Heating of Aluminium Exposed to Fire

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Summary

To evaluate the fire safety of a structure, either the standard temperature-time relation or a so-called natural fire safety concept may be applied. In the latter case, the layout of the fire compartment, the occupancy and the active measures are taken into account to determine the gas temperature.

This report gives the results of a study on the gas temperature in case of a natural fire safety concept, and the temperature development of fire exposed aluminium members. The influence of design parameters on the temperature development is investigated, and the range of maximum temperatures to be expected is given.

As reference, heating of aluminium sections exposed to a standard fire is studied. The gas temperature in natural fires was determined with a software programme. A parameter study was carried out with the most important parameters that influence the maximum gas temperature and the fire duration. For these gas temperatures, it was determined how much insulation is required to protect the aluminium members.

The research showed that the maximum gas temperature varies significantly for different layouts and occupancies, from more than 1400 °C to only 200 °C. Also the period with high temperatures varies, from less than 20 minutes to more than 120 minutes. Contrarily to the standard fire, the fire growth phase and the decay phase are taken into account in case of natural fire safety concepts.

The most important parameters determining the maximum gas temperature in the natural fire safety concept are:

- The ventilation (total opening area in relation to the total area of the boundary enclosure);
- The heat release of the fire;
- The heat losses through the boundary, related to the materials of which the boundary enclosure is composed.

The most important parameter determining the period with high temperatures is the design fire load density. This design fire load density is related to the characteristic fire load density, the active fire fighting measures and the danger of fire activation. This danger of fire activation is related to the occupancy and the compartment floor area. Also the maximum rate of heat release influences the period at high temperatures, as fierce fires last shorter.

The characteristic fire load density, the fire growth rate, the maximum rate of heat release and the danger of fire activation all depend on the occupancy of the structure. The occupancy is therefore an important parameter for the gas temperature.

The research showed that only in case of gas temperatures remaining below the critical temperature, or gas temperatures with a very short period at temperatures above the critical temperature, insulation is not required for aluminium members applied inside a fire compartment. Such designs are exceptional. Thus, in many cases, insulation is required to protect internal load bearing aluminium members. The critical temperature is important for the required insulation thickness; a member with a critical temperature of 150 °C may require several times thicker insulation than a member with the same member factor but with a critical temperature of 350 °C.
The member temperature of externally applied aluminium members that are not engulfed in flames depends on the distance between the column and the openings, the fire load density and the compartment size. It further depends on the critical temperature, to determine whether or not insulation is required. Hence, both for members inside the compartment and for externally applied members, research to the mechanical response of the member in order to accurately determine the member temperature is relevant.
Symbol list

Index \( a_l \) = Aluminium
Index \( g \) = Gas
Index \( p \) = Insulation layer

\( \alpha_c \) = Coefficient of heat transfer by convection [W/m\(^2\)K]
\( \lambda \) = Conductivity [W/mK]
\( \sigma \) = Constant of Stephan-Bolzman (=5,67 \cdot 10^8 W/m\(^2\)K\(^4\))
\( \rho \) = Density [kg/m\(^3\)]
\( \theta \) = Temperature [°C]
\( \varepsilon_f \) = Emissivity of the flames [-]
\( \varepsilon_m \) = Emissivity of the member [-]
\( \delta_i \) = Factor taking into account the active fire fighting measure ‘i’ [-]
\( \delta_{q1} \) = Factor taking into account the fire activation risk due to the size of the compartment [-]
\( \delta_{q2} \) = Factor taking into account the fire activation risk due to the type of occupancy [-]
\( b \) = Window width [m]
\( c \) = Specific heat [J/kgK]
\( d \) = Thickness [mm]
\( h \) = Window height [m]
\( h_{con} \) = Convective heat flux [W/m\(^2\)]
\( h_{eq} \) = Weighted average of window heights on all walls [m]
\( h_i \) = Height of vertical opening ‘i’ [m]
\( h_{rad} \) = Radiative heat flux [W/m\(^2\)]
\( k_{sh} \) = Correction factor for the shadow effect [-]
\( q_{f,d} \) = Design value of the fire load density [MJ/m\(^2\)]
\( q_{f,k} \) = Characteristic fire load density per unit floor area [MJ/m\(^2\)]
\( s \) = Distance between window and column [m]
\( t \) = Time [sec]
\( A_m \) = Exposed surface area of the member per unit length [m\(^2\)]
\( A_m/V \) = Section factor [m\(^{-1}\)]
\( A_t \) = Total area of the boundary enclosure (floor, ceiling and walls, including openings) [m\(^2\)]
\( A_v \) = Total area of vertical openings on all walls [m\(^2\)]
\( A_{v,i} \) = Area of vertical opening ‘i’ [m\(^2\)]
\( I_r \) = Radiative heat flux from flames and openings to the member [W/m\(^2\)]
\( O \) = Opening factor [m\(^{1/2}\)]
\( T_0 \) = Room temperature (=293 K)
\( T_m \) = Member temperature [K]
\( V \) = Volume of the member per unit length [m\(^3\)]
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Heating of Aluminium Exposed to Fire
1 Introduction

To evaluate the fire safety of a structure, either the standard temperature-time relation or a so-called natural fire safety concept may be applied. In the latter case, the specific layout and use of the building is taken into account to determine the gas temperature. This report gives the results of a study on the gas temperature in case of a natural fire safety concept, and it discusses the heating of fire exposed aluminium members. The influence of design parameters on the temperature development is investigated, and the range of maximum temperatures to be expected is given. The cases for which the aluminium member does not have to be insulated are determined. The report is a background document for the PhD research “local buckling of slender aluminium sections exposed to fire”.

Chapter 2 gives the input-variables such as section dimensions and thermal properties of the insulation material, applied in the research.

Heating of aluminium exposed to a standard fire is discussed in chapter 3. This is used as the reference case when discussing heating by natural fire safety concepts.

In chapter 4, the most important parameters influencing the gas temperature-time relation in case of a natural fire are identified. These parameters have been varied in the current study and the resulting gas temperature-time curves are given in this chapter.

Chapter 5 discusses heating of non-insulated aluminium members that are applied inside the fire compartment, exposed to the gas temperature-time curves of the previous chapter. The cases for which it is necessary to insulate these members are identified.

Chapter 6 discusses heating of insulated aluminium members that are applied inside the fire compartment. The parameters which have an important influence on the required insulation thickness are determined.

Chapter 7 gives the temperature of non-insulated external aluminium members. Whether or not it is necessary to insulate such members is investigated.

An evaluation of the results of the current study and conclusions are given in chapter 8.
2 Selection of input variables

2.1 Section factors

The temperature development in non-insulated members depends on the section factor \( A_m/V \). This is also an important parameter for the temperature development in case of protected members.

Two sections were studied for unprotected members:

- Section one is a square hollow section with dimensions 100 x 100 x 8 mm. This section is relatively stocky (section factor \( A_m/V = 136 \text{ m}^{-1} \));
- Section two is a square hollow section with dimensions 50 x 50 x 1 mm. This is a relatively slender section (section factor \( A_m/V = 1020 \text{ m}^{-1} \)).

2.2 Fire and member properties

The convection coefficient \( \alpha_c \) to determine the heat flux for convection \( h_{con} \) was taken as: \( \alpha_c = 25 \text{ W/m}^2\text{K} \) in case of a standard fire and \( \alpha_c = 35 \text{ W/m}^2\text{K} \) in case of a natural fire safety concept. These values are according to EN 1991-1-2.

It is assumed that the section is covered with soot. The emissivity of the member \( \varepsilon_m \) to determine the heat flux for radiation \( h_{rad} \) is taken as \( \varepsilon_m = 0.7 \). This value is given in EN 1999-1-2.

In case of members applied inside the fire compartment, it is further assumed that the section is fully engulfed in flames. In this case, the radiation temperature is assumed to be equal to the gas temperature according to EN 1991-1-2.

The physical properties of aluminium and steel are taken according to the values specified in EN 1999-1-2 and EN 1993-1-2, respectively.

2.3 Physical properties of the insulation material

The physical properties of the insulation materials are determined in tests on heated steel sections and are related to the temperature of the steel section. In the Finite Element model used in this study (Annex C), the material properties of the insulation material should be specified as a function of the temperature of the insulation material. No attempt was made to generate such data in the current study. Instead, the arbitrary – but not unrealistic – relation between thermal conductivity and temperature according to Figure 2.1 was applied. The density and the specific heat were assumed to remain unchanged during heating: \( \rho_p = 60 \text{ kg/m}^3 \) and \( c_p = 1030 \text{ J/kgK} \).
It has been verified whether these thermal properties of the insulation material are representative for that of a real insulation material (Annex A).

### 2.4 Critical temperatures

No specific design was taken into consideration. Therefore, no actual value for the critical temperature of the aluminium structure could be derived. Instead, a range of critical temperatures was defined for which the required insulation was determined.

To select these critical temperatures, the relation between 0.2% proof stress and the member temperature of some widely applied alloys were considered (Figure 2.2).

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**Figure 2.1** – Relation between thermal conductivity and temperature of the insulation applied in the Finite Element models

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**Figure 2.2** – Relation between the relative value for the 0.2% proof stress and the member temperature
The ratio between the total load to be taken into account in case of fire and the total load to be taken into account in normal temperature design depends largely on the ratio between permanent load and variable load. Both ratios are low in case of aluminium. Ranby [9] states that the percentage of the load in fire design is approximately 60% of the load in normal temperature design for steel structures. In the report on the pilot tests [8], it was elaborated that this percentage is approximately 40% for aluminium structures.

Figure 2.2 shows that the 0.2% proof stress is reduced to 40% of the initial proof stress at a temperature of approximately 220 °C to 300 °C, depending on the alloy and the temper. The strength reduces from 80% to 20% in a temperature range from approximately 150 °C to 350 °C. According to EN 1999-1-2 it may be assumed that the simple calculation models are satisfied if the aluminium temperature does not exceed 170 °C.

On the basis of the above, the critical temperatures taken into consideration were 150 °C to 350 °C. For reference, also a steel section was for some cases considered in this study. The critical temperature for steel was assumed ranging from 400 to 600 °C.
Heating of Aluminium Exposed to Fire
3 Heating by the standard fire

This chapter gives an overview of heating of aluminium by a standard fire. This is used as reference for heating by the natural fire safety concept. The relation between gas temperature and time for a standard fire is given in equation (2.1).

\[ \theta_g = 20 + 345 \cdot \log(8t + 1) \quad (t \text{ in min}) \]  

(2.1)

Heating of non-insulated aluminium is discussed in paragraph 3.1. The insulation thickness required in order to keep the aluminium temperature below the critical temperature is given in paragraph 3.2.

3.1 Heating of non-insulated members

The temperature development of non-insulated members in this study was determined using the equations in EN 1999-1-2 and EN 1991-1-2. The procedure is given in Annex C.

Figure 3.1 gives the temperature development of the sections in time. The left-hand picture gives the results for a thermal exposure period of 120 minutes. The right-hand picture gives results of the same calculations, but for a thermal exposure period of 30 minutes.

The red curve shows the gas temperature, the blue curve gives the temperature development of the slender aluminium section \((t = 1 \text{ mm}, A_m/V = 1020 \text{ m}^{-1})\) and the green curve gives the temperature development of the stocky aluminium section \((t = 8 \text{ mm}, A_m/V = 136 \text{ m}^{-1})\). For reference, also the temperature development of the stocky section in steel is given (pink curve).

Both the aluminium and the steel sections require insulation in order to meet requirements on the fire resistance, even for a short fire exposure period of 30 minutes.

Figure 3.1 – Temperature development in unprotected aluminium and steel sections exposed to the standard fire
3.2 Heating of insulated members

EN 1999-1-2 gives an equation to determine the member temperature of insulated members exposed to the standard fire. It can be shown that this equation provides unreliable results in case of natural fire safety concepts, see Annex C. Therefore, in this study, the temperature development of insulated members was determined with Finite Element simulations both for the natural fire safety concept and for the standard fire. The model applied is described in Annex C as well.

Figure 3.2 gives the temperature development of the slender insulated sections in time. The slender section (t = 1 mm, $A_o/V = 1020 \text{ m}^{-1}$) was protected with insulation with various thicknesses. The right-hand graph gives the same results as the left-hand graph, but zoomed in for temperatures up to 400 °C.

As can be seen in the graphs, the temperature of the insulated members is characterised by a period during which the temperature remains almost unchanged at room temperature, and a period with an increasing temperature. Figure 3.3 gives the results for a fire resistance of 30 minutes.

![Figure 3.2 – Temperature development in insulated aluminium sections exposed to the standard fire (120 min)](image-url)
Based on several FE calculations with various thicknesses, Figure 3.4 gives the relation between the thickness of the insulation layer and the maximum aluminium temperature. Results are given both for the slender section \((A_m/V = 1020 \, \text{m}^{-1})\) and for the stocky section \((A_m/V = 136 \, \text{m}^{-1})\).

In the temperature range from 150 to 350 °C, the relation between insulation thickness and aluminium temperature is approximately linear. In case of the slender section and a fire resistance period of 120 minutes, only a small increase in insulation thickness is required to decrease the maximum temperature in this temperature range, however in case of a fire resistance period of 30 minutes and in case of a stocky section with both fire resistance periods, a significant increase in the amount of insulation is required to reduce the critical temperature from 350 to 150 °C.
4 Gas temperatures in a natural fire safety concept

In a natural fire safety concept, a specific building layout is taken into account. Based on a pilot study in Annex B, the most important parameters in the design that influence the temperature-time curve were selected. With these parameters, mentioned in paragraph 4.1, a parameter study was carried out. Paragraph 4.2 gives the global layout of the compartments considered and paragraph 4.3 gives the fire loads considered. The resulting temperature-time curves of the parameter study are given in paragraph 4.4. The study is presented in a similar way as in the Cardington 2 project, comprising a research to heating of steel members in an office building (Twilt et al., [12]).

4.1 Important parameters for the natural fire safety concept

From a pilot study (Annex B), it appeared that the most important parameters determining the maximum gas temperature in the natural fire safety concept are:

- The ventilation condition;
- The design fire load density;
- The materials of which the boundary enclosure are composed.

The ventilation condition denotes the amount and sizes of windows in relation to the total area of the boundary enclosure. This is an important parameter which was varied in the parameter study (paragraph 4.2).

The design fire load density \( q_{f,d} \) is obtained by multiplying the characteristic fire load density \( q_{f,k} \) with a factor taking into account the fire activation risk due to the size of the compartment \( \delta_{q1} \), a factor taking into account the fire activation risk due to the occupancy \( \delta_{q2} \), and the factors taking into account the active fire fighting measures applied \( \delta_{ni} \):

\[
q_{f,d} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \prod_{i} \delta_{ni}
\]

(4.1)

In here, \( m \) is the combustion factor, which may be assumed equal to 0.8 if the combustible material is mainly composed of cellulosic material.

The characteristic fire load density depends on the type and amount of combustible materials present in the compartment. This should be determined for every type of structure and fire scenario considered in the design. For some types of occupancy, EN 1991-1-2 provides values for the characteristic fire load densities. These values were used in the current study.

Besides the characteristic fire loads, the combustible contents of a fire compartment are also characterised by the rate of heat release. The rate of heat release is also given for the types of occupancy specified by EN 1999-1-1. The rate of heat release was not explicitly varied in the parameter study. Its influence on the gas temperature is given in Annex B.

The danger of fire activation is in EN 1991-1-2 related to the compartment floor area and to the occupancy of the structure.

The maximum gas temperature also depends on the boundary enclosure of the compartment. In case of thick walls consisting of heavy materials, the boundary enclosure has a significant thermal capacitance, which reduces the maximum gas
temperature (Annex B). One of the main reasons to apply aluminium, however, is the low dead weight of the structure. In such cases, the use of heavy materials for walls, floor and ceiling is not a logic choice. In this study, a light-weight boundary enclosure was applied with a low thermal capacitance.

4.2 Layout of the compartments

The compartment considered is a box of which the length is twice as large as the width. Two compartment sizes were considered:

- Length x width = 40 m x 20 m = 800 m²;
- Length x width = 20 m x 10 m = 200 m².

Both compartments have a height of 3 m and a flat roof.

It should be noted that existing temperature models, including OZONE, are not validated for the large compartment of 800 m². This case is taken into account in the current study because similar compartment sizes are applied often in practice.

The factors taking into account the fire activation risk ($\delta_{q1}$) are equal to 1.7 and 1.47 for the compartments of 800 and 200 m², respectively.

Various opening areas were considered in this study. All openings had a height of 3 m, i.e. they run from floor to roof and had various widths. The widths of the four opening areas that are referred to in this document are indicated by the hatched areas in Figure 4.1.

To denote the amount and sizes of openings relative to the boundary enclosure, EN 1991-1-2 introduces the opening factor ($O$), which is defined according to equations (4.2) and (4.3).

$$O = \frac{A_i \sqrt{h_{eq}}}{A_i}$$  \hspace{1cm} (4.2)

$$h_{eq} = \frac{i A_i h_i}{A_i}$$  \hspace{1cm} (4.3)

The opening factors for the large and small fire compartments are different. The values are denoted in the figure.
4.3 Fire loads considered

The 80% fractile of the characteristic fire load densities, prescribed by EN 1991-1-2, are given in Figure 4.2 for the occupancies distinguished in the code.

For the parameter study, three occupancies with accompanying fire load densities were selected:

- Dwelling, with relatively high fire load density. The factor taking into account the fire activation risk due to the type of occupancy ($\delta_q^2$) is, in accordance with EN 1991-1-2, equal to 1.0. The fire growth rate for this occupancy is, in accordance with EN 1991-1-2, classified as ‘medium’ and the maximum rate of heat release ($RHR_f$) = 250 kW/m$^2$;
- Office, with intermediate fire load density. $\delta_q^2$ is 1.0, fire growth rate is medium and $RHR_f$ = 250 kW/m$^2$;
- Transport, with low fire load density. $\delta_q^2$ is 0.85, fire growth rate is slow and $RHR_f$ = 250 kW/m$^2$;

Figure 4.1 – Ventilation conditions considered

The materials of which the boundary enclosure (floor, ceiling, walls) is composed of are given in Table B 2 of Annex B.
Three types of active fire fighting measures were considered in the parameter study. The fire fighting measures taken into account in the different designs are indicated with colours in Table 4.1. The product of the factors for active measures, as given in EN 1991-1-2 and applied in this study, are also indicated in this table.

Table 4.1 – Reduction factors on the fire load density for active fire fighting measures

<table>
<thead>
<tr>
<th>Active measure</th>
<th>Reduction factor</th>
<th>$0.78$</th>
<th>$0.50$</th>
<th>$0.26$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water extinguishing system</td>
<td>0.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ 1 independent water supp</td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ 2 independent water supp</td>
<td><strong>0.7</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire detection by heat</td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire detection by smoke</td>
<td><strong>0.73</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic alarm transmission</td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work fire brigade</td>
<td>0.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off site fire brigade</td>
<td><strong>0.78</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Staircase overpressure</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The design fire load densities taken into account in the designs are given in Figure 4.3.
4.4 Gas temperature

The gas temperature has been determined with OZONE. This software program determines the gas temperature based on the layout of the fire compartment and the fire load density. The program meets the basic requirements set by EN 1999-1-2, has a theoretical background and was validated with fire tests (Cadorin et al. [3]). The software program is based on the European project “Valorisation Project Natural fire safety concept”. The Dutch version of the final report of this project is given by Twilt [10].

Figure 4.4, Figure 4.5 and Figure 4.7 the temperature-time curves for the different compartment designs considered for dwelling, office and transport occupancy, respectively. The different colours indicate different opening factors, with the colour indication according to Figure 4.1. The three curves of the same colour are the result of calculations with the different active fire fighting measures taken into account. In every case considered, the longer fires are the result of calculations with few active measures (only off-site fire brigade) and the shorter fires are the result of calculations with all active measures considered in this study. Note that the scale of the vertical axis of Figure 4.7 is different from that of the other two figures.

From these figures, it can be concluded that the opening factor influences the maximum temperature and the design fire load density mainly influences the fire duration. Only in case of very low fire load densities, such as for the transport occupancy, the maximum rate of heat release \( (RHR_f) \) is not yet reached at the end of the fire, so that the fire load density also influences the maximum temperature.

In the same figures, the standard fire is indicated with a black curve. Depending on the lay-out of the compartment, the maximum temperature in the natural fire safety concept may be lower or higher than the temperature after two hours of exposure to the standard fire.
In case of a standard fire, the temperature increases at increasing time. Therefore, longer fire resistance periods result in higher maximum temperatures to be applied in the design. In case of a natural fire, however, the decay phase is taken into account. It is therefore less appropriate to apply the conventional fire resistance requirements of 30, 60, 90 or 120 minutes in a natural fire safety concept. Instead, two requirements are investigated in this study:

- The structure should survive the fire, i.e. the critical temperature should not be reached;
- Persons inside the compartment should be able to escape safely before the structure collapses.

General values for the time in order to meet the latter requirement were not found in literature. According to Marchant [11], the escape time in a fire situation has three main components, namely the time between ignition of the fire to perception of the emergency, the time between perception and awareness of the need to escape and the travel time to a place of safety. It is clear that these times are different for e.g. a hospital or a school. In this research, the second requirement was expected to be met when the critical time was not reached within 30 minutes after fire ignition. In some cases, it may be more convenient to specify a fire resistance period from the beginning of flash-over instead of fire ignition, however, fire ignition was taken, because some of the natural fire safety concepts don’t show flash-over (see for example the temperature-time curves for transport occupation in Figure 4.7).

![Figure 4.4 – Gas temperature-time curves for dwelling occupancy with fire compartment 200 m²](image-url)
Figure 4.5 – Gas temperature-time curves for office occupancy with fire compartment 200 m²

Figure 4.6 – Gas temperature-time curves for office occupancy with fire compartment 800 m²
Figure 4.7 – Gas temperature-time curves for transport occupancy with fire compartment 200 m²

Figure 4.8 – Gas temperature-time curves for transport occupancy with fire compartment 800 m²
5 Heating of non-insulated members

This chapter shows how fast unprotected aluminium heats and in which cases aluminium may be applied without insulation. For this purpose, the temperature development in aluminium members was determined for the natural fire safety concepts studied in the previous chapter.

5.1 Example of a temperature-time curve

As an example, Figure 5.1 gives the temperature of aluminium and steel sections exposed to the gas temperature (red curve) of a certain natural fire (office occupancy, \( A = 200 \text{ m}^2 \), \( O = 0.09 \text{ m}^{1/2} \), active measures = off site fire brigade). The sections are assumed to be covered with soot. It should be noted that aluminium melts at a temperature of approximately 600 °C; the figure thus gives realistic results only up to this temperature.

![Temperature-time curve](image)

The figure shows that the slender aluminium section (\( t = 1 \text{ mm} \), \( A_m/V = 1020 \text{ m}^{-1} \)) follows the gas temperature almost without delay. Also the stocky aluminium and steel sections (\( t = 8 \text{ mm} \), \( A_m/V = 136 \text{ m}^{-1} \)) show a similar temperature-time curve as the gas temperature. The maximum temperature of aluminium members is therefore in this and in similar cases almost equal to the maximum gas temperature in the natural fire safety concept. Hence, for unprotected members, the maximum gas temperature is a proper indication for whether the member may be applied unprotected.

5.2 Maximum member temperature as a function of design parameters

For each of the structures studied in the parameter study, the maximum member temperature was determined for the stocky and for the slender section. Figure 5.2, Figure 5.3 and Figure 5.5 give the maximum member temperature of the stocky section (\( A_m/V = 136 \text{ m}^{-1} \)) on the vertical axes as a function of the opening factor on the horizontal axis. The upper graphs in the figures refer to the demand ‘the structure should survive the fire’ and the lower graphs refer to the demand ‘people should escape safely, so that the critical temperature may not be reached within 30 minutes after fire ignition’. The different curves indicate different active measures taken in the
design, resulting in different design fire load densities. The colours of these curves refer to the colours in Table 4.1. Note that the opening factors for the different compartment sizes, and therefore also the horizontal axes in the figures, are different.

Note that aluminium alloys melt at a temperature of approximately 600 °C, so that the graphs only provide realistic results up to this temperature.

The maximum (aluminium and gas) temperatures occur at a certain opening factor. For larger opening areas, the maximum gas temperature is lower because in that case more exchange occurs between hot gasses from the compartment and cold gasses from outside. For smaller opening areas, the maximum gas temperature is lower because the supply of oxygen is then limited.

![Graph](image)

**Figure 5.2 – Maximum temperature of unprotected aluminium members for different lay-outs with dwelling occupancy (upper picture: maximum temperature during the entire fire, lower picture: temperature indicated is reached after 30 minutes)**
Figure 5.3 – Maximum temperature of unprotected aluminium members for different active measures with office occupancy with area 200 m² (upper: criterion 1, lower: criterion 2)
Figure 5.4 – Maximum temperature of unprotected aluminium members for different active measures with office occupancy with area 800 m² (upper: criterion 1, lower: criterion 2)
Figure 5.5 – Maximum temperature of unprotected aluminium members for different active measures with transport occupancy with area 800 m² (upper: criterion 1, lower: criterion 2)

It was noted before that the opening factor influences the maximum gas temperature and that the maximum member temperature is almost equal to this maximum gas temperature. The figures show that, indeed, the maximum member temperature depends on the opening factor.

According to the results of this study, the fire load density only influences the maximum gas temperature in case of very low fire load densities, i.e. in case of transport occupancy. The figures show that the maximum member temperature depends only marginally on the fire load density in case of other occupancies than transport.

Thus, for normal or large fire load densities, application of active fire fighting measures will not reduce the member temperature in case of unprotected members. On the contrary, in a research to heating of steel members in an office compartment (Cardington 2) by Twilt et al [12], it was found that active fire fighting measures does influence the member temperature of unprotected members. The difference between these researches is that in the current research, a light and well-insulated boundary enclosure was applied. As a result, the gas temperature remains at or near its maximum for a certain period. Because of an other boundary enclosure applied in Cardington 2, the gas temperature increased until its maximum and decreased as soon as this
maximum was reached. To illustrate this, the left-hand picture in Figure 5.6 gives the gas temperature of a compartment with boundary enclosure as applied in the current research, and the right-hand picture gives the gas temperature of the same compartment, but with a heavier and not-insulated boundary enclosure. Only in the latter case, reduction of the design fire load influences the maximum gas temperature.

![Graph showing gas temperature](image)

**Figure 5.6** – Gas temperature for boundary enclosure applied in the current research (left-hand) and with a heavy boundary enclosure without insulation (right-hand)

The dashed lines in the figures indicate the range of selected critical temperatures. It is shown that, when demanding that the structure should survive the fire, the aluminium temperature remains in the range of selected critical temperatures only in case of transport occupancy in combination with a large opening factor. In all other cases, insulation is required in order to meet the fire resistance requirements.
6 Heating of insulated members

In this chapter, it is determined how much insulation is required and what parameters influence the thickness of the insulation layer.

6.1 Example of some temperature-time curves

As an example, Figure 6.1 gives the temperature development in time of the insulated slender section \( (A_m / V = 1020 \text{ m}^{-1}) \), with various thicknesses of the insulation layer, exposed to a certain natural fire (office occupancy, \( A = 200 \text{ m}^2, O = 0.09 \text{ m}^{1/2} \), active measures = off site fire brigade). The values in the legend represent the thickness of the insulation layer. The thicknesses are selected in such a way that the member temperature is equal to the selected critical temperatures, ranging from 150 to 350 °C.

![Temperature development in the insulated slender section](image)

Figure 6.1 – Temperature development in the insulated slender section \( (A_m / V = 1020 \text{ m}^{-1}) \) exposed to a certain natural fire for criterion 1

It is shown that the required insulation may become very thick. In practice, it may become uneconomic or difficult to apply such thick insulation layers. In this study, no attention was paid to this problem, the study only shows the influence of the design and the allowed critical temperature on the theoretical insulation thickness required.

The figure also shows that the aluminium member needs to be so heavily insulated, that the aluminium temperature may still increase several hours after the decay phase has been started. Note that the values for the relative proof stress in EN 1999-1-2 are valid for thermal exposure periods of up to 2 hours. These values cannot be used in natural fires without checking the validity for such long thermal exposure periods.

The above given example shows the insulation thickness to be applied in order to meet the requirement ‘the structure should survive the fire’. Figure 6.2 shows the time-temperature curves when the requirement is ‘the critical temperature should not be reached within 30 minutes after fire ignition’ for the same natural fire safety concept. Compared to the first demand, a much thinner insulation layer is now required. This is caused by the fact that only a few minutes before the 30 minutes expire, flash-over
occurs. As a result, the temperature remains at a relatively low level during a major part of the 30 minutes.

Figure 6.2 – Temperature development in the insulated slender section \( (A_m/V = 1020 \text{ m}^{-1}) \) exposed to a certain natural fire for criterion 2

Figure 6.3 gives the relation between the thickness of the insulation layer and the maximum aluminium temperature. Results are given both for the slender section \( (A_m/V = 1020 \text{ m}^{-1}) \) and for the stocky section \( (A_m/V = 136 \text{ m}^{-1}) \). It is shown that a large difference exists in the amount of insulation necessary to protect the slender or the stocky section.

Figure 6.3 – Relation between insulation thickness and maximum member temperature in case of a certain natural fire (left-hand: crit. 1, right-hand: crit. 2)

6.2 Parameter study to required insulation thickness

For each of the structures studied in the parameter study, the maximum member temperature was determined for the slender section \( (A_m/V = 1020 \text{ m}^{-1}) \) and the stocky section \( (A_m/V = 136 \text{ m}^{-1}) \) with various thickness of the insulation layer. Figure 6.4,
Figure 6.5 and Figure 6.8 give some examples of the maximum member temperature of on the vertical axes as a function of the insulation thickness on the horizontal axis. The left-hand graphs in the figures refer to the demand ‘the structure should survive the fire’ and the right-hand graphs to ‘the critical temperature may not be reached within 30 minutes after fire ignition’. The different colours of curves indicate different opening factors and different curves of the same colour indicate different active measures taken into account (i.e. different design fire load densities). The curves thus correspond to the designs of which the gas temperature is given in Figure 4.4 up to Figure 4.8. Note that the scales of the horizontal axes of the different graphs are not equal.

Other results of the parameter study are given in Annex D.
Figure 6.6 – Relation between insulation thickness and maximum aluminium temperature for various natural fire safety concepts with office occupancy, area 200 m², stocky section (left-hand: criterion 1, right-hand: criterion 2)

Figure 6.7 – Relation between insulation thickness and maximum aluminium temperature for various natural fire safety concepts with office occupancy 800 m², area 200 m², slender section (left-hand: criterion 1, right-hand: criterion 2)
The parameter study showed that, in case of the demand ‘the structure should survive the fire’, the required insulation thickness in order to remain below the critical temperature depends both on the maximum temperature and on the fire duration. Contrary to non-insulated members, active measures taken into account in the design thus reduce the required insulation thickness, since they reduce the design fire load. This is also visible in the above given left-hand figures, because the different curves with the same colour (i.e. different active measures but the same opening factor) are not on top of each other. In every case considered, the curve of one colour that requires the highest insulation thickness results from calculations with few active measures (only off-site fire brigade) and the lowest insulation thickness required results from calculations with all active measures considered in this study (see Table 4.1).

The curves for the demand ‘the structure should survive the fire’ also show that, for many lay-outs of the compartment, a considerable increase in insulation thickness is required in order to reduce the maximum member temperature with e.g. 50 ºC. This is especially evident for the transport occupancy. It may therefore be relevant to carry out research on the mechanical behaviour of aluminium structures exposed to fire, so that the critical temperature can be accurately determined in the design.

In case of the demand ‘the critical temperature should not be reached within 30 minutes of fire ignition’, the application of active measures do not significantly contribute to a reduction of the required insulation thickness. In this case, only a few millimetres extra insulation is required in order to reduce the maximum member temperature.

Some additional results of the parameter study are shown in the figures below.
Figure 6.9, Figure 6.10 and Figure 6.11 give the relations between the opening factor on the horizontal axis and the insulation thickness on the vertical axis. The different curves indicate different maximum member temperatures. The different plots are related to different active fire fighting measures taken into account. These fire fighting...
measures are indicated by colour codes in the heads of the plots, which refer to Table 4.1. Figure 6.9 and Figure 6.10 give results for the requirement ‘the structure should survive the fire’ and office and transport occupancy, respectively. Figure 6.11 gives the results for the requirement ‘the critical temperature may not be reached within 30 minutes after fire ignition’.

Only in case of the latter requirement, a maximum in the curves was detected for a certain opening factor. For larger opening areas, the maximum gas temperature was lower because in that case more exchange occurs between hot gasses from the compartment and cold gasses from outside. For smaller opening areas, the maximum gas temperature is limited because the fire is then ventilation controlled. This maximum was not detected in case of the first requirement, as a ventilation controlled fire results on the one hand in lower maximum gas temperatures but on the other hand in longer fire durations.

Figure 6.9 – Required insulation thickness as a function of opening factor for an office occupancy
Figure 6.10 – Required insulation thickness as a function of opening factor for transport occupancy (demand: structure should survive the fire)
and the requirement ‘the structure should survive the fire’. The different plots are related to different opening factors, as indicated in the heads of the figures. It is shown that the design fire load density has an important influence on the required insulation thickness.

Figure 6.12 – Required insulation thickness as a function of the design fire load density (demand: structure should survive the fire)
Heating of Aluminium Exposed to Fire
7 Heating of external, non-insulated members

In this chapter, it is determined whether or not external aluminium members that are not engulfed in flames require insulation in order to meet fire safety requirements. The method to determine the member temperature is given in paragraph 7.1.

Columns in between openings and columns opposite an opening were studied ascertain from two arbitrarily shown compartment lay-outs. The lay-out of the compartments is given in paragraph 7.2.

The results of the study are given in paragraph 7.3.

7.1 Method description to determine the member temperature

The member temperature was determined by using the method described in Annexes B and G of EN 1991-1-2 and Annex B of EN 1999-1-2. Some important parameters that are taken into account in the procedure described in these Annexes are the design value of the fire load, the dimensions of the openings and the distance from the openings to the exposed member. Equation (4.4), which is given in EN 1999-1-2, is the basis of the method to determine the member temperature.

\[
\sigma \cdot T_m^4 + \alpha_c \cdot T_m = I_z + \alpha_c \cdot T_0
\]  

(4.4)

The left-hand side of this equation considers the member, the right-hand side considers the surroundings. The method considers steady-state conditions for the various parameters. This means that it is not possible to determine the temperature development in time; only the maximum member temperature can be determined.

The heat flux from flames and openings to the member \((I_z)\) was determined with the program SHADOW (vs 1.0) [4]. The heat flux determined by this program is based on the equations in EN 1991-1-2. The value of the convection coefficient \((\alpha_c)\) was determined with an equation given in EN 1991-1-2.

Note that equation (4.4) does not take into account the emissivity of the member. In the method, the emissivity of the member is implicitly assumed as 1.0. This results in conservative values for the member temperature in case of material with a low emissivity, such as plain aluminium.

7.2 Compartment lay-out

The lay-out of the compartments considered in this study are shown in Figure 7.1. The compartment sizes are:

- Compartment 1: width x depth = 20 x 10 m² \((A_f = 200 \text{ m}^2)\);
- Compartment 2: width x depth = 20 x 40 m² \((A_f = 800 \text{ m}^2)\);

The windows are indicated with blue and the aluminium columns for which the temperature is determined are indicated with grey. For each compartment, a column in between openings and a column opposite an opening are considered. The wall that is closest to the aluminium columns has equal dimensions and openings for both compartments.

Some dimensions of this wall were varied in order to determine the influence of the dimensions on the member temperature. These dimensions are:

- The distance \((s)\) between column and windows;
• The window height \((h)\);
• The window width \((w)\).

All windows were assumed to have equal sizes. Also the design value of the fire load density was varied, between 800 MJ/m\(^2\) (corresponding to a dwelling with no other active measures than off-site fire brigade) and 200 MJ/m\(^2\) (the lower border of the application area of the equations).

The walls of the compartment are assumed to remain intact during the fire and they are assumed to be insulated such that the column facing the wall is not heated by conduction through the wall.

The columns are heated by convection and by radiation from the windows and flames. They are not engulfed in flames.

Figure 7.1 – Lay-out of compartment 1 and compartment 2
7.3 Results

The results of the calculations for the column between openings and the column opposite an opening are discussed separately in the following paragraphs.

7.3.1 Column between openings

The member temperature as a function of the distance between column and windows (s) is given in Figure 7.2. The different curves indicate different values for the design fire load density \(q_{fd}\). The left-hand graph considers compartment 1 \((A_f = 200 \text{ m}^2)\) and the right-hand graph gives the results of compartment 2 \((A_f = 800 \text{ m}^2)\).

Figure 7.2 – Column between openings: member temperature as a function of distance \(s\) for different values of \(q_{fd}\) (left-hand: compartment 1, right-hand: compartment 2)

It is shown that the distance between the column and the windows is an important parameter for the member temperature. It mainly depends on this distance and on the critical temperature of the member to determine whether or not insulation is required on the external member. Hence, it is relevant to accurately determine the critical temperature.

Figure 7.3 gives the member temperature as a function of the window size for a distance between column and windows of 1 m and a design fire load density of 278 MJ/m², corresponding to office occupancy with outside fire brigade as active measure. It is shown that the window size has a small influence on the member temperature (provided all windows have equal dimensions).
7.3.2 *Column opposite an opening*

The member temperature as a function of the distance between column and windows (s) is given in Figure 7.4. The different curves indicate different values for the design fire load density ($q_{f,d}$). The left-hand graph considers compartment 1 ($A_f = 200 \text{ m}^2$) and the right-hand graph gives the results of compartment 2 ($A_f = 800 \text{ m}^2$).

Figure 7.4 – Column opposite an opening: member temperature as a function of distance s for different values of $q_{f,d}$ (left-hand: compartment 1, right-hand: compartment 2)
It is shown that, also in case of members opposite an opening, the distance between the column and the window is an important parameter for the member temperature. Other important parameters are the design fire load and the compartment size. In case of a small distance between the external member and the window ($s$) or a large design fire load ($q_{f,d}$), insulation is required. In case of a large value for $s$ and a low value for $q_{f,d}$, it depends on the critical temperature of the member to determine whether or not insulation is required on the external member.

Figure 7.5 gives the member temperature as a function of the window size for a distance between column and window of 5 m and a design fire load density of 278 MJ/m$^2$. It is shown that the window size has a small influence on the member temperature (provided all windows have equal dimensions).

![Figure 7.5 – Column opposite an opening: member temperature as a function of the window size](image-url)
8 Evaluation and conclusions

8.1 Evaluation

This report evaluates the gas temperature and aluminium member temperature for various internal fires, depending on the layout of the fire compartment, the occupancy and the active measures. The aluminium members applied inside the compartment were assumed to be fully engulfed in flames, while the external members were assumed not to be engulfed in flames. The gas temperature was determined with the software programme OZONE and the input parameters were equal to the values given in EN 1991-1-2.

The research showed that the maximum gas temperature varies significantly for different layouts, from more than 1400 °C to 200 °C. Also the period with high temperatures varies, from less than 20 minutes to more than 120 minutes. For most designs considered, the decay phase in the natural fire started within 30 to 60 minutes after fire ignition.

For reference, the temperature of a standard fire is 840 °C after 30 minutes, 950 °C after 60 minutes and 1050 °C after 120 minutes. The standard fire has no decay phase.

The most important parameters determining the maximum gas temperature in the natural fire safety concept are:

- The ventilation (total opening area in relation to the total area of the boundary enclosure);
- The heat release of the combustible contents of a fire compartment;
- The heat losses through the boundary, related to the materials of which the boundary enclosure is composed.

The most important parameter determining the period with high temperatures is the design fire load density. This design fire load density is related to the characteristic fire load density, the active fire fighting measures and the danger of fire activation. The danger of fire activation is related to the occupancy and the compartment floor area. Also the maximum rate of heat release influences the period at high temperatures, as fierce fires last shorter.

The characteristic fire load density, the fire growth rate, the maximum rate of heat release and the danger of fire activation all depend on the occupancy of the structure. The occupancy is therefore an important parameter for the gas temperature-time relation.

The research showed that only in case of gas temperatures remaining below the critical temperature, or gas temperatures with a very short period at temperatures above the critical temperature, insulation is not required on aluminium members applied inside the compartment. Such designs only occur in case of low design fire loads in combination with large openings. In all other cases, insulation is required to protect load bearing aluminium members.

The equation in EN 1999-1-2 for insulated members is not suited to determine the required insulation thickness in case of fires with a decay phase. The temperature of insulated members was therefore determined in this study with finite element models in DIANA vs. 9.1.
To determine the required thickness of the insulation layer for aluminium members applied inside the compartment, critical temperatures were assumed ranging from 150 °C to 350 °C. In this temperature range, the 0,2 % proof stress of most aluminium alloys reduces from approximately 80 % to 20 % of the 0,2 % proof stress at room temperature. According to EN 1999-1-2 it may be assumed that the simple calculation models are satisfied if the aluminium temperature does not exceed 170 °C.

For the structures and cases evaluated in this report, it is evaluated how much more insulation is then required when the actual critical temperature had been 350 °C:

- In case of the standard fire, 1,2 to 2,2 times thicker insulation is required to maintain the temperature at 170 °C;
- For most of the natural fires evaluated in this report, 1,5 to 3,5 times thicker insulation is required to maintain the temperature at 170 °C;

In addition, the insulation layer required in order to keep the aluminium temperature below 170 °C is for many designs so thick that it may be uneconomical, difficult or even impossible to apply this insulation layer.

From this, it is concluded that evaluating the mechanical response of the fire exposed aluminium structure, so that the actual critical temperature is approached better in the design, is relevant. Therefore, research to the mechanical response of fire exposed aluminium is useful.

Also studied were externally applied aluminium members that are not engulfed in flames. For members in between openings, the member temperature mainly depends on the distance between the column and the openings. In case of members opposite an opening, also the fire load density and the compartment size determine the member temperature. Depending on these parameters and on the critical temperature, the members can or cannot be applied without insulation. Hence, also for external applied members research to the mechanical response of fire exposed aluminium is useful.

Members integrated in the rest of the structure were not considered in this research. It is expected that the application of such members requires significantly less or even no insulation.

Two requirements on the fire resistance were taken into account in the natural fire safety concepts in this research:

- The structure should survive the fire;
- The critical temperature should not be reached within 30 minutes after fire ignition.

The results show that the selection of a requirement has a large influence on the insulation thickness required. For some compartment lay-outs, more insulation is necessary to meet the first requirement than in case of two hours exposure to the standard fire, while for other lay-outs, less insulation is required. In case of the second demand, in almost all cases researched less insulation is required as in case of ½ hour exposure to the standard fire.

The influence of the relation between time and gas temperature on the required insulation thickness turns out to be relevant. The results show that various natural fire safety concepts may require insulation layers that vary more than 10 times in thickness. Therefore, selection of an appropriate fire concept in the design is important.
8.2 Conclusions

Depending on the layout of the compartment, the natural fire safety concept may be more or less favourable than the standard fire.

When applying the standard fire in the design, aluminium load-bearing components will have to be insulated in almost all cases in order to meet the requirements on the fire resistance.

In case of a natural fire safety concept, it depends on the following parameters whether or not insulation is required, and how much insulation is required:
- Critical temperature of the component;
- Section factor;
- Total area of opening factor of the compartment;
- Boundary enclosure of the compartment;
- Amount and type of combustible materials;
- Application of active measures, which are taken into account by reduction factors in the design value of the fire load density.

Also in case of application of a natural fire safety concept, aluminium load-bearing components inside a compartment will have to be insulated in many cases in order to meet the requirements on the fire resistance.

Insulation is required in fewer cases for external applied load-bearing components. An important parameter for the maximum member temperature for external applied members is the distance between the member and the opening(s).
9 References

A  **Thermal properties of insulation material**

The physical properties of the insulation materials are determined in tests on heated steel or aluminium sections and are related to the temperature of the section. In a Finite Element model, the material properties of the insulation material should be specified as a function of the temperature of the insulation material. The temperature of the insulation material is however usually different from the aluminium temperature. Consequently, the data on the thermal conductivity determined in tests cannot be applied directly in the Finite Element models.

Data of the thermal conductivity as a function of the temperature of the insulation layer were not found in literature and no attempt was made to generate these data in the current study. Instead, the arbitrary relation between thermal conductivity and temperature according to Figure A 1 was applied. The density and the specific heat were assumed to remain unchanged during heating: \( \rho_p = 60 \text{ kg/m}^3 \) and \( c_p = 1030 \text{ J/kgK} \).

![Figure A 1 – Relation between thermal conductivity and temperature of the insulation applied in the Finite Element models](image)

To check whether the arbitrary insulation properties are representative for that of a real insulation material, a finite element calculation of an insulated member exposed to the standard fire was compared with the results of a calculation according to equation (4.6). (In the latter case, the thermal properties are related to the aluminium temperature.) As no complete set of data was found on the thermal conductivity of insulation material determined in tests on aluminum members, the thermal conductivity used in this study was according to tests on heated steel sections. Note that, as the thermal properties of aluminium differ from that of steel, the values for the thermal conductivity of the insulation material are probably not applicable for aluminium structures.

As reference, the thermal properties of Rockwool were applied in the calculations. The density and specific heat applied were \( \rho_p = 60 \text{ kg/m}^3 \) and \( c_p = 1030 \text{ J/kgK} \), respectively. The thermal conductivity is given in Figure A 2.
The left-hand picture in Figure A 3 gives the temperature development of insulated aluminium members determined with equation (4.6) and the thermal conductivity according to Figure A 2. The required thickness in order to obtain an aluminium temperature after 120 minutes of 150 to 350 °C was 150 to 120 mm. The right-hand picture gives the temperature development determined with DIANA and the thermal conductivity according to Figure A 1.
The required insulation thickness determined with FEM is approximately equal to the required insulation thickness according to the original equation in EN 1999-1-2 for the selected critical temperatures. Also the relations between time and aluminium temperature for these two methods are approximately equal. Based on this, it is concluded that the FEM models gives similar results as the original equation in EN 1999-1-2 for the data on the thermal conductivity specified, at least in case of the standard fire.
B Natural fire safety concepts for various layouts

The gas temperature in a natural fire safety concept depends on the layout of the compartment. In this Annex, the influence of design parameters of the structure on the gas temperature is studied by varying some of the most important parameters.

In the orientating study, it was determined that the amount and sizes of the openings and the design value of the fire load density are important parameters for the maximum temperature and the fire duration. The influence on the temperature-time curve for these parameters was studied extensively and results are given in the main document. The parameters that influence the gas temperature, but that are not (extensively) taken into account in the parameter study are discussed in the current Annex.

Paragraph B.1 discusses all parameters that are related to the occupancy. The influence of the boundary enclosure on the gas temperature is given in paragraph B.2. The fire growth rate and the maximum heat release, which are related to the type of combustible material (and therefore also to the occupancy) are discussed in paragraphs B.3 and B.4, respectively.

B.1 Occupancy

Various types of occupation are distinguished in EN 1991-1-2. The type of occupation determines the fire load parameters to be taken into account and a parameter for the danger of fire activation ($\delta_{q2}$). The values are given in Table B 1.

Table B 1 – Parameters for different types of occupation (EN 1991-1-2)

<table>
<thead>
<tr>
<th>Occupation</th>
<th>$\delta_{q2}$ [-]</th>
<th>$q_{f,k}$ [MJ/m$^2$]</th>
<th>$t_\alpha$ [s]</th>
<th>RHR$_f$ [kW/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>1,00</td>
<td>948</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Hospital room</td>
<td>-</td>
<td>280</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Hotel room</td>
<td>1,00</td>
<td>377</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Library</td>
<td>-</td>
<td>1824</td>
<td>150</td>
<td>500</td>
</tr>
<tr>
<td>Office</td>
<td>1,00</td>
<td>511</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Classroom of a school</td>
<td>-</td>
<td>347</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Shopping centre</td>
<td>-</td>
<td>730</td>
<td>150</td>
<td>250</td>
</tr>
<tr>
<td>Theatre (cinema)</td>
<td>-</td>
<td>365</td>
<td>150</td>
<td>500</td>
</tr>
<tr>
<td>Transport (public space)</td>
<td>-</td>
<td>122</td>
<td>600</td>
<td>250</td>
</tr>
</tbody>
</table>

In all cases where EN 1991-1-2 does not give a value for factor $\delta_{q2}$ a value of 1,0 is applied in OZONE, except for a transport occupation where 0,85 is applied.

Figure B 1 gives the gas temperature for the distinguished occupations for which the fire growth rate and maximum rate of heat release are equal to that of the reference design (dwelling). Figure B 2 gives the gas temperature for distinguished occupations with different fire growth rates and maximum rate of heat release.
Figure B 1 – Temperature for various occupations with equal values for $t_a$ and $RHR_f$
B.2 Boundary enclosure

The thermal capacity of the boundary enclosure is taken into account in OZONE. The amount of heat absorbed by the boundary enclosure depends on the specific heat, the density, the coefficient of conductivity and the thickness of the layers of which the boundary enclosure is composed.

The effects of the boundary enclosure on the temperature are shown in Figure B 3.

Figure B 3 – Gas temperature for variation in boundary enclosure

The red curve indicates the gas temperature of a reference structure with properties according to Table B 2.
Table B 2 – Composition of the boundary enclosure

<table>
<thead>
<tr>
<th>Floor</th>
<th>Material (from inside to outside)</th>
<th>Thickness [cm]</th>
<th>Unit Mass [kg/m³]</th>
<th>Conductivity [W/mK]</th>
<th>Specific Heat [J/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Glass wool &amp; Rock wool</td>
<td>2</td>
<td>60</td>
<td>0.037</td>
<td>1030</td>
</tr>
<tr>
<td></td>
<td>Light Perforated Bricks</td>
<td>10</td>
<td>700</td>
<td>0.15</td>
<td>840</td>
</tr>
<tr>
<td></td>
<td>Steel [EN1994-1-2]</td>
<td>0.5</td>
<td>7850</td>
<td>45</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Glass wool &amp; Rock wool</td>
<td>5</td>
<td>60</td>
<td>0.037</td>
<td>1030</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ceiling</th>
<th>Material (from inside to outside)</th>
<th>Thickness [cm]</th>
<th>Unit Mass [kg/m³]</th>
<th>Conductivity [W/mK]</th>
<th>Specific Heat [J/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gypsum board [EN12524]</td>
<td>2</td>
<td>900</td>
<td>0.25</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Steel [EN1994-1-2]</td>
<td>0.5</td>
<td>7850</td>
<td>45</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Glass wool &amp; Rock wool</td>
<td>5</td>
<td>60</td>
<td>0.037</td>
<td>1030</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Walls</th>
<th>Material (from inside to outside)</th>
<th>Thickness [cm]</th>
<th>Unit Mass [kg/m³]</th>
<th>Conductivity [W/mK]</th>
<th>Specific Heat [J/kgK]</th>
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</thead>
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<td></td>
<td>Gypsum board [EN12524]</td>
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<td>900</td>
<td>0.25</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Steel [EN1994-1-2]</td>
<td>0.3</td>
<td>7850</td>
<td>45</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Glass wool &amp; Rock wool</td>
<td>5</td>
<td>60</td>
<td>0.037</td>
<td>1030</td>
</tr>
</tbody>
</table>

The blue line indicates the same boundary enclosure, but without insulation on the walls (i.e. gypsum board and mineral wool are removed). In case of the green line, a mineral wool layer of 150 mm encloses the entire area. If heavy walls, floors and ceilings are applied, the temperature is according to the purple line. For this case the steel plates with thickness 3 mm covering the walls are replaced by 100 mm middle-weight concrete, in the floor 200 mm middle-weight concrete is applied and in the ceiling 100 mm middle-weight concrete is applied instead of a steel plate with thickness 5 mm. The figure shows that in this case, the temperature does not change significantly, because the mineral wool layer prevents the concrete from heating. If the mineral wool layer is removed (light blue line) the gas temperature decreases.

### B.3 Fire growth rate

The fire growth rate indicates the time $t_\alpha$ required to reach a rate of heat release of 1 MW. For dwellings, hospital rooms, hotel rooms, offices and classrooms, EN 1991-1-2 specifies a medium fire growth rate, which corresponds to $t_\alpha = 300$ s. The blue curve in Figure B 4 indicates a fast fire growth rate ($t_\alpha = 150$ s), while the green curve indicates a slow fire growth rate ($t_\alpha = 600$ s). It is shown the fire growth rate does not significantly change the maximum temperature and the period at high temperature. The fire growth rate influences the time after the start of the fire where the temperature becomes high.
B.4 Maximum rate of heat release

The rate of heat release is the amount of energy released by the fire per time unit and per unit floor area. The maximum rate of heat release (RHRf) \([\text{kW/m}^2]\) is used in the calculation of the horizontal plateau of the rate of heat release. The rate of heat release for libraries and theatres given in EN 1991-2 is 500 kW/m², for all other occupancies it is 250 kW/m². In Figure B 5, the red curve gives the temperature in an office for a rate of heat release of 250 kW/m². The blue curve gives the temperature development for a rate of heat release of 500 kW/m², while the other parameters remain equal. It is shown that a higher rate of heat release results in a higher maximum gas temperature.
Figure B 5 – Gas temperature for variation in maximum rate of heat release
C Determination of member temperature - time relations

The equation according to EN 1999-1-2 was used to determine the aluminium temperature of unprotected members:

\[
\Delta \theta_{al} = k_{sh} \frac{1}{c_{al} \cdot \rho_{al}} A_{m} \left( h_{con} + h_{rad} \right) \Delta t \quad \text{(time step \( \leq 5 \) sec)} \tag{4.5}
\]

Symbols used are given in the symbol list on page 3. The symbols and the equation (and all other equations in this document) are explained in the literature research.

EN 1999-1-2 also provides an equation to determine the temperature of insulated aluminium members exposed to the standard fire. This equation is given by Wickström [13].

\[
\Delta \theta = \frac{\lambda_{al}}{c_{al} \times \rho_{al}} \left( \frac{1}{1 + \phi/3} \right) \left( T - \theta \right) \Delta t \left( e^{\phi/10} - 1 \right) \Delta T \quad \text{(time step \( \leq 30 \) sec)} \tag{4.6}
\]

With \( \phi = \frac{c_{p} \cdot \rho_{al} \cdot d_{p}}{c_{al} \cdot \rho_{al}} \frac{A_{m}}{V} \) and \( \Delta \theta \geq 0 \)

Equation (4.6) is suited to study heating of aluminium members exposed to a standard fire. However, when this equation is applied to a natural fire safety concept, the equation gives an unreliable member temperature. Figure C 1 gives an example. According to the results of the calculation with this equation, the member temperature increases instantly when the gas temperature decreases. Besides, from this point the heavily insulated members heat quicker than the members with thin insulation thickness. This does not approach the temperature development of a real section.

![Figure C 1 – Example of the time-temperature relation in a natural fire safety concept (red curve) and an insulated member](image-url)
Equation (4.6) is thus not suited to study insulated members exposed to a natural fire. To determine the temperature of the protected aluminium members, finite element models were made in the program DIANA, vs. 9.1. CQ8HT square elements with 8 nodes per elements were applied to model aluminium and insulation. BC3HT linear elements with 3 nodes were applied to model the boundary from the gas to the insulation. Because of symmetry, it is only necessary to model ¼ of the insulated member. The Finite Element mesh of a square hollow section with wall thickness 1 mm and insulation thickness 25 mm is shown in Figure C 2. The elements representing the aluminium section are shown in red. The elements representing the insulation layer are shown in orange. The boundary elements are shown in yellow.

Figure C 2 – Finite element mesh
D Parameter study to required insulation thickness

Figure D 1 – Relation between insulation thickness and maximum aluminium temperature for various natural fire safety concepts with dwelling occupancy, area 800 m², stocky section (left-hand: criterion 1, right-hand: criterion 2)

Figure D 2 – Relation between insulation thickness and maximum aluminium temperature for various natural fire safety concepts with office occupancy, area 800 m², stocky section (left-hand: criterion 1, right-hand: criterion 2)
Figure D 3 – Relation between insulation thickness and maximum aluminium temperature for various natural fire safety concepts with transport occupancy, area 200 m², slender section (left-hand: criterion 1, right-hand: criterion 2)

Figure D 4 – Relation between insulation thickness and maximum aluminium temperature for various natural fire safety concepts with transport occupancy, area 200 m², stocky section (left-hand: criterion 1, right-hand: criterion 2)
Figure D 5 – Relation between insulation thickness and maximum aluminium temperature for various natural fire safety concepts with transport occupancy, area 800 m², stocky section (left-hand: criterion 1, right-hand: criterion 2)