20.22	15.1	6.47	47.3	0.00	305760.0
120 mm	32.62	9.4	21.26	14.4	6.98	43.8	0.06	5096.0
130 mm	33.09	9.2	22.63	13.5	7.17	42.6	0.38	804.6
140 mm	33.97	9.0	23.58	13.0	7.62	40.1	0.81	377.5
150 mm	34.60	8.8	24.57	12.4	7.72	39.6	1.31	233.4
200 mm	36.19	8.4	27.88	11.0	8.46	36.1	2.82	108.4
300 mm	37.66	8.1	31.03	9.9	9.05	33.8	4.13	74.0
400 mm	38.00	8.0	32.76	9.3	10.30	29.7	6.19	49.4
500 mm	38.60	7.9	33.64	9.1	11.00	27.8	7.64	40.0

Table 8: time versus maximal heat flux with 4 mm glass

6-16-6 mm glass	**Time in seconds**							
	Small space				Large space			
	Element open		Element half open		Element open		Element half open	
Distance between window and element	Maximum incident radiation window [kW/m²]	Time [s]	Maximum incident radiation window [kW/m²]	Time [s]	Maximum incident radiation window [kW/m²]	Time [s]	Maximum incident radiation window [kW/m²]	Time [s]
100 mm	30.38	15.1	18.57	24.7	6.33	72.5	0.00	458640.0
110 mm	31.53	14.5	20.22	22.7	6.47	70.9	0.00	458640.0
120 mm	32.62	14.1	21.26	21.6	6.98	65.7	0.06	7644.0
130 mm	33.09	13.9	22.63	20.3	7.17	64.0	0.38	1206.9
140 mm	33.97	13.5	23.58	19.5	7.62	60.2	0.81	566.2
150 mm	34.60	13.3	24.57	18.7	7.72	59.4	1.31	350.1
200 mm	36.19	12.7	27.88	16.5	8.46	54.2	2.82	162.6
300 mm	37.66	12.2	31.03	14.8	9.05	50.7	4.13	111.1
400 mm	38.00	12.7	32.76	14.0	10.30	44.5	6.19	74.1
500 mm	38.60	11.9	33.64	13.6	11.00	41.7	7.64	60.0

Table 9: time versus maximal heat flux with 6 mm glass

Conclusions of the simulation

Here the conclusions are given for as well the old simulations (which you will find in the appendix), as well as for the new simulations with the distances of the element of 75, 100, 125 and 150 mm.

Conclusions for the simulation in the small space:

- The average and maximum radiation are the closest to each other in a closed position.
- The optimal distance between the window and the element in open position will be between 150 and 200 mm for both glass types. The optimal distance between the window and the element in half open position will be between 140 and 150 mm for both glass types. The optimal distance between the window and the element in closed position will be between 130 and 140 mm for both glass types. However, these results from the old TRISCO simulations are not trustworthy enough. Refining the grid and do further simulations will improve the accuracy of the optimal distance.
- When the element is in a more closed position the optimal distance between the element and the window will be smaller.
- The temperature of the glass is in all the three positions around the same value for each distance.
- The average radiation with the element opened and half opened will not exceed the 15 W/m^2 which was set in the program of requirements. The maximum radiation and the radiation on the closed element will exceed this number.

Conclusions for the simulation in the large space:

- The optimal distance between the window and the element in open position will be between 130 and 140 mm when the 4 mm glass is used. For the 6 mm glass type the optimal distance in this position will be between 150 and 200 mm. The optimal distance between the window and the element in closed position will be between 100 and 110 mm for both types of glass. However, these results from the old TRISCO simulations are not trustworthy enough. Refining the grid and do further simulations will improve the accuracy of the optimal distance.
- When the element is in a more closed position the optimal distance between the element and the window will be smaller.
- When the element is half opened in the old simulations the temperatures of the window are very low, with a small deviation at 130 and 140 mm. This applies for both types of glass.
- As well the average radiation as the maximum radiation will not exceed 15 W/m^2, except for the maximum radiation at 400 & 500 mm when the element is fully closed.

Conclusions for both the simulations in the small and the large space:

- When the element is placed closer to the fire, the incident radiation on the element is higher as shown in as well the new simulations as the old simulations. This also applies for the temperature. This has to do with the fact that the amount of energy will decrease, when the distance to the heat source increases. This is also explained in the theory of fire where the heat intensity of a line source is explained.
- How closer the fire retardant shading element to the window is, the higher the temperature on the window will be. This has also to do with the relation between the distance to the heat source and the corresponding energy decrease. Also when this distance is smaller there is more heat radiation from the heated element to the glass pane.
- As shown in the tables the biggest influence on the temperature increase of the inner glass pane is the heat transfer by radiation.
- The differences in thickness of the glass panes hardly had any effect in the simulation only the extra mass when the 6 mm glass was used showed a tiny difference in the end temperatures.
- When the element was half opened, the temperature and radiation on the element were lower in comparison to the closed element. This has also to do the relation between distance to the source and the intensity of the radiation.

5. Measurements

Measuring plan

In this chapter the goal, the method and the types of measurements and materials are explained.

The goal of the measurements is to get to know the heat accumulation in the glass, with and without the sunshading element and with and without a fire retardant coating. Also the time is measured in which the element closes automatically. The specific goals of these tests are as follows:

- To get to know the heat accumulation in the 4 mm glass over time, without an element
- To get to know the heat accumulation in the 6 mm glass over time, without an element
- To get to know the time in which the system closes automatically
- To get to know the heat accumulation in the 4 mm glass:
  - With an open shading element which closes automatically and with a lamellae thickness of 0.8 mm and 75 mm distance between the window and the element
  - With an open shading element which closes automatically and with a lamellae thickness of 0.8 mm and 100 mm distance between the window and the element
  - With a closed element which closes automatically and with a lamellae thickness of 0.8 mm and 75 mm distance between the window and the element
  - With a closed shading element which closes automatically and with a lamellae thickness of 0.8 mm and 100 mm distance between the window and the element
  - With a closed element which closes automatically and with a lamellae thickness of 0.8 mm and 75 mm distance between the window and the element and a fire retardant coating on the lamellae.
- To get to know the heat accumulation in the 6 mm glass:
  - With an open shading element which closes automatically and with a lamellae thickness of 0.8 mm and 75 mm distance between the window and the element
  - With an open shading element which closes automatically and with a lamellae thickness of 0.8 mm and 100 mm distance between the window and the element
  - With an open shading element which closes automatically and with a lamellae thickness of 0.8 mm and 75 mm distance between the window and the element
  - With an open shading element which closes automatically and with a lamellae thickness of 0.8 mm and 100 mm distance between the window and the element
  - With a closed element which closes automatically and with a lamellae thickness of 0.8 mm and 75 mm distance between the window and the element and a fire retardant coating on the lamellae.

These goals will result in the following types of measurements:

- 4 mm / without an element
- 4 mm / open element with a thickness of 0.8 mm / 75 mm distance
- 4 mm / open element with a thickness of 0.8 mm / 100 mm distance
- 4 mm / closed element with a thickness of 0.8 mm / 75 mm distance
- 4 mm / closed element with a thickness of 0.8 mm / 100 mm distance
- 4 mm / open element with a thickness of 0.8 mm / 75 mm distance / fire retardant coating
- 6 mm / without an element
- 6 mm / open element with a thickness of 0.8 mm / 75 mm distance
- 6 mm / open element with a thickness of 0.8 mm / 100 mm distance
- 6 mm / closed element with a thickness of 0.8 mm / 75 mm distance
- 6 mm / closed element with a thickness of 0.8 mm / 100 mm distance
- 6 mm / open element with a thickness of 0.8 mm / 75 mm distance / fire retardant coating

Materials

To get this prototype made and tested the following materials are needed:

- Steel plate: 28 steel lamellae of 458 x 30 x 0.8 mm (these plates can be re-used)
- Fire retardant coating for steel (Tangit FP800 is used)
- Steel wire
- Nylon wire
- Steel frame with mounting options for the element
- Steel pipe for mounting the element
- 4 mm glass 6 panes: 400 x 625 mm
- 6 mm glass 6 panes: 400 x 625 mm
- Stopwatch
- Infra-red measurement tool (a Fluke 62 max+ IR thermometer is used)
- Heat resistant suits
- Bricks to absorb and radiate the heat
- Fire extinguisher or other safety measures

Method

To simulate a fire in an oven as real as possible the oven is first heated till 700 degrees with bricks on the inside which accumulate the heat as shown in photo 5. Then the oven is opened with the use of heat-resistant clothing and the frame is placed in the opening of the oven as shown in photo 6. This way the element is quickly exposed to high temperatures. Every 10 seconds the temperature of the glass is measured with an infrared thermometer. This measurement is done in the centre of the glass pane. The temperature of the oven is noted every 30 seconds. With the use of a stopwatch also the time till the element closes is measured. In the meanwhile everything is recorded, so the time, temperatures and the whole process can later be reviewed. At page 67 the method is explained by pictures from the measurement with the fire retardant coating.

Fire retardant coating

For the the last measurement a fire retardant coating is applied to one side of the lamellae. Here a Tangit FP800 coating is used, which should be fire retardant for 90 minutes, when applied correctly. The lamellae are provided with 1.5 till 1.7 mm coating, which when it was dry shrinks till 0.7 till 1.0 mm. This coating is from the type of char forming coating. This coating becomes active in the condensed phase and is based on phosphorus. The coating is preventing oxygen supply which is needed for the fire, so it protects the underlying structure from the heat. Hereby the temperature rise of the glass will delay. [Kandola et al., 2012]

In Photo 7 & 8 on the right the fire retardant coating was applied to two lamellae as test lamellae and it has expanded from 0.9 and 0.8 to respectively 3.1 till 9.0 mm and 2.3 till 4.0 mm, because of the exposure to heat.

Photo 6: oven with the bricks inside

Photo 7: oven with the steel element without the glass

Photo 8: expanded fire coating from 0.9 (dried) mm to 3.1 - 9.0 mm

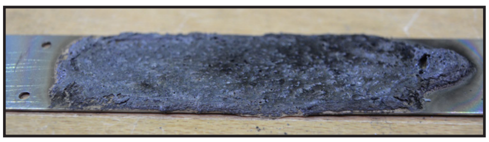


Photo 9: expanded fire coating from 0.8 (dried) mm to 2.3 - 4.0 mm

Test measurement

In this chapter the results of the test measurement is shown and evaluated. These results are shortly discussed here and also in the reflection, because they are only test results where also a different glass thickness was used.

A test measurement was done in order to see if the mechanism would work and to test the measuring method and the prototype. The results in the table show a temperature increase in the glass, until the glass broke because of thermal stresses. The test was done with 5 mm glass, a thickness which will not be used in the real measurements.

Time with 5 mm glass and 10 cm distance	Temperature in degrees Celsius
0 sec.	37,6
10 sec.	38,8
20 sec.	(5)42,2
30 sec.	(4)47,1
40 sec.	48,8
50 sec.	53,5
60 sec.	66,4
70 sec.	(4)79,8
80 sec.	(4)88,5
90 sec.	97,2

Table 10: results of the test measurement

The mechanism did close itself but there is not a time registered in which this mechanism did close itself, because we first placed the element in the oven and after that we placed the glass in the frame, because otherwise it was not possible to place the prototype into the oven with the heat-resistant suit on. So this was not representative for a real fire. The purpose of the test was to see how the mechanism worked and to test the method and the prototype. One of the conclusions is that the prototype has to be provided with handles in order to place the prototype including the glass easy in the oven at once with the heat-resistant suits on. The lamellae closed because of the melting wire.

Also the temperatures which are noted are discussable. A TU Delft student was asked to help and to write the temperatures down that we told her and not the numbers on the screen of the oven, every ten seconds. After the test she said she missed a number probably at 50 seconds, so she wrote down what she thought it was. Also she wrote sometimes a 4 or a 5 in front of the numbers, because perhaps sometimes she took the numbers on the screen from the oven or she made her own numbers, but in any case not always the numbers that were told her. With the next measurements I will note the temperatures myself, in order to know the correct temperatures are written down.

In the photo 9 is visible how the wire in front is melted away and the lamellae are closed. In the other photo is the prototype out of the oven and as you can see the glass is broken because of the thermal stresses. The starting point of the glass breakage is shown in the orange circle. The lamellae in the photo look skewed but this happened while taking the frame out of the oven. The metal lamellae did not bend because of the heat, so they could be used again.

Photo 10: closed element and melted wire

Photo 11: broken glass after the test measurement

Results

After the test measurement the method of the measurements and the prototype was adjusted and the real measurements were done. In this chapter the results of these measurements are shown. In the appendix the tables are shown with all the temperatures and the times in which the system closed and the elapsed time before the glass pane broke.

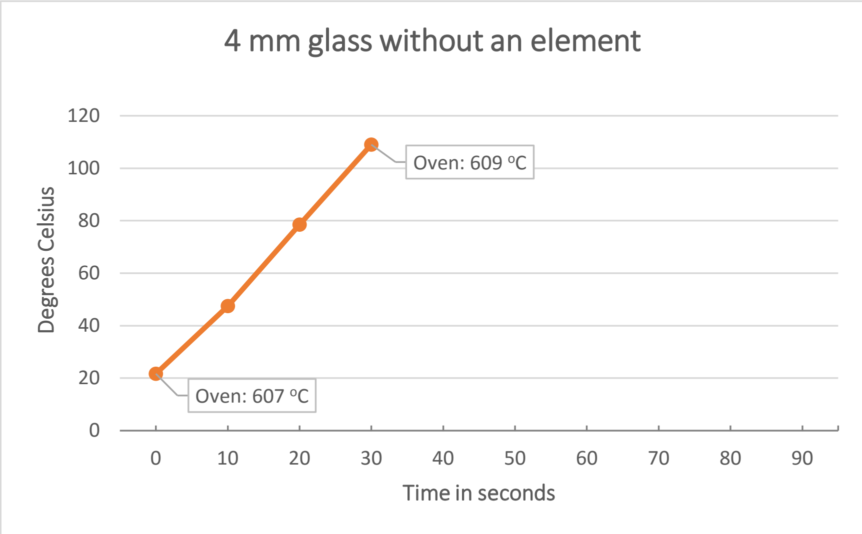
The first measurements consisted of only 4 and 6 mm glass, without an element in order to compare the results of the measurements with the element to. When the oven was heated till 700 degrees Celsius the frame with the glass was put in and the temperature rise in the glass was measured. In the graphs you see the glass is heated up very quickly when 4 mm thickness is used in comparison to 6 mm glass.

At the bottom of the page an overview is given of the temperature increase rate. This is the rate in which the glass pane heats up in degrees Celsius per second.

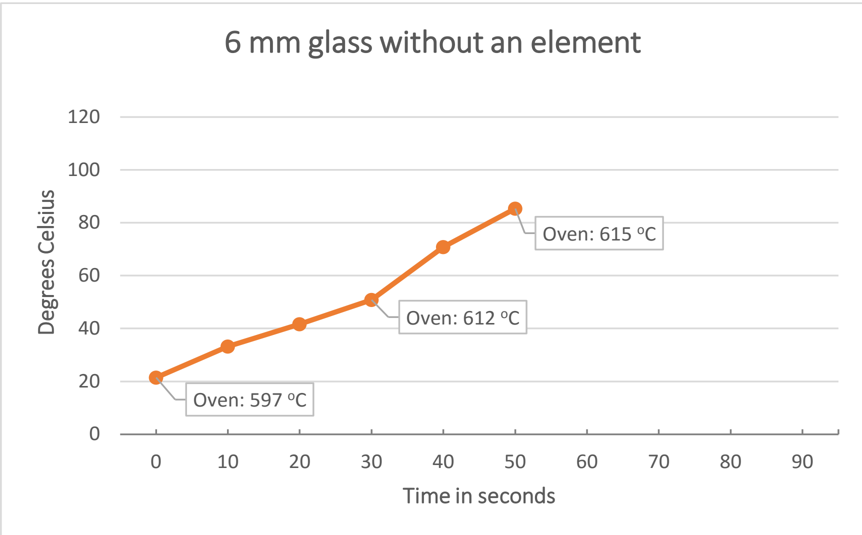
The temperature rise in the glass is lower in the 6 mm glazing in comparison to the 4 mm glass panes. This because there is more mass to spread the heat in. So it takes longer for the whole glass pane to be heated. The glass breaks earlier with the 6 mm glass pane than when the 4 mm glass pane is used (as shown in the results on the following pages).

When the element is at 75 mm distance the 4 mm glass panes have higher temperature increase rates per second in comparison to the 6 mm glass panes.

Ash shown in the table there is a big difference in the temperature increase rate between the 4 mm and the 6 mm glass panes, but there is not much of a difference when the element is placed at 100 mm from the window or when it is placed 75 mm from the window.



Graph 7: 4 mm glass pane without an element



Graph 8: 6 mm glass pane without an element

Temperature increase rate											
ºC / sec	4 mm	6 mm	4 mm open - before closing	4 mm open - after closing	4 mm open-average	4 mm closed	4 mm fire retar-dant coating	6 mm open - before closing	6 mm open - after closing	6 mm open-average	6 mm closed
100 mm	2.2	1.3	2.2	1.6	1.7	0.5	-	1.6	1.0	1.0	0.3
75 mm			2.7	1.5	1.7	0.4	0.6	1.5	0.9	1.0	0.3

Table 11: temperature increase rate

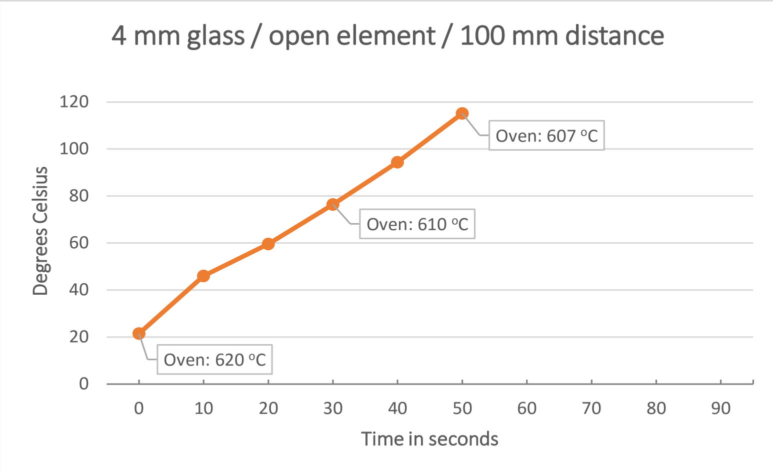
On the next page an overview is given of the measurements with the corresponding time in seconds till the glass breaks in seconds and the temperature of the glass when it breaks. In the next pages you will find the results of these measurements. As calculated from the simulations (in the chapter Time versus heat flux) the nylon wire had to break in around 10 seconds for the 4 mm glass pane and around 15 seconds for the 6 mm glass pane, otherwise the glass is too long exposed to the high temperatures and it will break. As shown from the measurements the nylon wire breaks in around 9 seconds.

The measurement with the longest time before the glass pane broke is the 6 mm glass with the closed element at 75 mm distance. Even at the measurement with the fire retardant coating the glass pane broke earlier. Also at the measurement with the fire retardant coating the temperature inside the oven is around 100 degrees Celsius higher than with the other measurements, because of the burning of the coating. Therefore the temperature increase rate is higher than with the closed element and 4 mm glass, but this is not an equal comparison because of the other indoor temperature of the oven.

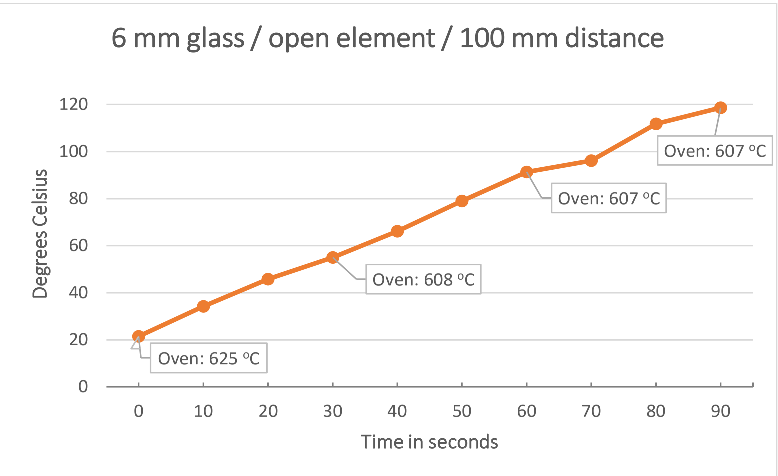
Measurement	**Time till the glass breaks in seconds**	**Temperature of the glass when it breaks in degrees Celsius**	**Time till the element closes in seconds**
4 mm without element	39	109.0	-
6 mm without element	51	85.4	-
4 mm with open element at 100 mm distance	55	115.1	11
6 mm with open element at 100 mm distance	95	118.7	8
4 mm with closed element at 100 mm distance	62	55.1	-
6 mm with closed element at 100 mm distance	47	36.4	-
4 mm with open element at 75 mm distance	50	103.8	7
6 mm with open element at 75 mm distance	81	99.1	8
4 mm with closed element at 75 mm distance	87	70.0	-
6 mm with closed element at 75 mm distance	209	89.7	-
4 mm with closed element at 75 mm distance and a fire retardant coating	133	102.5	-

Table 12: overview of the times and temperatures of the measurements

Results of the measurements at 100 mm distance



Graph 9: 4 mm glass / open element / 100 mm distance



Graph 11: 6 mm glass / open element / 100 mm distance

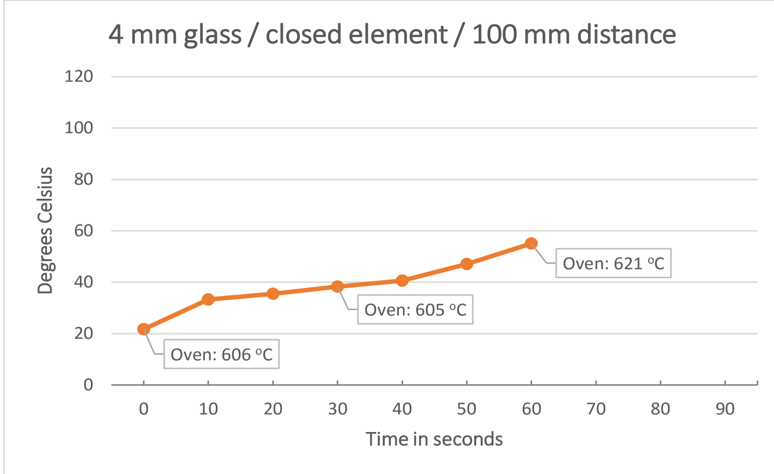
Here the results are shown of the temperature rise in the glass pane, with the element open and the element closed at two different distances. The temperature of the glass is measured until it breaks. In the graphs also every 30 seconds the temperature of the oven is given. Photos of the measurements are shown in the appendix.

The average temperature increase at the measurement of 6 mm glass with the element open is around 1 degree Celsius per second.

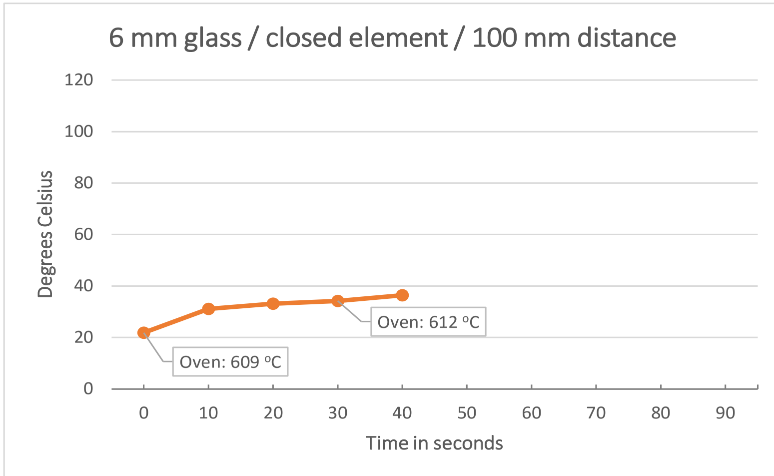
In the first 10 seconds the temperature increase with the open element at 100 mm distance the temperature increase rate is almost the same as without the element. This because the element then is still opened and the nylon wire is melting away.

The measurement with 6 mm glass and the element closed has the lowest temperature rise per second, because of the bigger mass.

In the measurement of graph 15 the glass pane broke earlier than expected. When the open element and the closed element are compared, the results show that the closed element is preventing the glass from heating quickly.

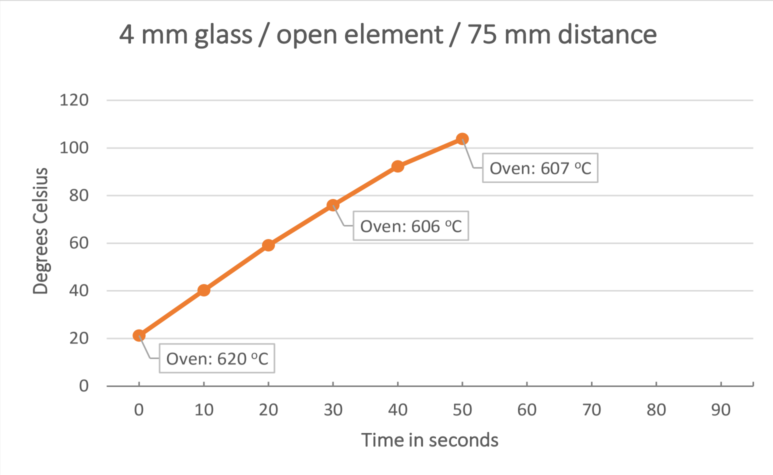


Graph 10: 4 mm glass / closed element / 100 mm distance



Graph 12: 6 mm glass / closed element / 100 mm distance

Results of the measurements at 75 mm distance

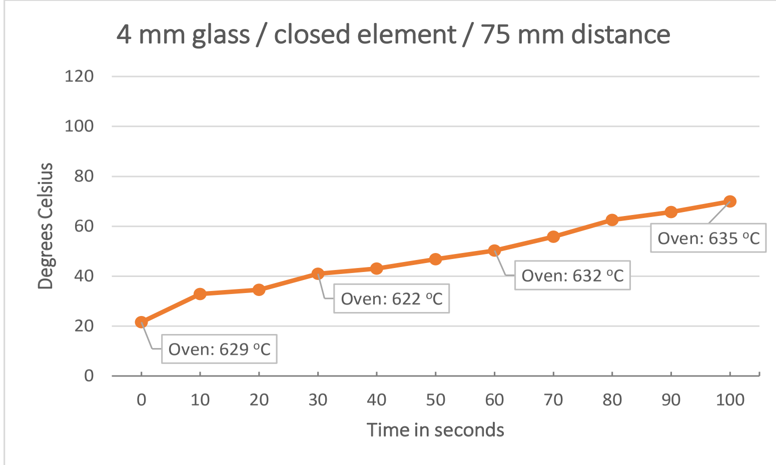


Graph 13: 4 mm glass / open element / 75 mm distance

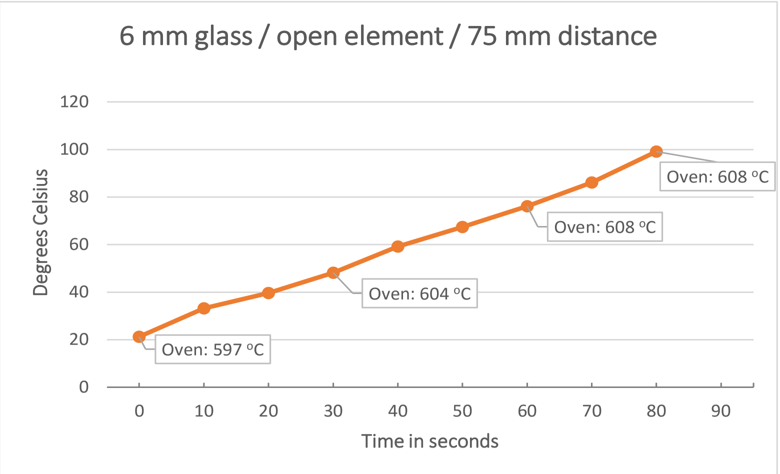
The temperature with the 4 mm glass and the closed element smoothly increases. At the 6 mm glass the temperature goes up and down, this is shows that the glass pane is not heated equally and while measuring not always the exact same spot on the glass is measured.

When the closed element is at 75 mm distance instead of 100 mm distance, it takes longer for the glass to heat and to break. With the element open higher temperatures are reached because there is more exposure to the heat source.

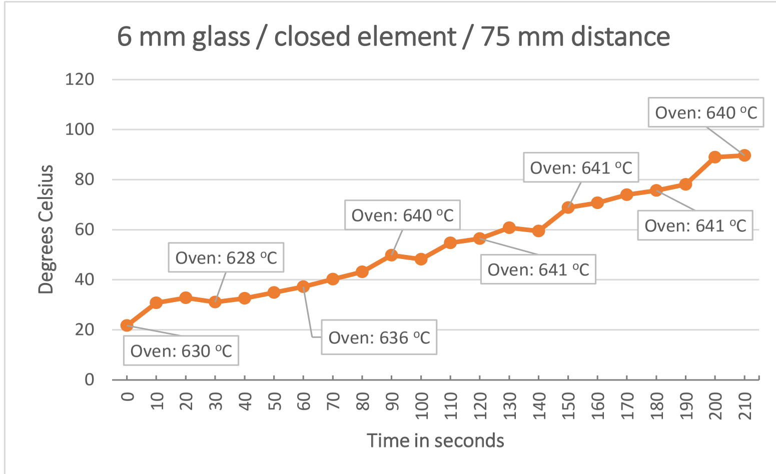
The first 10 seconds of the 4 mm glass pane with the open element at 75 mm distance show a slower temperature increase in comparison to the measurement with the element at 100 mm distance.



Graph 14: 4 mm glass / closed element / 75 mm distance



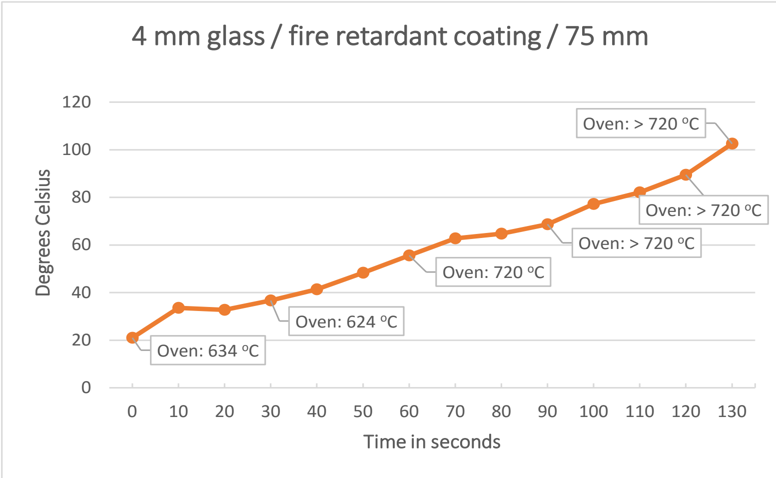
Graph 15: 4 mm glass / open element / 75 mm distance



Graph 16: 6 mm glass / closed element / 75 mm distance

Results

Here the results are shown of the measurement with the fire retardant coating. On the next page the method of the measurements are shown with some explanation.



Graph 17: 4 mm glass / fire retardant coating / 75 mm

In comparison to the closed element at 75 mm distance, the closed element with the fire retardant coating keeps the glass from breaking only for 46 seconds longer. This was very quick, knowing that the fire retardant coating is resistant for 90 minutes. The breakage of the glass pane is probably caused by the high air temperature in the oven and the conduction of the heat from the metal frame to the glass pane, because the glass was not completely insulated from the metal frame.

An important note to this graph is that the temperature in the oven is more than 100 degrees higher than with the other measurements, because of the burning coating. After 720 degrees there is no oven temperature, because the system shuts down the oven automatically when a maximum of 20 degrees above the set temperature is reached, to prevent overheating.

There is no measurement done with a fire retardant coating and the 6 mm glass pane. Because it was not safe enough to do the measurements at the place where the oven was located. With the first measurement with the fire retardant coating a lot of smoke was released by the burning coating and because there was no exhaust it was not completely healthy to work over there with these types of measurements.

During the measurement the coating caught fire and expanded. Hereby flames arose in the oven. When the glass broke only smoke escaped through the glass and not the flames. So the closed element with the fire retardant coating prevented raging flames to the outside and thus flash-over.

Photo 12: the burned fire retardant coating

In the photo you see that the fire retardant coating is expanded (from 0.7-1.0 mm to 2 till 3 centimeters) and burned. In the appendix more photos are shown.

Method in pictures

To prevent the glass from be heated from the outside the heat elements in the door of the oven were covered by a steel plate while the oven was opened. This was also to limit the heating of the space.

Inside the oven a pile of bricks was placed to accumulate the heat and radiate the heat while the door of the oven was opened.

The element was placed in the oven and every 10 seconds the temperature of the middle of the glass pane was measured with an infrared meter.

After 130 seconds the glass pane broke and a bit of the smoke, produced by the burning fire retardant coating, was released. The flames are kept inside by the fire retardant coating and the element, so the spread of fire is prevented.

The element was taken out of the oven by the handles. The fire retardant coating burned and expanded in the oven.

A lot of smoke was produced by the burning coating. But the element, even when the glass was broken, kept most of the smoke inside.

Conclusion of the measurements

Conclusions for the measurements with the element at a distance of 100 mm
When the 4 mm glass pane is used without the element the time in which the glass withstand the temperature is shorter in comparison to 6 mm, but the glass temperature is higher.

When the element is closed the temperature when the glass breaks is lower than when the element is open. With the element open the temperature of the glass in increasing till 115 till 120 degrees Celsius, then it breaks.

Conclusion for the measurement with 4 mm glass and 100 mm distance with the element open:

- Before the closing of the system there is a slower temperature increase in the glass (1,26 degrees Celsius / second and 1,63 degrees Celsius per second after the closing of the element)

Conclusions for the measurement with 6 mm glass and 100 mm distance with the element open:

- When the mechanism closed the element the temperature rise is decreasing.
- The time before the glass pane breaks is longer in comparison to 4 mm.
- The temperature rise in the glass is lower than when the 4 mm glass pane is used.

Conclusions for the measurement with 6 mm glass and 100 mm distance with the element closed:

- The glass breaks earlier than when the element is first opened, this because the glass is first exposed to the radiation of the fire. After the system is closed, it is exposed to the radiation of the element.
- The glass breaks earlier than when the 4 mm glass pane is used but there is a very slow temperature rise of 0,14 degrees Celsius per second in the glass till the glass breaks at a temperature of 36.4 degrees Celsius.

Conclusions for the measurements with the element at a distance of 75 mm
With the element at a distance of 75 mm from the glass it takes longer for the glass to break in comparison to a distance of 100 mm.

Conclusion for the measurement with 4 mm and 75 mm distance with the element closed:

- The 4 mm glass pane has a lower temperature increase rate per second (0.43 degrees Celsius/second) in comparison to the 6 mm glass plane (0.82 degrees Celsius/second)

Conclusion for the measurements with 6 mm and 75 mm distance with the element closed:

- The temperature rise of the glass fluctuates, this is a result of the unequal heating of the window and because of the measurements which are not exactly at the same spot on the glass every time that the temperature is measured.
- When the 6 mm glass pane broke, the glass shattered instead of cracking, this because of the higher pressure in the oven.

Conclusion for the measurements with 4 mm and 75 mm distance with the element closed and the fire retardant coating:

- The glass pane broke earlier than expected, because the coating had a 90 minutes fire resitance.
- The temperature inside the oven was around 100 degrees Celsius higher in comparison to the other measurements, because of the burning of the coating.
- There are some fluctuations in these measurements, so with every measurement not exactly the same spot is measured.
- The temperature increase rate is higher than without the fire retardant coating, because of the higher temperature in the oven.
- At the same measurement without the fire retardant coating a higher temperature is reached, although the glass broke earlier with this measurement without the coating.
- The flames in the oven, because of the burning fire retardant coating, did not come through the element, so the element prevented the spread of fire via the outside, even when the glass was broken.

Comparison of the measurements with the element at 75 and at 100 mm distance
The temperature increase rate in the 4 mm glass with the element at 100 mm was 0,42 degrees Celsius/second in comparison to the 0,43 degrees Celsius/second with the element at 75 mm. So there is hardly any difference in temperature increase between the different distances of the element. At a distance of 75 mm the glass temperature has a higher maximum and thus, with the same temperature increase rate, it took longer for the glass to break. The temperature increase in the 6 mm glass with the element closed at 100 mm was 0,14 degrees Celsius/second in comparison to the 0,82 degrees Celsius/second with the element at 75 mm. So it took longer to heat the glass with the element at 100 mm distance, but the glass broke earlier and at a lower temperature.

In comparison to the measurement with the element at 100 mm distance it took longer for the glass pane to break, because of the distance to the heat source. Also when the element was closed the element protected the glass pane from the heat, whereby the temperature increase was not as fast as with the element opened at the start.

The nylon wire melted in around 10 seconds. In comparison to the time calculated in the chapter Time versus heat flux this is right in time.

In comparison to the simulations the measurements also show that when the element is placed further away from the heat source the temperature on the glass pane is lower. However the simulations do not show the temperature rise in the glass pane over time, as is the case with the measurements, so now only the end results of the simulations could be compared. With more accurate measurements and simulations also the influence of the radiation from the element to the window could be analysed seperate from the radiation from the heat source to the element and from this the optimal distance could be concluded.

6. Discussion

Discussion

After the research, the simulations, the prototypes and the measurements there is a lot to discuss. The discussion is divided into the different subjects namely simulations, measurements and design.

Simulations

The simulations are done in two different computer programs, namely TRA and TRISCO, because there was no decent and simple fire simulation program available for free and the programs that were available were too complicated for the time which was available. Now simulation programs are used which are meant to simulate heat transfers in a room and other building physics subjects. These programs are not completely designed for high temperatures such as fires. Because this was all to develop a concept for an alternative design solution for fire retardant glazing these simulations in a building physics program is not harmful, but for further research it is advisable to do the simulations in a program which is developed for simulating fires. Also further simulations with these programs can be done, but than it is better to add the RADCON module for the TRISCO simulations, which is more detailed when it concerns heat radiation.

For the simulations a room temperature of 24,9 degrees Celsius was taken. This is however a bit high in comparison to the measured room temperature of around 21-22 degrees Celsius in the space where the measurements took place. For the next time this can be adjusted, although such a small temperature difference will not make a difference when there is a fire. These simulations are done in two standard rooms, a large and a small one. In real life the rooms may be different, so difference in temperatures may occur then.

The optimal distance for the measurements, which should be concluded from the results of the simulations, is not used for the measurements because of the strange and sudden temperature drop. This could possibly be because the program TRISCO is not programmed for such high temperatures and the grid was maybe not refined enough. Therefore now two different distances of 75 and 100 mm are used, which is a trustworthy alternative in order to lose as less space as possible, to see the difference between the two distances and so that the element is not placed too close to the heat source. Also simulations are done with these distances in order to be able to compare the measurements with the simulation.

The simulation had, in relation to the measurements, a whole different scale and size. The size of the window in the measurements was a lot smaller, because of the opening in the oven. Because here only a concept was tested this is not very important, but when definitive tests are done, this difference of scale should be kept in mind. Because the sizes of the glass will have an influence then in the temperature differences between the centre of the glass and the edges.

In the simulations smoke is not taken into account. The temperature of the smoke must be really high before it will radiate heat, that in these simulations of a concept idea this is negligible. But in a real fire the temperature will become really high, then it should be taken into account.

In the old TRISCO simulation the sloped elements are simulated as three blocks. But this way there will be a problem with the thickness in the corners of the blocks. So next time the blocks should have an overlap as shown in the figure 36.

Unfortunately the simulations did not give a result of the temperature rise over time, but only in the end situation. This way the temperature rise over time could not be compared to the measurements. For further measurements it is recommendated to do the simulations in a program which can also show the temperature rise of the glass over time.

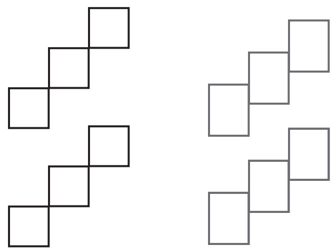


Figure 38: blocks with an overlap

Measurements

The measurements in the oven were a good starting point to see if the mechanism would close when exposed to high temperatures and to get a feeling of the temperature and the behaviour of glass in such high temperatures. The measurements are not performed via methods or rules which are given in the Dutch Building Decree. On the one hand because it is just a concept idea of a fire retardant sunshading element and on the other hand because not all the equipment was available. But also here further measurements are advisable, because not all the variables are tested, like other thicknesses of glass, other sizes of the prototype or other materials and also it was not tested via the rules of the Dutch Building Decree. Also in comparison to the real fire test I saw at Efectis, the measurements I did in the oven are not even close to that type of measurements, but for the concept design and without all that kind of equipment it was a good alternative. At the real fire test at Efectis the window was placed in front of a very large oven. There were thermocouples connected to approximately every 15 cm^2, which were connected to a computer. So during the test the temperature of around 100 different places on the window were measured. Also tensioned wires were connected to the glass and the frame in order to measure the inflection. With these measurements the element is exposed to a regular fire curve (as explained in the theory). So there are big differences between the fire test at Efectis and our measurements, concerning the amount of measurement points, the accuracy of the measurements and the temperature curve to which the element was exposed.

The fire was simulated by heating the oven till 700 degrees before the frame with the glass and the sunshading element was placed in the opening of the oven. Of course this is not very similar because in reality the window is slower exposed to such high temperatures. Therefore the measurements at Efectis were exposed to heat equal to the regular fire curve.

The results of the test measurement is also discussable, because not the right temperatures were written down. However these results are not used, because it was just a test measurement.

Also the measurements with the infrared meter are done in approximately the middle of the glass pane. Of course not always the precise middle of the glass pane was taken. And then every ten seconds the temperature was measured. But sometimes it was a fraction before or a fraction of a second after ten seconds, because of the responsiveness of the person who measured and because of the reaction time of the infrared measurement tool. Therefore also fluctuations of the glass temperature in the results are shown. To get fully reliable results it is important that with measurements in the future every time the temperature on the same spot is measured and when it is possible also the temperatures at different places on the glass are measured. This way you will get a clearer view on the temperature differences in the glass and get a relation to the thermal breakage of the glass.

Also the simulations are done with a lamellae thickness of 1 mm, while the measurements where done with 0.8 mm thickness. Because the lamellae did not bend the thickness could even be thinner. This way there is less material used and a better view to the outside, while the function stays the same. Further measurements with different thicknesses should be done in order to prove this.

At last also because the element with the glass and the lamellae has to be manually placed in the oven every time the oven had a different starting temperature when the element was placed. Also the time in which the element was exposed to the high temperature of the oven, when the element was not place yet differs. These are all little factors which have an influence on the results. Fortunately, these kinds of little temperature differences will not make a difference during a fire in real life, because of the high temperature and the unpredictableness of fire.

The measurement with the fire retardant coating cannot be equally compared to the rest of the measurements, because the temperature inside the oven was around 100 degrees Celsius higher.

Design

The design is not definitive. The mechanism should be a bit adjusted so the lamellae could be easily adjusted into the different positions. However the lamellae of the fire retardant shading element cannot yet be fully pulled up and automatically go down in case of fire. They can only be fully taken away. However there are already sunshading products which can be fully pulled up, so this was here not further researched. When these kinds of products are used there should also be a nylon wire which in case of fire melts away and causes the whole system to fall down properly when it is pulled up.

If in reality the glass breaks it is not a problem, as long as the flames are stopped by the fire retardant sunshading element in order to prevent flash-over. Then there is only extra oxygen supply to the fire. Now the measurements are done till the glass breaks, but in reality this should not be a problem, as long as the spread of fire via flash-over is prevented at least for the first 15- 30 minutes until the firefighters are present to further prevent the spread of fire.

In this design the shading element in on the inside of the building and is thus not as efficient as shading on the outside of the building, however the specifics of the glass are becoming better every day so there is less heat coming inside the building. These used principle of the venetian blinds are also still one of the most common types which are used in public buildings for sunshading, so although it is not as efficient as shading on the outside this was a good starting point. Further development may also result in a fire retardant shading element on the outside of the building. Then, of course, it has to meet far more criteria which was already explained in the design study and the durability chapter.

Recommendation

After the research, the simulations, the measurements and the prototypes the following there are some recommendations for further research and further tests in order to improve the concept of the fire retardant sunshading product.

It is advisable to also do the simulations in a program which is built for simulating fires, like Brando or TRISCO with the RADCON expansion. Because now the simulations were done in two different programs. They give a good approximation, but it could be improved so they will give a more reliable result. Also a program which can show the temperature rise in the glass pane over time will help to compare these results better to the results of the measurements.

When further research is done and other measurements take place, it is recommended to perform these measurements according to the rules of the Dutch Building Decree and the NEN 6069 and NEN 3885, because for now the prototype was tested without these rules because this was just a concept. More measurements of the same type will increase the accuracy of the results. Also tests with other types and thicknesses of the glass or with double-glass are advisable to do, because now the tests are only done with a single glass pane. Where the theory says that a single glass pane will break during a fire in the first 2 minutes, double glass will break in 2 till 5 minutes. So doing measurements also with double glass will be useful in order to compare them. Also test with other fire retardant coatings or heat reflective coatings on the lamellae are advised to perform in order to compare the results to get the best fire retardant properties. A test that will measure the time till flash-over via the outside occurs with the use of the fire retardant shading element is also advisable. For the measurements with the fire retardant coating (and also for all the other measurements) it is advisable to perform these measurements under safer conditions. So an exhaust for the smoke is recommended as well as a facemask and also a fire/smoke detector and good fire-fighting equipment.

The design of the fire retardant shading element is equal to a normal inside sunshading, which has the possibility to be integrated into the wall. Further design studies and material studies can be done in order to improve the mechanism, so that it can also be pulled up. This pulling up of the lamellae is already shown in normal sunshading, so it is possible. Only in case of fire a wire has to melt and the whole shading has to fall down in order to prevent flash-over.

The connection with the metal bridge between the nylon wire and the steel wire, like a ladder cord, for the measurements and the prototype is not very stable. If a ladder cord can be developed with a nylon wire, a steel wire and a steel bridge the element and the mechanism would be improved, just as shown in photo 5 on page 37. Also measurements can be done with the nylon wire at the side of the room and the steel wire at the side of the window (figure 37b), in order to measure the difference in the time that the system closes. For the fire retardant coating, which is not very stable when exposed to much UV, it is best to keep it at the bottom of the lamellae and thus to keep the nylon wire at the window side (figure 37a)

Another point that can be further developed is the design. A design of a fire retardant sunshading, but then with another type of sunshading as a starting point or a design with less and thinner lamellae for example Because now for the materials of the lamellae steel is used, but when further research and tests are done these lamellae could possibly be thinner so less material is used or be made from another material, with minimal the same performance, which works better and can resist higher temperatures or could be cheaper also in production.

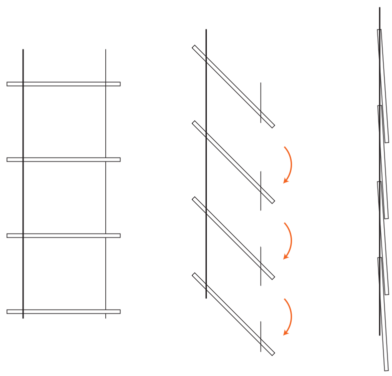


Figure 39a: Metal wire on the left, nylon wire on the right (window side)

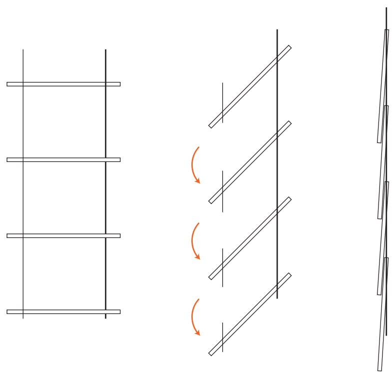


Figure 39b: Metal wire on the right, nylon wire on the left (roomside)

7. Conclusion

Conclusion of the design

Looking at the program of requirements the design for the fire retardant shading element meets the criteria for the sunshading performance because the shades are manually adjustable from almost transparent to fully closed, but cannot be fully pulled up. It can also be integrated in the wall and produced into different colours. This way the fire retardant shading element will look like normal shading only the materials and properties will differ. For the fire retardant shading element steel lamellae are used instead of aluminium which is now often used for normal shading, because steel can withstand higher temperatures. Because of the high temperatures during the fire the nylon wire will melt (in around 10 seconds already) and break, so the system is self-closing without the use of electricity or human effort. Only the nylon wire is not optimal when it comes to UV light, but with an UV coating this should be covered.

The system is not yet able to meet the requirements for the heat flux (not more than 15 kW/m^2 at 1 meter distance from the window) and the temperature (not above 140 degrees at the non-fire side). This was also not measured because the lack of equipment. Here just concept for a product is developed. When it is further developed and further measurement with other equipment are done it may meet also these high requirements from the Dutch Building Decree.

The old simulations which were made in order to determine the optimal distance where not very reliable, because of the strange temperature drop, probably because of the high temperatures and the (lack of) accuracy in the refining of the grid. That is why for the measurements the two distances of 75 mm and 100 mm are used between the element and the window. Also new simulations were made with these distances in order to compare them to the results of the measurements. When the element is placed closer to the window, it takes longer for the glass to break, because the incident radiation on the lamellae is lower because of the distance. However, old the simulations showed also that when the element is placed closer to the window the temperature on the window will be higher, because there is more incident heat radiation from the heated element to the glass pane. So placing the element closer to the window is better in order to lose less space and also for the incident heat radiation from the fire. When the space between the window and the element is less there is also less space which is heated by the direct sunlight. Still an optimal distance has to be found between the incident heat radiation from the fire and the radiation from the heated element to the glass pane, because this has a negative influence on keeping the temperature of the glass lower. When the simulations also showed the temperature rise in the glass over time the simulations could be better compared to the measurements.

The cost of the new system has to be lower than the average costs of 250 till 550 euro per square meter for fire retardant glazing plus the costs of a shading element (20 till 150 euros). HR+++ glass costs around 120 euro per square meter. So with the fire retardant shading element the total costs will lie between 140 and 270 euros, which is still cheaper than the fire retardant glazing with a sunshading element (between 270 and 700 euros).

From the measurements was learned that the glass pane had to be fully insulated to prevent the conduction of heat from the steel frame to the glass pane. In normal windows the glass is connected to the frame in a different way. Here is the glass also fully insulated from the frame. To prevent heating or melting (dependent on the material) of the frame of the window the frame can be coated with an fire retardant coating. But then after the fire the frame cannot be re-used, because of the expanded coating. So it is better to let the element fully seal the window, including the frame. Also hindering of the element by the inventory should be prevented in order to ensure that the system will close properly in case of fire.

The fire retardant shading element will prevent the spread of fire via flash-over. Because of the fire retardant coating the element becomes an equal to the combination of fire retardant glazing with an epoxy interlayer and with the intumescent coating. Because the element will form a whole, just like the epoxy interlayer, while the intumescent coating on the element will prevent the spread of fire and the oxygen supply for the underlying structure.

Answers to the research questions

Here a short summary of the answers to the research questions are given. For a fully answer also the chapter were you will find the answer is given.

In which way is it possible to use sunshading as a fire retardant element, such that it will be an alternative design solution for fire retardant glazing in public buildings in Holland?
In this thesis a concept is developed for an inside sunshading element which also functions as a fire retardant element. The starting point of the design are horizontal venitian blinds, which can be manually adjusted from horizontal (fully opened) to fully closed. With the use of a nylon wire at the window side the sunshade system will close automatically in case of fire, because the wire melts away at higher temperatures. The bottom of the lamellae are provided with a fire retardant coating. So when the nylon wire melts away and the system closes, the window is protected from the heat source because of this fire retardant coating. With a steel cover with also a fire retardant coating the mounting principle is out of sight. The whole element can also be completely integrated into the wall or can be completely taken of for maintenance, or cleaning, or be stored when it is just not necessary anymore. Also less lamellae could be used in order to get a clearer view to the outside, but then the depth of the lamellae has to be larger, in order to still cover the whole window when fully closed.

What are the criteria and specifications of the fire retardant element?
The design of the system which will function as well as sunshading as well as a fire retardant product, which functions as an alternative design solution for fire retardant glazing, has to meet different criteria. Here the most important criteria are shown in the program of requirements, with how these criteria are applied to the concept design:

- *Integrity:* *To meet criteria E for fire retardant glazing, the system has to stop the spread of fire and smoke from the fire side to the non-fire side.*
  The fire retardant shading element prevents the spread of fire via flash-over from the fire side to the non-fire side. When the glass is not breaking also the smoke is stopped. If not, still the spread of fire is prevented, only there is a large oxygen supply to the fire and an exhaust for the smoke.
- *Heat flux:* *Besides integrity the system also has to stop heat flux from the fire side to the non-fire side to meet the criteria of EW fire retardant glazing. This only applies when the heat flux at the non-fire side at 1 meter distance will not exceed 15 KW/m^2 during a certain period of time [Van der Veek et al., 2005].*
  The element is not tested in the same way as the tests are done in order to get an EW classifications. Also the heat flux is not measured.
- *Temperature:* *The system also has to stop heat from the fire side to the non-fire side. When the average temperature on the not-heated side will not rise above 140 degrees Celsius and the local maximum temperature on the not-heated side will not rise above 180 degrees Celsius and the radiation at the non-fire side at 1 meter distance will not exceed 15 kW/m^2 it will meet the EI criteria of fire retardant glazing. [Van der Veek et al., 2005]*
  Only the temperature of the glass was measured, not the temperature at 1 meter distance.
- *Costs:* *The cost of the new system has to be lower than the average costs of 250 till 550 euro per square meter for fire retardant glazing.*
  The costs of the new system will lie between 140 and 270 euro per square meter.
- *Sunshading:* *The system has to function as sunshading, which is manually adjustable from almost transparent and fully opened to fully closed.*
  The fire retardant shading element is manually adjustable from almost transparent to fully closed. However, the system cannot yet be fully pulled up.
- *Esthetical:* *From an architectural viewpoint the shading/fire retardant system has to make an esthetical contribution to the design and it must be possible to be integrated into the wall.*
  The system can be integrated into the wall and it looks like a normal sunshading element.
- *Self-closing:* *In case of fire the system has to close automatically, without the use of electricity or human effort. This way the chance of failure during a fire is lowered.*
  Because of the melting nylon wire the system will close itself in around 10 seconds.
- *Material:* *The material has to be UV resistant and at the same time fire retardant and non-flammable. Also it has to be UV proof. These properties can be divided over different places of the element.*
  The lamellae are made of steel, which has an excellent resistance against UV and can withstand high temperatures. The nylon wire has to be coated with an UV coating in order to get it resistant againt UV.
- *Glass:* *4 mm and 6 mm glass panes are used for the measurements and for the simulations 4/16/4 and 6/16/6 mm glass panes are used.*
  The same glass panes are used. Further measurements with double glass just like in the

simulations will improve this research.

- *Distance:* *The optimal distance between the window and the fire retardant shading element has to be determined by heat transfer simulations of the fire.*
  For the prototype the distances of 75 and 100 mm are used, because the simulations did not give a thrustworthy result. So in order to lose as less space as possible and to be able to compare the different results caused by the different distances these distances are taken.

These requirements will result into a concept design for a fire retardant sunshading element. The rest of the explanation you will find in the chapter of Design Research.

- What are the current rules in the Netherlands regarding fire resistance of windows?
  The current rules and regulations regarding fire resistance of windows in public buildings in Holland are explained in the theoretical framework fire. Most of these rules are set in the Dutch Building Decree. These rules are mostly to prevent the spread of fire via flash-over or fire penetration and to secure the safety of fleeing people. Also important is that if a deviation of these rules is necessary equivalence to these rules must be demonstrated. With a fire retardant sunshading element this becomes important, because it should be (almost) equivalent to the specifics of fire retardant glazing.
- What are the current criteria for fire retardant glazing and how does it work?
  A single pane of float glass will crack during the first two minutes of a fire. A double pane of float glass will crack between 2 and 5 minutes of fire. This is not enough to be considered fire safe, therefore fire safety glass is produced. There are three different kinds of classifications for fire safety glazing, namely E (integrity), EW (integrity plus heat flux control) and EI (integrity and insulation) [NEN-EN 1999-1-2:2007 & NEN-EN 12101-9:2004]. The specific criteria are explained in the theoretical framework of fire. The principle of fire retardant glazing is that because of the heat the inner glass pane breaks and a chemical reaction occurs, which result in an expansion of the surface which is the fire retardant layer. This way the radiation and the temperature are reduced, because the heat transfer by convection is limited and the heat flux is absorbed. A more detailed explanation of the different types of fire retardant glazing and their working principle you can find in the theoretical framework of fire.
- What criteria should the fire retardant sunshading element meet?
  The fire retardant element should prevent the fire from spreading through the window, via the outside of a building to another building (part), this is called flash-over. Also the system should function as a normal sunshading. The specific criteria are explained earlier in this chapter and in the program of requirements in the Design research chapter.
- What is the influence of the distance between the element and the window?
  When the element is placed closer to the window and thus further away from the heat source the intensity decreases. This is explained in the theory of fire where the inverse squared-law is explained, but this law only applies for a point source. In case of the measurements a line source applies. This is also explained in the theory of fire. However an optimum still has to be found between the intensity from the heat source to the element and the intensity from the element to the window, because the distance between the window and the element influences the distance between the element and the heat source. Also to ensure fully sealing of the window the element cannot be placed very far away from the window. To get to know the optimal distance between the window and the element simulations were done. However they did not give a trustworthy result of the sudden temperature drop. Therefore other distances were taken for the prototypes. More information of the simulations you can find in the chapter Simulations.
- What is the critical time in which the system has to close in order to prevent the window from breaking?
  For the 4 mm glass pane the system has to close within 39 seconds, otherwise the glass will break. This is shown in the measurement with the glass panes of 4 and 6 mm without the element. For the 6 mm glass pane the system has to close within 50 seconds. As measured, the nylon wire will break around 10 seconds. These results are shown in the tables of the results of the measurements and in the appendix.
- How to ensure that the system will close automatically in case of fire?
  Because of the nylon wire, which melts at high temperatures, the lamellae will close automatically in case of fire. The imposition of the lamellae will lapse. This way the lamellae will close automatically in case of fire, without the use of electricity and human effort. A more detailed explanation is given in the chapters Design of the mechanism and in The prototype of steel.
- How to ensure natural ventilation via the window and what will be the influence during fire?
  Windows behind the system can be opened through the lamellae or in case of automatic windows, which are applied more often nowadays, the window is able to open. The distance of the opening is however dependent on the distance between the window and the shading element. In a lot of public buildings there are not many manually openable windows, because the buildings are provided with an advanced climate control system. In case of fire these windows have to close automatically or otherwise they will be a big oxygen source for the fire and the fire will increase and the smoke will have a way out.

Which materials will be used?
For the fire retardant shading element the materials steel and nylon are used. Also a fire retardant coating for the lamellae needs to be used and possible an UV coating for the nylon wire, in order not to break because of the sunlight.

- What kind of materials is best to use for the sunshading?
  Materials which have a high resistance against UV are best to use for the sunshading. This to limit the chance of wearage of the material by the UV light. Steel has an excellent UV resistance. The nylon wire however is not so resistant to UV, but a coating can make it more UV resistant. More information is given in the material study.
- What kind of materials is best to use for the fire resistance?
  Materials which can withstand the high temperatures are best to use for the fire resistance. That is why steel is used in the prototype. For the wire which has to melt away at relatively lower temperatures a material which cannot withstand high temperatures but still is strong enough to hold the lamellae is suitable. Also good UV resistance is required, because it is exposed to UV in the window all day. Also a material coated with an UV coating is a good possibility. More information is given in the chapters of the prototypes and in the material study.
- What will be the influence of UV over time?
  Because the fire retardant shading element will be on the inside of the window the element will suffer less from UV radiation than on the outside of the window, because a part of the UV radiation is stopped by the glass. The nylon wire will be provided with an UV coating. The downside of the lamellae will be provided with a fire retardant coating, however this will not be exposed to direct UV light. The top of the lamellae is not coated with an UV coating, because steel already has an excellent resistance to UV radiation. A more detailed explanation is given in the Durability, Concept design and Material study chapters.
- What is the sustainability of the materials?
  For the lamellae the material steel is used, because it is very well reusable and recyclable. The nylon wire however will melt away in case of fire and the fire retardant coating will expand is case of fire, so they are not reusable. More about the materials and sustainability is explained in the Material Study and the Durability chapter.

What will be the durability of the element?
The shading element is placed on the inside of the window. This will reduce the chance of wearing and damage in relation to shading on the outside of a building. Wearage of the wires because of changing the position of the shading elements should be checked. Also the fire retardant coating should be checked regularly. In case of damage the lamellae can be easily taken of the system, because of the easy mounting principle. This way it is easy to replace the lamellae with new ones. More about the durability is explained in the Durability chapter.

- How is the price in relation to current fire retardant glazing and sunshading?
  The cost of the new system has to be lower than the average costs of 250 till 550 euro per square meter for fire retardant glazing plus the costs of a shading element. For normal horizontal venetian blinds the prices varies between 20 and 150 euros, dependent on the material and the size. So the total costs will be between 250 and 700 euros, for the fire retardant glazing with a shading element on the inside. HR+++ glass costs around 120 euro per square meter. So with the fire retardant shading element the total costs will lie between 140 and 270 euros, which is still cheaper than the fire retardant glazing with a sunshading element.
- How to prevent malfunction, possible damage and wearing?
  Regular checks on the metal wire, the nylon wire and the fire retardant coating are necessary in order to prevent malfunction and wearing. The lamellae can be easily taken of and changed in case of damage. A larger explanation is given in the chapter Durability.
- What will be the performance of the sunshading element in relation to thermal comfort?
  For now the fire retardant shading element will be on the inside of the window. Sunshading elements on the inside of a building is not as effective as on the outside of the building, because the glass of the windows is heated as well as the space between the window and the shading. However, also the specifications of the glass are improving every day. So there is still a bit of heat coming into the space, because the shading is inside instead of outside, however the shading element will still prevent the sun from directly shining into the space and the change on wearing and damage is less when the shading element is on the inside. In the durability chapter this is further explained.

What will be the influence of a fire retardant sunshading element on a fire and what will be the consequence for the fire fighters?
If the whole concept of the fire retardant sunshading element is working properly a couple of things happen. The produced smoke will not have a way out through the window, because it is still a whole, so it will find its way through the cracks and other openings while the temperature in the room will still rise. Because the window will not break there is no extra ventilation through the broken window. When there is less oxygen supply to the fire, the fire will extinguish quicker. Because of the window and the sunshading element the fire will not spread to other buildings or other building parts via the outside and the fire fighters will still be able to enter the building through the window if they want, because the sunshading element is not totally fixed to the wall.

In case the glass breaks during the fire then the spread of fire via flash-over is prevented by the fire retardant shading element. Only a big vent for the fire will rise, because of the broken glass and the smoke will escape. Changing the glass afterwards is still cheaper than fire retardant glazing with a separate shading element.

8. Evaluation

Evaluation

After almost finishing the graduation process I can say that it went very well and I learned a lot about fire and fire safety. So for me one of the most important goals is definitely reached. Here the simulations, the measurements, the design and the process are evaluated.

In the P2 phase I made a planning for the rest of the graduation period. Although there was enough time planned for all the different things, especially the practical things took more time than I thought. Were the wooden prototype was build in two days, the steel prototype took three weeks. This was mostly because of the trial and error with the lamellae and the closing mechanism. Also every time I was depended on other people or materials it took more time than expected. But this time was also filled with other activities for this thesis and it gave me the space to rethink the things that I had done and was doing, so this was a good learning process.

Because of the strange temperature drop in the old simulations from TRISCO, these results are doubtful. Probably the program is not completely suitable for these high temperatures and the grid was not accurate enoguh. It was good to take other distances for the measurements and to do new measurements with these distances, so I was able to compare them to the results of the measurements. I think the simulations are more accurate when also the RADCON module in the TRISCO simulation is applied for the radiation, because this is the biggest heat transfer during a fire.

Before the real measurements it was good to have a test measurement. This test resulted in adjusting the prototype and method for the measurements.

The measurements all went well, but especially the last measurement with the burning fire retardant coating showed that it was not very safe to work with the oven at where it is placed now. There was no exhaust and no fire distinguisher and smoke alarm. Also it was good to do the measurements with at least two people, so in case when something went wrong, there is always another person to help. Because with such high temperatures it is good to be careful.

The measurement with the fire retardant coating gave a lot of smoke. At the moment the glass pane broke only smoke escaped through the hole in the glass. The flames in the oven, because of the burning coating, did not come through the element and the hole in the glass. So the element prevented flash-over very well. The time in which the element could withstand flash-over was not measured, because of safety reasons. There was no exhaust the whole space was smoky and smelled a lot. Looking back this was not very healthy although the manual of the fire retardant coating said it would not be dangerous. Placing an exhaust above the oven is a good solution to prevent this with the next measurements.

After this research I can say that a good concept design is developed for a fire retardant sunshading element. Of course it still needs further research and further product development and more measurements with different variables and also the pull-up mechanism needs attention, but in base this fire retardant shading element can be used as an alternative design solution for fire retardant glazing. Also test conform the NEN and the Dutch Building Decree and a test at TNO or Efectis are then valuable. For now these measurements give a good result of what to expect. When there was more time for the oven available also more tests could be done, but with the measurements that are done now good comparisons can be made. However one measurement of each variable gives not a very accurate result and it is unfortunate that the measurement with the fire retardant coating did not give a remarkably different result than the result of the measurement with the closed element without the fire retardant coating. Probably because the glass was insulated from the frame at the front and the back with rubber tape, but this tape was not provided at the top, bottom and the sides, so the steel frame was still directly in touch with the glass pane.

9. Reflection

Reflection

The subject fire safety for this master thesis is born while doing the bachelor and as well the master at the Faculty of Architecture & the built environment at the Delft University. After all the theory and projects I barely learned anything about fire safety, although it has been become more important in the building industry. To fill this gap of knowledge before graduating the decision had been made to do my final thesis about the subject of fire safety. The subject fire safety does not directly fit into the building technology theme of the graduation lab, actually with none of the themes of the graduation lab, but because it is a broad subject and also related to building (parts) and safety in buildings there are a lot of subjects which correspond.

I started with randomly searching for problems, recent fires in buildings and other subjects concerning fire safety in buildings as a graduation topic. This range of articles and problems was so big and often there was not just one building problem that searching for a subject and a research question this way was very confusing. So I started with a new approach in order to find a topic. Now the starting point of the graduation topic was contacting the fire safety department of The Hague and the Dutch Institute of Physical Safety to ask what the current biggest problems are concerning fire safety in buildings. This way I would get a clear answer from the people who know most about fire and fire safety. One of the biggest problems was the lack of integration between fire safety and design. Also the growing demand for fire retardant glazing in public buildings and monuments and their relatively high price per square meter is a current topic. Asking these people for problems and topics concerning fire safety in buildings has led to a relevant question for this graduation topic, namely "In which way is it possible to use sunshading as a fire retardant element, such that it will be an alternative design solution for fire retardant glazing in public buildings in Holland?". This method with questioning the ones who know most about fire safety was a very well working approach. This way the subject is a relevant problem and because these people are experienced with fires in buildings the problem is well-grounded.

The research question should result in a concept of a sunshading product which also functions as a fire retardant product and thus as a substitute for fire retardant glazing. This was a very clear topic, also for me to know which result this whole research should give. This concept product should be a clear design alternative for the expensive (250- 550 euro per square meter) fire retardant glazing and also be a design solution for fire retardant glazing in monuments. In order to delimit the question the choice is made to specify this only for public buildings in Holland, this with regards to the regulations in the Dutch Building Decree which result in more specific specifications in the program of requirements in comparison to a product which may be used in all buildings in Holland. If, in the end, a concept design for a product is developed, the product may be further developed into a product which also functions in for example residential buildings, but then it also has to meet other criteria according to the Dutch Building Decree. The method for this concept was to do research which will result in the program of requirements for the concept. Also the rules and regulations in Holland are applied to this and therefore I delimited the question in order to get a specific concept, which later may be applied to other building types.

Because I knew barely anything about fire safety after I had chosen the topic, I started with doing some research about fire safety, fire development, the current rules and regulations and fire retardant products. I also did some research about sunshading and the sunshading products. This resulted in a schematic overview with the advantages and disadvantages when it would be used as a fire retardant product. From this overview I could conclude that inside sunshading was the best option to use for the further development of the concept. Making this overview helped me also to get a sort of SWAT analysis of the sunshading.

Figure 40: imulation in TRA

The question rose about what will be the optimal distance between the sunshading / fire retardant element and the window, in order not to break the glass in case of fire. Therefore I made simulations of a small and a big room with different distances between the element and the window in the programs TRA for the radiation of the fire and TRISCO for the heat transfer from the element to the window. Because fire is very unpredictable the simulations where only important to get a global idea and feeling of the optimal distance and the material temperatures. These simulations also gave me a good feeling about the temperatures in a fire.

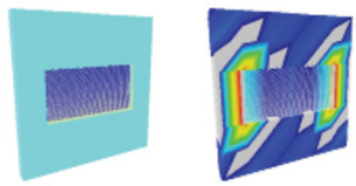
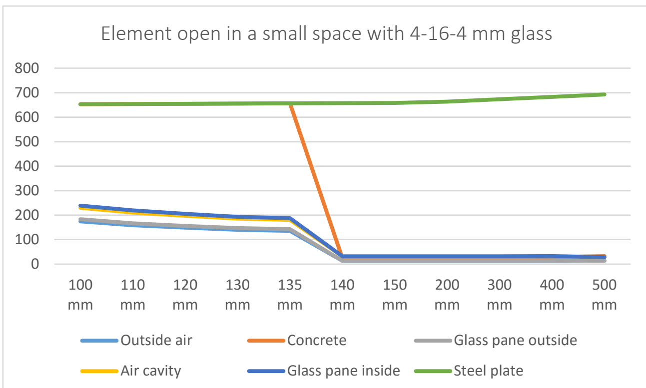


Figure 41: simulation in TRISCO

However, the results from TRISCO showed an unexplainable sudden decrease in temperature, which is shown in the diagram on the right. Possible because of the high temperatures and the not correct defined grid, this sudden temperature drop occurred in the program. So if the distance in between 130 and 140 millimetres between the element and the window is the most optimal is discussable. In order to lose as less space as possible for the concept the distances of 75 mm and 100 mm were taken for the prototype. This problem of sudden decrease in temperature could possibly be prevented when an official fire simulation



Graph 18: sudden temperature drop

program, for example Brando, was used. However this was not available for free online or within the available software of the university. The new measurements with the distances of the measurements however gave a more thrustworthy result and also were better to compare to the measurements. Because this whole research is about developing a concept and fire is very unpredictable this simulation method is not very harmful. For developing a real product better simulations would improve the product.

The method in this period (between P1 and P2) was to get to know a lot about fire, fire safety, rules, fire retardant products and sunshading products and to get a clear overview of all the information and to form a program of requirements before the design phase.

The research and the simulations I did are not directly visible into the design, but the research did result in certain specifications for the program of requirements of the element. For example the type and place of the sunshading / fire retardant element was a result of the research. The choices regarding the materials where substantiated by a material study. Because the simulations took place in order to get to know the optimal distance also here the goal was very clear.

After the simulations the design phase had started. In this phase (between P2 and P3) the design of the element and mechanism are developed in combination with a material study. Because of the high temperatures during a fire steel was one of the most obvious materials.

For me this phase was hard, because I'm very result oriented and this phase was about thinking, sketching and trial and error, so although I did a lot of work personally it felt like I had not accomplished that much. I started to make a model out of wood in order to get the sketches and thoughts into a model. I first measured the dimensions of the oven and made a model out of wood, which could be used as a starting point for the prototype made out of steel. This in order to test the mechanism and to check the dimensions, because when I make it in steel the dimensions have to be correct, because steel is hard to adjust. For me the model in wood made me think about the actual connections between the lamellae and the mechanism. Also it raised a lot of questions about the mechanism and the materials. During this phase it was important to keep in mind that I have to develop a concept for a fire retardant sunshading product and I do not have to develop a complete product which can be sold directly. This way some of the questions I had became more important and other questions faded because sometimes I can be too much of a perfectionists. This wooden model was made in just one day, so this was very promising for the steel model. However this model took weeks, because steel is not that easy to adjust as wood. So also in these weeks it felt like I had not accomplished that much, but on the other hand I had made one of the most important things of this whole research.

For the lamellae I first made a model out of play cards. Although the scale was totally wrong an important problem came to light. When the holes for the wire were made perpendicular to the cards, the system would not fully close, because the wire had to make a strange angle. See the schematic view of the lamellae and the wires below. When the holes where made at an angle of around 45 degrees or less this problem was solved and the system was able to close better.

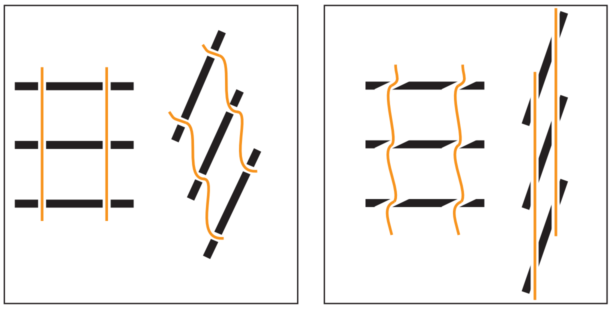


Figure 42: schematic view of the perpendicular and sloped holes

Making the lamellae out of wood was easy, because this could also be done with knotting a wire. Then with making the steel lamellae the problems occurred. This phase was literally trial and error, because the steel wire could not be knotted as easily as normal wire and when the whole element was assembled the rotating mechanism did not work, although it worked when only three lamellae were assembled. Because of the knots and the heavier weight of the steel in comparison to the weight of the wood and the playing cards it did not work when the whole element was assembled. Then I tried to fold the steel wire around the lamellae, but in the end also the rotating mechanism did not work. So then I replaced the steel wire in front with a plastic wire,

which in case of higher temperatures would burn or melt. This way in each case the self-closing mechanism of the lamellae was taken care of, although the rotating mechanism did not work perfectly. The method of

making models in different materials worked very well in order to solve some problems and also it made me think about the properties of the different materials and their connections. The trial and error part of the steel lamellae however did not work for me. It was very frustrating to spend a day on assembling the lamellae and to see that it would not work in the end. But this also resulted in thinking about other ways to assembly the lamellae and try again till it would work. So with a little perseverance this phase was still very informative.

At Wednesday the 16th of March a test measurement was done in the oven in order to test the method, the prototype and the mechanism. While making the prototype I did not think of placing the element with the glass plate in the oven with a heat-resistant suit on, so we had to place the element in parts in the oven. First the steel element with the sunshading lamellae and after that we placed the glass into the frame. This resulted in the conclusion that handles have to be made in front of the prototype in order to handle it and place it in the oven including the glass plate. Also because of the time it took for the lamellae to shut down could not be measured precisely, but it was already nice to see that the melted wired caused the closing of the system. Therefore with the real measurements everything will be recorded so this time will be measured afterwards. The temperatures the girl who helped us wrote down are also discussable. Although we explained very clear to her what to do, the wrong temperatures are written down. For me it was very clear that I would write the temperatures down myself the next time and then with the use of the handles on the prototype it is possible to place it in the oven by another person. In the end having a test measurement before the real measurement was very useful.

In order to do the measurements I reserved the oven for three days, because the rest of the month the oven would be in use by other students. It was already sure that not all the measurements could take place in three days, so I decided to do first the set of 100 mm completely. After everything was settled, the man who would help me with doing the measurements was ill. Fortunately I have some good friends who were able to help me at the last moment. This time I made sure to do the measurements myself or to check them when I was not able to do them myself. During the measurements it appeared that the handles on the frame were a big advantage, so it was good to perform first a test measurement, before the real measurements. The measurements with the fire retardant coating were very stressful. Because of the lack of a smoke/fire detector and the place where the oven is located is not very safe to work I was really afraid that something would catch fire. Fortunately only the fire retardant coating burned and produced a lot of smoke and the measurement went well, with a lot of help from Kees. Because it was not very safe and healthy with all the smoke without an exhaust we decided to do only one measurement with the fire retardant coating. For me it felt like a very good decision because fire is very unpredictable and the measurements with the burning coating were not very safe. After all the measurements I heard about the safety report that had to be filed before the oven was used in other ways than was explained in the agreement. But when I heard this it was already too late, but for the next time it is good to make a safety report and to think about everything that would happen or could go wrong with these types of measurements.

Where I first thought that the P1 phase was for choosing the subject, the P2 phase for doing the research, the P3 phase for the design by research of research by design, the P4 phase for the definitive design and at last the P5 phase for building the prototype and evaluation, I switched some phases because my prototype is also used for executing the tests in the oven. So during the P2 research phase I did a study to get to know which type of sunshading is best to use as a fire retardant element and what type of self-closing mechanism could work in combination with this type of shading. During the P3 phase I started to develop this mechanism and this sunshading into a prototype, so this prototype can be used for testing. This way the research by design is done on the basis of the wooden and steel prototypes and the tests in the oven in the P4 phase. First a test was done in order to see possible buckling or melting of the steel plates of the element and in order to evaluate the method and the prototype. After that adjustments were made to the steel prototype and possibly also to the method and then measurements with different distances between the element and the glass and with different glass thicknesses were done. This way I could use the last phase after the P4 to do the rest of the measurements with a distance of 75 mm and with a fire retardant coating. After that I will evaluate the design, the prototype, the measurements and the results.

With the end of the graduation process in sight I have to say that I have learned a lot from this thesis. One of the main goals was to get to know the basic knowledges and principles about fire safety and this goal is definitively reached. By doing this research with making the prototypes and doing the measurements my curiosity to fire safety and all the things about this topic that I do not know yet only has grown. For me it is clear that I want to proceed my further career within this discipline.

10. Literature

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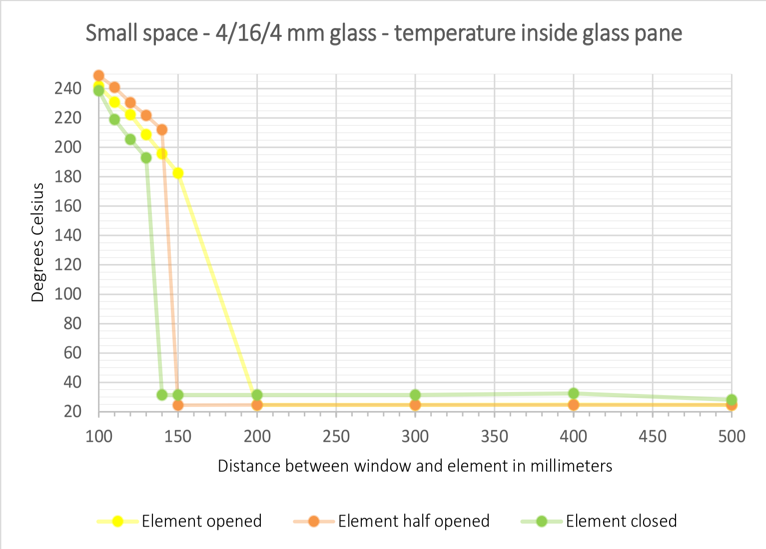
11. Appendices

Appendices:

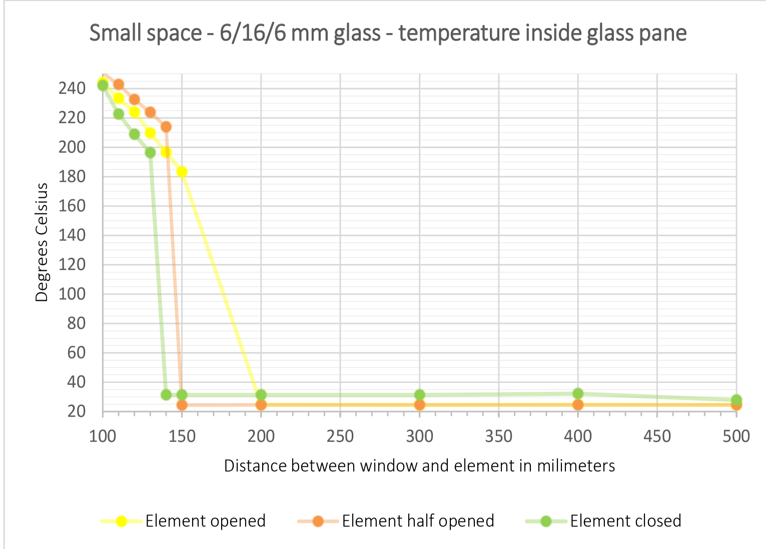
- Results of the old simulation in TRISCO
- Results of the old TRISCO simulation- small space with 4/16/4 mm glass
- Results of the old TRISCO simulation- small space with 6/16/6 mm glass
- Results of the old TRISCO simulation- large space with 4/16/4 mm glass
- Results of the old TRISCO simulation- large space with 6/16/6 mm glass
- Tables with the results of the measurements
- Photos of the measurements

Results of the old simulation in TRISCO

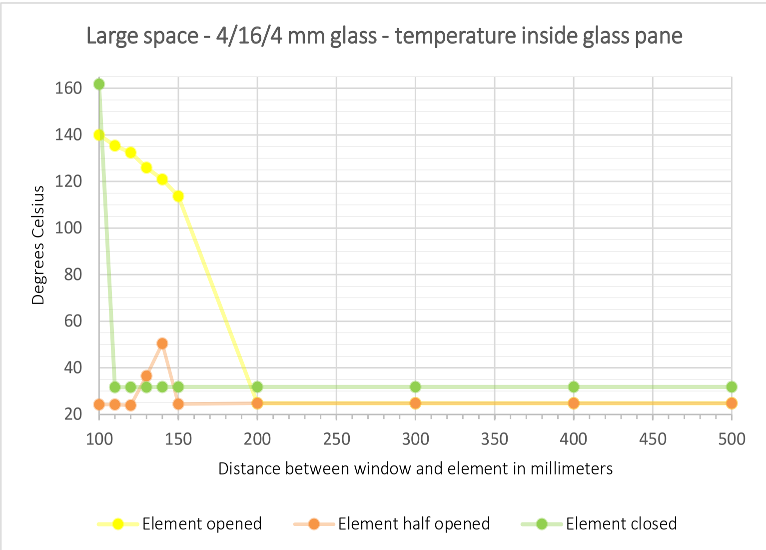


Graph 19: small space - 4/16/4 mm glass - temperature inside glass pane

Here the results of the TRISCO simulations are shown for a fire in a small space, with two different glass thicknesses, namely 4/16/4 mm and 6/16/6 mm. The maximum incident heat flux and corresponding temperature of the element from the TRA simulations are used in this simulation as the temperature of element. Here only the temperature of the inside glass pane is shown, because this pane is the first to be exposed to the heat and in the simulation program TRA was double glazing not possible. As shown there is a strange temperature drop between 130 and 140 mm for the closed element, between 140 and 150 mm for the half opened element and between 150 and 200 mm for the open element for both glass thicknesses.



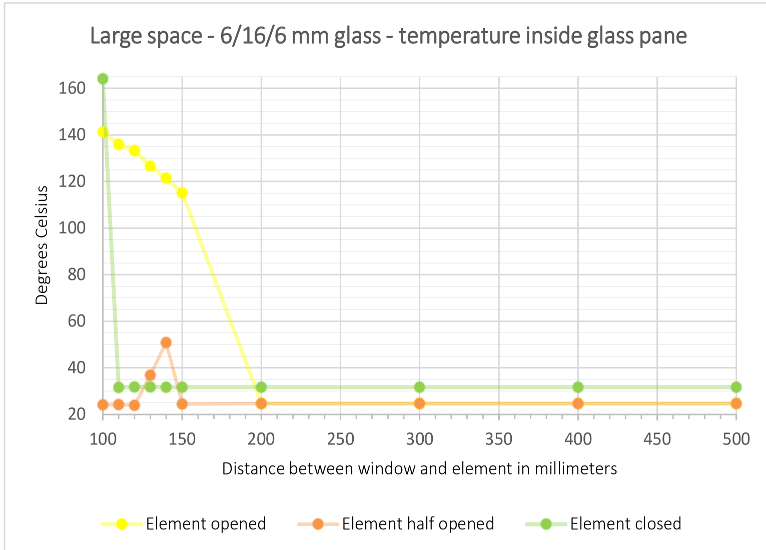
Graph 20: small space - 6/16/6 mm glass - temperature inside glass pane



Graph 21: large space - 4/16/4 mm glass - temperature inside glass pane

Here the results of the TRISCO simulations are shown for a fire in a large pace, with two different types of glass with different glass thicknesses, namely 4/16/4 mm and 6/16/6 mm. The maximum incident heat flux and corresponding temperature of the element from the TRA simulations are used in this simulation as the temperature of element.

Also here there the unexplainable temperature drop occurs, for the closed element earlier than for the open element. Another unexplainable thing is the temperature increase and decrease for the half opened element between 120 and 150 mm.



Graph 22: large space - 6/16/6 mm glass - temperature inside glass pane

Results of the old TRISCO simulation - small space with 4/16/4 mm glass

Small space 4-16-4 mm glass		Element open (fully horizontal) Temperature [°C]										
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**135 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	197.39	188.55	181.61	170.59	165.86	160.06	149.44	11.56	11.56	11.51	11.56
Concrete	300 mm	585.54	593.44	600.73	603.82	608.81	609.52	613.53	21.32	21.32	21.35	21.32
Glass outside pane	4 mm	204.42	195.26	188.06	176.63	171.72	165.71	154.68	11.83	11.83	11.78	11.83
Air cavity glass	16 mm	234.13	223.60	215.32	202.16	196.50	189.58	176.86	24.54	24.54	24.60	24.54
Glass inside pane	**4 mm**	**241.76**	**230.89**	**222.34**	**208.73**	**202.89**	**195.73**	**182.58**	**24.71**	**24.71**	**24.76**	**24.71**
Steel plate	**1 mm***	**585.54**	**593.44**	**600.73**	**603.82**	**608.81**	**609.52**	**613.53**	**623.24**	**632.28**	**634.29**	**637.81**
Inside air	24.9 °C	585.54	593.44	600.73	603.82	608.81	609.52	613.53	623.24	632.28	634.29	637.81

Small space 4-16-4 mm glass		Element half open (45 degrees) Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	199.27	192.95	184.73	177.87	170.15	11.69	9.66	9.66	9.66	9.66
Concrete	300 mm	487.86	503.86	513.45	525.58	533.68	21.32	15.19	15.19	15.19	15.19
Glass outside pane	4 mm	207.16	200.57	192.00	184.85	176.80	11.95	9.90	9.90	9.90	9.90
Air cavity glass	16 mm	240.34	232.64	222.62	214.26	204.85	24.29	24.51	24.51	24.51	24.51
Glass inside pane	**4 mm**	**248.86**	**240.88**	**230.49**	**221.82**	**212.06**	**24.45**	**24.67**	**24.67**	**24.67**	**24.67**
Steel plate	**1 mm***	**487.86**	**503.86**	**513.45**	**525.58**	**533.68**	**541.86**	**567.58**	**590.03**	**601.66**	**607.40**
Inside air	24.9 °C	487.86	503.86	513.45	525.58	533.68	541.86	567.58	590.03	601.66	607.40

Small space 4-16-4 mm glass		Element closed Temperature [°C]										
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**135 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	174.45	158.18	148.69	140.07	136.04	12.76	12.76	12.76	12.76	12.93	14.13
Concrete	300 mm	652.73	653.83	654.94	656.04	656.54	23.04	23.04	23.04	23.04	29.34	32.68
Glass outside pane	4 mm	182.97	166.28	156.23	147.12	142.85	13.15	13.15	13.15	13.15	13.07	14.23
Air cavity glass	16 mm	229.90	210.79	197.72	185.86	180.31	31.32	31.32	31.32	31.32	32.27	28.03
Glass inside pane	**4 mm**	**238.57**	**219.01**	**205.37**	**193.01**	**187.23**	**31.50**	**31.50**	**31.50**	**31.50**	**32.42**	**28.14**
Steel plate	**1 mm***	**652.73**	**653.83**	**654.94**	**656.04**	**656.54**	**657.14**	**658.23**	**663.48**	**673.42**	**682.68**	**692.33**
Inside air	24.9 °C	652.73	653.83	654.94	656.04	657.14	657.14	658.23	663.48	673.42	682.68	692.33

*results are equal with a steel plate of 2 mm. In reality 2/3rd of the shading element is 2 mm and 1/3rd of the shading element is 1 mm because of the overlap

Results of the TRISCO old simulation - small space with 6/16/6 mm glass

Small space 6-16-6 mm glass		Element open (fully horizontal) Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	193.07	184.66	177.25	166.19	155.87	145.49	11.45	11.85	11.41	11.45
Concrete	300 mm	585.54	593.44	600.73	603.82	609.52	613.53	21.34	21.34	21.37	21.34
Glass outside pane	4 mm	203.42	194.54	186.71	175.03	164.13	153.16	11.85	11.85	11.80	11.85
Air cavity glass	16 mm	232.70	222.50	213.51	200.09	187.53	174.90	24.37	24.37	24.44	24.37
Glass inside pane	**6 mm**	**244.00**	**233.31**	**223.88**	**209.78**	**196.59**	**183.32**	**24.71**	**24.61**	**24.69**	**24.61**
Steel plate	**1 mm***	**585.54**	**593.44**	**600.73**	**603.82**	**609.52**	**613.53**	**623.24**	**632.28**	**634.29**	**637.81**
Inside air	24.9 °C	585.54	593.44	600.73	603.82	609.52	613.53	623.24	632.28	634.29	637.81

Small space 6-16-6 mm glass		Element half open (45 degrees) Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	194.00	187.98	180.03	173.41	165.89	11.46	9.59	9.59	9.59	9.59
Concrete	300 mm	487.86	503.86	513.45	525.58	533.68	24.59	15.24	15.24	15.24	15.24
Glass outside pane	4 mm	205.62	199.15	190.70	183.65	175.65	11.85	9.95	9.95	9.95	9.95
Air cavity glass	16 mm	238.20	230.64	220.78	212.54	203.21	24.16	24.38	24.38	24.38	24.38
Glass inside pane	**6 mm**	**250.78**	**242.82**	**232.41**	**223.72**	**213.87**	**24.40**	**24.62**	**24.62**	**24.62**	**24.62**
Steel plate	**1 mm***	**487.86**	**503.86**	**513.45**	**525.58**	**533.68**	**541.86**	**567.58**	**590.03**	**601.66**	**607.40**
Inside air	24.9 °C	487.86	503.86	513.45	525.58	533.68	541.86	567.58	590.03	601.66	607.40

Small space 6-16-6 mm glass		Element closed Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	170.80	154.93	145.71	137.34	12.64	12.64	12.64	12.64	12.86	14.06
Concrete	300 mm	652.73	653.83	654.94	656.04	23.07	23.07	23.07	23.07	29.40	32.73
Glass outside pane	4 mm	183.33	166.83	156.81	147.70	13.22	13.22	13.22	13.22	13.07	14.20
Air cavity glass	16 mm	229.36	210.50	197.53	185.74	31.08	31.08	31.08	31.08	31.91	27.66
Glass inside pane	**6 mm**	**242.13**	**222.60**	**208.81**	**196.29**	**31.35**	**31.35**	**31.35**	**31.35**	**32.13**	**27.82**
Steel plate	**1 mm***	**652.73**	**653.83**	**654.94**	**656.04**	**657.14**	**658.23**	**663.48**	**673.42**	**682.68**	**692.33**
Inside air	24.9 °C	652.73	653.83	654.94	656.04	657.14	658.23	663.48	673.42	682.68	692.33

*results are equal with a steel plate of 2 mm. In reality 2/3rd of the shading element is 2 mm and 1/3rd of the shading element is 1 mm because of the overlap

Results of the TRISCO old simulation - large space with 4/16/4 mm glass

Large space 4-16-4 mm glass		Element open (fully horizontal) Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	116.20	112.40	109.98	104.70	100.64	94.70	11.51	11.51	11.51	11.51
Concrete	300 mm	314.83	317.85	328.45	332.26	341.01	342.91	21.35	21.35	21.35	21.35
Glass outside pane	4 mm	119.99	116.07	113.54	108.07	103.86	97.72	11.78	11.78	11.78	11.78
Air cavity glass	16 mm	135.92	131.48	128.54	122.29	117.46	110.42	24.60	24.60	24.60	24.60
Glass inside pane	**4 mm**	**140.00**	**135.42**	**132.38**	**125.93**	**120.94**	**113.68**	**24.76**	**24.76**	**24.76**	**24.76**
Steel plate	**1 mm***	**314.83**	**317.85**	**328.45**	**332.26**	**341.01**	**342.91**	**356.41**	**366.59**	**386.67**	**397.16**
Inside air	24.9 °C	314.83	317.85	328.45	332.26	341.01	342.91	356.41	366.59	386.67	397.16

Large space 4-16-4 mm glass		Element half open (45 degrees) Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	14.25	13.87	17.05	30.38	41.66	11.55	9.70	9.70	9.70	9.70
Concrete	300 mm	25.54	25.25	34.38	74.39	112.73	24.61	14.70	14.70	14.70	14.70
Glass outside pane	4 mm	14.62	14.23	17.52	31.36	43.07	11.81	9.94	9.94	9.94	9.94
Air cavity glass	16 mm	24.05	24.09	23.77	35.48	48.97	24.34	24.60	24.60	24.60	24.60
Glass inside pane	**4 mm**	**24.21**	**24.26**	**23.93**	**36.52**	**50.48**	**24.50**	**24.76**	**24.76**	**24.76**	**24.76**
Steel plate	**1 mm***	**24.85**	**24.85**	**34.38**	**74.39**	**112.73**	**146.42**	**216.79**	**259.88**	**311.77**	**341.39**
Inside air	24.9 °C	24.85	24.85	34.38	74.39	112.73	146.42	216.79	259.88	311.77	341.39

Large space 4-16-4 mm glass		Element closed Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	119.93	13.44	13.44	13.44	12.95	12.95	12.95	12.95	12.95	12.95
Concrete	300 mm	421.30	20.74	20.74	20.74	23.26	23.26	23.26	23.26	23.26	23.26
Glass outside pane	4 mm	125.51	13.86	13.86	13.86	13.34	13.34	13.34	13.34	13.34	13.34
Air cavity glass	16 mm	156.12	31.51	31.51	31.51	31.63	31.63	31.63	31.63	31.63	31.63
Glass inside pane	**4 mm**	**161.76**	**31.69**	**31.69**	**31.69**	**31.82**	**31.82**	**31.82**	**31.82**	**31.82**	**31.82**
Steel plate	**1 mm***	**421.30**	**422.35**	**423.27**	**424.31**	**425.36**	**426.38**	**431.6**	**442.31**	**453.37**	**464.39**
Inside air	24.9 °C	421.30	422.35	423.27	424.31	425.36	426.38	431.6	442.31	453.37	464.39

*results are equal with a steel plate of 2 mm. In reality 2/3rd of the shading element is 2 mm and 1/3rd of the shading element is 1 mm because of the overlap

Results of the TRISCO old simulation - large space with 6/16/6 mm glass

Large space 6-16-6 mm glass		Element open (fully horizontal) Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	113.92	109.66	107.61	102.31	98.29	93.20	11.41	11.41	11.41	11.41
Concrete	300 mm	314.83	317.85	328.45	332.26	341.01	342.91	21.37	21.37	21.37	21.37
Glass outside pane	4 mm	119.50	115.01	112.85	107.26	103.02	97.66	11.80	11.80	11.80	11.80
Air cavity glass	16 mm	135.22	130.09	127.60	121.23	116.36	110.24	24.44	24.44	24.44	24.44
Glass inside pane	**4 mm**	**141.25**	**135.89**	**133.28**	**126.60**	**121.50**	**115.08**	**24.69**	**24.69**	**24.69**	**24.69**
Steel plate	**1 mm***	**314.83**	**317.85**	**328.45**	**332.26**	**341.01**	**342.91**	**356.41**	**366.59**	**386.67**	**397.16**
Inside air	24.9 °C	314.83	317.85	328.45	332.26	341.01	342.91	356.41	366.59	386.67	397.16

Large space 6-16-6 mm glass		Element half open (45 degrees) Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	14.03	13.67	16.77	29.79	40.80	11.40	9.63	9.63	9.63	9.63
Concrete	300 mm	25.50	25.36	34.38	74.39	112.73	24.59	14.75	14.75	14.75	14.75
Glass outside pane	4 mm	14.58	14.19	17.47	31.23	42.87	11.80	9.99	9.99	9.99	9.99
Air cavity glass	16 mm	23.94	23.99	23.66	35.28	48.68	24.23	24.48	24.48	24.48	24.48
Glass inside pane	**4 mm**	**24.18**	**24.22**	**23.90**	**36.83**	**50.91**	**24.47**	**24.72**	**24.72**	**24.72**	**24.72**
Steel plate	**1 mm***	**24.85**	**24.85**	**34.38**	**74.39**	**112.73**	**146.42**	**216.79**	**259.88**	**311.77**	**341.39**
Inside air	24.9 °C	24.85	24.85	34.38	74.39	112.73	146.42	216.79	259.88	311.77	341.39

Large space 6-16-6 mm glass		Element closed Temperature [°C]									
Specifications		**100 mm**	**110 mm**	**120 mm**	**130 mm**	**140 mm**	**150 mm**	**200 mm**	**300 mm**	**400 mm**	**500 mm**
Outside air	4.9 °C	117.60	13.33	13.33	13.33	12.83	12.83	12.83	12.83	12.83	12.83
Concrete	300 mm	421.30	20.74	20.74	20.74	23.31	23.31	23.31	23.31	23.31	23.31
Glass outside pane	4 mm	125.81	13.95	13.95	13.95	13.41	13.41	13.41	13.41	13.41	13.41
Air cavity glass	16 mm	155.85	31.30	31.30	31.30	31.43	31.43	31.43	31.43	31.43	31.43
Glass inside pane	**4 mm**	**164.15**	**31.58**	**31.85**	**31.85**	**31.71**	**31.71**	**31.71**	**31.71**	**31.71**	**31.71**
Steel plate	**1 mm***	**421.30**	**422.35**	**423.27**	**424.31**	**425.36**	**426.38**	**431.6**	**442.31**	**453.37**	**464.39**
Inside air	24.9 °C	421.30	422.35	423.27	424.31	425.36	426.38	431.6	442.31	453.37	464.39

*results are equal with a steel plate of 2 mm. In reality 2/3rd of the shading element is 2 mm and 1/3rd of the shading element is 1 mm because of the overlap

Tables with the results of the measurements - 100 mm

Time with 4 mm glass without an element	Temperature in degrees Celsius
0 sec.	21.7
10 sec.	47.5
20 sec.	78.5
30 sec.	109.0
Breakage after	39 seconds

Time with 6 mm glass without an element	Temperature in degrees Celsius
0 sec.	21.4
10 sec.	33.2
20 sec.	41.6
30 sec.	50.8
40 sec.	70.8
50 sec.	85.4
Breakage after	51 seconds

Time with 4 mm glass with the open element at 100 mm.	Temperature in degrees Celsius
0 sec.	21.5
10 sec.	46.0
20 sec.	59.6
30 sec.	76.4
40 sec.	94.4
50 sec.	115.1
Breakage after	55 seconds
Closing element	11 seconds

Time with 6 mm glass with the open element at 100 mm.	Temperature in degrees Celsius
0 sec.	21.5
10 sec.	34.2
20 sec.	45.8
30 sec.	55
40 sec.	66.2
50 sec.	79
60 sec.	91.3
70 sec.	96.2
80 sec.	111.8
90 sec.	118.7
Breakage after	1 min. 35 sec.
Closing element	8 seconds

Time with 4 mm glass with the closed element at 100 mm.	Temperature in degrees Celsius
0 sec.	21.7
10 sec.	33.3
20 sec.	35.5
30 sec.	38.3
40 sec.	40.6
50 sec.	47.1
60 sec.	55.1
Breakage after	1 min. 2 sec.

Time with 6 mm glass with the closed element at 100 mm.	Temperature in degrees Celsius
0 sec.	21.9
10 sec.	31.1
20 sec.	33.1
30 sec.	34.2
40 sec.	36.4
Breakage after	47 seconds

Tables with the results of the measurements - 75 mm

Time with 4 mm glass with the open element at 75 mm.	Temperature in degrees Celsius
0 sec.	21.2
10 sec.	40.3
20 sec.	59.2
30 sec.	76.0
40 sec.	92.3
50 sec.	103.8
Breakage after	50 seconds
Closing element	7 seconds

Time with 6 mm glass with the open element at 75 mm.	Temperature in degrees Celsius
0 sec.	21.2
10 sec.	33.2
20 sec.	39.6
30 sec.	48.2
40 sec.	59.2
50 sec.	67.4
60 sec.	76.2
70 sec.	86.1
80 sec.	99.1
Breakage after	1 min. + 21 sec.
Closing element	8 seconds

Time with 4 mm glass with the closed element at 75 mm.	Temperature in degrees Celsius
0 sec.	21.6
10 sec.	32.9
20 sec.	34.6
30 sec.	41.0
40 sec.	43.1
50 sec.	46.8
60 sec.	50.3
70 sec.	55.8
80 sec.	62.5
90 sec.	65.7
1 min. + 40 sec.	70.0
Breakage after	1 min. 27 sec.

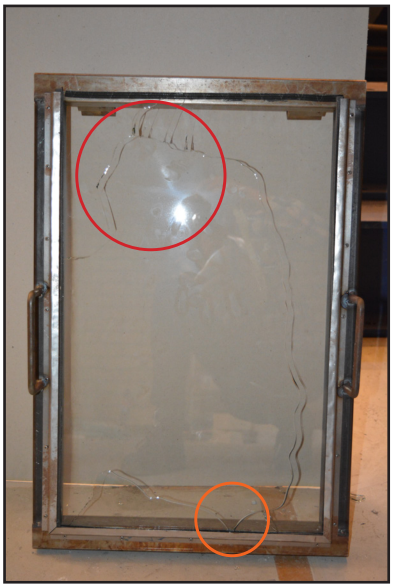
Time with 6 mm glass with the closed element at 75 mm.	Temperature in degrees Celsius
0 sec.	21.7
10 sec.	30.8
20 sec.	31.1
30 sec.	32.6
40 sec.	32.8
50 sec.	34.9
60 sec.	37.2
70 sec.	40.2
80 sec.	43.2
90 sec.	48.2
100 sec.	49.8
110 sec.	54.7
120 sec.	56.5
130 sec.	59.5
140 sec.	60.8
150 sec.	68.8
160 sec.	70.7
170 sec.	74.0
180 sec.	75.7
190 sec.	78.1
200 sec.	89.0
210 sec.	89.7
Breakage after	3 min. 29 sec.

Time with 4 mm glass with the element at 100 mm and a fire retardant coating	Temperature in degrees Celsius
0 sec.	21
10 sec.	33.6
20 sec.	32.7
30 sec.	36.7
40 sec.	41.4
50 sec.	48.3
60 sec.	55.6
70 sec.	62.8
80 sec.	64.7
90 sec.	68.7
100 sec.	77.2
110 sec.	82.1
120 sec.	89.5
130 sec.	102.5
Breakage after	2 min. 13 sec.

Photos of the measurements

4 mm glass without an element. Breakage at 109 degrees Celsius.

Because of the high temperature the whole glass pane was shattered. The glass started to break at the bottom



6 mm glass without an element. Breakage at 85.4 degrees Celsius.

The glass pane broke at the bottom first as shown in the orange circle. The red circle indicates the breakage of the glass while cooling down.

4 mm glass with the open element at 100 mm distance. Breakage at 115.1 degrees Celsius.

The glass pane started to break on the left side.
Note: in this picture the lamellae in the back are not in the right place.

6 mm glass with the open element at 100 mm distance. Breakage at 118.7 degrees Celsius.

The glass pane started to break at the top. All the breakage is mostly in vertical direction.

4 mm glass with the closed element at 100 mm distance. Breakage at 55.1 degrees Celsius.

Also with this 4 mm glass pane and an element the glass started to break at the left.

6 mm glass with the closed element at 100 mm distance. Breakage at 36.4 degrees Celsius.

Also with this 4 mm glass pane and an element the glass started to break also at the top of the pane.

4 mm glass with the open element at 75 mm distance. Breakage at 103.8 degrees Celsius.

Just like the measurements with 4 mm glass at 100 mm distance the glass pane broke at the left side.

6 mm glass with the open element at 75 mm distance. Breakage at 99.1 degrees Celsius.

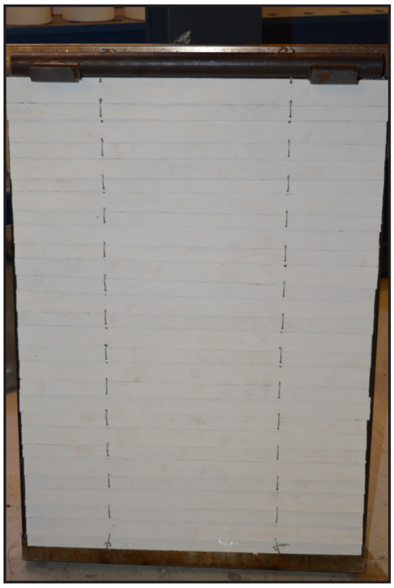
4 mm glass with the closed element at 75 mm distance. Breakage at 70.0 degrees Celsius.

In comparison to the other 4 mm glass panes with an element the pane started to break at the top.

6 mm glass with the closed element at 75 mm distance. Breakage at 89.7 degrees Celsius.

Also here the glass pane started to break at the top.

4 mm glass with the closed element at 75 mm distance and a fire retardant coating. Breakage at 102.5 degrees Celsius.



Closed element with fire retardant coating of 0.7-1.0 mm thick. Before the measurement.

Closed element with the burned and expanded fire retardant coating after the measurement. At some places there is no burned coating because it fell of when we put wet towels on the element in order to prevent further smoke production.

Photo of the expanded fire retardant coating. The coating has expanded from 0.7-1.0 mm to 2-3 centimetres.

Photo of the expanded fire retardant coating.