Building component exposure feature in Argos

- 1D heat transfer module in Argos

-User guide

-Theory manual

-Validation report

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User guide

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Table of contents

1. Using the building component exposure feature

This description of the heat transfer module is divided into 3 parts.

User Guide. How to use the module **(this document)**
Theory manual. Theoretical background for the module
Validation report. Validation of the heat transfer module

Note:
The heat transfer coefficient (h) is another name for the film coefficient used in the parameters menu in Argos.

2. Objective

The new heat transfer module was developed to enable 1-dimensional analyses of temperature or radiation exposure on a building component to be performed.

Areas where the new exposure module can be used

- Ignition of surfaces caused by radiation, see Figure 1
- Calculation of the required amount of fire protective cladding
- Calculation of the temperature of steel bars in concrete
- Simulation of the ISO standard fire test curve on a building component
- Simulation of a cone calorimeter test

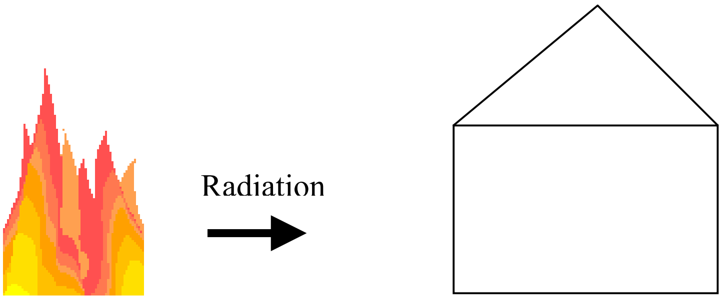


Figure 1 Radiation from a fire on to a building

3. New exposure curves in the fire menu

There are 2 types of exposure, which can be applied to either side of a building component.

- Constant temperature
- Dynamic Exposure
    - Time temperature curve
    - Time radiation curve

Constant temperature gives a constant temperature in the surrounding air for the whole duration of the exposure and is entered directly in the exposure screen, see page 8.

The dynamic exposure gives either a varying time temperature curve or a time varying radiation curve. Two new types of curves have been added under the Fire menu in the left panel, Figure 4 and Figure 5, so that the user can input varying time curves.

A number of standard fire curves and radiation curves have been added for your convenience, but the user can always add more curves.

3.1. Time temperature curves

A total of 5 preset time temperature curves have been added.

The new time temperature curves are:
- External fire exposure curve (EN 1363-2)
- Hydrocarbon curve (EN 1363-2)
- ISO 834 standard heating curve (EN 1363-1)
- RABT (Germany)
- RWS tunnel lining curve (The Netherlands)

The first three curves are defined by functions. However, in Argos, for simplicity, the interface only accepts data points (e.g. a time and a temperature). Therefore these continuous functions have been transcribed as discrete points, see Figure 2, and with sufficient accuracy that the difference between the integral of the curves for the continuous functions and the discrete functions is less than 0.3 %. This difference or error is equal to the area between the two curves in Figure 2.

It is a normal requirement in performing a fire test that the allowed percentage deviation in the area of the curve of the average temperature recorded versus time and the area of the specified temperature-time curve may vary between limits of 2.5 and 15 %, see EN1363-1 and EN1363-2. The difference of 0.3% between the two data curves is thus considered negligible.

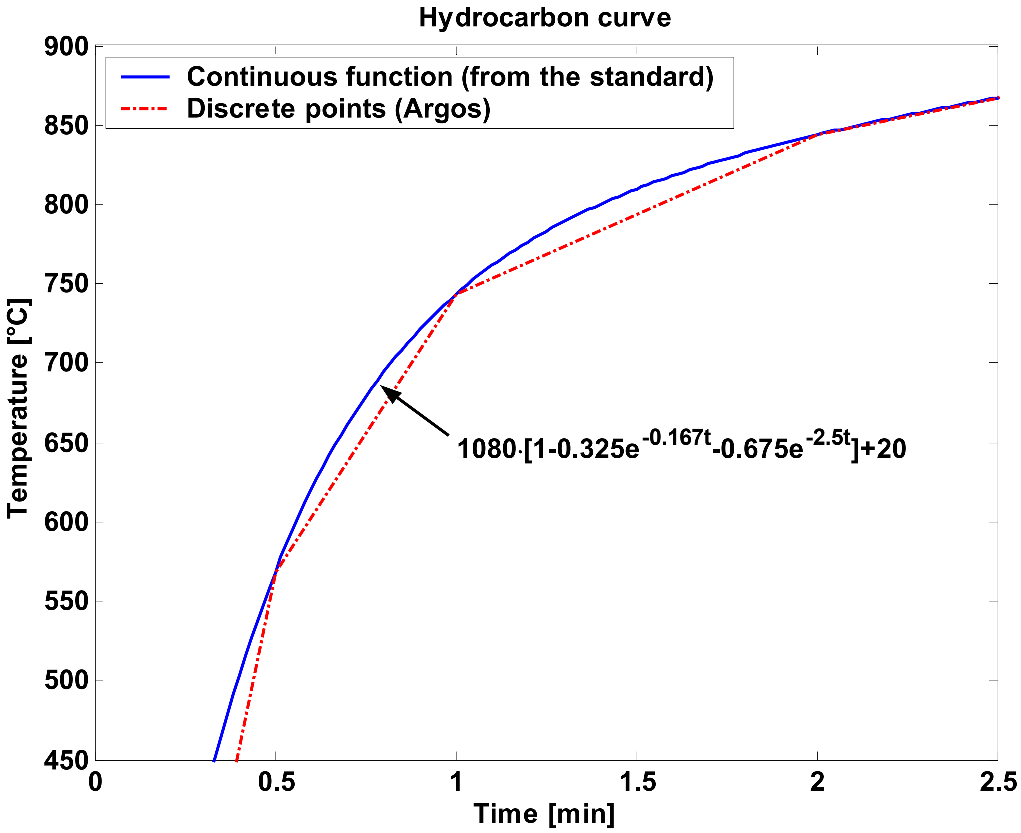


Figure 2 Turning the hydrocarbon curve into discrete points

The last two curves are for tunnels. The RABT curve ("Richtlinien für die Ausstattung und den Betrieb von Straßentunneln" is a German tunnel fire curve, which with small modifications is also used in France and Japan. Please note that the RABT curve given here remains at 1200 °C for 30 minutes. If required, for specific types of exposure, the heating period can be extended to 60 minutes or more.

The RWS tunnel lining curve (Rijkswaterstaat, Ministry of Transport in the Netherlands) is a tunnel fire curve, which is used to test tunnel linings in the Netherlands. This curve is the most severe of all test curves, Figure 3.

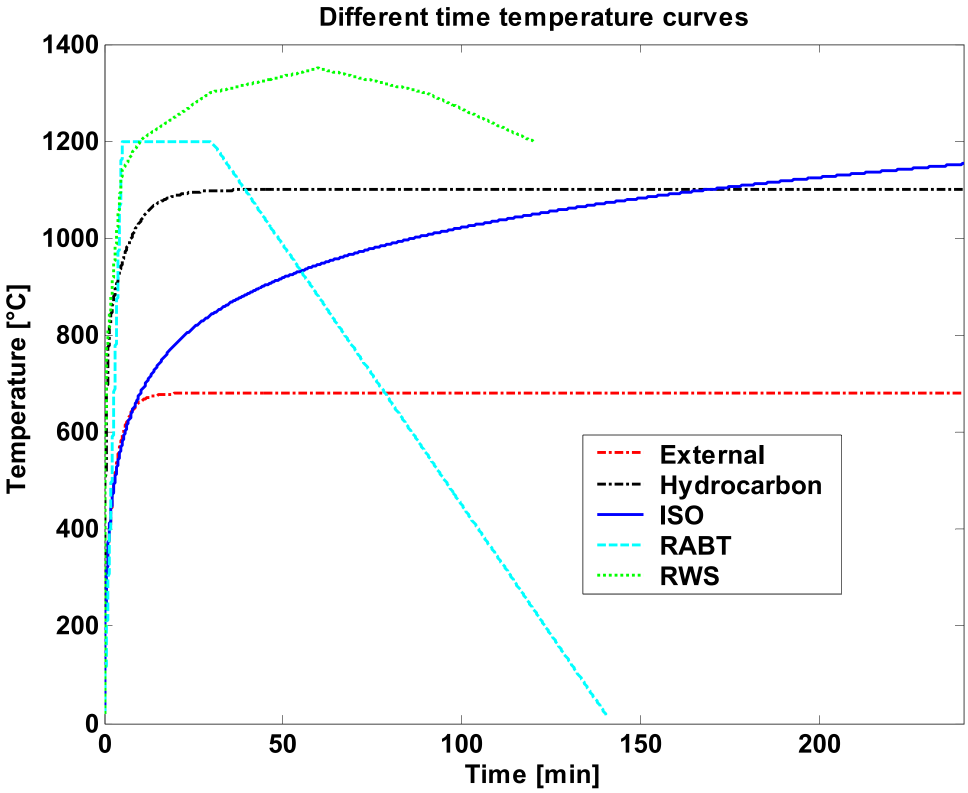
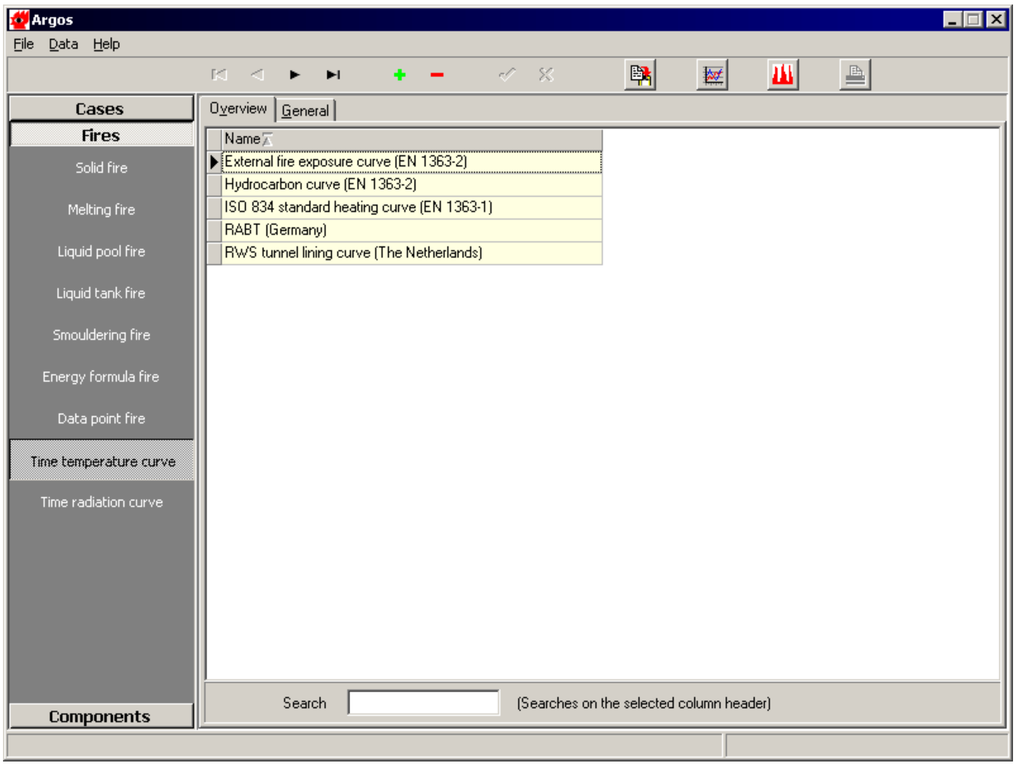


Figure 3 Time temperature curves in Argos



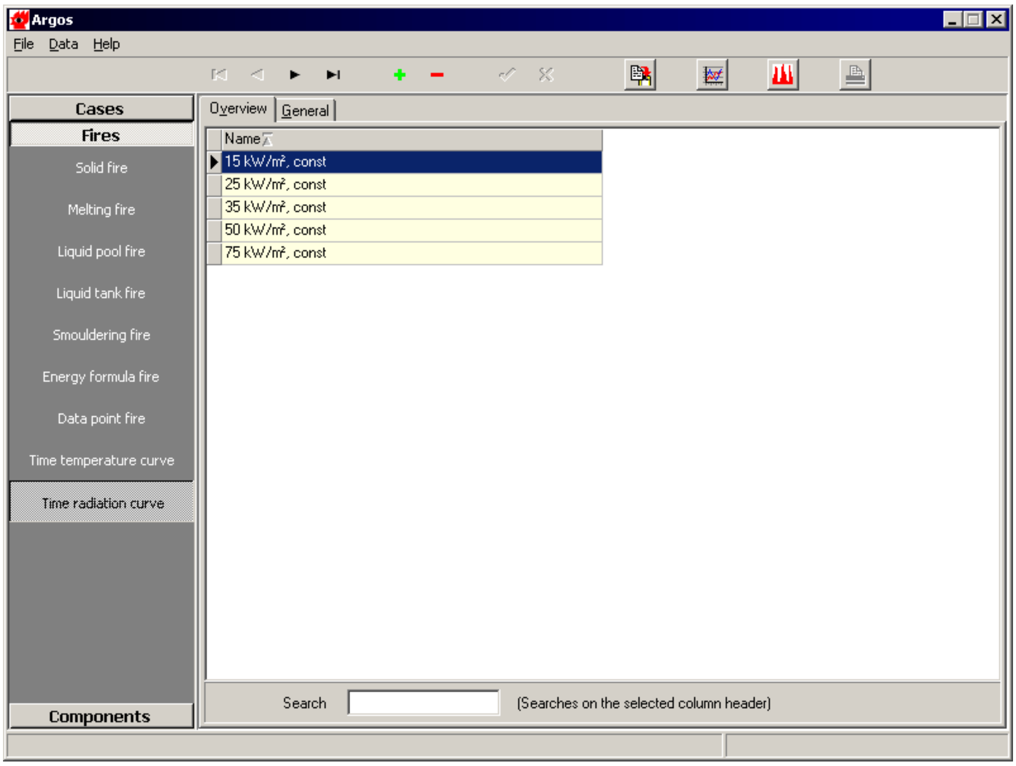
Name
External fire exposure curve (EN 1363-2)
Hydrocarbon curve (EN 1363-2)
ISO 834 standard heating curve (EN 1363-1)
RABT (Germany)
RWS tunnel lining curve (The Netherlands)

Figure 4 Time temperature curves have been added to the fire menu

3.2. Time radiation curves

A number of time radiation curves have also been added to Argos. The preset curves all give constant radiation for 1 hour at different levels, Figure 5. These different levels could be used to simulate a cone calorimeter test.

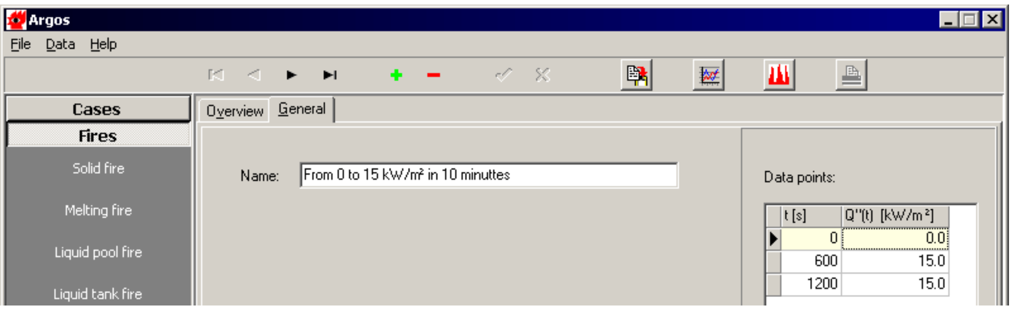
- 15 kw/m^2
- 25 kw/m^2
- 35 kw/m^2
- 50 kw/m^2
- 75 kw/m^2



Name
15 kW/m^2, const
25 kW/m^2, const
35 kW/m^2, const
50 kW/m^2, const
75 kW/m^2, const

Figure 5 Time radiation curves have been added to the fire menu

Insert a new curve by clicking on the insert button (green plus sign). Below is a curve, where the radiation increase from 0 to 15 kW/m^2 in 10 minutes and then stays at that level for a further 10 minutes, Figure 6.



Name: From 0 to 15 kW/m^2 in 10 minuttes

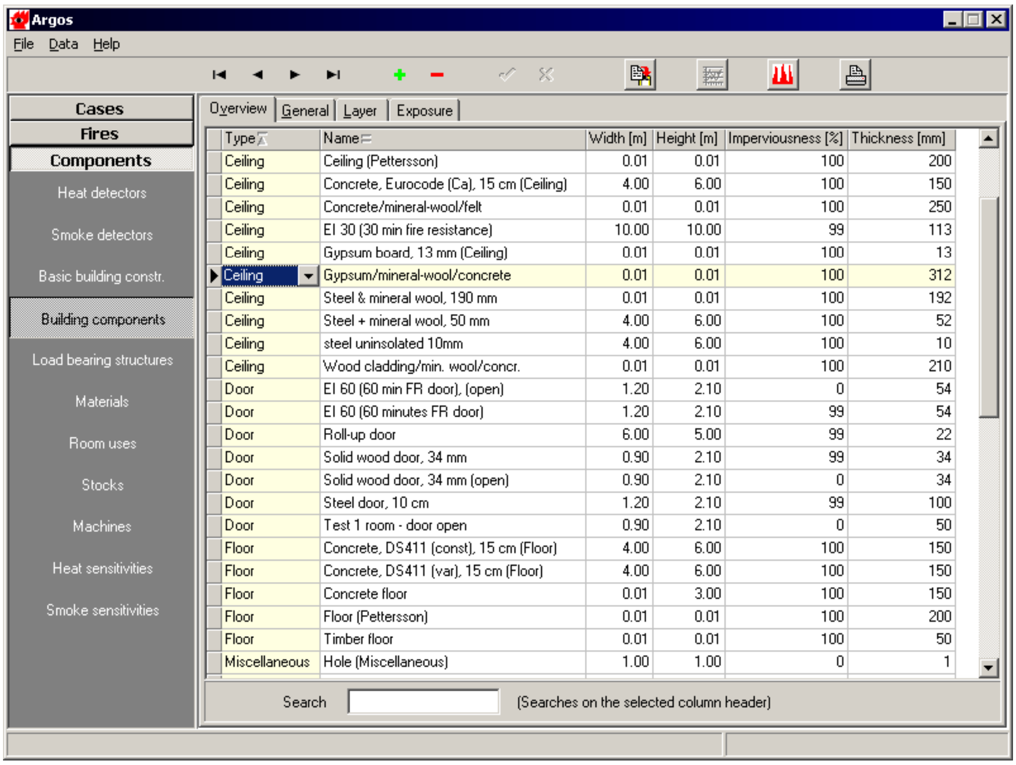
Data points:

t [s]	Q''(t) [kW/m^2]
0	0.0
600	15.0
1200	15.0

Figure 6 Example of varying time radiation data point set

4. Procedure

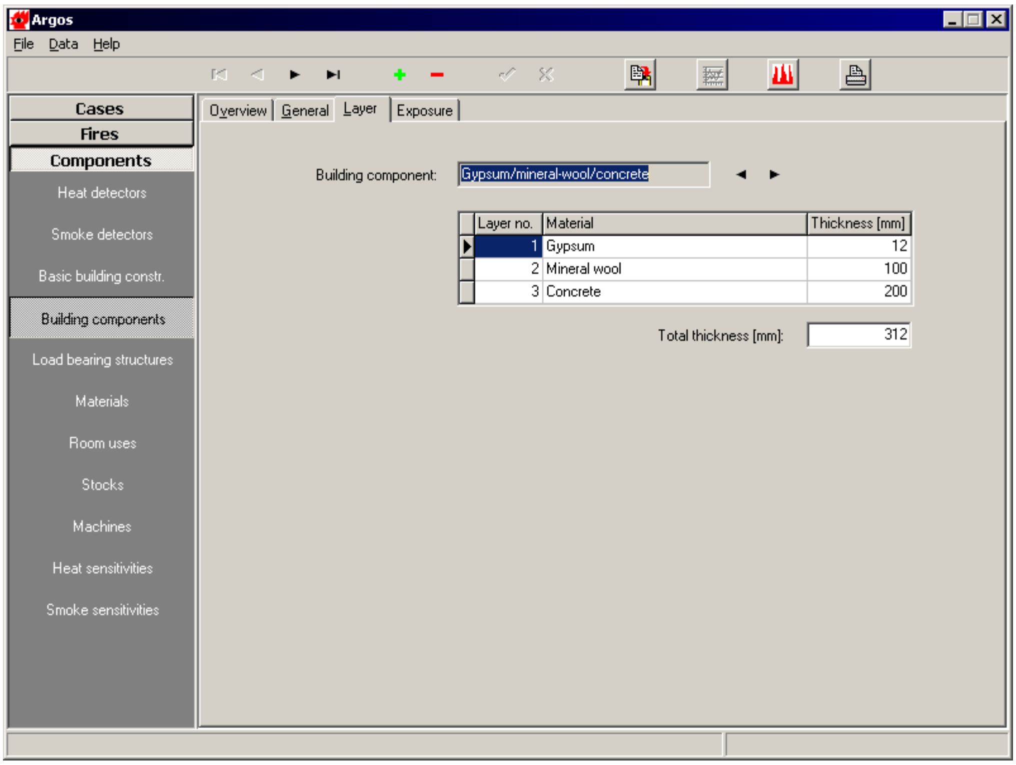
In order to expose a building component in Argos, first click on the Components tab in the left menu. Then click on Building components. The picture below is then seen, Figure 7.



Type	Name	Width [m]	Height [m]	Imperviousness [%]	Thickness [mm]
Ceiling	Ceiling (Pettersson)	0.01	0.01	100	200
Ceiling	Concrete, Eurocode (Ca), 15 cm (Ceiling)	4.00	6.00	100	150
Ceiling	Concrete/mineral-wool/felt	0.01	0.01	100	250
Ceiling	EI 30 (30 min fire resistance)	10.00	10.00	99	113
Ceiling	Gypsum board, 13 mm (Ceiling)	0.01	0.01	100	13
Ceiling	Gypsum/mineral-wool/concrete	0.01	0.01	100	312
Ceiling	Steel & mineral wool, 190 mm	0.01	0.01	100	192
Ceiling	Steel + mineral wool, 50 mm	4.00	6.00	100	52
Ceiling	steel uninsolated 10mm	4.00	6.00	100	10
Ceiling	Wood cladding/min. wool/concr.	0.01	0.01	100	210
Door	EI 60 (60 min FR door), (open)	1.20	2.10	0	54
Door	EI 60 (60 minutes FR door)	1.20	2.10	99	54
Door	Roll-up door	6.00	5.00	99	22
Door	Solid wood door, 34 mm	0.90	2.10	99	34
Door	Solid wood door, 34 mm (open)	0.90	2.10	0	34
Door	Steel door, 10 cm	1.20	2.10	99	100
Door	Test 1 room - door open	0.90	2.10	0	50
Floor	Concrete, DS411 (const), 15 cm (Floor)	4.00	6.00	100	150
Floor	Concrete, DS411 (var), 15 cm (Floor)	4.00	6.00	100	150
Floor	Concrete floor	0.01	3.00	100	150
Floor	Floor (Pettersson)	0.01	0.01	100	200
Floor	Timber floor	0.01	0.01	100	50
Miscellaneous	Hole (Miscellaneous)	1.00	1.00	0	1

Figure 7 Building components overview

Clicking on the Layer tab shows how the building component is constructed.



Building component: Gypsum/mineral-wool/concrete

Layer no.	Material	Thickness [mm]
1	Gypsum	12
2	Mineral wool	100
3	Concrete	200

Total thickness [mm]: 312

Figure 8 Layers in a building component

The layer with the lowest number is at the left (see Figure 9 and Figure 10) and any combination of numbering can be used. Using numbers in succession, such as 1 2 3, is recommended, as this makes interpretation easier. For a room simulation, the lowest layer numbers corresponds to the material at the lower ceiling surface and the highest number to the material at the upper ceiling surface.

Gypsum/mineral-wool/concrete

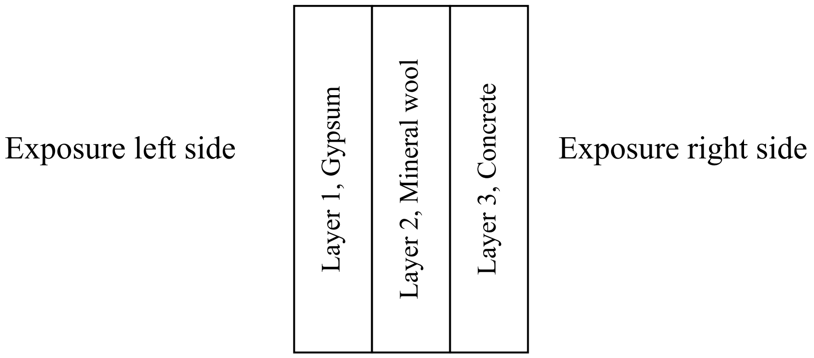
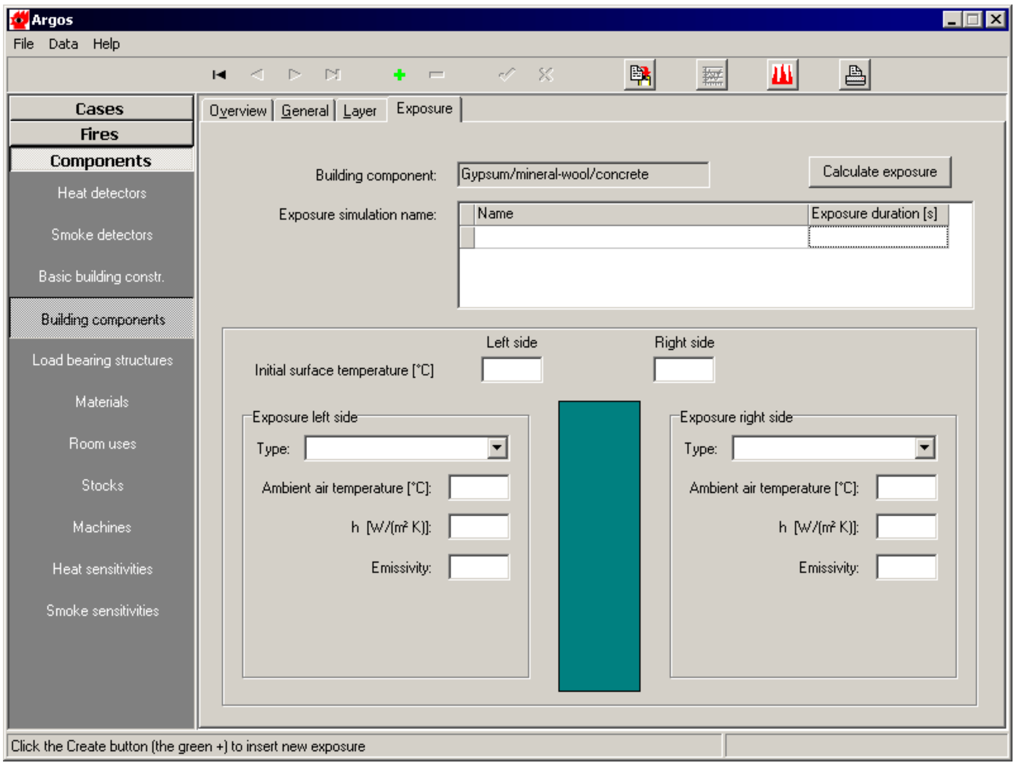


Figure 9 Layers in a building component

This means that gypsum is the layer to the left and concrete the layer to the right. Setting the layer number of Gypsum to 4 would move gypsum to being the material on the right and mineral wool to being the material on the left.



Building component: Gypsum/mineral-wool/concrete

Click the Create button (the green +) to insert new exposure

Figure 10 Initial exposure tab before an exposure is added

Several different exposures can be coupled to the same object.

There are 2 types of exposure, which can be applied to either side of a building component.

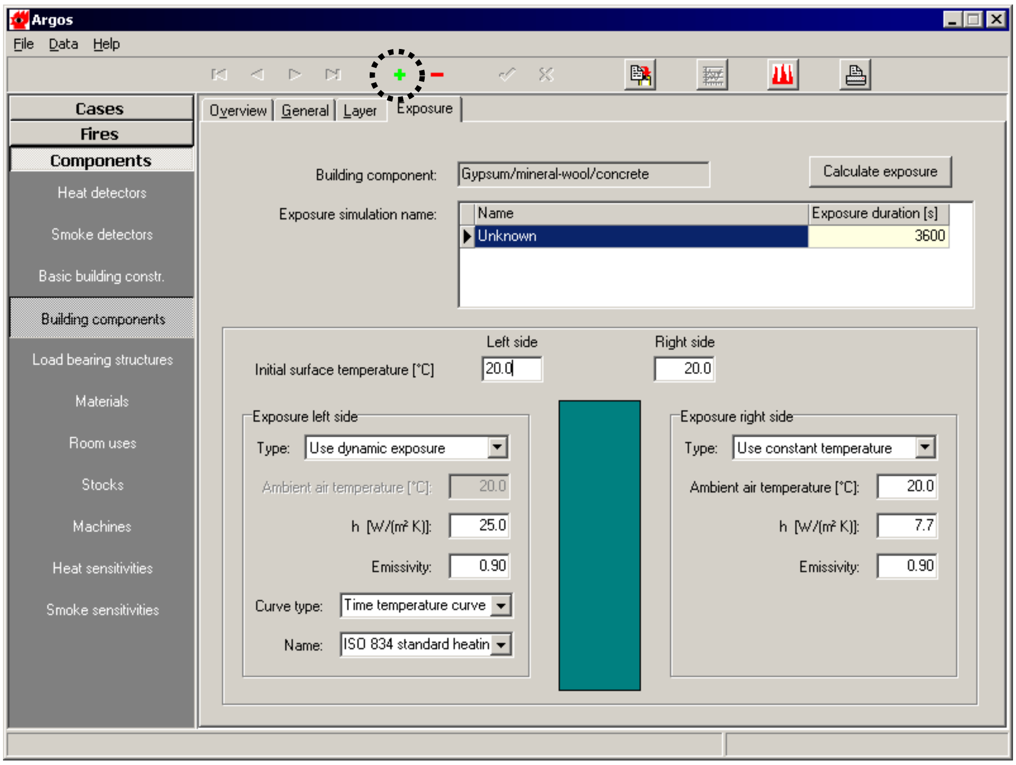
- Constant temperature

- Dynamic Exposure
  - Time temperature curve
  - Time radiation curve

Constant temperature gives a constant temperature in the surrounding air for the whole duration of the exposure. This exposure type is often used on the cold side of a component, where dynamic exposure is used on the hot side of the component.

4.1. Time temperature curve exposure

In order to insert a new exposure on a building component, click the green “+” sign, Figure 11. This will subject the left side to the ISO 834 standard heating curve (dynamic) with a constant temperature of 20°C on the right side (default setup).



Building component: Gypsum/mineral-wool/concrete

Exposure simulation name:

Name	Exposure duration [s]
Unknown	3600

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side
Type: Use dynamic exposure
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 25.0
Emissivity: 0.90
Curve type: Time temperature curve
Name: ISO 834 standard heatin

Exposure right side
Type: Use constant temperature
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 7.7
Emissivity: 0.90

Figure 11 Insert a new exposure by clicking the green “+” sign

The above setup is typical for simulation of an oven test, where one side is exposed to the fire and the other side is exposed to the cold surroundings.

4.2. Viewing and export of the results from the exposure calculation

To calculate the exposure, click on the “Calculate exposure” button.

This will calculate the exposure for the duration given in “Exposure duration” and give the graph shown in Figure 12. The graph shows the temperature profile across the building component after 10 different times. The left side is at 0 mm and the right side is at the total thickness of the component, in this case 312 mm. It can been seen from Figure 12 that the temperature has increased in the first 2 layers, gypsum and mineral wool, but the concrete in the third layer is still cold.

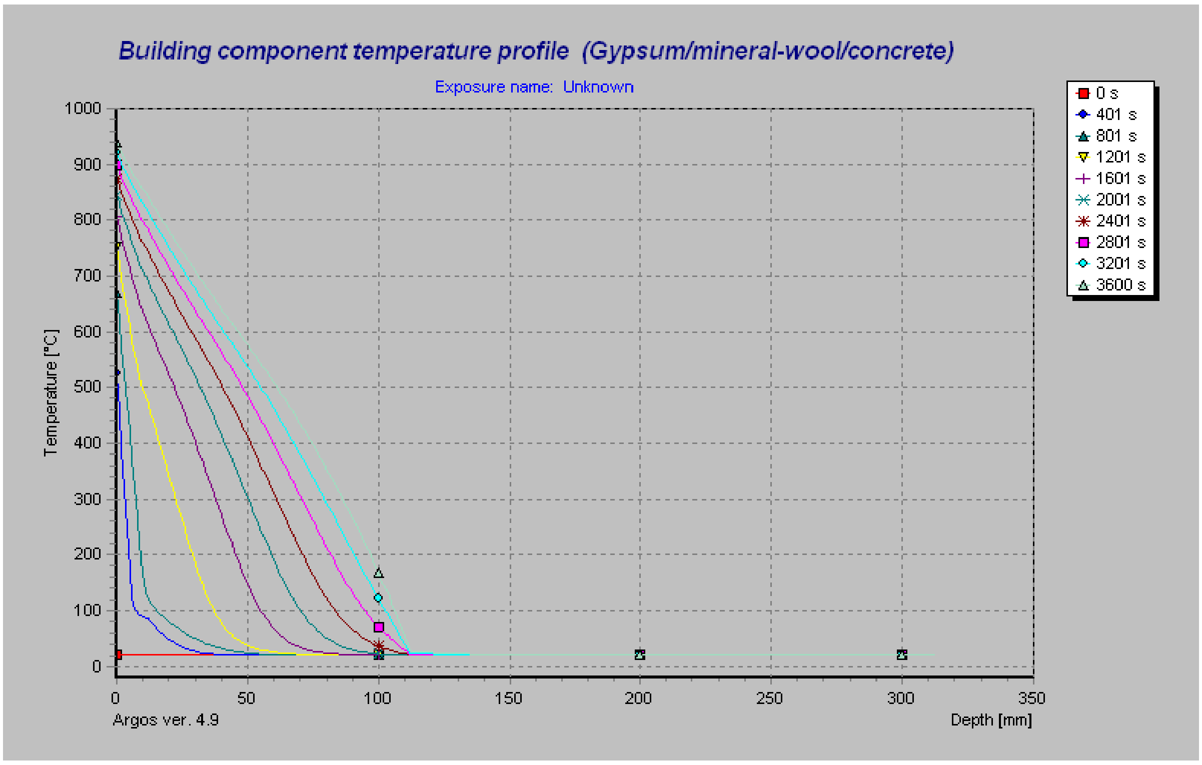


Figure 12 Result of exposure calculation

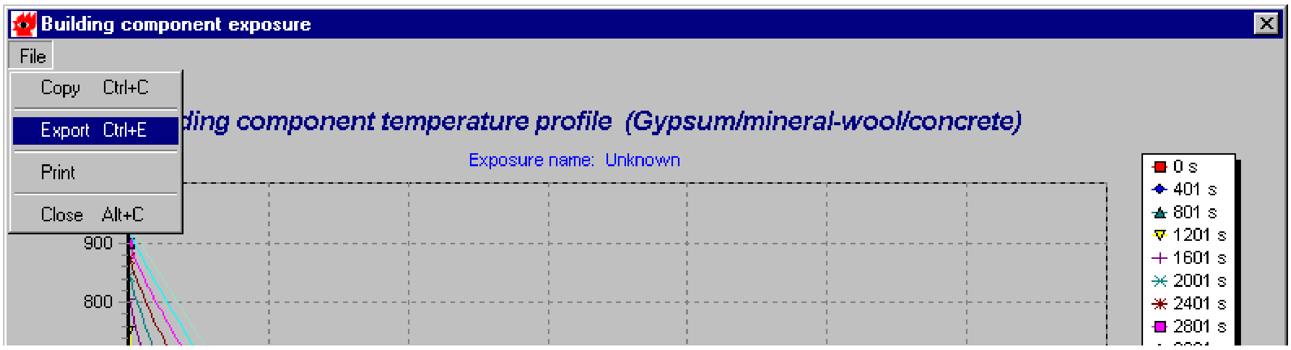


Figure 13 Exporting results from exposure calculation

To export the simulation results to a text file for further processing in Excel or similar, click **Export** in the file menu, Figure 13. Clicking **Export** in the file menu asks for the preferred minimum period between the displayed time steps. The default value is 60 seconds and the minimum value is 1 second.

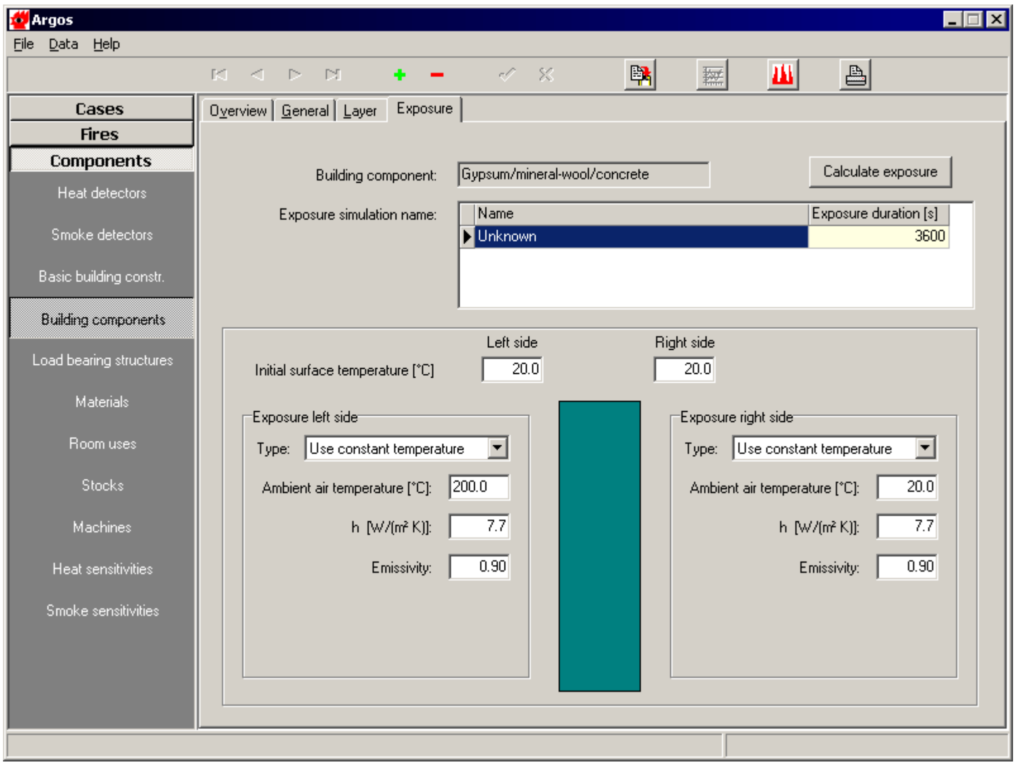
The exported data is saved to a tab separated text file which can be imported into Excel or similar programs. The location of the file is .\argos\export and the file is given the extension ".txt". To import the file into Excel, click **Open** in the File menu in Excel and change the file type to "text files". Find your exported file with the ".txt" extension in the export directory, click Open and then click Finish.

Note: If the component is more than 256 mm thick, Excel can not import all data, as the maximum number of columns in Excel is 256. During the import in Excel use the feature "Do not import this column". Alternatively, use a program such as Matlab, which does not have this limitation.

4.3. Constant temperature exposure on both sides

Constant temperature on both sides can also be used, such as in the example below, Figure 14, where the left side is subjected to an air temperature of 200 °C and the right side to an air temperature of 20 °C, for a total time of 1 hour (3600 seconds).

The calculation is performed by clicking on the “Calculate exposure” button.



Building component: Gypsum/mineral-wool/concrete

Exposure simulation name:

Name	Exposure duration [s]
Unknown	3600

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side
Type: Use constant temperature
Ambient air temperature [°C]: 200.0
h [W/(m² K)]: 7.7
Emissivity: 0.90

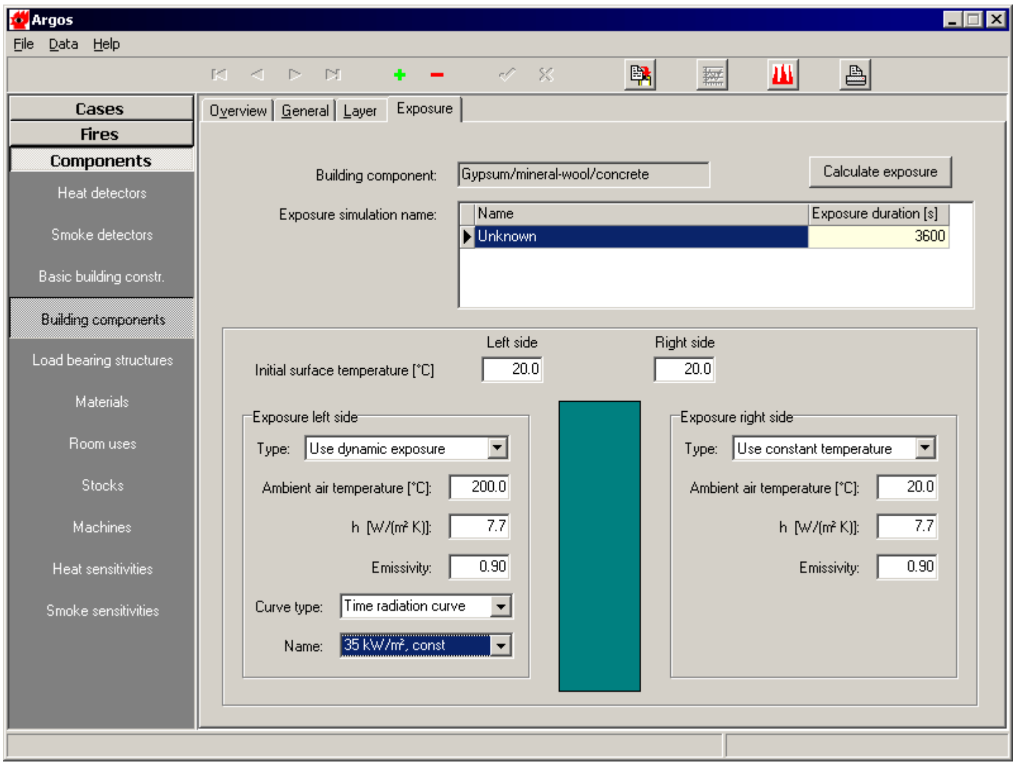
Exposure right side
Type: Use constant temperature
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 7.7
Emissivity: 0.90

Figure 14 Constant temperatures on both sides of a component

4.4. Time radiation curve exposure

Another combination is to use the time radiation curve on the left side and a constant temperature on the right side, see Figure 15. Here the time radiation curve is the predefined 35 kW/m^2 constant curve.

This kind of setup is useful if a component is subjected to radiation in the open or in a large room, where the air is cold.



Building component: Gypsum/mineral-wool/concrete

Exposure simulation name:

Name	Exposure duration [s]
Unknown	3600

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side
Type: Use dynamic exposure
Ambient air temperature [°C]: 200.0
h [W/(m^2 K)]: 7.7
Emissivity: 0.90
Curve type: Time radiation curve
Name: 35 kW/m^2, const

Exposure right side
Type: Use constant temperature
Ambient air temperature [°C]: 20.0
h [W/(m^2 K)]: 7.7
Emissivity: 0.90

Figure 15 Radiation on the left side of the component

4.5. Initial surface temperature

The default temperature of the component at the start is 20 °C, but this can also be changed by the user, in the two fields called initial surface temperature left side and initial surface temperature right side. These two fields are just above the dark green box, symbolising the wall, as shown in Figure 15

The program performs a steady state simulation of the temperature based on these two surface temperatures, before the transient (time dependent) simulation is started. For example, setting the initial surface temperature at the left side to 30 °C and at the right side to 20 °C, gives a straight temperature line through a material consisting of just 1 layer.

5. Heat transfer coefficient

The heat transfer coefficient between a fluid (air) and a solid component is dependent on a number of factors. One factor is the velocity of the fluid, which is further dependant on whether or not convection is free or forced. The temperature of the fluid and of the solid also play an important role. Argos uses constant default values for the heat transfer coefficient but in some cases it could be desirable to use other figures.

The purpose of this chapter is to illustrate how the heat transfer coefficient can vary based on geometry and temperature of the component.

The default values for the heat transfer coefficient are given in the table below. The default values can be changed in the parameters menu in Argos.

	h [$W/(m^2 K)$]
Constant temperature, wall hotter than air	7.7
Time temperature curve, air hotter than wall	25
Time radiation curve, wall hotter than air	7.7

For the time temperature curve, a default value of 25 $W/(m^2 K)$ is used on the hot side. A high value of h gives a more conservative prediction of the wall temperature, where the hot air will heat up the wall faster when the heat transfer coefficient is high. Furthermore the value of 25 $W/(m^2 K)$ is a standard value, used when doing simulations of fire tests in an oven.

For the time radiation calculation, the surrounding air will often be cold compared to the wall. This is also the case for the cold side of a wall in an oven test. Here the cold air will lower the temperature of the wall. Therefore setting h to a lower value gives a more conservative estimation of the wall temperature. A heat transfer coefficient of 7.7 $W/(m^2 K)$ is used as a default value in Argos, but the user can change this figure.

5.1. Heat transfer coefficient for free convection

The time radiation curve could be used to predict ignition of a surface far removed from the fire. This could be a fire in the open, where you want to estimate if a nearby building can be ignited, Figure 16.

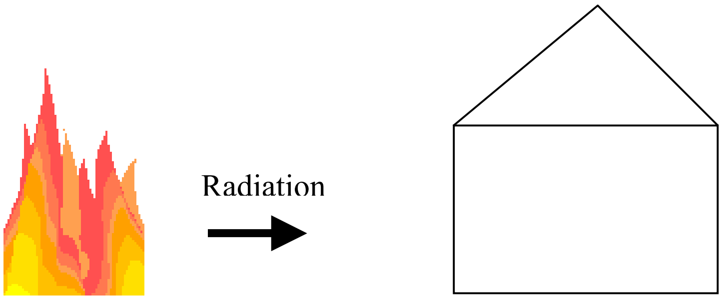


Figure 16 Radiation from a fire on to a building

The radiation from the fire will impact the vertical wall and the roof. Assuming there is no wind, only free convection will take place at the surface. A number of empirical formulas exist based on the Grashof number. Calculation of the heat transfer coefficient on a vertical and inclined plate and a horizontal plate have been done, based on the formulas given in **Kanury**. A characteristic length of 2 m has been used in both cases, Figure 17 and Figure 18.

It can been seen from Figure 17 that the heat transfer coefficient is equal to 9 W/(m^2 K) for a vertical plate at 300 °C, but at an angle of 60° the heat transfer coefficient at the same temperature is about 7 W/(m^2 K).

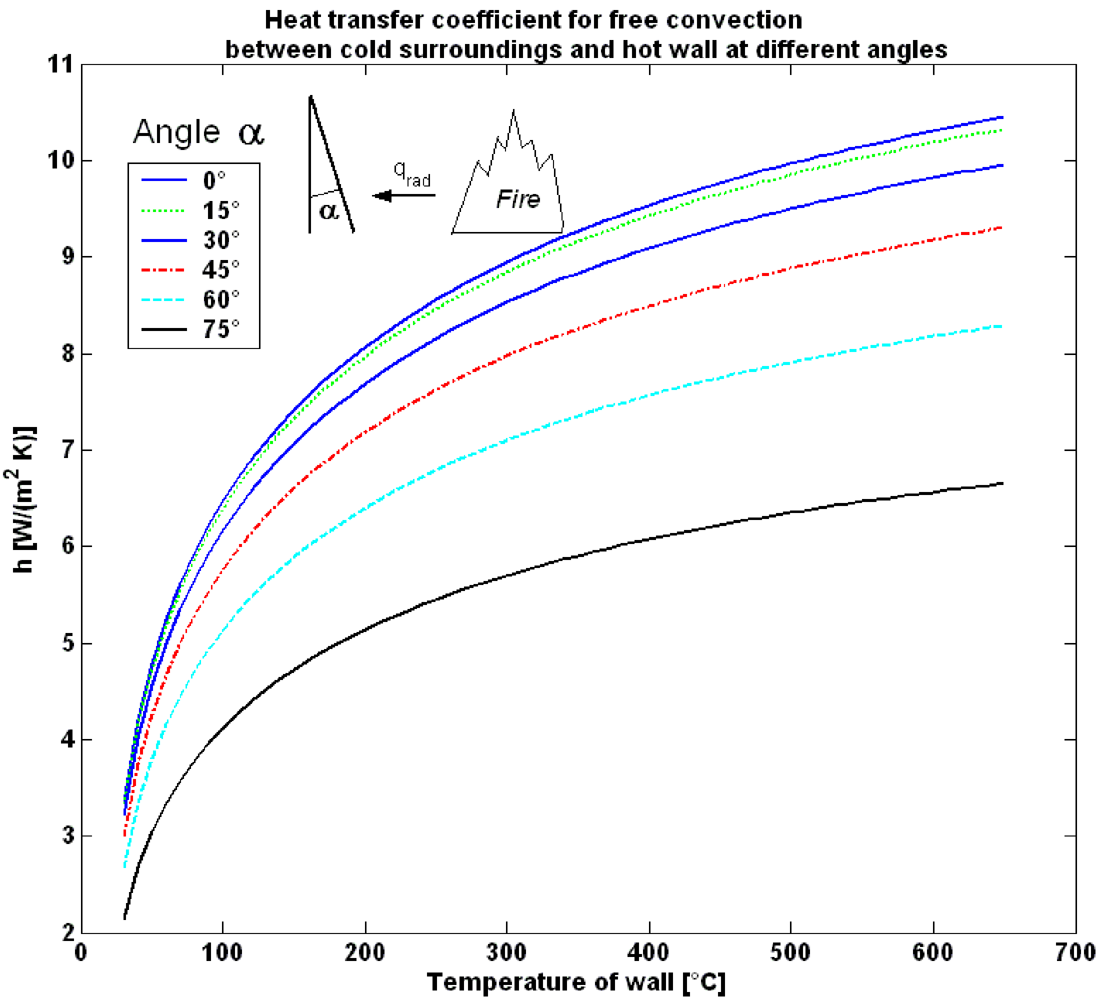


Figure 17 Heat transfer coefficient on a 2 m high plate at different angles

For a plate heated face up, the heat transfer coefficient at a temperature of 50 °C is 5 W/(m^2 K) and for the same plate heated face down the heat transfer coefficient is about 1 W/(m^2 K), Figure 18. Both plates have a characteristic length of 2 meters.

The case with the plate heated face down should not be confused with a room fire simulation. Here the surrounding air is hotter than the ceiling and the fire itself will create a ceiling jet, which will give forced convection at the ceiling and therefore a higher heat transfer coefficient.

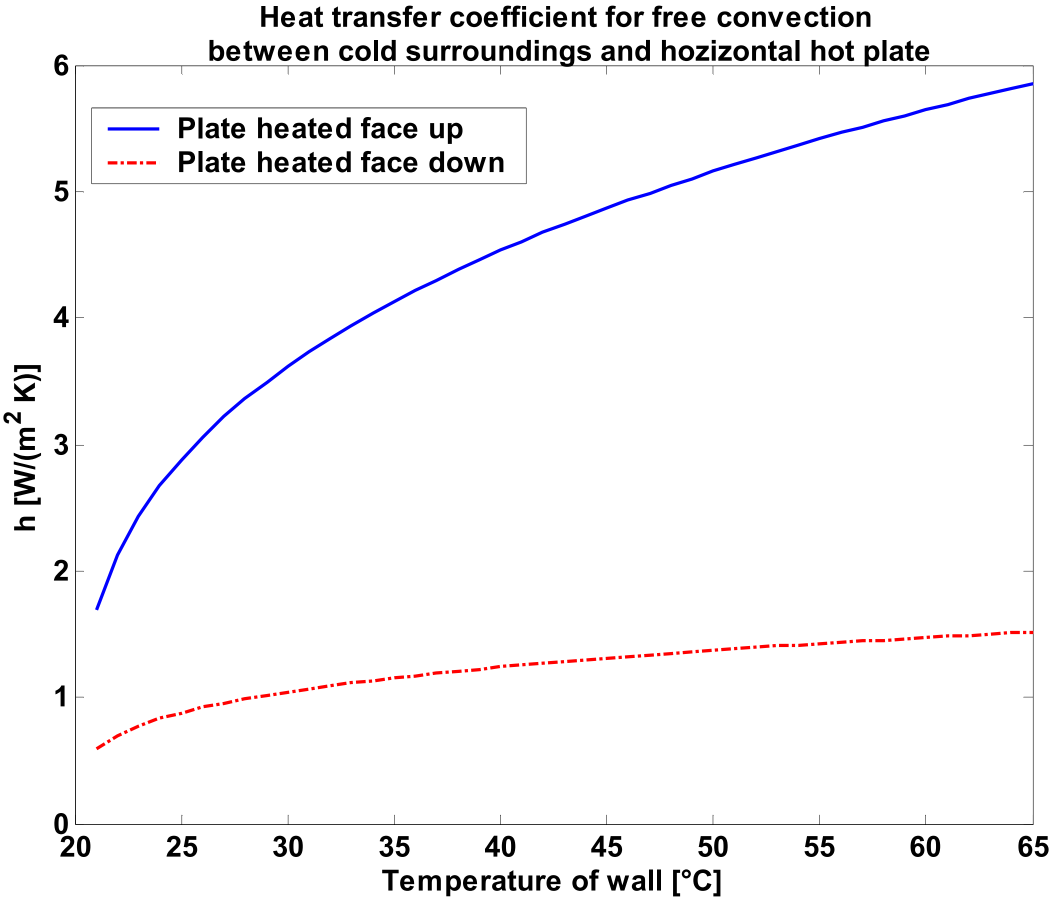


Figure 18 Heat transfer coefficient on a horizontal plate

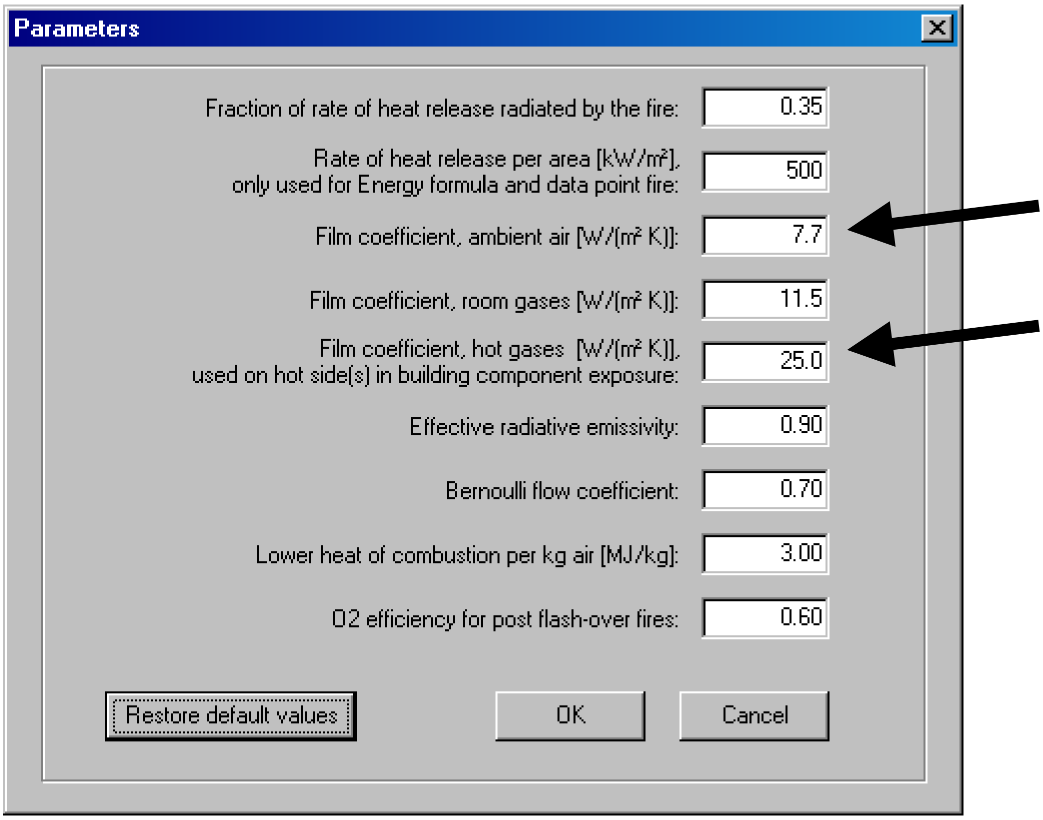
5.2. Heat transfer coefficient for forced convection

For forced convection, the heat transfer coefficient will be higher than for free convection, so using the default values can be recommended.

The interested reader can look in Kanury or other texts to find formulas for calculating the heat transfer coefficient for forced convection.

5.3. Changing the default heat transfer coefficient (film coefficient)

The default heat transfer coefficient (film coefficient) can be changed in the parameters menu. Note the two default values of 7.7 W/(m^2 K) for ambient air and 25 W/(m^2 K) for hot gasses in contact with the wall.



Fraction of rate of heat release radiated by the fire: 0.35
Rate of heat release per area [kW/m²], only used for Energy formula and data point fire: 500
Film coefficient, ambient air [W/(m² K)]: 7.7
Film coefficient, room gases [W/(m² K)]: 11.5
Film coefficient, hot gases [W/(m² K)], used on hot side(s) in building component exposure: 25.0
Effective radiative emissivity: 0.90
Bernoulli flow coefficient: 0.70
Lower heat of combustion per kg air [MJ/kg]: 3.00
O2 efficiency for post flash-over fires: 0.60

6. References

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CEN
August 1999

European Standard EN 1363-2
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Introduction to Combustion Phenomena, 4th edition
Gordon & Breach
New York 1985

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Information für Verkehrsteilnehmerinnen und Verkehrsteilnehmer
Bundesministerium für Verkehr, Bau- und Wohnungswesen
Bonn, August 2004

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Theory manual. Theoretical background for the module **(this document)**
Validation report. Validation of the heat transfer module

2. Objective

The new heat transfer module was developed to enable 1-dimensional analyses of temperature or radiation exposure on a building component to be performed.

Areas where the new exposure module can be used include

- Ignition of surfaces caused by radiation, see Figure 1
- Calculation of the required amount of fire protective cladding
- Calculation of the temperature of steel bars in concrete
- Simulation of the ISO standard fire test curve on a building component
- Simulation of a cone calorimeter test

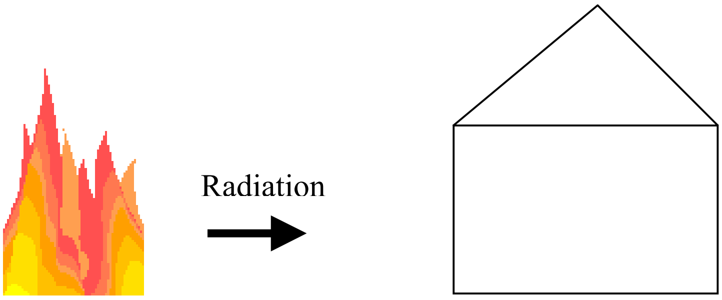

Figure 1 Radiation from a fire on to a building

2.1. Motivation

The heat equation comprises partial differential equations, meaning that the solution is dependent on time and place. The equation can either be solved by an explicit or implicit method.

The original Argos code uses an explicit method, as this is less demanding of the computer for solution. It also includes a limitation which divides each layer into 12 discrete slabs. This means that a building material, consisting of up to 3 layers, could be divided into 36 slabs. This limitation could, in some circumstances, lead to undesirable results, as shown in Figure 2. Here the temperature at the surface is the same for the explicit and the implicit method, but at depths from 10 mm to 35 mm, the temperature profile predicted by the explicit method is not correct. This does not affect room simulation results but it does not give a correct picture of the temperature profile in the ceiling.

Furthermore, the explicit method puts limitations on the maximum size of the time steps used. For these reason, Argos will in future use the implicit method instead of the explicit method for calculating heat transfer in the building components.

Note:
Currently, the new heat transfer module is used for the building component exposure feature, but it has not been implemented in the room fire simulations, where the explicit method is still used.

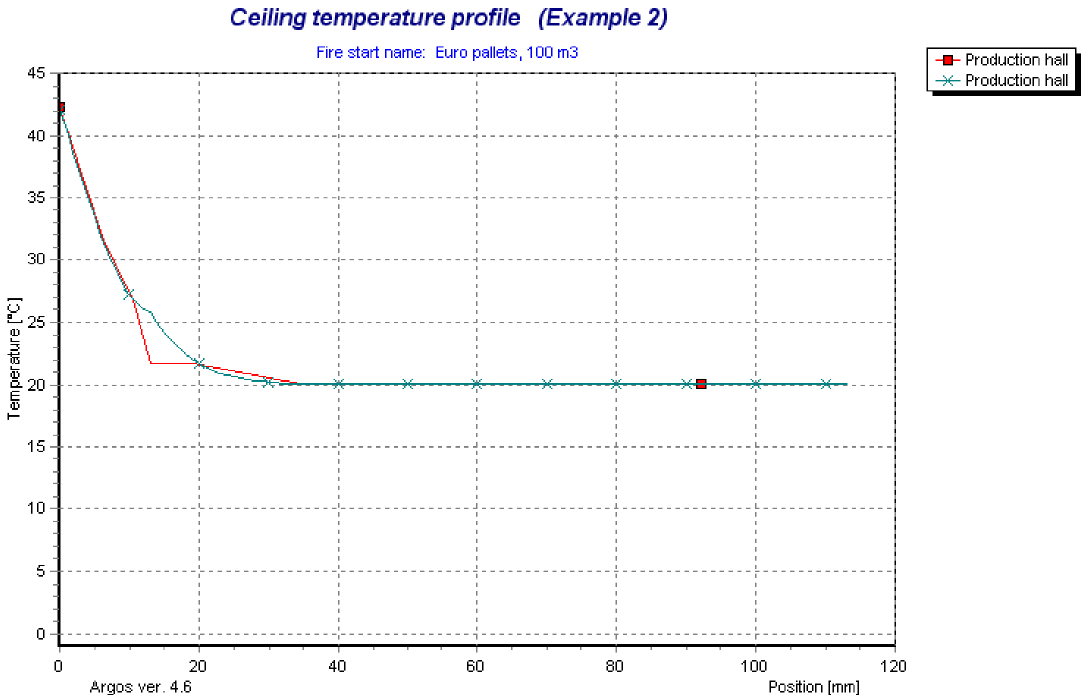

Figure 2 Difference between results of explicit (squares) and implicit (stars) numerical solution methods in Argos

3. Heat equation

The heat equation is given below

$$\rho(T)\cdot c_p(T)\cdot\frac{\delta T}{\delta t}=\frac{\delta}{\delta x}\left(k(T)\cdot\frac{\delta T}{\delta x}\right)$$

where:

T is temperature in [K] of the solid
t is the time in [s] from ignition,
ρ(T) is the density in [kg/m3] of the solid material at the temperature T
Cp(T) is the heat capacity in [J/(kg K)] of the solid material at the temperature T
k(T) is the thermal conductivity in [W/(m K)] of the solid material at the temperature T

Note that all the parameters (ρ, Cp and k) are functions of the temperature of the solid material.

In order to solve the equation it is discretised according to the finite volume method. (Patankar or Versteeg et al.).

Below is the discretised equation (fully implicit method) in 1 dimension. The naming of the nodes is given in Figure 3.

$$\rho\cdot c\cdot\frac{\left(T_P^{i+1}-T_P^{i}\right)}{dt}\cdot dx=\frac{k_W}{dx_W}\left(T_W^{i+1}-T_P^{i+1}\right)-\frac{k_E}{dx_E}\left(T_P^{i+1}-T_E^{i+1}\right)$$

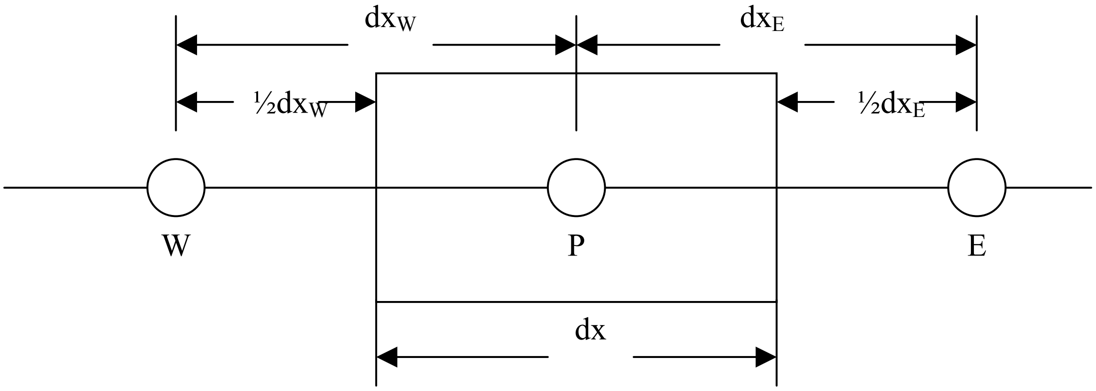

Figure 3 Naming convention for the discretised equation.

The above discretised equation is easy to solve inside a layer but raises two issues which need to be resolved. The first issue is the thickness dx of the individual slabs and the second issue is boundary conditions.

Thickness of slabs and boundary conditions will be covered in detail here, since standard textbooks on the subject, such as Patankar and Versteeg, do not cover these topics.

3.1. Division of layers into slabs

A building component can comprise several layers. In order to solve the heat equation in a particular layer, the layer needs to be divided into thinner slabs with a thickness dx.

Thermal diffusivity is defined by

$$\alpha \equiv \frac{k}{\rho \cdot c_p}$$

"Thermal energy diffuses rapidly though substances with high α and slowly through those with low α." (Pitts & Sissom, page 4).

Thermal diffusivity is chosen to find the size of the slabs, by keeping the Fourier number constant. This ensures that materials with a steep temperature gradient are divided into more slabs than material with a more flat temperature gradient.

The Fourier number is defined by

$$Fo = \frac{\alpha \Delta t}{dx^2}$$

When using the explicit method, the Fourier number has to be less than 0.5. If this value is kept constant it can be used to find a suitable dx.

$$dx = \sqrt{\frac{\Delta t}{Fo} \cdot \alpha} \quad [m]$$

Setting the time step, Δt=1 s, and keeping the Fourier number at 0.5 gives

$$dx = \sqrt{\frac{1s}{0.5} \cdot \alpha} \quad [m]$$

Thermal diffusivity and thus also dx, vary with temperature. This is particularly noticeable for a material as gypsum, which has a very low thermal diffusivity at 100 °C. For a given layer, the same value of dx is used throughout the layer as shown in Figure 4, this value being found by using the minimum value of α.

Furthermore, the size of the slabs has been fixed at either 0.1mm, 0.5mm or 1mm, as this makes it easier to post-process the calculation.

The following rules are used for division of a layer into slabs with thickness dx:

If

$$1\,mm \leq k\sqrt{\alpha_{\min}} \qquad , \qquad then\ dx = 1\,mm$$

$$0.5\,mm \leq k\sqrt{\alpha_{\min}} < 1\ mm \qquad , \qquad then\ dx = 0.5\,mm$$

$$k\sqrt{\alpha_{\min}} < 0.5\ mm \qquad , \qquad then\ dx = 0.1\,mm$$

Where $k = \sqrt{\frac{1s}{0.5}} = \sqrt{2}\ s^{0.5}$

A minimum of 10 slabs has been imposed. A layer of 1 mm thickness will thus always be divided into 10 slabs, regardless of the thermal diffusivity of the material.

Below is shown an example of how the thickness of the slabs is dependent on the material, assuming that the thermal diffusivity is independent of temperature, see Table 1. Note that the results below can be different from the divisions made in Argos, where the material properties are temperature dependent.

	α [m^2/s]	$\sqrt{\alpha}\ \left[10^{-3}\ m/\sqrt{s}\right]$	dx [mm]
Copper	$1.2*10^{-4}$	11.0	1
Aluminium	$9.1*10^{-5}$	9.5	1
Steel (mild)	$1.3*10^{-5}$	3.6	1
Concrete	$5.7*10^{-7}$	0.75	1
Brick (common)	$5.2*10^{-7}$	0.72	1
Mineral wool, slabs	$5.1*10^{-7}$	0.71	1
Gypsum plasterboard	$4.1*10^{-7}$	0.64	0.5
Lightweight concrete	$3.0*10^{-7}$	0.55	0.5
Glass (plate)	$3.7*10^{-7}$	0.61	0.5
Cork plates	$1.6*10^{-7}$	0.40	0.5
Wood (Fir)	$9.6*10^{-8}$	0.31	0.1
Fibre insulating board	$8.6*10^{-8}$	0.29	0.1

Table 1 Thermal properties for some common materials and resulting dx (First 2 colums from table 6.1 in Karlsson & Quintiere, except for the properties for wood, which is from table B-2 in Pitts)

3.2. Boundary conditions

At the boundary of the wall, heat is transferred by convection and radiation. The convection term is linear, but the radiation term is highly nonlinear.

In order to solve the boundary conditions and obtain the value directly at the boundary, the cell at the boundary is only half the size of the other cells. This gives the following discretised equation at the boundary, where dx is divided by 2 to account for the half cell, see Figure 4. All the indices are at the new time step, i+1, as the equation is written fully implicit. The only exception is T_B^i on the left side of the equation, where the temperature difference for time i to i+1 is calculated.

$$\rho \cdot c \cdot \frac{(T_B^{i+1} - T_B^i)}{dt} \cdot \frac{dx}{2} = h\left(T_F^{i+1} - T_B^{i+1}\right) + \varepsilon\sigma\left(\left(T_F^{i+1}\right)^4 - \left(T_B^{i+1}\right)^4\right) - \frac{k_I}{dx_I}\left(T_B^{i+1} - T_I^{i+1}\right)$$

In order to solve the above equation together with the other parts of the wall, the radiation term needs to be linearised. This has been done by introducing the variable C_1, which is kept constant during one iteration for a given time step. It is then updated, when a new solution is achieved by calculating a new T_B^{i+1*} and inserted in the equation for C_1. This process is repeated, until the square of the normalised temperature change is below a given threshold level.

$$\varepsilon\sigma\left((T_F^{i+1})^4 - (T_B^{i+1})^4\right) = \varepsilon\sigma\left(\left(T_F^{i+1}\right)^2 + \left(T_B^{i+1*}\right)^2\right)\left(T_F^{i+1} + T_B^{i+1*}\right)\left(T_F^{i+1} - T_B^{i+1}\right) = C_1\left(T_F^{i+1} - T_B^{i+1}\right)$$

$$C_1 = \varepsilon\sigma\left(\left(T_F^{i+1}\right)^2 + \left(T_B^{i+1*}\right)^2\right)\left(T_F^{i+1} + T_B^{i+1*}\right)$$

$$T_B^{i+1*} = T_B^i \cdot (1 - relaxation) + T_B^{i+1} \cdot relaxation$$

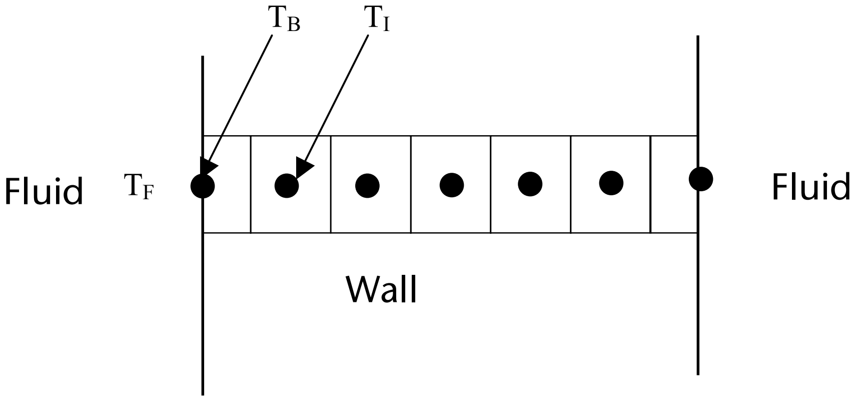

Figure 4 Argos uses a half cell size at the boundary

3.3. Source terms at the boundary

The boundary conditions are inserted by applying the source terms S_p and S_u at the boundary nodes.

For convection

$q'' = h \cdot (T_F - T_B)$

gives the terms

$S_p = -h$

$S_u = h \cdot T_F$

Radiation (incident)

$q'' = r''$

gives the terms

$S_p = 0$

$S_u = \varepsilon \cdot r''$

Radiation from a hot fluid

$q'' = C_1 \cdot (T_F - T_B)$

gives the terms

$S_p = -C_1$

$S_u = C_1 \cdot T_F$

Note that the radiation from a hot fluid is written in the same way as convection by using the term C_1.

3.4. Solution algorithm

The above equations for 1 dimensional heat transfer give a system of linear equations, which can be written in matrix form. For further details, the reader is referred to the following:

$$\begin{bmatrix} 1 & & & & \\ -\beta_1 & D_1 & -\alpha_1 & & \\ & -\beta_2 & D_2 & -\alpha_2 & \\ & & -\beta_3 & D_3 & -\alpha_3 \\ & & & & 1 \end{bmatrix} \begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix}$$

This matrix is sparsely populated and the TriDiagonal Matrix Algorithm (TDMA), also called the Thomas Algorithm, has been chosen to solve the equation system. This algorithm is very efficient for sparsely populated matrixes and also fast.

This method is then used iteratively in order to account for the non-linear boundary conditions as described in the previous section.

For further details please see Patankar or Versteeg et al.

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Building component exposure feature in Argos

- 1D heat transfer module in Argos

Validation report

February 2005

Bjarne Husted and David Westerman
Danish Institute of Fire and Security Technology

Table of contents

1. Validation of the building component exposure feature

The description of the heat transfer module is divided into 3 parts.

User Guide. How to use the module
Theory manual. Theoretical background for the module
Validation report. Validation of the heat transfer module **(this document)**

2. Objective

The new heat transfer module was developed to enable 1-dimensional analyses of temperature or radiation exposure on a building component to be performed.

Areas where the new exposure module can be used include

- Ignition of surfaces caused by radiation, see Figure 1
- Calculation of the required amount of fire protective cladding
- Calculation of the temperature of steel bars in concrete
- Simulation of the ISO standard fire test curve on a building component
- Simulation of a cone calorimeter test

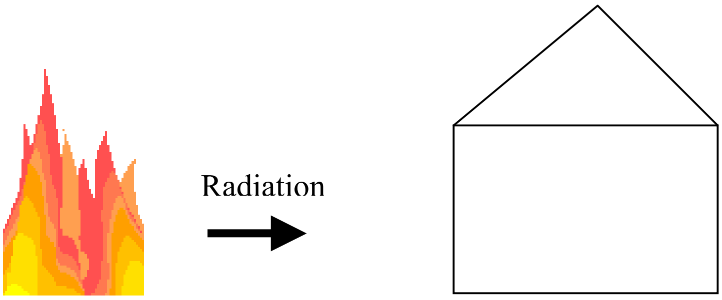


Figure 1 Radiation from a fire on to a building

3. Validation

The aim of this validation is to verify that the new building exposure feature gives the correct results in all situations.

Three different kinds of exposure can be imposed in Argos:

- Constant temperature
- Variable temperature
- Variable radiation

It has also been the intention that the validation is reproducible. Validations against analytical solutions have thus been sought but this is only possible for the simplest setup. All the required information is made available, so that the interested reader can rework the simulations.

3.1. What difference is acceptable?

There are large uncertainties in performing a fire simulation. The primary uncertainty is the size of fire but also material properties are almost never known exactly. Thus a simulation can never exactly reflect reality and a certain level of difference between "exact" solutions and simulations can be allowed.

A difference of up to 1% between Argos calculations and reference calculations is considered to be acceptable, as this is well below the uncertainties introduced by other factors.

3.2. Cases for verification

Five cases have been selected for verification.

1. Constant temperature (Argos compared with analytical solution)
2. Constant radiation (Argos compared with numerical solution in Matlab)
3. Variable temperature and variable thermal properties (Argos compared with numerical solution in Matlab)
4. Variable temperature and variable thermal properties (Argos compared with TEMPER-1)
5. Material consisting of one layer compared to a material consisting of 2 layers

Case number 1 covers the constant temperature case. Case 2 covers the variable radiation case, although the radiation curve used is constant. Cases 3 and case 4 cover variable temperature exposure. Finally, case 5 checks that the inter-boundary node between 2 layers is calculated correctly.

3.3. Heat equation

The heat equation that is solved by analytical methods, in Argos, Matlab and in Temper-1 is given below.

$$\rho(T) \cdot c_p(T) \cdot \frac{\delta T}{\delta t} = \frac{\delta}{\delta x}\left(k(T) \cdot \frac{\delta T}{\delta x} \right)$$

where:

T is temperature in [K] of the solid
t is the time in [s] from ignition,
ρ(T) is the density in [kg/m^3] of the solid material at temperature T
Cp(T) is the heat capacity in [J/(kg K)] of the solid material at temperature T
k(T) is the thermal conductivity in [W/(m K)] of the solid material at temperature T

Note that all the parameters (ρ, Cp and k) are functions of the temperature of the solid material.

3.4. Grid size and time step in numerical solutions

The grid size or mesh size and the time step in numerical solutions influences the accuracy. In general, a finer grid size or smaller time step gives higher accuracy.

In comparing two numerical solutions, the same grid size has, as far as possible, been used. Matlab can automatically refine the mesh, but as the mesh size in Argos is fairly fine, at 1 mm, this is not considered to be a problem.

Argos always uses a time step of 1 second.

Temper-1 simulations use a time step of 30 seconds.

Matlab uses an adaptive time-step algorithm, similar to the one used in Argos when performing a room fire simulation. The time step in Matlab is automatically adjusted so that the error is below a given level. In Matlab code: *options = odeset('AbsTol', 1e-8, 'RelTol', 1e-6*). Therefore the exact time step taken in Matlab is not known. See Matlab user guide for more details on the partial differential equation solver, search on **pdepe.**

3.5. Boundary conditions

The same boundary conditions have been used for all the cases. The exact setup of the boundary condition in Argos is shown in each case by providing a screen dump of the exposure setup.

4. Cases with 1 layer of material

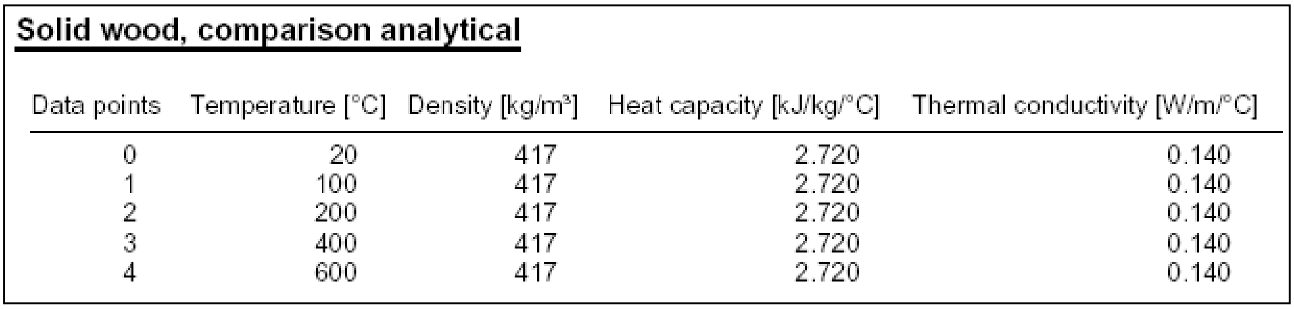
4.1. Constant temperature exposure

Wood (50 mm thick) with the thermal properties given in Table 1 is subjected to the exposure shown in Table 3. The initial temperature of the wood is 20°C and for the short duration of the exposure it can be considered semi-infinite[1] in thickness.

Thermal properties of wood (fir)			
Conductivity	k	0.14	W/(m °C)
Density	ρ	417	kg/m³
Specific heat capacity	c	2720	J/(kg °C)
Thermal diffusivity	α	**1.23E-07**	m²/s

Table 1 Thermal properties of wood (from table A.2 in Chapman)

The table below shows how the thermal properties given in Table 1 are entered into Argos, Table 2.



Solid wood, comparison analytical

Data points	Temperature [°C]	Density [kg/m³]	Heat capacity [kJ/kg/°C]	Thermal conductivity [W/m/°C]
0	20	417	2.720	0.140
1	100	417	2.720	0.140
2	200	417	2.720	0.140
3	400	417	2.720	0.140
4	600	417	2.720	0.140

Table 2 Thermal properties for wood in Argos

Figure 2 shows how the values in Table 3 are entered into Argos.

Properties for calculation			
Exposure time	t	**600.0**	s
Temperature of solid at start	T_0	**20**	°C
Gas temperature	T_g	**200**	°C
Heat transfer coefficient	h	**12**	W/(m² °C)
Depth	x	**0.01**	m

Table 3 Constant temperature is applied for 10 minutes

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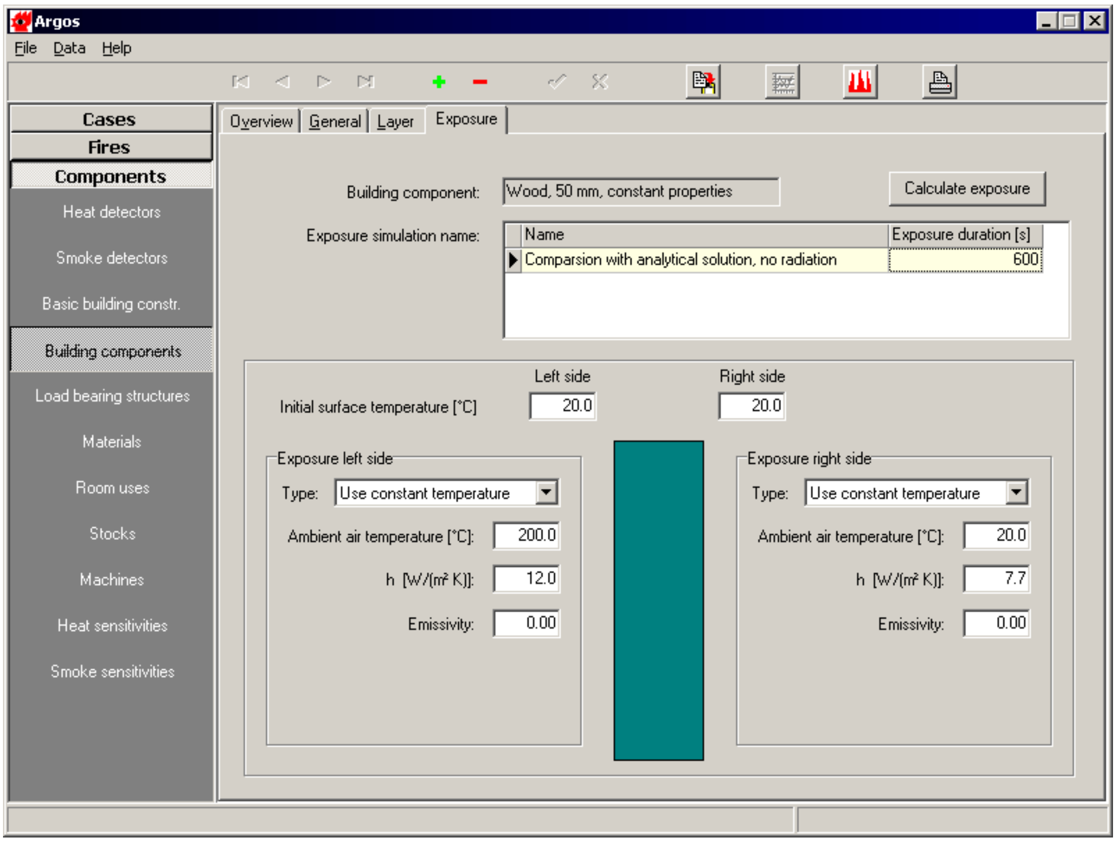
[1] Unbounded in one direction or dimension



Building component: Wood, 50 mm, constant properties

Exposure simulation name:

Name	Exposure duration [s]
Comparsion with analytical solution, no radiation	600

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side
Type: Use constant temperature
Ambient air temperature [°C]: 200.0
h [W/(m² K)]: 12.0
Emissivity: 0.00

Exposure right side
Type: Use constant temperature
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 7.7
Emissivity: 0.00

Figure 2 Setup of the constant temperature comparison in Argos

If only thetemperature step is applied, an analytical solution can be found from the formula below, *Magnusson*.

$$\frac{T(x,t)-T_0}{T_g-T_0} = 1-erf(\bar{x})-\exp\left(\frac{hx}{k}+\frac{h^2\alpha t}{k^2}\right)\cdot\left[1-erf\left(\bar{x}+\frac{h\sqrt{\alpha t}}{k}\right)\right] \quad where \quad \bar{x}=\frac{x}{2\sqrt{\alpha t}}$$

Table 4 shows that there is very good agreement between Argos and the analytical solution.

	Argos [°C]	Analytical solution [°C]
Temperature at surface	107.90	107.93
Temperature 1 cm below surface	48.54	48.57

Table 4 Results from comparison with analytical solution

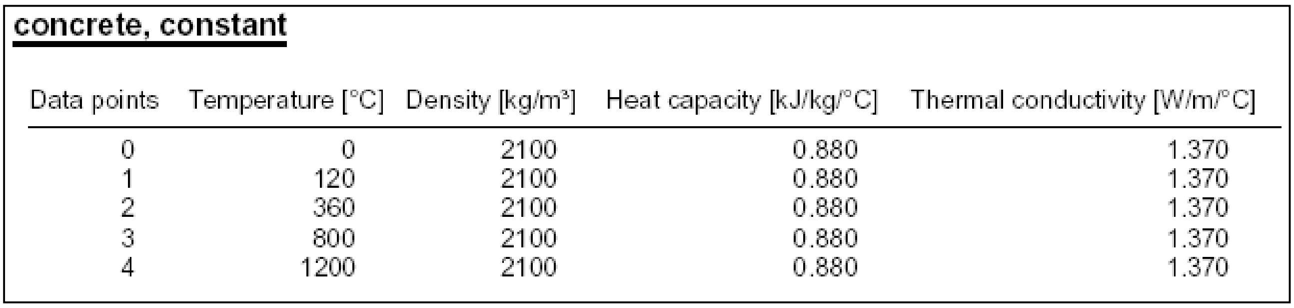
4.2. Constant radiation exposure

A 150 mm thick concrete wall is subjected to a radiation level of 15 kW/m^2 for 10 minutes. The ambient temperature is 20°C.

The thermal properties of concrete are the same at all temperatures, as shown in Table 5 and entered into Argos as shown in Table 6.

Conductivity	1.37 W/(m °C)
Density	2100 kg/m^3
Specific heat capacity	880 J/(kg °C)

Table 5 Thermal properties of concrete (from table A.2 in Chapman)



concrete, constant

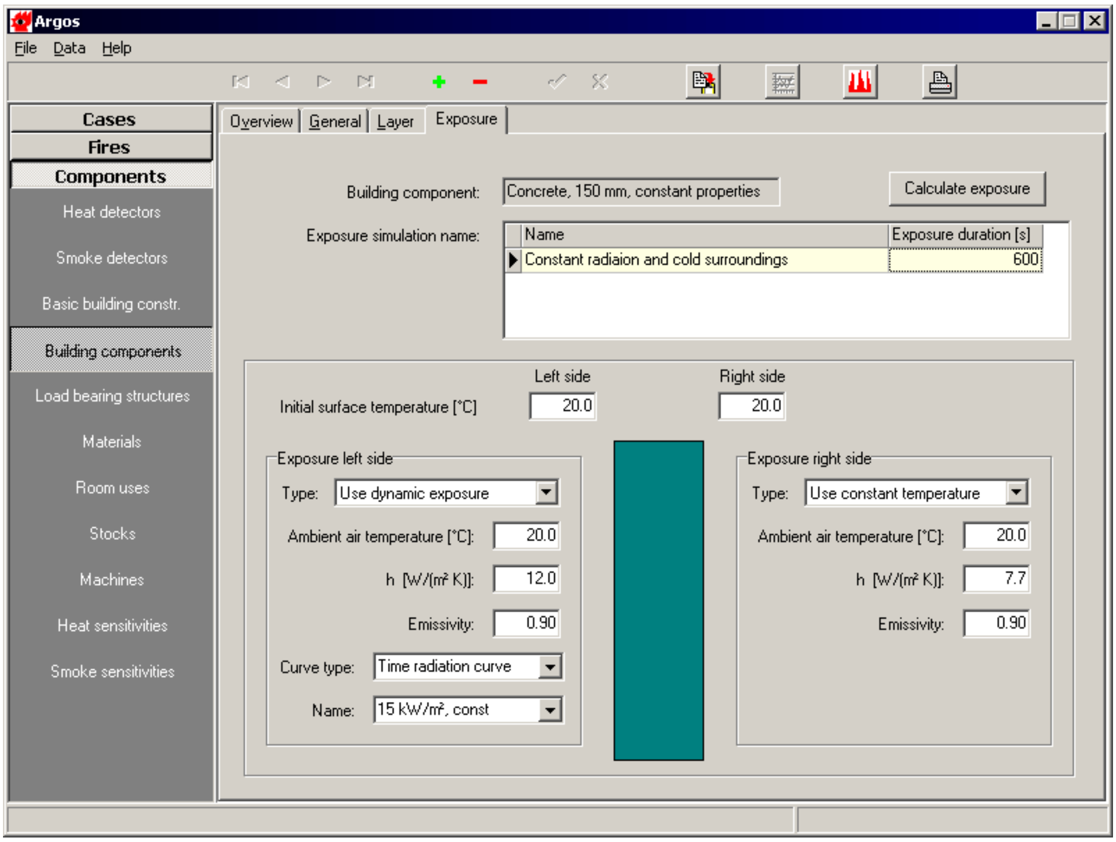
Data points	Temperature [°C]	Density [kg/m³]	Heat capacity [kJ/kg/°C]	Thermal conductivity [W/m/°C]
0	0	2100	0.880	1.370
1	120	2100	0.880	1.370
2	360	2100	0.880	1.370
3	800	2100	0.880	1.370
4	1200	2100	0.880	1.370

Table 6 Thermal properties for concrete in Argos

The properties for the calculation setup are given in Figure 3, where one side of the concrete wall is subjected to a radiation level of 15 kW/m^2. The concrete wall is simultaneously cooled by cold air at 20°C, with a heat transfer coefficient of 12 W/(m^2 °C). The emissivity (absorption) of the wall is 0.9, so the wall only receives 0.9*15 kW/m^2 = 13.5 kW/m^2. Heat is also radiated from the surface, using 0.9 as the emissivity.

The same setup has been modelled in Matlab 6 using the partial differential equation solver and with the same grid as in Argos.

Comparing the results, it can be seen, as shown in Figure 4, that the difference between the two numerical solutions is less than 0.2%. Thus Argos gives correct results for radiation exposure.



Building component: Concrete, 150 mm, constant properties

Exposure simulation name:

Name	Exposure duration [s]
Constant radiaion and cold surroundings	600

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side
Type: Use dynamic exposure
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 12.0
Emissivity: 0.90
Curve type: Time radiation curve
Name: 15 kW/m², const

Exposure right side
Type: Use constant temperature
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 7.7
Emissivity: 0.90

Figure 3 Setup of the constant radiation comparison in Argos

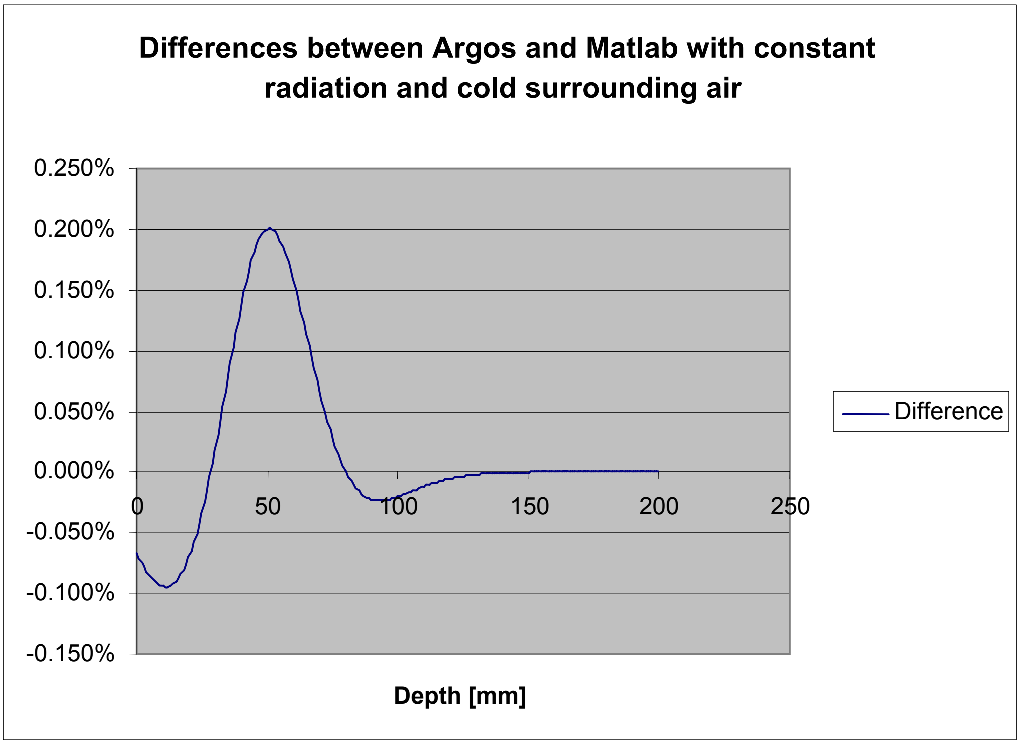
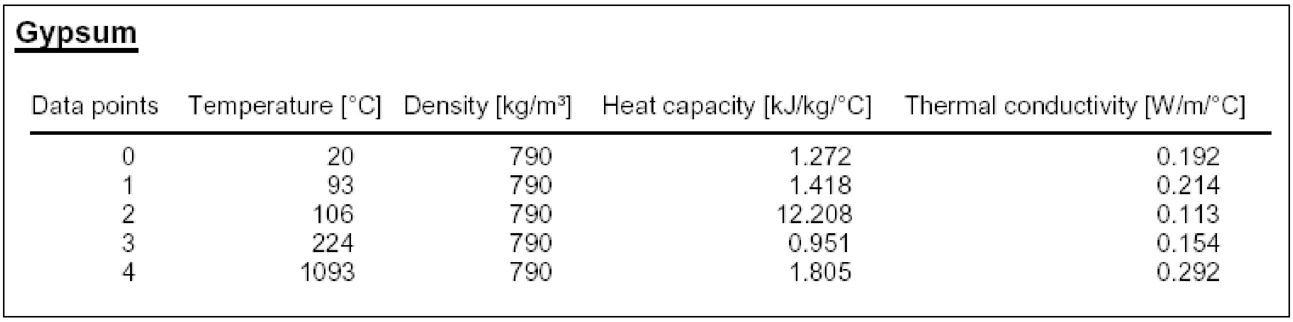


Figure 4 Comparison of constant radiation in Argos and Matlab

4.3. Variable thermal properties

A 13 mm thick gypsum board, which, as shown in Table 7, has thermal properties varying with temperature, is subjected to the temperature curve given in Figure 5. The graph for this curve is shown in Figure 6. The results are compared to a numerical simulation in Matlab.

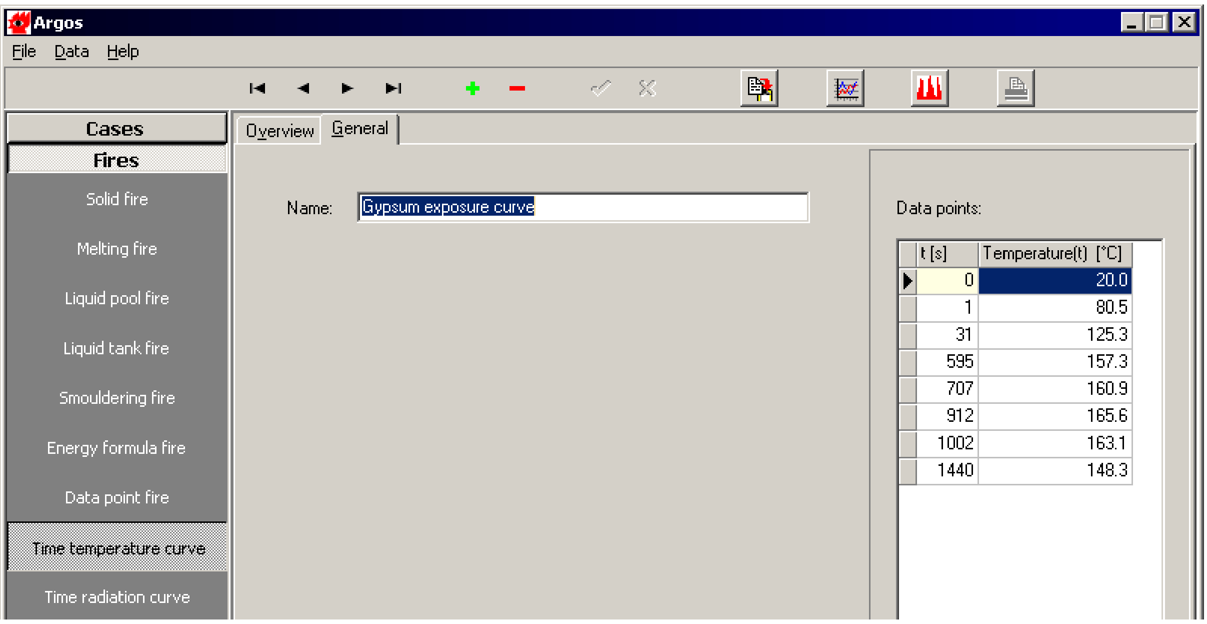
As gypsum has highly variable thermal properties, it is very useful for verification purposes. In Argos, the thermal properties vary linearly between 2 temperatures and this variation was also carried out using Matlab.



Gypsum

Data points	Temperature [°C]	Density [kg/m³]	Heat capacity [kJ/kg/°C]	Thermal conductivity [W/m/°C]
0	20	790	1.272	0.192
1	93	790	1.418	0.214
2	106	790	12.208	0.113
3	224	790	0.951	0.154
4	1093	790	1.805	0.292

Table 7 Thermal properties for gypsum in Argos



Name: Gypsum exposure curve

Data points:

t [s]	Temperature(t) [°C]
0	20.0
1	80.5
31	125.3
595	157.3
707	160.9
912	165.6
1002	163.1
1440	148.3

Figure 5 Temperature curve used for variable thermal properties

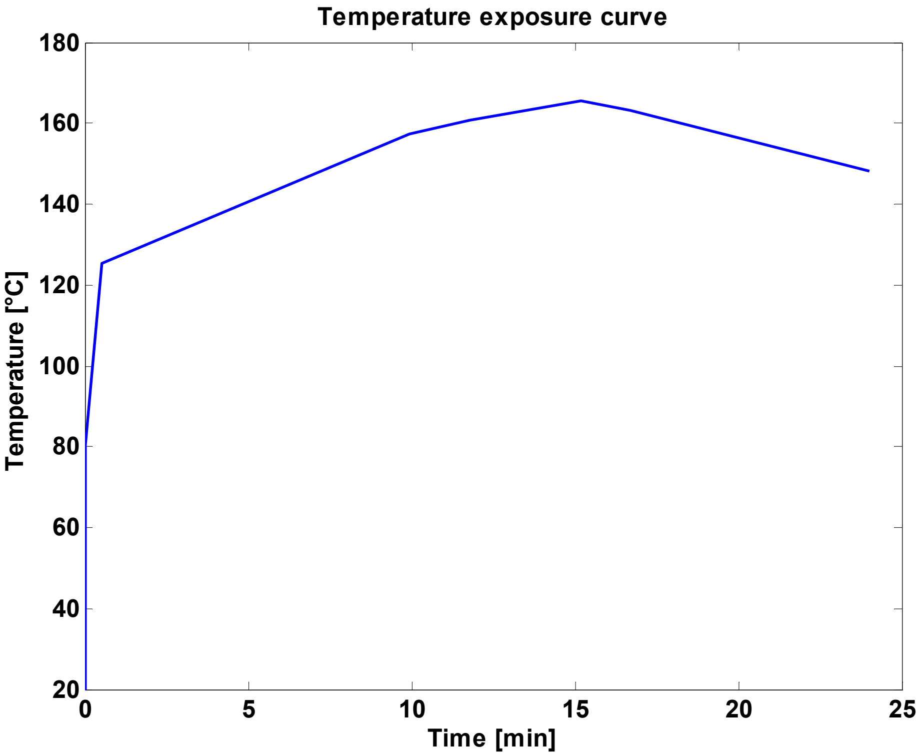
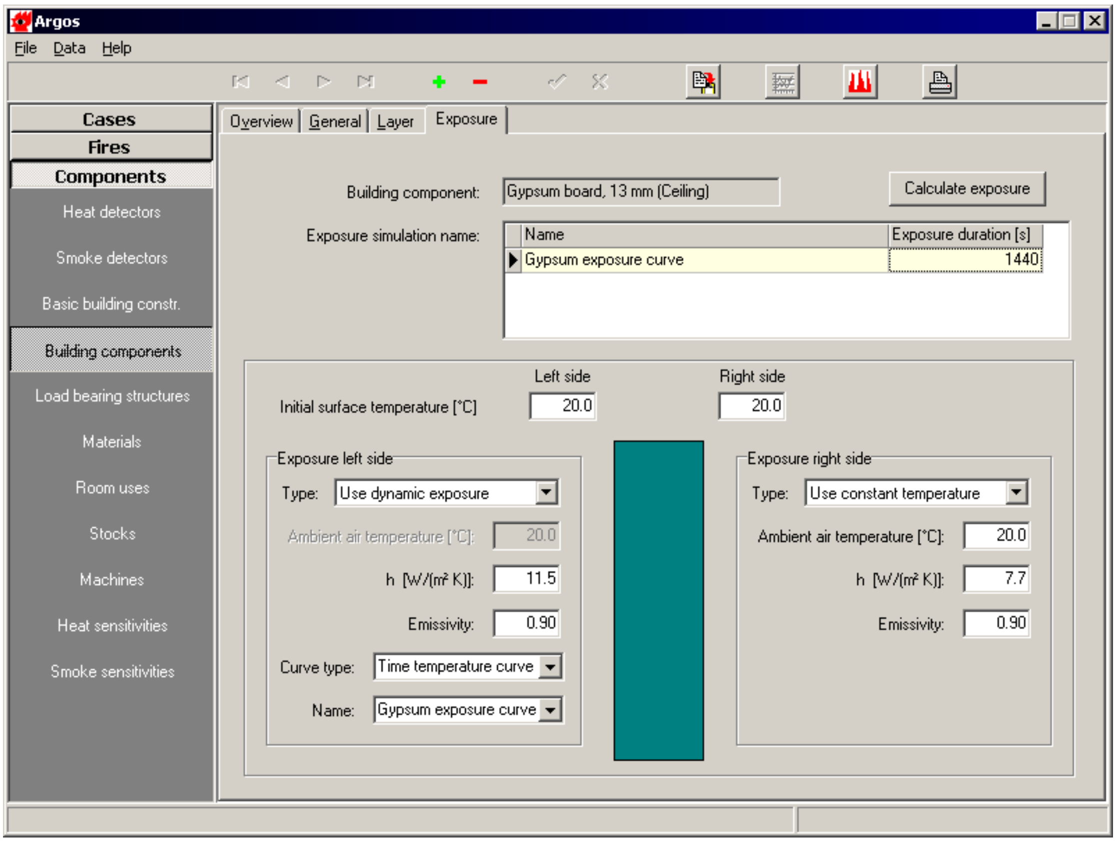


Figure 6 Graph of temperature curve used for variable thermal properties



Building component: Gypsum board, 13 mm (Ceiling)

Exposure simulation name:

Name	Exposure duration [s]
Gypsum exposure curve	1440

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side

Type: Use dynamic exposure

Ambient air temperature [°C]: 20.0

h [W/(m² K)]: 11.5

Emissivity: 0.90

Curve type: Time temperature curve

Name: Gypsum exposure curve

Exposure right side

Type: Use constant temperature

Ambient air temperature [°C]: 20.0

h [W/(m² K)]: 7.7

Emissivity: 0.90

Figure 7 Setup of the gypsum exposure curve in Argos

The setup for the exposure of gypsum is shown in Figure 7 Setup of the gypsum exposure curve in Argos. The comparison between Argos and Matlab is shown in Figure 8. It can be seen that the results are very similar, so Argos appears to treat variable thermal properties correctly.

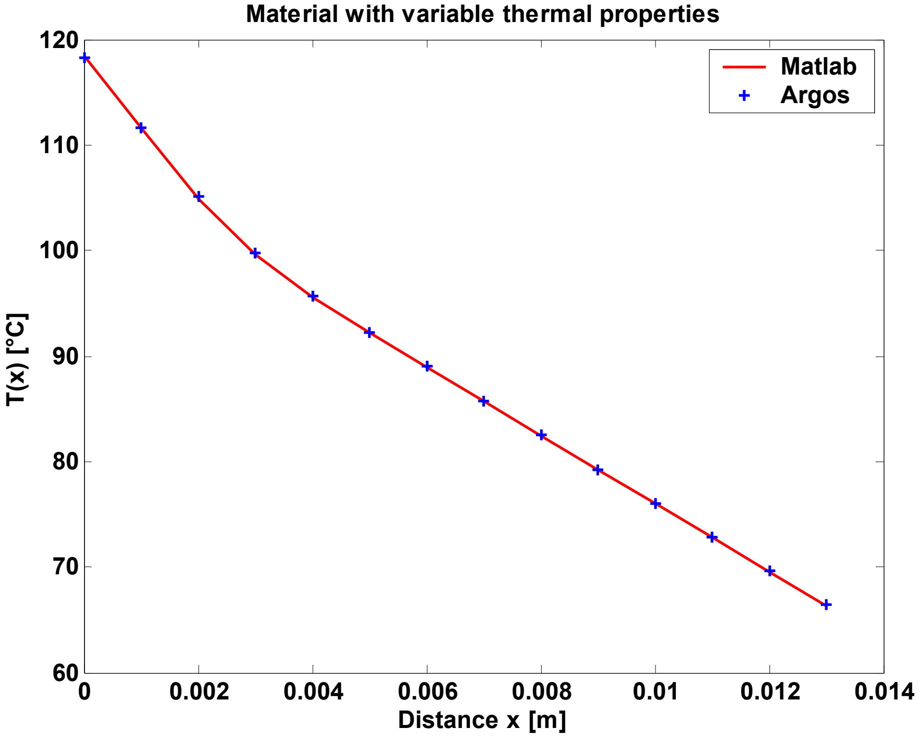
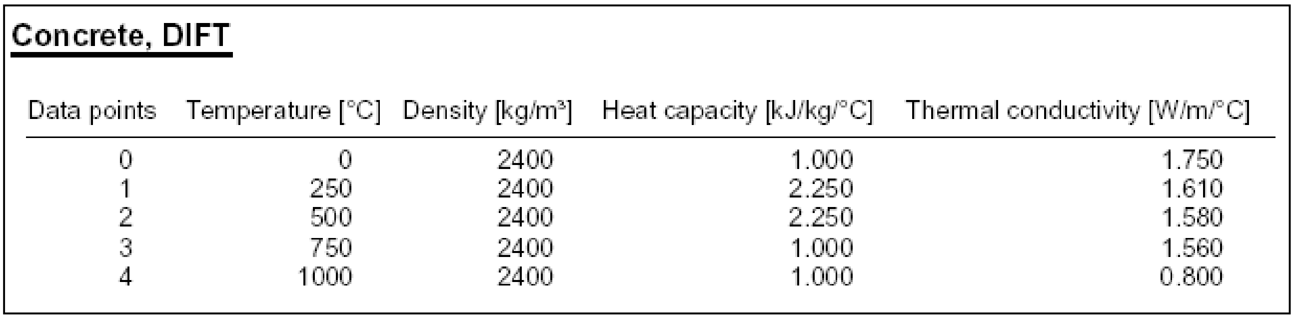


Figure 8 Comparison of gypsum exposure result in Matlab and Argos

4.4. Comparison with Temper-1

Finally, the calculations in Argos were compared with a calculation performed using the program TEMPER-1, developed by Dr. Niels Andersen from DIFT. Temper-1 has been used for more than 15 years and has shown good agreement with actual fire tests performed at DIFT. Temper-1 solves the heat equation using a combination of explicit and implicit methods.

The material used in the simulation was 200 mm concrete, with the properties given in Table 8.

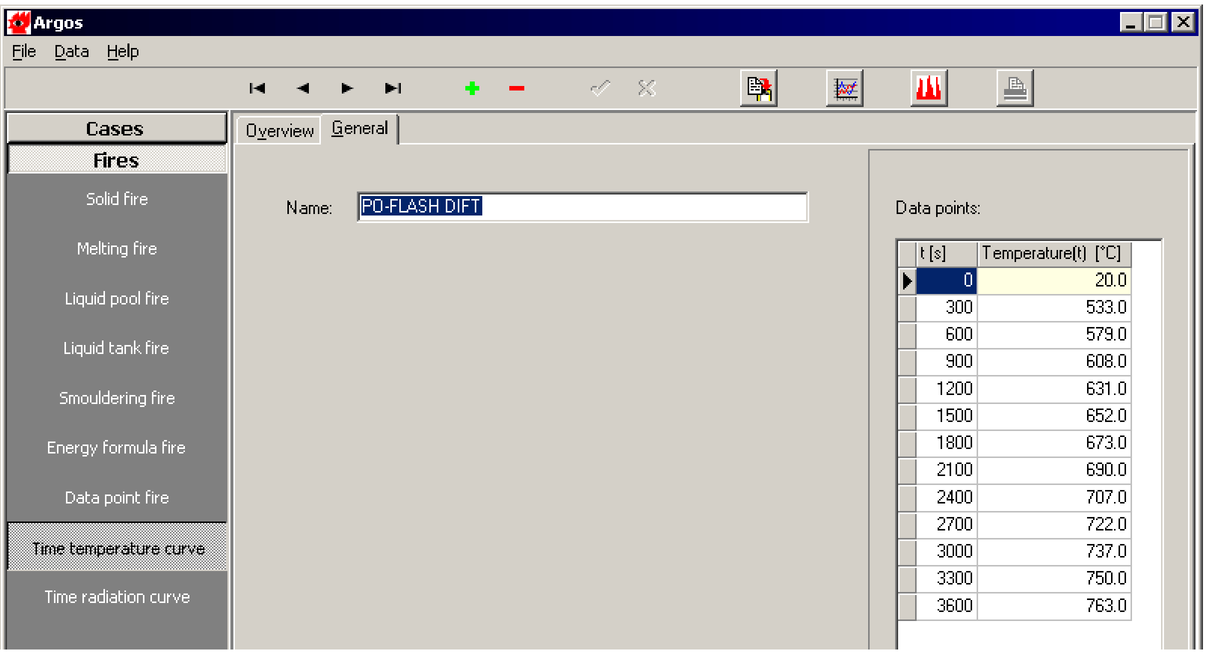


Concrete, DIFT

Data points	Temperature [°C]	Density [kg/m³]	Heat capacity [kJ/kg/°C]	Thermal conductivity [W/m/°C]
0	0	2400	1.000	1.750
1	250	2400	2.250	1.610
2	500	2400	2.250	1.580
3	750	2400	1.000	1.560
4	1000	2400	1.000	0.800

Table 8 Thermal properties for concrete in Argos

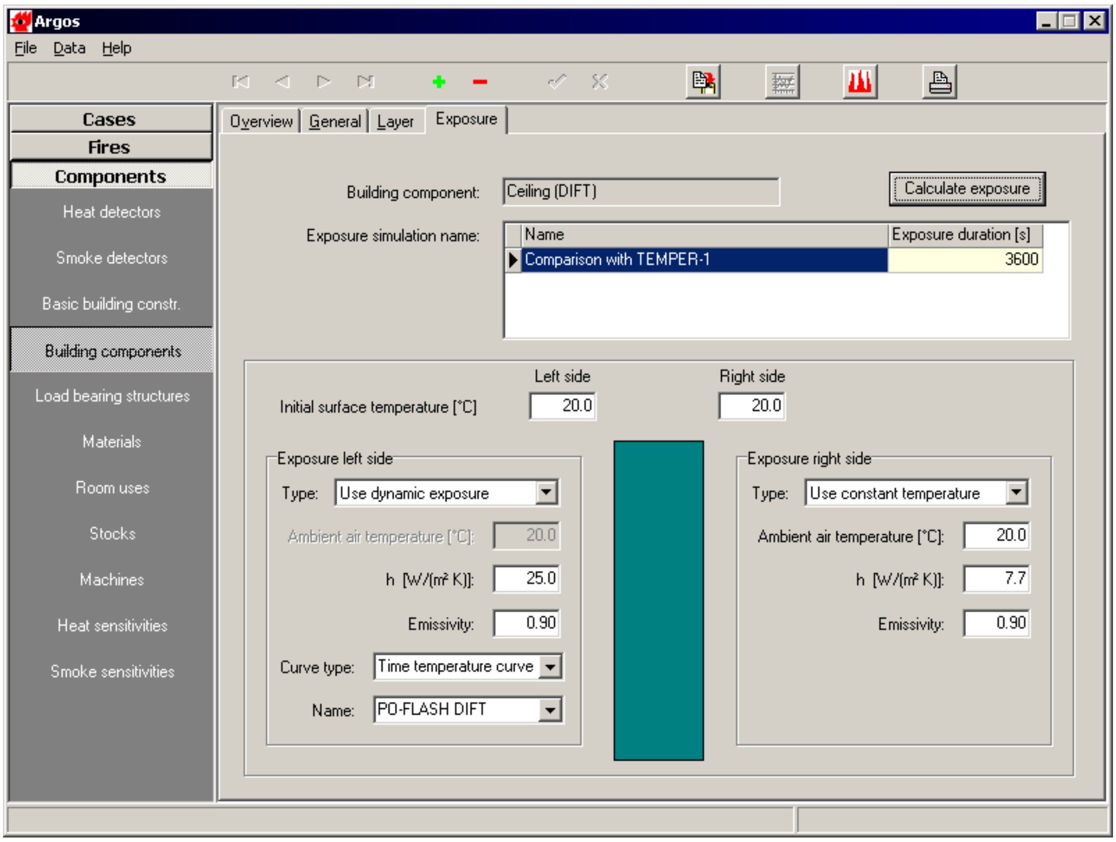
The temperature curve used was taken from the room fire simulation PO-FLASH in Argos, where the ceiling was modified to consist of 200 mm concrete (Concrete, DIFT) with the thermal properties shown in Table 8. The temperature curve was then further modified, so that values were produced for every 5 minutes, see Figure 9.



Name: PO-FLASH DIFT

t [s]	Temperature(t) [°C]
0	20.0
300	533.0
600	579.0
900	608.0
1200	631.0
1500	652.0
1800	673.0
2100	690.0
2400	707.0
2700	722.0
3000	737.0
3300	750.0
3600	763.0

Figure 9 Temperature curve used for the comparison with Temper-1



Building component: Ceiling (DIFT)

Exposure simulation name:

Name	Exposure duration [s]
Comparison with TEMPER-1	3600

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side

Type: Use dynamic exposure

Ambient air temperature [°C]: 20.0

h [W/(m² K)]: 25.0

Emissivity: 0.90

Curve type: Time temperature curve

Name: PO-FLASH DIFT

Exposure right side

Type: Use constant temperature

Ambient air temperature [°C]: 20.0

h [W/(m² K)]: 7.7

Emissivity: 0.90

Figure 10 Setup of comparison with Temper-1

The results of the simulation in Temper-1 are given in *Appendix A, Calculation in TEMPER-1, page 20.* Temper-1 used a time step of 30 seconds.

Argos used a time step of 1 second.

The results are compared in Figure 11 and it can be seen that there is good agreement between the results in Temper-1 and Argos.

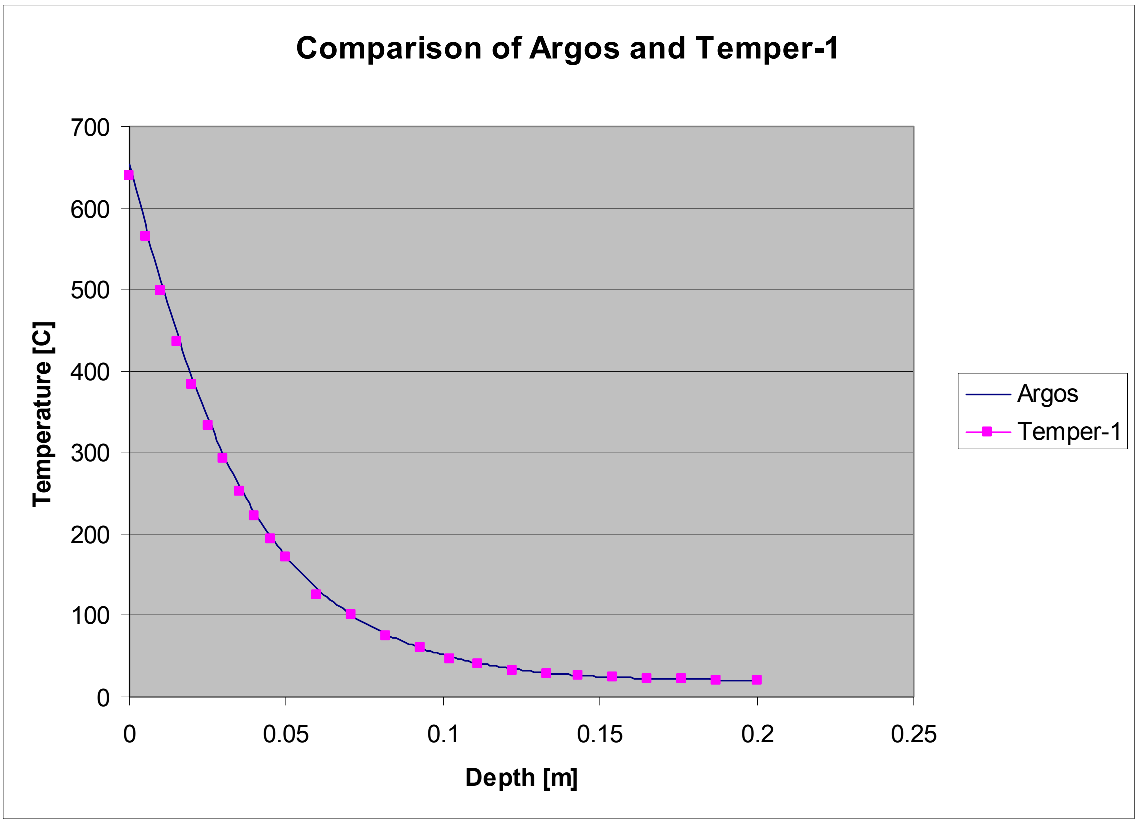


Figure 11 Comparison of Argos and Temper-1

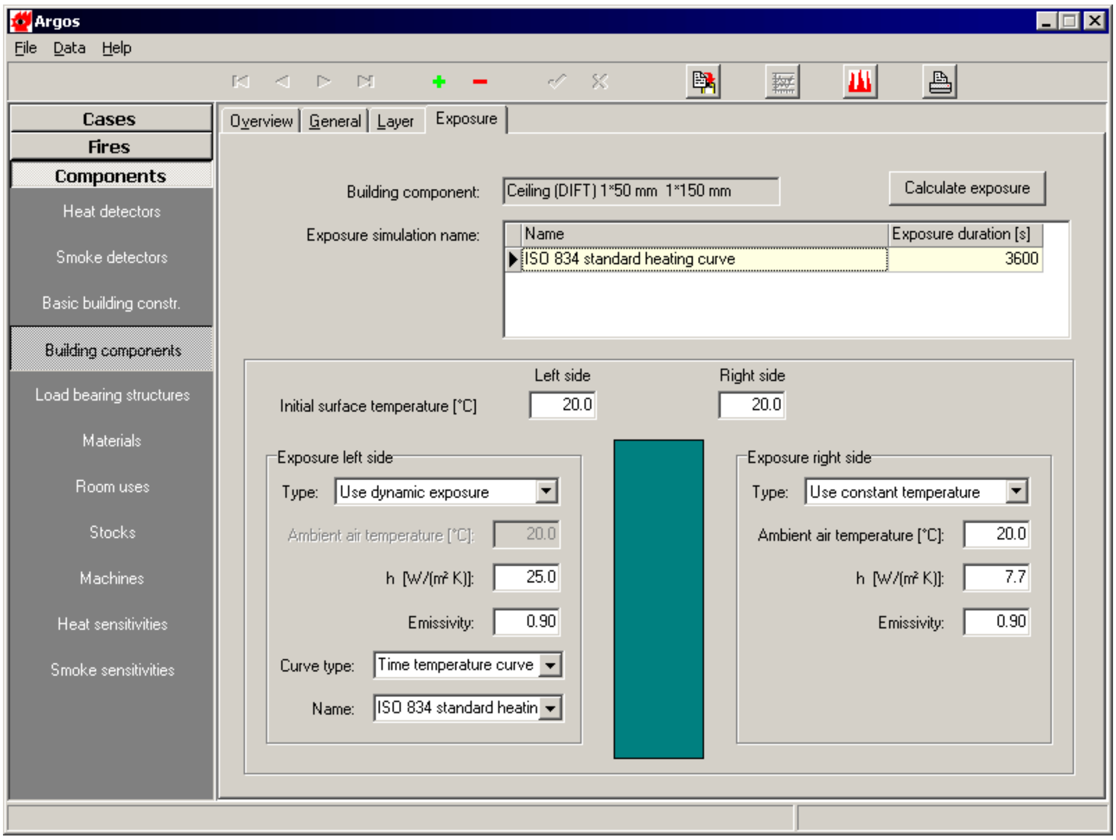
5. Cases with 2 layers of material

5.1. Interface between two layers

Argos currently can use a building component consisting of up to three different materials. In order to check that the interface between the materials is handled correctly, a test case has been designed where a concrete ceiling is modelled in two different ways. In the first model, the ceiling consists of two layers, the first layer having a thickness of 50 mm concrete (Concrete, DIFT) and the second layer having a thickness of 150 mm concrete (Concrete, DIFT). In the second model, the material consists of one layer of 200 mm thick concrete (Concrete, DIFT).

The concrete used is the same as in 4.4, with properties given in Table 8.

Both building components are exposed to the *ISO 834 Standard heating curve* for one hour. The setup of the first case, which is similar to the second case, is shown in Figure 12.



Building component: Ceiling (DIFT) 1*50 mm 1*150 mm

Exposure simulation name:

Name	Exposure duration [s]
ISO 834 standard heating curve	3600

	Left side	Right side
Initial surface temperature [°C]	20.0	20.0

Exposure left side

Type: Use dynamic exposure
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 25.0
Emissivity: 0.90
Curve type: Time temperature curve
Name: ISO 834 standard heatin

Exposure right side

Type: Use constant temperature
Ambient air temperature [°C]: 20.0
h [W/(m² K)]: 7.7
Emissivity: 0.90

Figure 12 Setup of the interface test case

If the interface between the materials is handled correctly in Argos, the results from the two simulations should be exactly the same. From Figure 13, it can be seen that the two results are equal. Note there is no discontinuity at a depth of 50 mm, where the interface between the two materials for the first case lies.

The concrete used has variable thermal properties and any error in handling this would also have emerged in Figure 13.

It can be concluded that Argos handles the interface between 2 layers of materials correctly.

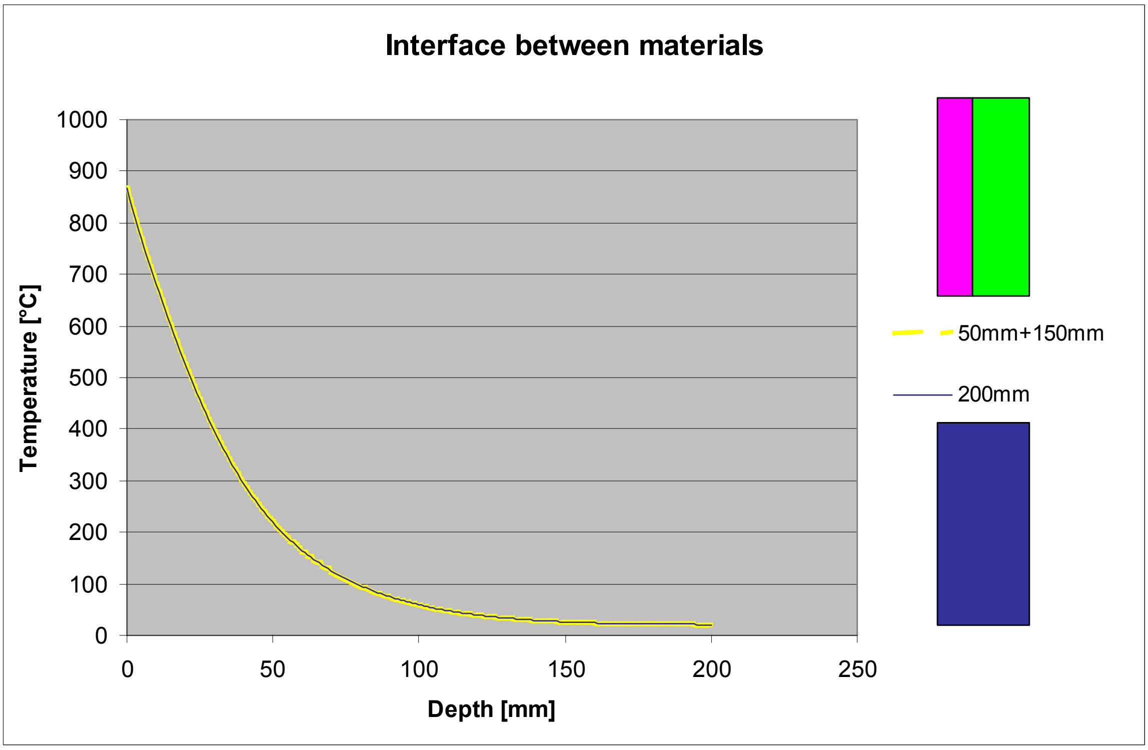


Figure 13 Comparison of ceiling consisting of 2 layers of concrete and 1 layer of concrete

6. Conclusion

The Argos exposure feature has been validated against 5 test cases.

One layer of material:

1. Constant temperature (Argos compared with analytical solution)
2. Constant radiation (Argos compared with numerical solution in Matlab)
3. Variable temperature and variable thermal properties (Argos compared with numerical solution in Matlab)
4. Variable temperature and variable thermal properties (Argos compared with TEMPER-1)

Two layers of materials:

1. Material consisting of one layer compared to a material consisting of two layers

Comparing ARGOS exposure calculations for four different cases with one layer of material and for one case with two layers of material has shown excellent agreement between results from Argos and the results for analytical or numerical solutions in Matlab.

The validation in this report shows that the implementation of the implicit numerical method for the 1D heat equation is successful and the results can be trusted.

7. References

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8. Appendix A, Calculation in TEMPER-1

```
TEMPER-1: Beregning af instationær varmeledning i plan eller krum væg

Dansk Brandteknisk Institut                    Sagsnummer           13:18:03
Jernholmen 12                                  Dato                 2004-11-18
2650 Hvidovre                                  Sagsbehandler        Niels Andersen

Argos test: PO-FLASH DIFT

Begyndelsestemperatur 20 grader C

Varmeovergangstal ved konvektion på ildside           25.0 W/m2/K
Absorptionskoefficient på ildsiden                    0.90
Samlet varmeovergangstal på kold side                 7.7 W/m2K
Beregningsinterval,sekunder:                          30

       Dx      ro    c     10    1250    1500    1750    11000     rm   rp  Materiale
 1 0.0100    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 2 0.0100    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 3 0.0100    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 4 0.0100    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 5 0.0100    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 6 0.0215    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 7 0.0215    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 8 0.0215    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
 9 0.0215    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
10 0.0215    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
11 0.0215    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
12 0.0215    2400    0  1.750  1.610  1.580   1.560    0.800              Argos test
C=O angiver at der anvendes variabel c fra tabel

Variabel c for element 1
        0      250      500      750     1000     2000
     1000     2249     2250     1000     1000      999

Tid   T(O)   Tl    T2     T3     T4      T5     T6      T7     T8      T9    T10    T11      T12    T13
5     533  91      41     26      21     20     20      20     20      20     20      20      20      20
         167    66     33      23     21      20     20     20      20     20      20     20     20
10    579 194     105     59      37     27     21      20     20      20     20      20      20      20
         275   149     82      48     32      25     21     20      20     20      20     20     20
15    608 259     157     96      61     42     26      21     20      20     20      20      20      20
         342   207    126      79     52      37     24     21      20     20      20     20     20
20    631 311     200    130      86     59     34      24     21      20     20      20      20      20
         394   255    164     108     73      51     29     22      20     20      20     20     20
25    652 356     238    161     110     77     44      28     22      21     20      20      20      20
         438   297    199     135     94      67     36     25      21     20      20     20     20
30    673 395     273    189     133     95     56      33     24      21     20      20      20      20
         478   334    230     161    114      82     44     28      23     21      20     20     20
35    690 430     305    216     155    112     67      39     27      22     21      20      20      20
         512   367    260     185    133      98     53     33      25     21      20     20     20
40    707 462     335    241     176    129     79      45     30      24     21      20      20      20
         543   398    288     208    152     113     62     38      27     22      21     20     20
45    722 490     362    265     196    146     90      52     34      26     22      21      20      20
         570   426    314     230    171     128     71     43      30     24      21     20     20
50    737 517     388    288     215    162    102      60     38      28     23      21      20      20
         595   452    338     251    188     143     81     49      33     25      22     21     20
55    750 541     412    311     234    178    114      67     43      30     24      22      21      20
         618   477    361     272    206     157     90     55      36     27      23     21     21
60    763 564     435    332     252    193    125      75     47      33     26      23      21      20
         640   499    383     292    222     171    100     61      40     29      24     22     21


Samlet varmetransport gennem  eksponeret side            88104 kJ
Samlet varmetransport gennem ueksponeret side                5 kJ

Varmeovergangstal på ueksponeret overflade ved udkriftstiderne:
  7.70   7.70   7.70   7.70   7.70   7.70   7.70   7.70   7.70   7.70   7.70   7.70

Varmeovergangstal på eksponeret overflade ved udkriftstiderne:
  70.5   87.7  100.6  112.3  123.6  134.9  145.3  155.7  165.6  175.4  184.8  194.1
```