Danish Institute of Fire and Security Technology

# Building component exposure feature in Argos

## - 1D heat transfer module in Argos

# Validation report

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# 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

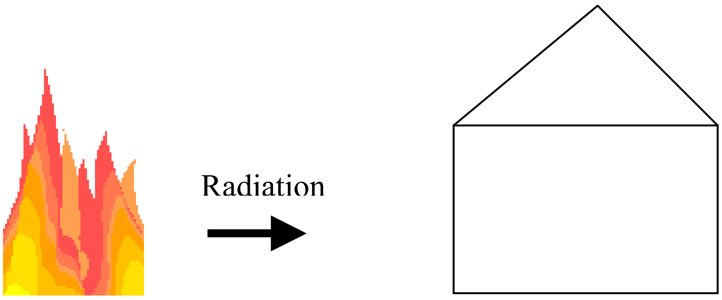


**Figure 1 Radiation from a fire on to a building**

## 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

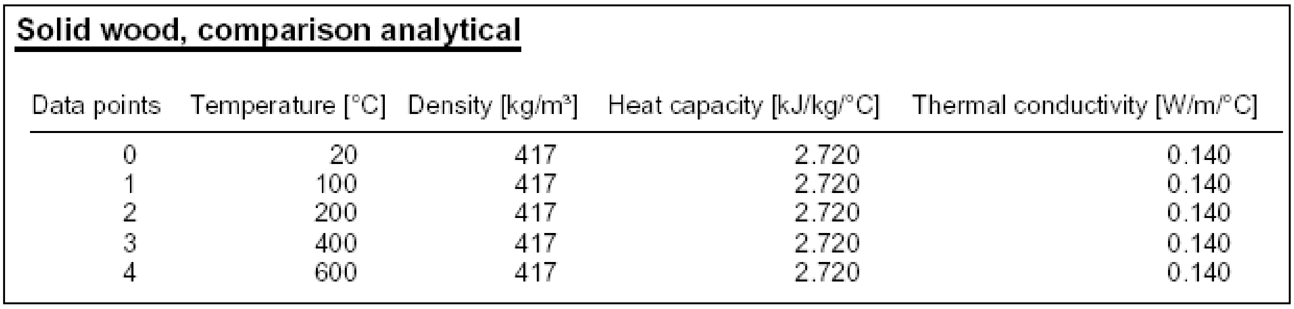
## 4.1. Constant temperature exposure

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 ºC) |
| Density | ρ | 417 | kg/m³ |
| Specific heat capacity | c | 2720 | J/(kg ºC) |
| 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 2 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** | ºC |
| Gas temperature | T_g | **200** | ºC |
| Heat transfer coefficient | h | **12** | W/(m² ºC) |
| Depth | x | **0.01** | m |

**Table 3 Constant temperature is applied for 10 minutes**

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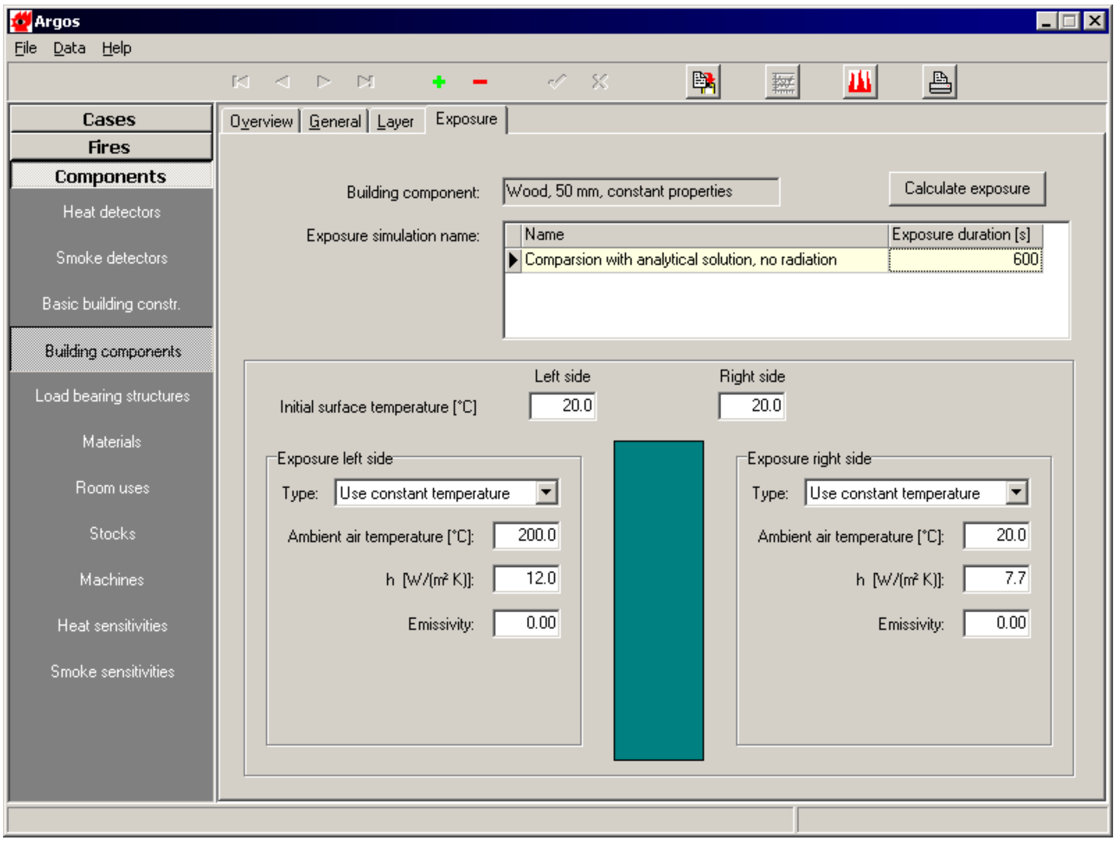
[1] Unbounded in one direction or dimension



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**

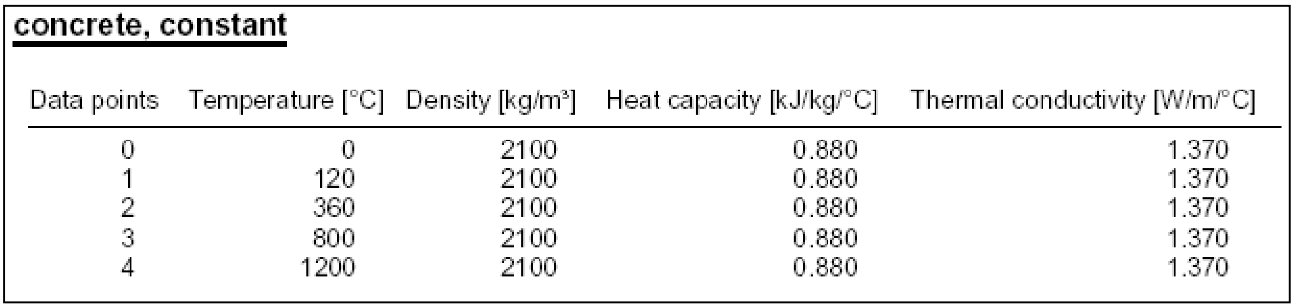
## 4.2. Constant radiation exposure

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**

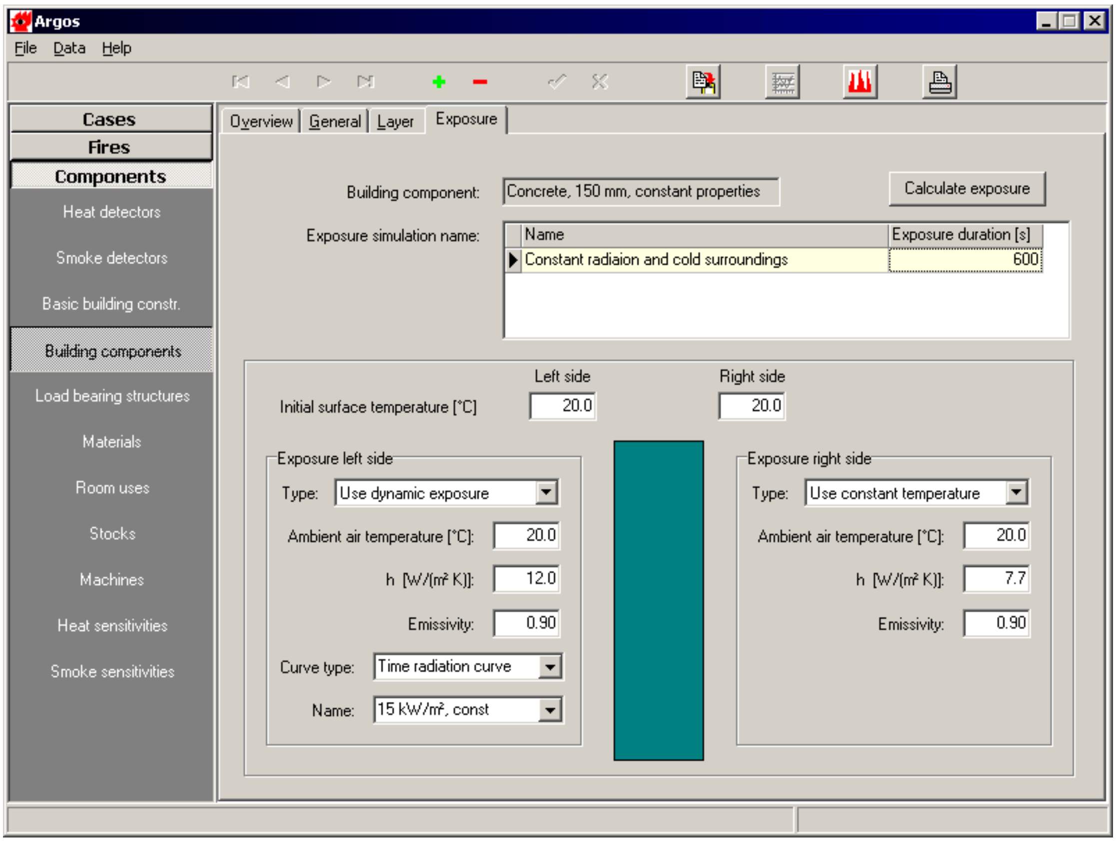
| Data points | Temperature [°C] | Density [kg/m³] | Heat capacity [kJ/kg/°C] | Thermal conductivity [W/m/°C] |
|---|---|---|---|---|
| 0 | 0 | 2100 | 0.880 | 1.370 |
| 1 | 120 | 2100 | 0.880 | 1.370 |
| 2 | 360 | 2100 | 0.880 | 1.370 |
| 3 | 800 | 2100 | 0.880 | 1.370 |
| 4 | 1200 | 2100 | 0.880 | 1.370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

**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**

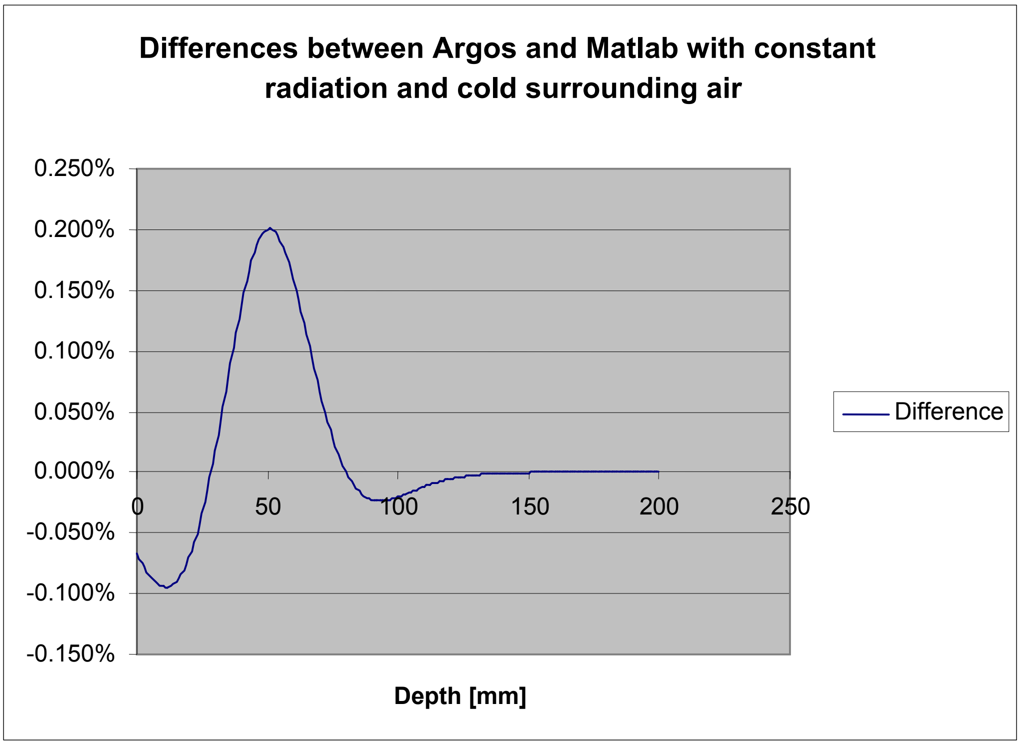


**Figure 4 Comparison of constant radiation in Argos and Matlab**

## 4.3. Variable thermal properties

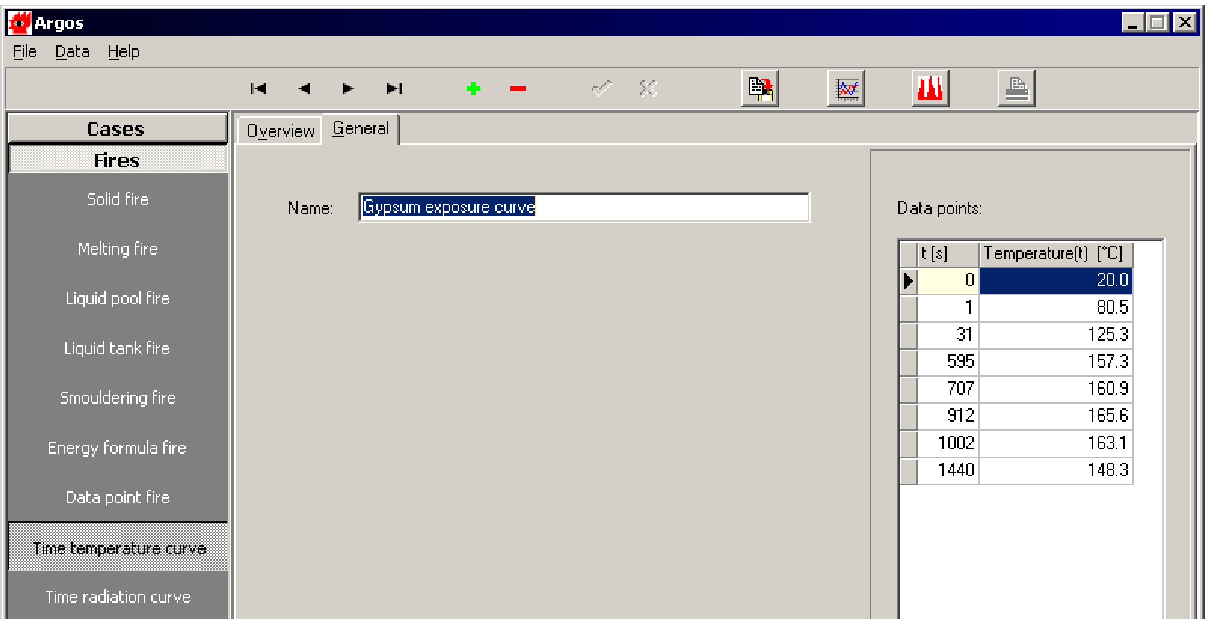
A 13 mm thick gypsum board, which, as shown in Table 7, has thermal properties varying with temperature, is subjected to the temperature curve given in Figure 5. The graph for this curve is shown in Figure 6. The results are compared to a numerical simulation in Matlab.

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**

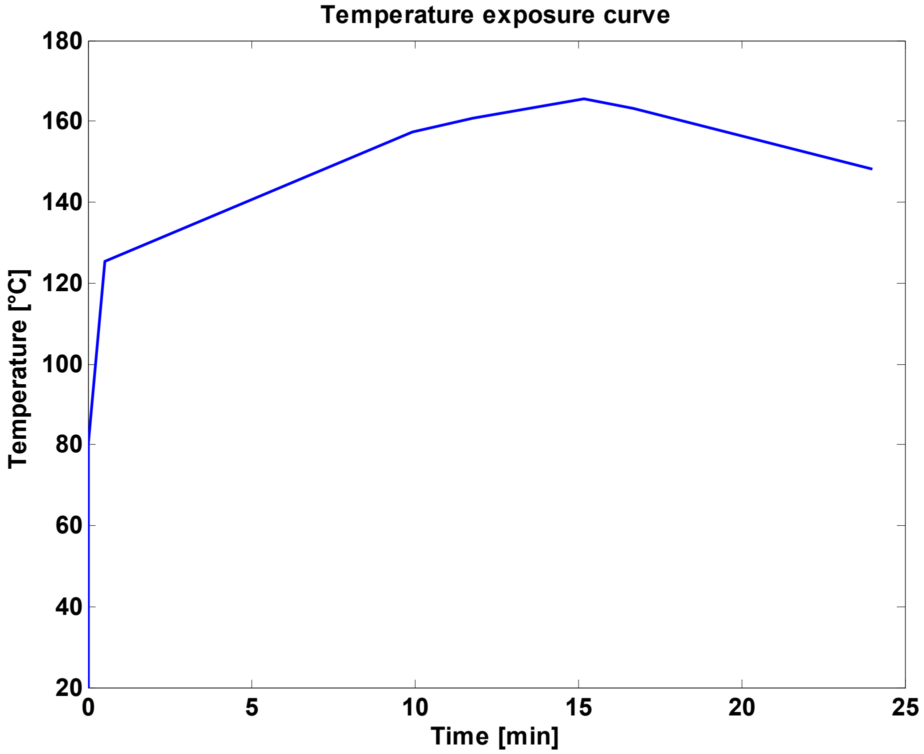
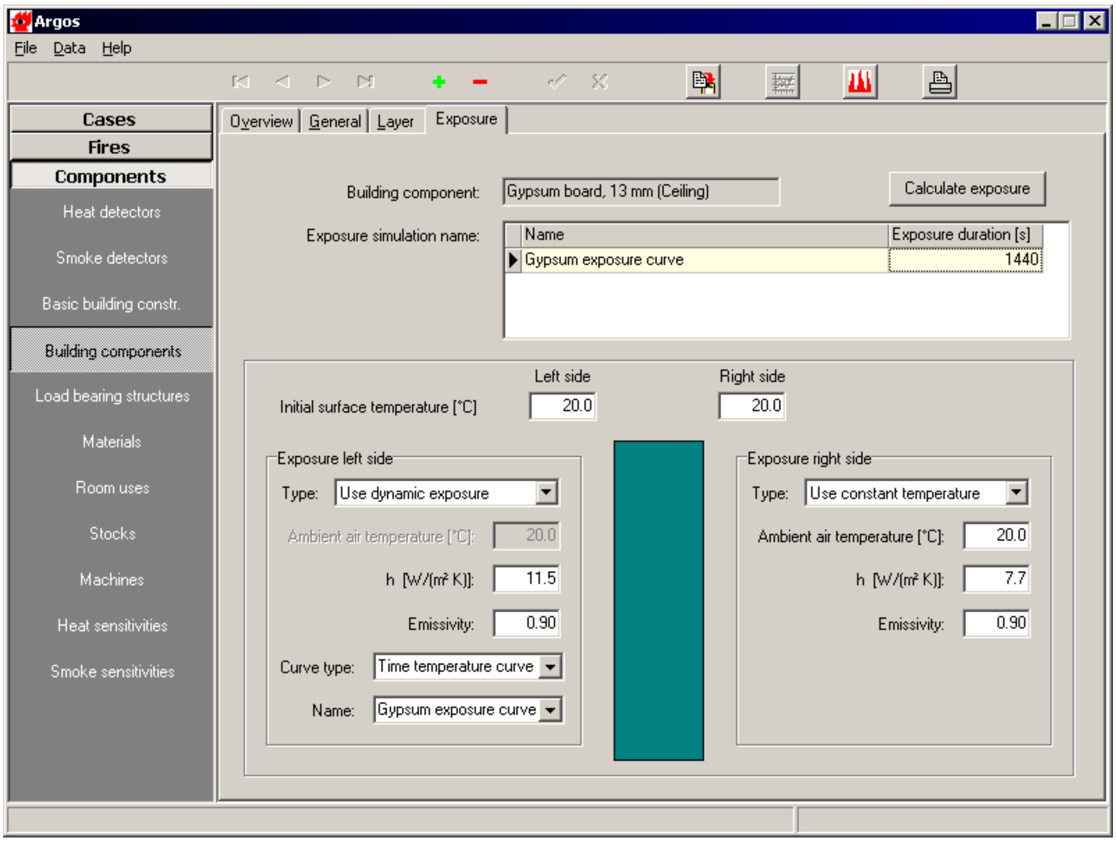


Figure 6 Graph of temperature curve used for variable thermal properties



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.

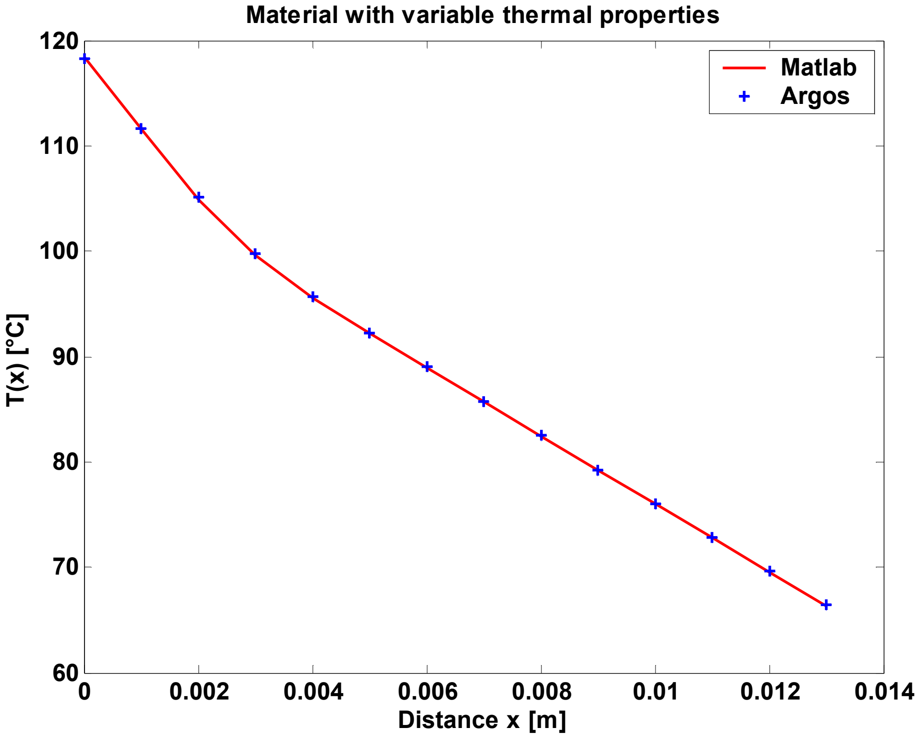
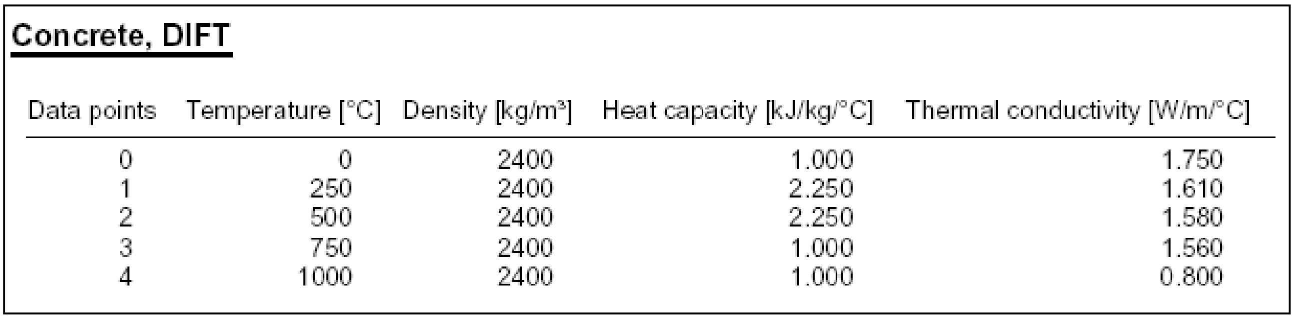


**Figure 8 Comparison of gypsum exposure result in Matlab and Argos**

## 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.

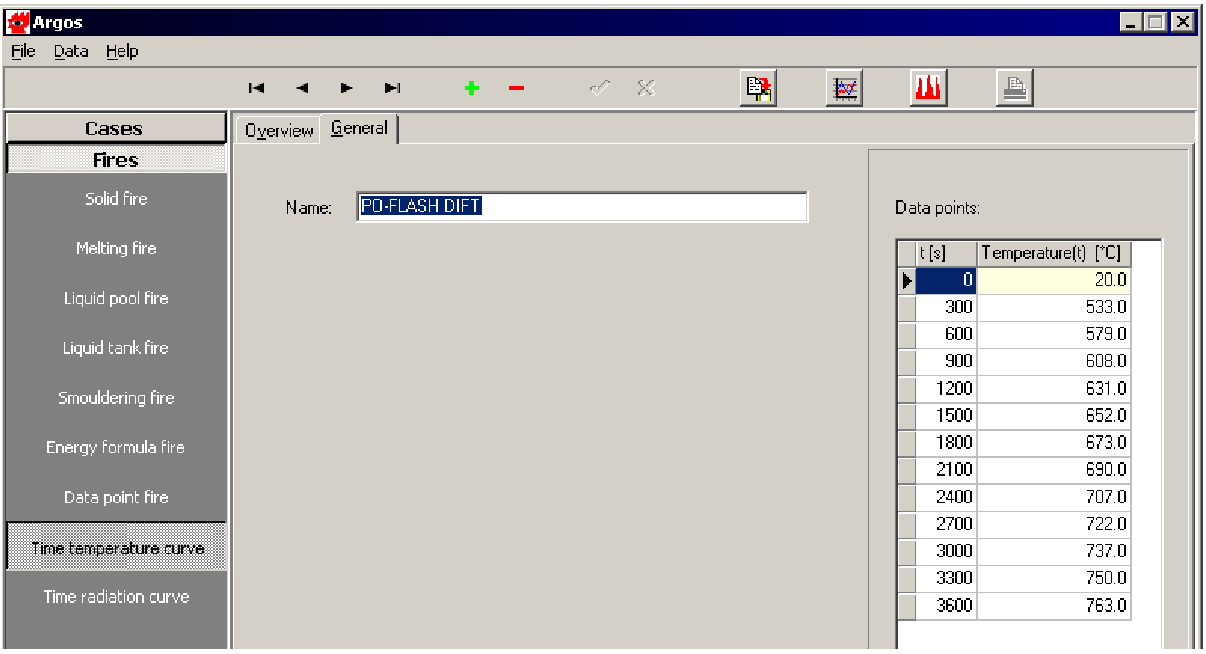


**Concrete, DIFT**

| 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.

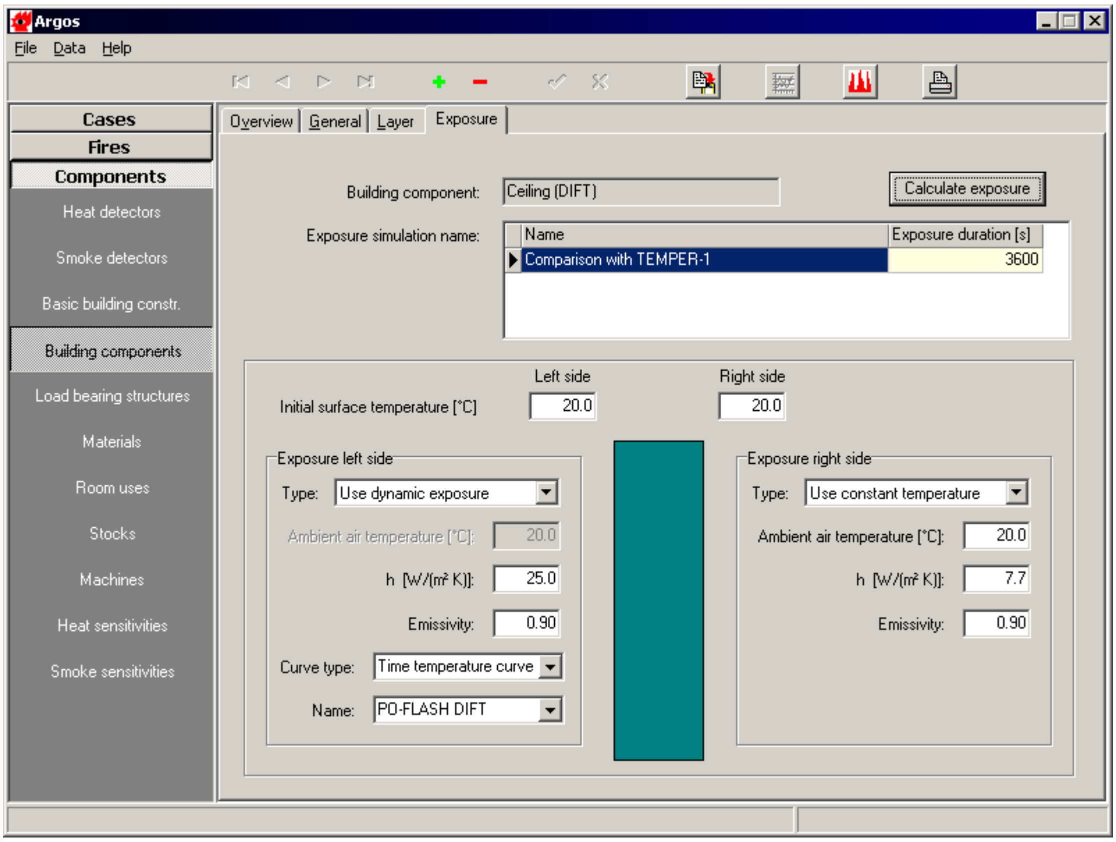


Name: PO-FLASH DIFT

Data points:

| 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.

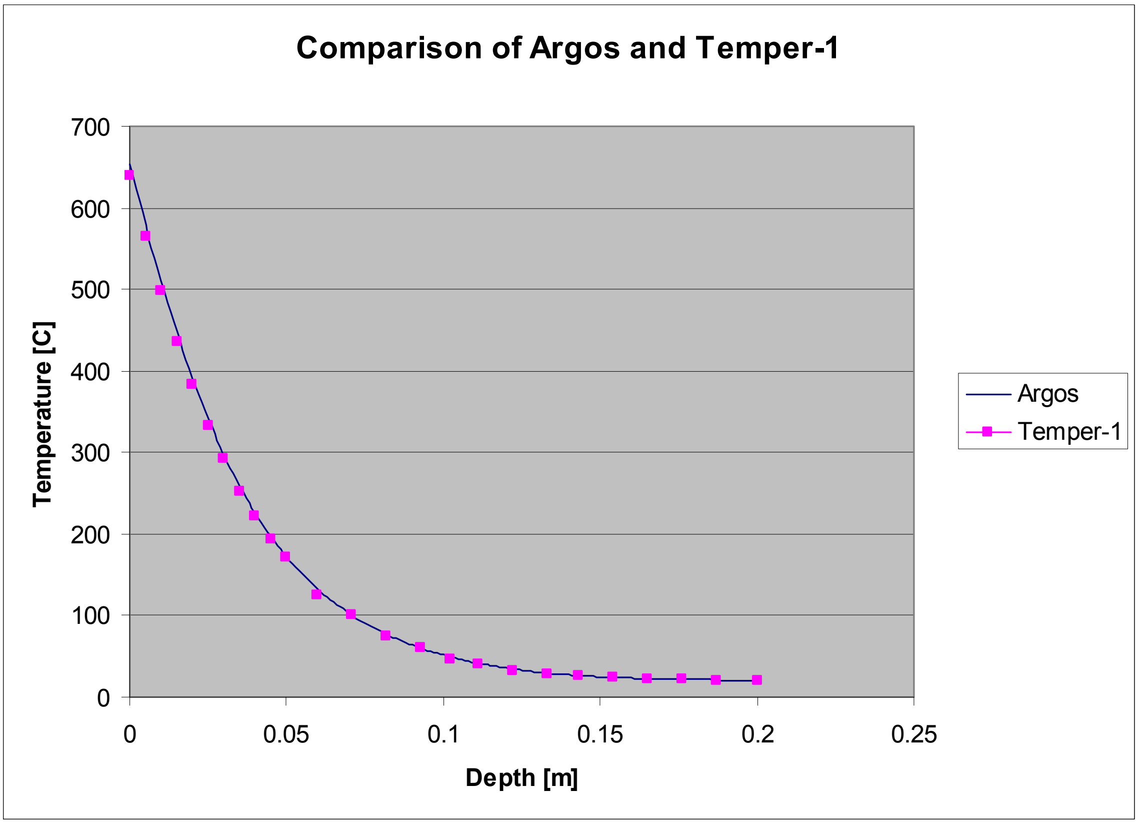


**Figure 11 Comparison of Argos and Temper-1**

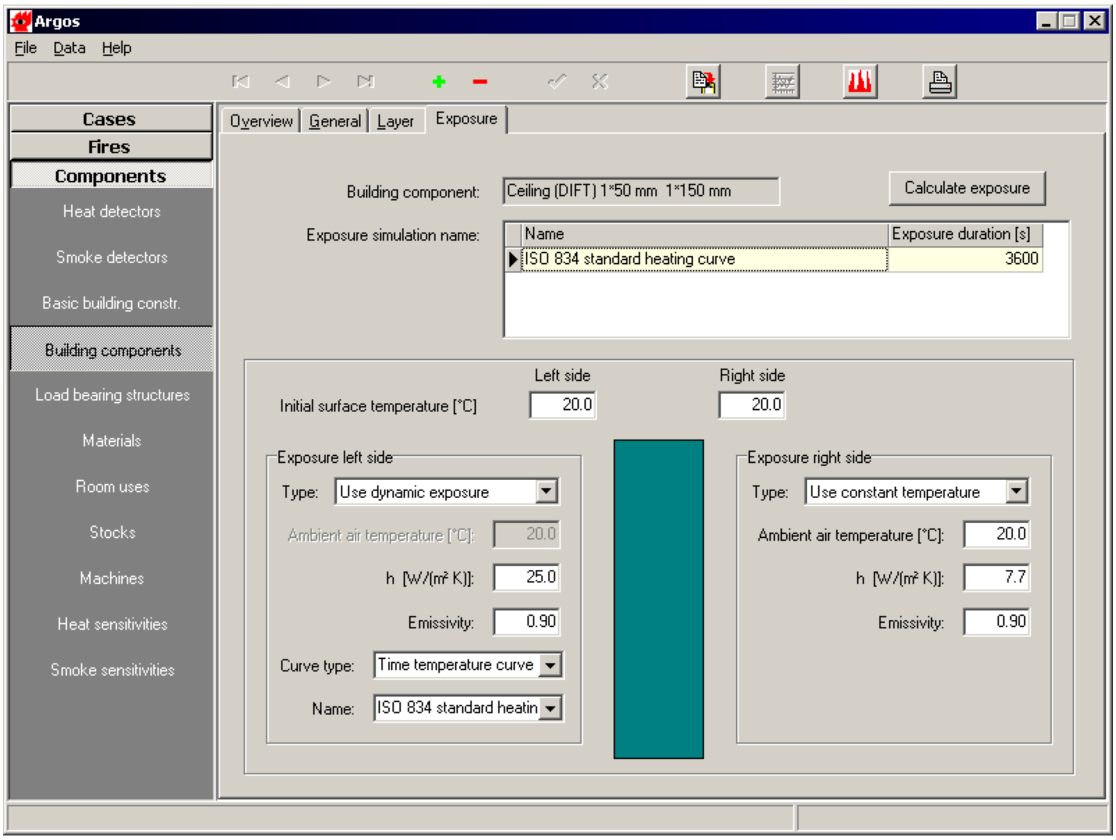
# 5. Cases with 2 layers of material

## 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.

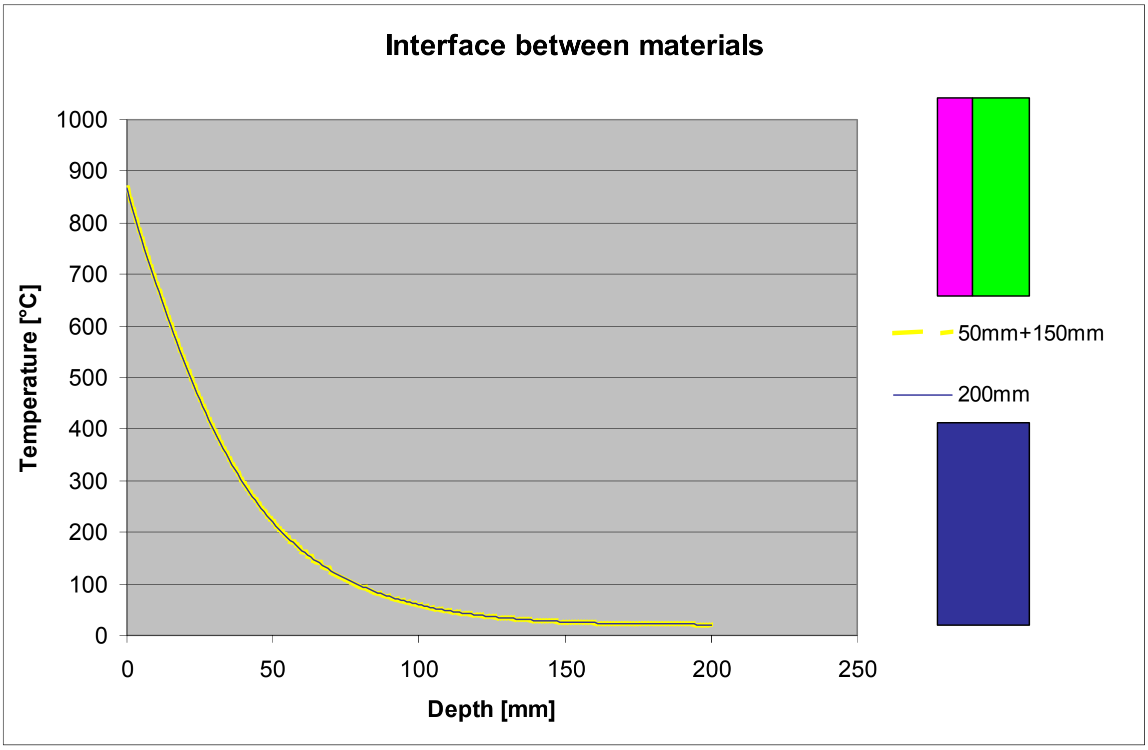


**Figure 13 Comparison of ceiling consisting of 2 layers of concrete and 1 layer of concrete**

## 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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An introduction to Computational Fluid Dynamics
Longman
England 1998

# 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
```