EN 1991-1-2

Basic design methods
Worked examples

Prof. VASSART Olivier
Chairman of the CEN/TC250 EC1/ Fire E.G.
ArcelorMittal R&D

email: olivier.vassart@arcelormittal.com
Basic design methods of EN1991-1-2

Fire part of Eurocode 1
Fire parts of Eurocodes 2 to 6 and 9

Following common layout to provide design rules for fire resistance of various types of structures:

- General
  - Scope, application field, definitions, symbols and units

- Basic principles
  - Performances requirements, design values of material properties and assessment approaches

- Material properties
  - Mechanical and thermal properties at elevated temperatures

- Assessment methods for fire resistance

- Constructional details

- Annexes
  - Additional information: common case - more detailed design rules
Fire resistance is defined in terms of time as follows:

- Relevant time of fire exposure during which the corresponding fire resistance function of a structure is maintained despite fire actions.

According to European standard, **3 criteria** to define the fire resistance:

- **R** – load bearing function
- **E** – integrity separating function
- **I** – thermal insulating separation function

Above criteria may be required individually or in combination:

- separating only: integrity (criterion **E**) and, when requested, insulation (criterion **I**)
- load bearing only: mechanical resistance (criterion **R**)
- separating and load bearing: criteria **R, E** and, when requested **I**
Fire resistance - European classes

R – load bearing function

Capacity of a structure to maintain its required mechanical resistance in case of fire
E – integrity separating function

Capacity of a structure to maintain its required integrity separating function to hot gases in case of fire

- With or without additional mechanical loading
- 200, 300, 400°C, …
- (no limitation)
Fire resistance - European classes

I – thermal insulation separating function

Capacity of a structure to maintain its required thermal insulation separating function in case of fire

- Average temperature rise \( \leq 140 \, \text{K} \) (under standard fire)
- Maximum temperature rise \( \leq 180 \, \text{K} \) (under standard fire)
Resistance to Fire - Chain of Events

1: Ignition

2: Thermal action

3: Mechanical actions

4: Thermal response

5: Mechanical response

6: Possible collapse
# Structural Fire Safety Engineering vs. Classification

<table>
<thead>
<tr>
<th>Prescriptive</th>
<th>Performance based</th>
</tr>
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<tbody>
<tr>
<td>standard fire</td>
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</tr>
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Objective of the classification

Describe the Thermal and mechanical behaviour of structures subjected to fire

Means

Normalised fire

Displacement

Time
## Structural Fire Safety Engineering vs. Classification

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Actions on Structures Exposed to Fire
EN 1991-1-2 - Prescriptive Rules

Design Procedures

Prescriptive Rules
(Thermal Actions given by Nominal Fire)

Performance-Based Code
(Physically based Thermal Actions)
### Nominal Temperature-Time Curve

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| Rate of heat release |
| Fire surface |
| Boundary properties |
| Opening area |
| Ceiling height |

| Exact geometry |
| + |

**No data needed**
Prescriptive Fire Regulations Defining ISO Curve Requirements

ISO-834 Curve (EN1364 -1)

\[ T = 20 + 345 \log (8t + 1) \]

- Has to be considered in the WHOLE compartment, even if the compartment is huge
- Never goes DOWN
- does not consider the PRE-FLASHOVER PHASE
- Does not depend on FIRE LOAD and VENTILATION CONDITIONS
Stages of a Natural Fire and the Standard Fire Curve

Temperature

- Pre-Flashover
- Post-Flashover 1000-1200°C

Flashover

Ignition - Smouldering

Heating

Cooling ....

ISO834 standard fire curve

Natural fire curve
Actions on Structures Exposed to Fire
EN 1991-1-2 - Performance Based Code

Design Procedures

Prescriptive Rules
(Thermal Actions given by Nominal Fire)

Performance-Based Code
(Physically based Thermal Actions)
Implemented in:

- EN 1991-1-2
- Some National Fire Regulations include now alternative requirements based on Natural Fire

**Natural Fire Safety Concept**

![Graph showing temperature and time relationship in a fire scenario](image)

**ISO curve**

**Implemented in:**
- EN 1991-1-2
- Some National Fire Regulations include now alternative requirements based on Natural Fire
NFSC Valorisation Project
**Natural Fire Model**

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<td>Opening area</td>
</tr>
<tr>
<td>Ceiling height</td>
</tr>
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+ Exact geometry
List of needed Physical Parameters for Natural Fire Model

Boundary properties
- Ceiling height
- Opening Area
- Fire surface
- Rate of heat release
Characteristics of the Fire Compartment

- Fire resistant enclosures defining the fire compartment according to the national regulations
- Material properties of enclosures: $c$, $\rho$, $\lambda$
- Definition of Openings
### Characteristic of the Fire for Different Buildings

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Fire Growth Rate</th>
<th>$R_{HR_f}$ [kW/m²]</th>
<th>$q_{f,k}$ [MJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>Medium</td>
<td>250</td>
<td>948</td>
</tr>
<tr>
<td>Hospital (room)</td>
<td>Medium</td>
<td>250</td>
<td>280</td>
</tr>
<tr>
<td>Hotel (room)</td>
<td>Medium</td>
<td>250</td>
<td>377</td>
</tr>
<tr>
<td>Library</td>
<td>Fast</td>
<td>500</td>
<td>1824</td>
</tr>
<tr>
<td>Office</td>
<td>Medium</td>
<td>250</td>
<td>511</td>
</tr>
<tr>
<td>School</td>
<td>Medium</td>
<td>250</td>
<td>347</td>
</tr>
<tr>
<td>Shopping Centre</td>
<td>Fast</td>
<td>250</td>
<td>730</td>
</tr>
<tr>
<td>Theatre (movie/cinema)</td>
<td>Fast</td>
<td>500</td>
<td>365</td>
</tr>
<tr>
<td>Transport (public space)</td>
<td>Slow</td>
<td>250</td>
<td>122</td>
</tr>
</tbody>
</table>
## Fire Load Density

### Compartment floor area $A_f$ [m²]

<table>
<thead>
<tr>
<th>$A_f$ [m²]</th>
<th>Danger of Fire Activation $\delta_{q1}$</th>
<th>Danger of Fire Activation $\delta_{q2}$</th>
<th>Examples of Occupancies</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1,10</td>
<td>0,78</td>
<td>Art gallery, museum, swimming pool</td>
</tr>
<tr>
<td>250</td>
<td>1,50</td>
<td>1,00</td>
<td>Residence, hotel, office</td>
</tr>
<tr>
<td>2500</td>
<td>1,90</td>
<td>1,22</td>
<td>Manufactory for machinery &amp; engines</td>
</tr>
<tr>
<td>5000</td>
<td>2,00</td>
<td>1,44</td>
<td>Chemical laboratory, Painting workshop</td>
</tr>
<tr>
<td>10000</td>
<td>2,13</td>
<td>1,66</td>
<td>Manufactory of fireworks or paints</td>
</tr>
</tbody>
</table>

### Function of Active Fire Safety Measures

- $q_{f,d} = \delta_{q1} \cdot \delta_{q2} \cdot \prod \delta_{ni} \cdot m \cdot q_{f,k}$

### Automatic Fire Suppression
- $\delta_{n1} = 0.61$
- $\delta_{n2} = 1.0$ or $0.87$ or $0.7$
- $\delta_{n3} = 0.87$ or $0.73$
- $\delta_{n4} = 0.87$
- $\delta_{n5} = 0.61$ or $0.78$
- $\delta_{n6} = 0.9$ or $1$ or $1.5$
- $\delta_{n7} = 1.0$ or $1.5$
- $\delta_{n8} = 1.0$
- $\delta_{n9} = 1.0$
- $\delta_{n10} = 1.5$
Rate of Heat Release Curve
Stationary State and Decay Phase

Growing phase

Fire Growth Rate = FGR

Ultra-Fast (FGR)
Fast (FGR)
Medium (FGR)
Slow (FGR)

Growing phase

RHR [MW]

RHR [MW]

0 5 10 15 20 25 30

0 5 10

t [min]

t [min]

70%
### Natural Simplified Fire Model

<table>
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<th>No data needed</th>
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### *) Simplified Fire Models

**Localised Fire**
- HESKESTADT
- HASEMI

\[ \theta(x, y, z, t) \]

**Fully Engulfed Compartment**
- Parametric Fire

\[ \theta(t) \text{ uniform in the compartment} \]

**Rate of heat release**
- Fire surface
- Boundary properties
- Opening area
- Ceiling height

### *) Advanced Fire Models

- Two-Zone Model
- Combined Two-Zones and One-Zone fire
- CFD

### *) Advanced Fire Models

- One-Zone Model

### *) Simplified Fire Models

- Exact geometry

<table>
<thead>
<tr>
<th>+/-</th>
<th></th>
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\[ + \]
Simplified Fire Models Localised Fire

LOCALISED FIRE

θ(x, y, z, t)

FULLY ENGULFED COMPARTMENT

θ(t) uniform in the compartment
Real Localised Fire Test
Annex C of EN 1991-1-2:

- Flame is not impacting the ceiling of a compartment ($L_f < H$)
- Fires in open air

\[
\Theta(z) = 20 + 0.25 \left(0.8 \, Q_c \right)^{2/3} \left(z - z_0 \right)^{-5/3} \leq 900^\circ C
\]

The flame length $L_f$ of a localised fire is given by:

\[
L_f = -1.02 \, D + 0.0148 \, Q^{2/5}
\]
Annex C of EN 1991-1-2:

- Flame is impacting the ceiling ($L_f > H$)

\[ Y = \text{Height of the free zone} \]

\[ \theta_g \]

$\theta = \text{Air Temperature at Beam Level}$

Calculated by CaPaFi
Simplified Fire Models

Fully Engulfed Compartment

**LOCALISED FIRE**

$\theta(x, y, z, t)$

**FULLY ENGULFED COMPARTMENT**

$\theta(t)$ uniform in the compartment
Real Fire Test Simulating an Office Building

Fully engulfed fire
Real Fire Test Simulating an Office Building

Demonstration test: set-up

Fire load with real office furniture

Openings with normal glazed windows
Real Fire Test Simulating an Office Building

Early stage of fire

Fully developed fire
Real Fire Test Simulating an Office Building

![Graph showing vertical displacement and temperature over time](image)

- Maximum vertical displacement
- Steel temperature
Annex A of EN 1991-1-2

Temperature [°C]

Iso-Curve

For a given b, q_{fd}, A_t & A_f
Natural Advanced Fire Model

*) Nominal temperature-time curve
Standard temperature-, External fire - & Hydrocarbon fire curve

*) Simplified Fire Models

Localised Fire
- HESKESTADT
- HASEMI
\[ \theta(x, y, z, t) \]

Fully Enquulfed Compartment
- Parametric Fire
  \[ \theta(t) \text{ uniform in the compartment} \]

Rate of heat release
Fire surface
Boundary properties
Opening area
Ceiling height

*) Advanced Fire Models

- Two-Zone Model
- Combined Two-Zones and One-Zone fire
- CFD

Exact geometry

No data needed
Advanced fire Models

LOCALISED FIRE

The Fire stays localised

The Fire switch to a fully engulfed fire

LOCALISED FIRE

FULLY ENGULFED COMPARTMENT
Advanced fire Models
Ignition
Localised Fire
Growing of Localised Fire
Theory of two zones models

Localised Fire

Ozone Software Model
Theory of two zones models

2 ➞ 1 zone: if one of the following criteria is reached

- $T_{\text{hot gases}} > 500 \, ^\circ\text{C}$
- Combustible material in the smoke and $T_{\text{smoke}} > 300 \, ^\circ\text{C}$
- Localised fire > 25 % of the compartment’s surface
- Smoke height > 80 % of the total height of the compartment
Theory of two zones models

Generalised Fire

Ozone Software Model

\[ Q = f(Z) \]

Fire: RHR, combustion products
Large Compartment Test
Fire Load
Large Compartment Test
External Flaming During the Test
Large Compartment Test
After the Test
Two Zone Calculation Software “OZone V2.2”
Software “OZone V2.2”
Definition of the Compartment
Software “OZone V2.2”

Definition of the boundaries

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [cm]</th>
<th>Unit mass [kg/m²]</th>
<th>Conductivity [W/mK]</th>
<th>Specific Heat [J/kgK]</th>
<th>Rel Emissivity Hot Surface</th>
<th>Rel Emissivity Cold Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1 Steel [EN1994-1-2]</td>
<td>0.1</td>
<td>7850</td>
<td>45</td>
<td>600</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Layer 2 Glass wool &amp; Rock wool</td>
<td>15</td>
<td>60</td>
<td>0.037</td>
<td>1030</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Layer 3 Steel [EN1994-1-2]</td>
<td>0.1</td>
<td>7850</td>
<td>45</td>
<td>600</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Enter each layer on a single row in the table above (up to four layers). Just click in a cell and edit its value. If not found in the list of materials you can define your own material, by filling in the appropriate cells. Define your layers starting from Layer 1 (Inside).

Define your openings if any (up to three openings in a single wall). Click in the desired cell and input your values. Start from Opening 1.

To delete or insert a row, right click on a row header and select the appropriate command from the popup menu.

Warning: no check is made regarding the dimensions of the openings!

Equal Diameter Groups

<table>
<thead>
<tr>
<th>Diameter [m]</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
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<td></td>
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Number of Openings

Variation

OK  Cancel
Software “OZone V2.2”
Definition of the fire

![Fire Design Software UI](image-url)
Software “OZone V2.2”
Criteria 2 zones – 1 zone

Transition (2 Zones to 1 Zone) Criteria

- Upper Layer Temperature \(\geq 500\) °C
- Combustible in Upper Layer + U.L. Temperature \(\geq\) Combustible Ignition Temperature \(= 300\) °C
- Interface Height \(\leq 0.2\) x Compartment Height
- Fire Area \(\geq 0.25\) x Floor Area

Select Analysis Strategy
- Combination (default)
- 2 Zones
- 1 Zone
OZone results: Input and Computed RHR

Rate of Heat Release

Analysis Name: Natural Fire Example

Peak: 50.63 MW At: 35.6 min
OZone results:
Gas Temperatures

Gas Temperature

Analysis Name: Natural Fire Example

Peak: 809 °C At: 41 min
OZone results:
Smoke Layer Thickness

![Graph showing smoke layer thickness over time.](image-url)
Compartment Fire test
Calibration of Software OZone: Gas Temp
Calibration of Software OZone: Steel Temp
Comparison BRE Test 4 - OZone Design fire

- **Gas Temp [°C]**
- **Time [sec]**

- **OZone Office Fast**
- **OZone Office Medium**
- **Test Average**
- **Test Max**
- **Test Min**

- $q_{f,d} = 511$ MJ/m²
- $RHR_f = 250$ kW/m²
Calibration of Software OZone: OZone Vs Ulster Test
Fire load energy density was 700 MJ/m²
The fire load can be achieved using 45 standard wooden cribs (1 m x 1 m x 0.5 m high), positioned evenly around the compartment (9.0 m x 15.0 m).
Calibration of Software OZone: OZone Vs Ulster Test
Calibration of Software OZone: OZone Vs Ulster Test

Temperature in the Middle of Compartment

Compartment Temperature

- Left Top Corner
- Left Bottom Corner
- Middle
- Right Top Corner
- Right Bottom Corner

Temperature (°C) vs Time (min)
Grid definition
Sofie Results: Gas Temperatures
Computer Fluid Dynamics: Free Software FDS
Definition of the mesh
Computer Fluid Dynamics: Free Software FDS
Resistance to Fire - Chain of Events

1: Ignition

2: Thermal action

3: Mechanical actions

4: Thermal response

5: Mechanical response

6: Possible collapse
Basis of Design and Actions on Structures

Actions for temperature analysis
Thermal Action
FIRE

Actions for structural analysis
Mechanical Action
Dead Load  G
Imposed Load  Q
Snow  S
Wind  W

S
G
Q

W

Fire
Room temperature

\[ E_d = \gamma_G \cdot G + \gamma_{Q,1} \cdot Q_1 + \sum_{i>1} \psi_{0,i} \cdot \gamma_{Q,i} \cdot Q_i \]

f.i.: Offices area with the imposed load \( Q \),
the leading variable action

\[ E_d = 1,35 \cdot G + 1,5 \cdot Q + 0,6 \cdot 1,5 \cdot W + 0,5 \cdot 1,5 \cdot S \]
Fire conditions ≡ Accidental situation

\[ E_{\text{fi},d} = G + \psi_{1\text{or}2,1} Q_1 + \sum_{i>1} \psi_{1\text{or}2,i} Q_i \]

f.i. : Offices area with the imposed load Q, the leading variable action

\[ E_{\text{fi},d} = G + 0,3 \ Q \]

Offices area with the wind W, the leading variable action

\[ E_{\text{fi},d} = G + 0,0 \ W + 0,3 \ Q \]
## Values of $\psi$ factors for buildings

<table>
<thead>
<tr>
<th>Action</th>
<th>$\psi_0$</th>
<th>$\psi_1$</th>
<th>$\psi_2$</th>
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<tr>
<td>Imposed loads in buildings, category (see EN 1991-1.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category A: domestic, residential areas</td>
<td>0,7</td>
<td>0,5</td>
<td>0,3</td>
</tr>
<tr>
<td>Category B: office areas</td>
<td>0,7</td>
<td>0,5</td>
<td>0,3</td>
</tr>
<tr>
<td>Category C: congregation areas</td>
<td>0,7</td>
<td>0,7</td>
<td>0,6</td>
</tr>
<tr>
<td>Category D: shopping areas</td>
<td>0,7</td>
<td>0,7</td>
<td>0,6</td>
</tr>
<tr>
<td>Category E: storage areas</td>
<td>1,0</td>
<td>0,9</td>
<td>0,8</td>
</tr>
<tr>
<td>Category F: traffic area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vehicle weight $\leq$ 30kN</td>
<td>0,7</td>
<td>0,7</td>
<td>0,6</td>
</tr>
<tr>
<td>Category G: traffic area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$30kN &lt;$ vehicle weight $\leq$ 160kN</td>
<td>0,7</td>
<td>0,5</td>
<td>0,3</td>
</tr>
<tr>
<td>Category H: roofs</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Snow loads on buildings (see EN1991-1.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finland, Iceland, Norway, Sweden</td>
<td>0,70</td>
<td>0,50</td>
<td>0,20</td>
</tr>
<tr>
<td>Remainder of CEN Member States, for sites located at altitude $H &gt; 1000$ m a.s.l.</td>
<td>0,70</td>
<td>0,50</td>
<td>0,20</td>
</tr>
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<td>Remainder of CEN Member States, for sites located at altitude $H \leq 1000$ m a.s.l.</td>
<td>0,50</td>
<td>0,20</td>
<td>0</td>
</tr>
<tr>
<td>Wind loads on buildings (see EN1991-1.4)</td>
<td>0,6</td>
<td>0,2</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (non-fire) in buildings (see EN1991-1.5)</td>
<td>0,6</td>
<td>0,5</td>
<td>0</td>
</tr>
</tbody>
</table>

(Reference: EN1990 - February 2002)
Worked examples of EN1991-1-2

Fire part of Eurocode 1
The Building (R+5)
The Building (R+5)

What do we need for the calculation?

Size of the compartment
Boundary properties
Ceiling height
Opening Area
Fire surface
Rate of heat release

Geometry

Fire
Size of the compartment

1 30 m 6

A

14 m

C
Ceiling height: 3.05 m
The Software Package that will be used to perform this calculation is OZone. This Software package has been developed by the University of Liège (Cadorin-Franssen) and is available for free download on:

http://www.argenco.ulg.ac.be/logiciel.php
http://www.arcelormittal.com/sections
Boundaries

Typical floor will be chosen:

- Exterior walls : 20 cm of normal concrete

- Slab : 15 cm of Normal concrete

- Ceiling : 15 cm of normal concrete
**Boundaries**

Enter each layer on a single row in the table above (up to four layers). Just click in a cell and edit its value. If not found in the list of materials you can define your own material, by filling in the appropriate cells. Define your layers starting from Layer 1 (Inside).

Define your openings if any (up to three openings in a single wall). Click in the desired cell and input your values. Start from Opening 1.

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## Boundaries

### Layers and Openings Wall 1

<table>
<thead>
<tr>
<th>Wall Length:</th>
<th>m</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [cm]</th>
<th>Unit mass [kg/m²]</th>
<th>Conductivity [W/mK]</th>
<th>Specific Heat [J/kgK]</th>
<th>Rel Emissivity Hot Surface</th>
<th>Rel Emissivity Cold Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1 Normal weight Concrete [EN1994-1-2]</td>
<td>20</td>
<td>2300</td>
<td>1.6</td>
<td>1000</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<th>Sill Height Hi</th>
<th>Soffit Height Hs</th>
<th>Width</th>
<th>Variation</th>
<th>Adiabatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Opening Factors

This point is one critical point.

The Eurocode is not providing the scenario that must be chosen to take into account the openings.

Openings can be doors, windows and general « porosity » of the building.

If no opening is taken into account from the beginning of the fire, the amount of oxygen in the compartment will be too small and the fire will not develop.
Opening Factors

Here are some information to help for definition of the scenario for the breaking of the windows:

In the literature, it can be found that:

- Normal glazing will start to break with a $\Delta T$ of 40°C on the glass

- Tempered glazing will start to break with a $\Delta T$ of 120°C on the glass

- Tempered glazing with reinforcement will start to break with a $\Delta T$ of 120°C on the glass (The reinforcement will melt at 300°C)
Luxembourgish authorities have realized a guide that needs to be followed when FSE is used. This guide will become official soon. But here is some extract for the non fire resistant glazing:

- Scenario 1: 90% of the glazing is open since the beginning

- Scenario 2:
  - Simple glazing: 100°C : 50% and 250°C: 90%
  - Double glazing: 200°C : 50% and 400°C: 90%
  - Triple glazing: 300°C : 50% and 500°C: 90%
Opening Factors

Assumptions for the façade:

- Ex. 1: 0.8m open all around the building
- Ex. 2: 1.5m open all around the building
- Ex. 3: full glazing Façade
### Opening Factors Ex.1

**Layers and Openings Wall 1 - ECW_Ex1**

**Wall Length:** 14 m

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<tr>
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<tr>
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<td>1.2</td>
<td>2</td>
<td>14</td>
<td>Stepwise</td>
</tr>
<tr>
<td>Opening 2</td>
<td></td>
<td></td>
<td></td>
<td>no</td>
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### Opening Factors

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Opening Factors

Parameters - ECW_Ex1

- Openings:
  - Radiation Through Closed Openings: 0.8 (0 - 1)
  - Bernoulli Coefficient: 0.7

- Physical Characteristics of Compartment
  - Initial Temperature: 293 K
  - Initial Pressure: 100000 Pa

- Parameters of Wall Material
  - Convection Coefficient at the Hot Surface: 25 W/m²K
  - Convection Coefficient at the Cold Surface: 9 W/m²K

- Calculation Parameters
  - End of Calculation: 7200 sec
  - Time Step for Printing Results: 60 sec
  - Maximum Time Step for Calculation: 10 sec
  - Extended Results

- Air Entrained Model: Heskestad

- Temperature Dependent Openings
  - Temperature Dependent: 400 °C

- Stepwise Variation
  - Temperature | % of Total Openings
  - 20 | 5
  - 200 | 50
  - 400 | 90

- Linear Variation
  - Temperature | % of Total Openings
  - 20 | 10
  - 400 | 50
  - 500 | 100

- Time Dependent Openings
  - Time | % of Total Openings
  - 0 | 5
  - 1200 | 100
## Definition of the fire

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Fire Growth Rate</th>
<th>$RHR_f$ [kW/m²]</th>
<th>Fire Load $q_{f,k}$ 80% fractile [MJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>Medium</td>
<td>250</td>
<td>948</td>
</tr>
<tr>
<td>Hospital (room)</td>
<td>Medium</td>
<td>250</td>
<td>280</td>
</tr>
<tr>
<td>Hotel (room)</td>
<td>Medium</td>
<td>250</td>
<td>377</td>
</tr>
<tr>
<td>Library</td>
<td>Fast</td>
<td>500</td>
<td>1824</td>
</tr>
<tr>
<td><strong>Office</strong></td>
<td><strong>Medium</strong></td>
<td><strong>250</strong></td>
<td><strong>511</strong></td>
</tr>
<tr>
<td>School</td>
<td>Medium</td>
<td>250</td>
<td>347</td>
</tr>
<tr>
<td>Shopping Centre</td>
<td>Fast</td>
<td>250</td>
<td>730</td>
</tr>
<tr>
<td>Theatre (movie/cinema)</td>
<td>Fast</td>
<td>500</td>
<td>365</td>
</tr>
<tr>
<td>Transport (public space)</td>
<td>Slow</td>
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</table>
### Definition of the fire

#### Danger of Fire Activation

<table>
<thead>
<tr>
<th>Compartments floor area $A_f$ [m²]</th>
<th>Danger of Fire Activation $\delta_{q1}$</th>
<th>Danger of Fire Activation $\delta_{q2}$</th>
<th>Examples of Occupancies</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.10</td>
<td>0.78</td>
<td>Art gallery, museum, swimming pool</td>
</tr>
<tr>
<td>250</td>
<td>1.50</td>
<td>1.00</td>
<td>Residence, hotel, office</td>
</tr>
<tr>
<td>2500</td>
<td>1.90</td>
<td>1.22</td>
<td>Manufactory for machinery &amp; engines</td>
</tr>
<tr>
<td>5000</td>
<td>2.00</td>
<td>1.44</td>
<td>Chemical laboratory, Painting workshop</td>
</tr>
<tr>
<td>10000</td>
<td>2.13</td>
<td>1.66</td>
<td>Manufactory of fireworks or paints</td>
</tr>
</tbody>
</table>

#### Equation

$$q_{f,d} = \delta_{q1} \cdot \delta_{q2} \cdot \prod \delta_{ni} \cdot m \cdot q_{f,k}$$

#### Active Fire Safety Measures

<table>
<thead>
<tr>
<th>Automatic Water Extinguishing System</th>
<th>Independent Water Supplies</th>
<th>Automatic fire Detection &amp; Alarm by Heat $\delta_{n3}$</th>
<th>Automatic Alarm Transmission to Fire Brigade $\delta_{n5}$</th>
<th>Work Fire Brigade $\delta_{n6}$</th>
<th>Off Site Fire Brigade $\delta_{n7}$</th>
<th>Safe Access Routes $\delta_{n8}$</th>
<th>Fire Fighting Devices $\delta_{n9}$</th>
<th>Smoke Exhaust System $\delta_{n10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.61</td>
<td>1.0, 0.87, 0.7</td>
<td>0.87 or 0.73</td>
<td>0.87</td>
<td>0.61 or 0.78</td>
<td>0.9 or 1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
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</table>
Definition of the fire

Active Fire Fighting Measures:
- Automatic Water Extinguishing System: $\delta_{n,1} = 0.61$
- Independent Water Supplies (1, 2): $\delta_{n,2} = 1$
- Automatic Fire Detection by Heat: $\delta_{n,4} = 0.73$
- Automatic Fire Detection by Smoke: $\delta_{n,5} = 1$
- Automatic Alarm Transmission to Fire Brigade: $\delta_{n,6} = 1$
- Work Fire Brigade
- Off Site Fire Brigade
- Safe Access Routes: $\delta_{n,8} = 1$
- Staircases Under Overpressure in Fire Alarm
- Fire Fighting Devices: $\delta_{n,9} = 1$
- Smoke Exhaust System: $\delta_{n,10} = 1$

Fire Info:
- Max Fire Area: 420 m²
- Fire Elevation: 0 m
- Fuel Height: 0 m

Design Fire Load:
- Fire Risk Area: 420 m²
- Danger of Fire Activation: $\delta_{q,1} = 1.59$
- Active Measures: $\prod \delta_{n,i} = 0.4453$
- $q_{f,d} = \delta_{q,1} \cdot \delta_{q,2} \cdot \prod \delta_{n,i} \cdot q_{f,k} = 289.4$ MJ/m²

Combustion:
- Combustion Heat of Fuel: 17.5 MJ/kg
- Combustion Efficiency Factor: 0.8
- Combustion Model: Extended fire duration
- Stoichiometric Coefficient: 1.27
Results for 0.8m windows

Gas Temperature

Time [min]

Temperature [°C]

Analysis Name:

- Hot Zone
Results for 0.8m windows

Oxygen Mass

Analysis Name:
Results for IPE450

Steel Temperature

Analysis Name:
Opening Factors Ex. 2

Layer 1
- Material: Normal weight Concrete [EN1994-1-2]
- Thickness: 20 cm
- Unit mass: 2300 [kg/m²]
- Conductivity: 1.6 [W/mK]
- Specific Heat: 1000 [J/kgK]
- Rel. Emissivity: 0.8
- Hot Surface
- Cold Surface

Layer 2
Layer 3
Layer 4

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Results for 1.5m windows

Gas Temperature

Analysis Name: Hot Zone
Results for 1.5m windows

Oxygen Mass

- Analysis Name: Oxygen Mass
Results for IPE450

Steel Temperature

- **Hot Zone**
- **Steel**

Analysis Name:
Opening Factors Ex. 3

### Layers and Openings Wall 1 - ECW_Ex3

#### Wall Length: 14 m

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<th>Material</th>
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<td>0.65</td>
<td>2.85</td>
<td>14</td>
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Results for full windows

Gas Temperature

Time [min]

Temperature [°C]

Analysis Name:

Hot Zone
Results for full windows

Oxygen Mass

[Graph showing the change in oxygen mass over time with the y-axis labeled 'kg' and the x-axis labeled 'Time [min]']
Results for IPE450

Steel Temperature

Analysis Name:
Worked examples of EN1991-1-2

Fire part of Eurocode 1 : Localised Fire
Hasemi method for localised fires

EN 1991-1-2 : 2002; Annex C

Non-dimensional parameters:
\[ Q^*_{H} = Q / (1,11 \cdot 10^6 \cdot H^{2.5}) \]
\[ Q^*_{D} = Q / (1,11 \cdot 10^6 \cdot D^{2.5}) \]
\[ y = \frac{r + H + z'}{L_h + H + z'} \]

Horizontal length on the ceiling:
\[ L_h = \left(2.9 \cdot H \cdot (Q^*_{H})^{0.33}\right) - H \]

Virtual vertical coordinate:
\[ z' = 2.4 \cdot D \cdot \left( Q^*_{D}^{2/5} - Q^*_{D}^{2/3} \right) \text{ when } Q^*_{D} < 1.0 \]
\[ z' = 2.4 \cdot D \left(1.0 - Q^*_{D}^{2/5}\right) \text{ when } Q^*_{D} \geq 1.0 \]

Heat flux:
\[ \dot{h} = 100 \, 000 \quad \text{if } y \leq 0.30 \]
\[ \dot{h} = 136 \, 300 \text{ to } 121 \, 000 \, y \quad \text{if } 0.30 < y < 1.0 \]
\[ \dot{h} = 15 \, 000 \, y^{3.7} \quad \text{if } y \geq 1.0 \]

Net Heat flux:
\[ \dot{h}_{\text{net}} = \dot{h} - \alpha_c \cdot (\Theta_m - 20) - \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot \left[ (\Theta_m + 273)^4 - (293)^4 \right] \]
Localised fire parameters

Building: Car park Auchan, Luxembourg
Type: Underground car park
Height: \( H = 2.7 \text{ m} \)
Horizontal distance from flame axis to beam: \( r = 0.0 \text{ m} \)
Diameter of flame: \( D = 2.0 \text{ m} \)
Steel Beam: IPE 550
Localised fire
Static system and section of the beam

16.8 m

IPE 550

b_{eff}

h_c

2.0 m
Localised fire Hypothesis

Diameter of the fire: \( D = 2.0 \text{ m} \)

Vertical distance between fire source and ceiling: \( H = 2.7 \text{ m} \)

Horizontal distance between beam and flame axis: \( r = 0.0 \text{ m} \)

Emissivity of the fire: \( \varepsilon_f = 1.0 \)

Configuration factor: \( \Phi = 1.0 \)

Stephan Boltzmann constant: \( \sigma = 5.67 \cdot 10^{-8} \text{ W/m}^2\text{K}^4 \)

Coefficient of the heat transfer: \( \alpha_c = 25.0 \text{ W/m}^2 \)

Steel profile: IPE 550

Section factor: \( \frac{A}{V} = 140.1/\text{m} \)

Unit mass: \( \rho_a = 7850 \text{ kg/m}^3 \)

Surface emissivity: \( \varepsilon_m = 0.7 \)
Localised fire
Rate of Heat Release

Curve of the rate of heat release of one car

From ECSC project: Development of design rules for steel structures subjected to natural fires in closed car parks.
\[ L_f = -1.02 \cdot D + 0.0148 \cdot Q^{2/5} = -2.04 + 0.0148 \cdot Q^{2/5} \]

if \( L_r \geq H \)  \( \implies \) Model A has to be used

if \( L_r < H \)  \( \implies \) Model B has to be used
1st case: The flame is not impacting the ceiling

The net heat flux is calculated according to Section 3.1 of EN 1991-1-2.

\[
\dot{h}_{net} = \alpha_c \cdot (\theta_{(z)} - \theta_m) + \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot \left( (\theta_{(z)} + 273)^4 - (\theta_m + 273)^4 \right) \\
= 25.0 \cdot (\theta_{(z)} - \theta_m) + 3.969 \cdot 10^{-8} \cdot \left( (\theta_{(z)} + 273)^4 - (\theta_m + 273)^4 \right)
\]
1st case: The flame is not impacting the ceiling

The gas temperature is calculated to:

\[ \theta(z) = 20 + 0.25 \cdot (0.8 \cdot Q)^{2/3} \cdot (z - z_0)^{-5/3} \leq 900 \, ^\circ C \]

\[ = 20 + 0.25 \cdot (0.8 \cdot Q)^{2/3} \cdot (4.74 - 0.0052 \cdot Q^{2/5})^{-5/3} \leq 900 \, ^\circ C \]

where:

- \( z \) is the height along the flame axis (2.7 m)
- \( z_0 \) is the virtual origin of the axis [m]

\[ z_0 = -1.02 \cdot D + 0.0052 \cdot Q^{2/5} = -2.04 + 0.0052 \cdot Q^{2/5} \]
2\textsuperscript{nd} case: The flame is impacting the ceiling

Net heat flux, if the flame is impacting the ceiling, is given by:

\[
\dot{h}_{\text{net}} = \dot{h} - \alpha_c \cdot (\theta_m - 20) - \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot \left( (\theta_m + 273)^4 - (293)^4 \right) \\
= \dot{h} - 25.0 \cdot (\theta_m - 20) - 3.969 \cdot 10^{-8} \cdot \left( (\theta_m + 273)^4 - (293)^4 \right)
\]
2nd case:
The flame is impacting the ceiling

The heat flux depends on the parameter $y$. For different dimensions of $y$, different equations for determination of the heat flux have to be used.

if $y \leq 0.30$: \[ \dot{h} = 100,000 \]

if $0.30 < y < 1.0$: \[ \dot{h} = 136,300 - 121,000 \cdot y \]

if $y \geq 1.0$: \[ \dot{h} = 15,000 \cdot y^{-3.7} \]

where: \[ y = \frac{r + H + z'}{L_h + H + z'} = \frac{2.7 + z'}{L_h + 2.7 + z'} \]
2\textsuperscript{nd} case:  The flame is impacting the ceiling

\[ y = \frac{r + H + z'}{L_h + H + z'} = \frac{2.7 + z'}{L_h + 2.7 + z'} \]

The horizontal flame length is calculated by:

\[ L_h = \left(2.9 \cdot H \cdot \left(Q_H^*\right)^{0.33}\right) - H = \left(7.83 \cdot \left(Q_H^*\right)^{0.33}\right) - 2.7 \]

where:

\[ Q_H^* = \frac{Q}{\left(1.11 \cdot 10^6 \cdot H^{2.5}\right)} = \frac{Q}{\left(1.11 \cdot 10^6 \cdot 2.7^{2.5}\right)} \]

The vertical position of the virtual heat source is determined by:

if \( QD^* < 1.0 \):

\[ z' = 2.4 \cdot D \cdot \left(\left(Q_D^*\right)^{2/5} - \left(Q_D^*\right)^{2/3}\right) = 4.8 \cdot \left(\left(Q_D^*\right)^{2/5} - \left(Q_D^*\right)^{2/3}\right) \]

if \( QD^* \geq 1.0 \):

\[ z' = 2.4 \cdot D \cdot \left(1.0 - \left(Q_D^*\right)^{2/5}\right) = 4.8 \cdot \left(1.0 - \left(Q_D^*\right)^{2/5}\right) \]

where:

\[ Q_D^* = \frac{Q}{\left(1.11 \cdot 10^6 \cdot D^{2.5}\right)} = \frac{Q}{\left(1.11 \cdot 10^6 \cdot 2.0^{2.5}\right)} \]
Temperature-time curve for the unprotected steel beam:

\[ \theta_{a,t} = \theta_m + k_{sh} \cdot \frac{A_m}{V} \cdot \frac{A_v}{c_a \cdot \rho_a} \cdot h_{net} \cdot \Delta t = \theta_m + \frac{1.78 \cdot 10^{-2}}{c_a} \cdot h_{net} \]

\[ \theta_{a,\text{max}} = 770 \, ^\circ\text{C} \]

at \( t_{\theta,\text{max}} = 31.07 \, \text{min} \)
Localised fire
Steel temperatures

Temperature-time curve for the unprotected steel beam:

\[ \theta_{a,t} = \theta_m + k_{sh} \cdot \frac{A_m/V}{c_a \cdot \rho_a} \cdot h_{net} \cdot \Delta t = \theta_m + \frac{1.78 \cdot 10^{-2}}{c_a} \cdot h_{net} \]

\[ \theta_{a,max} = 770 \, ^\circ C \]

at \( t_{\theta,max} = 31.07 \, \text{min} \)
### Position of the calculated point(s)

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<th>X [m]</th>
<th>Y [m]</th>
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**Position of the car(s)**

- **CAR 1**: 0 [m], 0 [m]
- **CAR 2**: 1 [m], 0 [m]
- **CAR 3**: 2 [m], 0 [m]
- **CAR 4**: 3 [m], 0 [m]
- **CAR 5**: 4 [m], 0 [m]

### CAR 1

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### CAR 5

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### Excel Spreadsheet Capafi

**Position of the calculated point(s)**

- **X [m]**
- **Y [m]**

**Position of the car(s)**

- **CAR 1**: 0 [m], 0 [m]
- **CAR 2**: 1 [m], 0 [m]
- **CAR 3**: 2 [m], 0 [m]
- **CAR 4**: 3 [m], 0 [m]
- **CAR 5**: 4 [m], 0 [m]

**Parameters**

- \(H_r = 3.000\) m
- \(H_o = 0.001\) m
- \(H_s = 0.300\) m
- **Coeff beam** = 1.000
- Fire diam D = 2.000 m
- \(A_m/V = 140.1\) m³
- \(A_w/V (box) = 130\) m³
- \(\rho_s = 7850\) kg/m³
- \(\alpha = 25\) W/m²K
- \(\varepsilon = 0.7\)
Worked examples of EN1991-1-2

Example of Application of buildings calculated with Natural Fire Safety Concept
Switzerland

Braun Building in Crissier
Production of Medical Material
Switzerland

BOBST Building in Lausanne
Offices + Production
Congress centre of EPFL in Lausanne
Crédit Suisse / HRS / Richter-Dahl&Rocha
France

Car park of Toulouse Blagnac Airport
Belgium

Greich Office Building in Liège
BARREIRO RETAIL PARK

Portugal
Portugal

Exhibition Center
IKEA shopping center in Lefkosa
Heron Tower – Arup Fire London
Fonds du Logement, 17 rue de Hollerich à Luxembourg Ville
Shopping centre
Residential
Chambre de Commerce Luxembourg
Office Building
Dexia-Bil in Esch sur Alzette
Office Building
Luxembourg

ArcelorMittal Office Building in Esch sur Alzette
ArcelorMittal Office Building in Esch sur Alzette
Thank you for your attention

... QUESTIONS?