Danish Institute of Fire and Security Technology

ARGOS

Theory Manual

(Version 8.02)

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ARGOS

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Edited by

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Foreword

This document was initially written by Niels Baden, who was the main developer of the original DOS version of Argos in 1990.

Thomas W. Sødring was a co-editor on the 2002 version of this manual.

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1.1 Model for fire development and smoke transport in up to ten rooms

Introduction

The model for fire development and smoke transport is a zone model as described in mathematical detail by Quintiere (1989).

The following basic assumptions are made:

- Each room is divided into 1 or 2 zones; a zone of cold gas and possibly above that a zone of hot combustion gas with entrained air.
- A maximum of ten rooms can be modelled.
- Before flashover, the fire is initially fuel controlled but becomes ventilation controlled if the oxygen level goes below 10.5 %. For more details see chapter 1.2.

1.2 Rate of heat release from fire

The rate of heat release from the fire is described by seven different models:

- Solid material fire.
- Melting material fire.
- Liquid pool fire.
- Liquid tank fire.
- Smouldering fire.
- Energy formula.
- Data points.

The rate of heat release is assumed independent of the oxygen mole fraction in the fire room, as long as the minimum oxygen mole fraction in any gas layer in the fire room is more than 10.5%. This oxygen level is typical for extinction of flames due to oxygen depletion, as in e.g. Tsuchiya & Mathieu (1991). If the minimum oxygen mole fraction in the fire room is less than 10.5%, then the rate of heat release calculated by means of the above mentioned fire models is reduced by a factor equal to $X_{O2}/(10.5\%)$, where X_{O2} is the actual minimum oxygen mole fraction in [%]. This unsophisticated approach reflects today's lack of useful models for combustion in oxygen depleted atmospheres. However, it makes certain that the rate of heat release is zero, when there is no more oxygen. In the intermediate region, $0 < X_{O2} < 10.5\%$, it tends to overestimate the rate of heat release. Thus, from a safety point of view, the calculations will be on the safe side.

The rate of heat loss due to radiation is assumed to be a fraction χ_{rad} of the total rate of heat release, $\dot{Q}$ in [kW]. The default value for χ_{rad} is 0.35 (35%), cf. Lees (1980), but for fuels where χ_{rad} has been measured, the measured value is used.

Thus the convective heat release, $\dot{Q}_c$ in [kW], is calculated as

$$\dot{Q}_c = (1 - \chi_{rad}) \cdot \dot{Q}$$

Solid material fire

The model for fires in solid materials takes into account the geometry of the fire object and is especially suited for modeling of fires in objects with a large void fraction, for example piles of pallets or racks with combustible goods. The model is based on the following assumptions:

- The fire object has the shape of a box with a given height, width and length,
- The fire starts at floor level at the middle of the long side of the object,
- The velocity of horizontal flame spread is constant,
- The vertical flame spread is exponential,
- The rate of heat release per volume flame zone is constant and
- The time interval from ignition of a partial volume till the same partial volume is burnt out (i.e. the local burn out time) is constant.

For a fire object of infinite height, width and length, the above assumptions lead to the following expression for the rate of heat release, $\dot{Q}$ in [kW], as a function of time, t in [s]:

$$\dot{Q} = q_{volume} \cdot \frac{\Pi}{2} \cdot \beta^2 \cdot h_{f0} \cdot [t^2 \cdot 2^{\frac{t}{t_2}} - (t - t_{burnt})^2 \cdot 2^{\frac{t - t_{burnt}}{t_2}}]$$

where:

q_{volume} is the rate of heat release per volume in the flame zone in [kW/m^3],

ß is the velocity of horizontal flame spread in [m/s],

h_{f0} is the initial flame height in [m],

t_2 is the doubling time for vertical flame spread in [s] and

t_{burnt} is the local burn out time in [s].

The assumed initial flame spread before the horizontal boundaries of the fire object are reached is illustrated in figure 1.

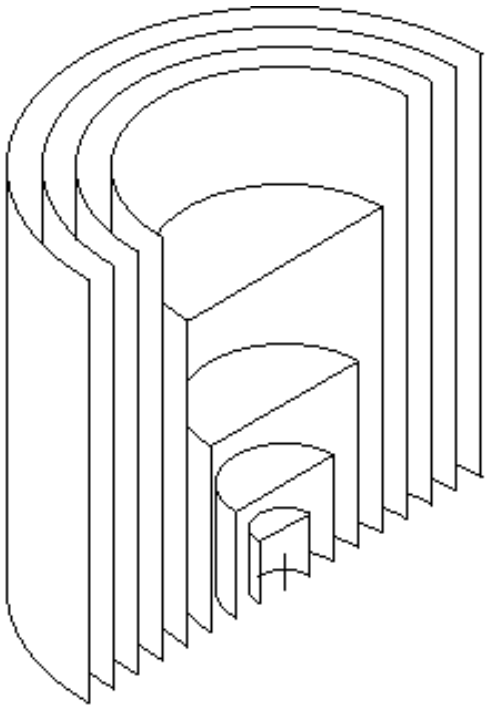

Figure 1: Flame spread in the solid material fire model.

The interaction with the horizontal boundaries of the fire object and the effect of the local burn out time is illustrated in figures 2 and 3.

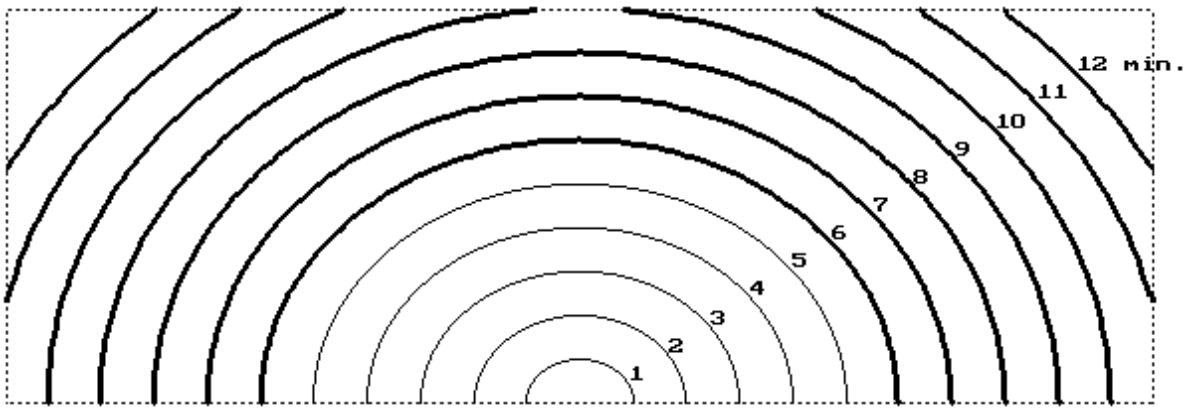

Figure 2: Horizontal flame spread in the solid material fire model. Ignition on long side. $t_{burnt} \approx 7$ min. Thick arcs correspond to the flame zone and thin arcs correspond to the burnt out zone.

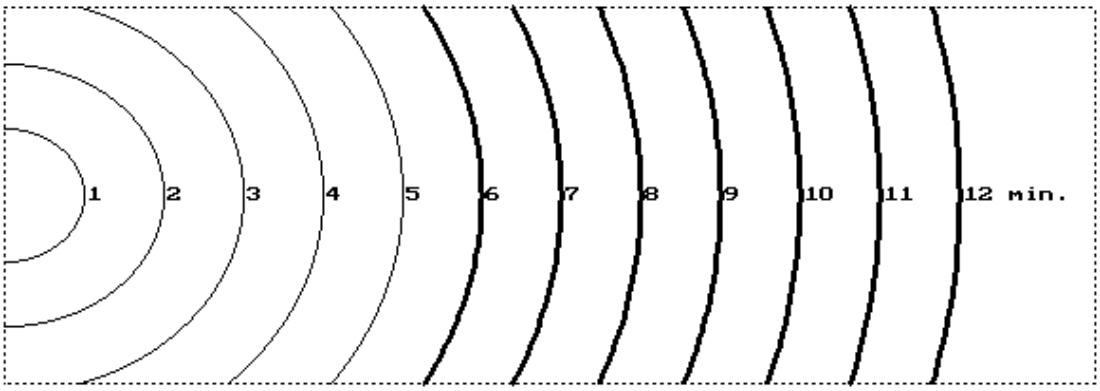

Figure 3: Horizontal flame spread in the solid material fire model. Ignition on short side. $t_{burnt} \approx 7$ min. Thick arcs correspond to the flame zone and thin arcs correspond to the burnt out zone.

Melting material fire

The model for fires in melting materials also accounts for the geometry of the fire object and is especially suited for modelling of fires in objects with a large void fraction, for example piles of polyethylene boxes. The model is based on the following assumptions:

- The fire object has the shape of a box with a given height, width and length.
- The fire object will gradually melt and burn as a pool fire underneath the object.
- The fire starts at the middle of the long side of the object.
- The velocity of horizontal flame spread is constant.
- The rate of heat release per area flame zone is constant.
- The time interval from ignition of a partial area till the same partial area is burnt out (i.e. the local burn out time) is proportional to the height of the object.

For a fire object of infinite width and length, the above assumptions lead to the following expression for the rate of heat release, $\dot{Q}$ in [kW], as a function of time, t in [s]:

$$\dot{Q} = q_{area} \cdot \frac{\pi}{2} \cdot \beta^2 \cdot [t^2 - (t - t_{height} \cdot H_{object})^2]$$

where:

q_{area} is the rate of heat release per area in the flame zone in [kW/m^2],

ß is the velocity of horizontal flame spread in [m/s],

t_{height} is the local burn out time per height of fire object in [s/m] and

H_{object} is the height of the fire object.

The interaction with the horizontal boundaries of the fire object and the effect of the local burn out time is the same as shown in figures 2 and 3 for fires in solid materials.

Liquid pool fire and liquid tank fire

The model for fires in liquids consists of 2 parts.

Firstly the heat release per area from a pool fire is calculated. This is to reflect the fact that heat release is influenced by the diameter of the fire. A fire covering a small area has a lower heat release rate per area than a fire covering a larger area. For more details, see Vytenis Brabrauskas, Heat Release Rates, Chapter 3-1, SFPE Handbook, 4th. edition, USA 2008.

The heat release per area is initially adjusted using the following formula based on the calculated maximum diameter and this value is used throughout the calculation:

$$q_{pool\_actual}'' = q_{pool\_max}'' \cdot (1 - e^{-k\beta * D})$$

q_{pool_actual}'' is the actual heat release rate per area

q_{pool_max}'' is the maximum heat release rate for a very large fire, corresponding to the field "Max. heat release rate" for liquid pool fires and liquid tank fires.

$k\beta$ is a physical constant depending on the fuel type and

D is the maximum calculated diameter of the pool (liquid pool fire or liquid tank fire)

For pool fires, the rate of heat release, q_{pool} in [kW], is calculated by means of the formula:

$$q_{pool} = q_{area\_actual}'' \cdot \mathrm{Min}\{ A_{\max}, \frac{V_1}{\delta_1} \}$$

where:

q_{area_actual}'' is the rate of heat release per area in [kW/m^2],

A_{max} is a specified maximum pool area in [m^2],

V_l is the net volume of liquid in [m^3] and

δ_l is equal to 0.01 m, the assumed minimum depth of the liquid pool.

That the fire will spread across the surface with a given rate is also taken into account. Thus the rate of heat release for a pool fire, $\dot{Q}$ in [kW] becomes:

$$\dot{Q} = \mathrm{Min}\{\alpha \cdot t^2, q_{pool}\}$$

where α is the parabolic fire growth parameter in [kW/s^2].

For liquid tank fires the formulas are more complex. A good description of the overall principles is given in the Argos User's Guide.

Smouldering fire

With this fire model, the rate of heat release is assumed to be equal to a specified constant value ($\dot{Q}$ in [kW]).

Energy formula

With this fire model, the rate of heat release, $\dot{Q}$ in [kW], is calculated by means of the formula:

$$\dot{Q} = \mathrm{Min}\ \{(A - F) \cdot t^2 + B \cdot t + C \cdot 1000 + D \cdot 2^{\frac{t}{E}}, q_{max} \cdot 1000\}$$

where t is the time from ignition in [minutes]. A, B, C, D, E, F and q_{max} are specified parameters.

Data points

With this fire model, the rate of heat release is determined by linear interpolation between specified values of $\dot{Q}$ and t.

1.3 Entrainment of air into hot gas plume from fire

The entrainment of air into the hot gas from the fire is modelled by use of an empirical expression. In Argos, two possibilities exist, the plume model by Heskestad (SPFE handbook, 2008) or the plume model by McCaffrey (1983).

Heskestad's formula is the preferred method, especially for strong plumes (large fires), because it does not use the Boussinesq approximation and it also takes the area of the fire into account. But the McCaffrey model, which was the original plume model in Argos, can also be used.

Heskestad plume model

The mass flow rate, m in [kg/s], with the rate of convective heat release, Q_c in [kW], and the height above the source of heat, z in [m], is calculated from the following equations:

Below flame:

$$m = 0 \qquad z \le 0$$

Flame region:

$$m = 0.0059 \cdot \dot{Q}_c \cdot \frac{z}{L} \qquad 0 < z \le L$$

Above height of flame:

$$m = 0.071 \cdot \dot{Q}_c^{1/3} \cdot (z - z_0)^{5/3} + 0.001917 \cdot \dot{Q}_c \qquad z > L$$

The formula for the flame height, L [m], is given in chapter 2.1. The formula for the virtual origin z_0 is given below

$$z_0 = 0{,}083\dot{Q}^{2/5} - 1.02D \text{ [m]}$$

where

$\dot{Q}$ is the rate of heat release (RHR) [kW] and

$D = \sqrt{\frac{4 \cdot Fire\ Area}{\Pi}}$: Diameter of the fire [m]

McCaffrey plume model

The variation of the mass flow rate, m in [kg/s], with the rate of convective heat release, Q_c in [kW], and the height above the source of heat, z in [m], is calculated from the following equations:

Continuous flame:

$$\frac{m}{\dot{Q}_c} = 0.011 \cdot \left(\frac{z}{\dot{Q}_c^{0.4}} \right)^{0.566} \qquad \text{for } 0 < \frac{z}{\dot{Q}_c^{0.4}} < 0.08$$

Intermittent:

$$\frac{m}{\dot{Q}_c} = 0.026 \cdot \left(\frac{z}{\dot{Q}_c^{0.4}} \right)^{0.909} \qquad \text{for } 0.08 < \frac{z}{\dot{Q}_c^{0.4}} < 0.20$$

Plume:

$$\frac{m}{\dot{Q}_c} = 0.124 \cdot \left(\frac{z}{\dot{Q}_c^{0.4}} \right)^{1.895} \qquad \text{for } 0.20 < \frac{z}{\dot{Q}_c^{0.4}} < \infty$$

For fires, the source of heat is assumed to be at floor level. Thus if the distance from floor to hot gas layer is z and the convective heat release rate from the fire is $\dot{Q}_c$, then the mass flow rate of hot gas with entrained air into the hot gas layer will be m.

1.4 Criteria for formation and diminishing of hot gas layers

The criterion for formation of hot gas layers is based on a formula presented by Alpert (1972).

Heat input to a room will result in a jet stream of hot gas and smoke under the ceiling. Formation of a hot gas layer is only allowed if the temperature of the jet stream is 10 K higher than the room temperature when it reaches a wall at the greatest possible horizontal distance from the source of heat. For this purpose, it is assumed that the net convective heat input to the room from fire and from other rooms enters the room at floor level. Thus this criterion should be disabled if the heat actually enters the room near the ceiling. This can be done by specifying the greatest possible horizontal distance in the room, r_{max}, equal to zero.

The jet stream temperature, T_{jet} in [K], is calculated according to the empirical formula:

$$T_{jet} = T_0 + \frac{5.38}{h} \cdot \left(\frac{\dot{Q}_c}{(1 - \chi_{rad}) \cdot r_{max}} \right)^{\frac{2}{3}}$$

where:

T_0 = 293.15 K is the initial room temperature,

$\dot{Q}_c$ is the net rate of convective heat input to the room from fire and from other rooms in [kW],

r_{max} is the greatest horizontal distance in the room in [m],

h is the height of the room in [m] and

χ_{rad} the radiative fraction of the rate of heat release [-].

The hot gas layer will diminish:

- If the mass content corresponds to less than 0.001 times the room volume filled with air at T_0, or

- If the temperature is less than T_0 + 0.3 K.

1.5 Transport of gases between rooms

The transport of gases between rooms and between rooms and surroundings is determined by:

- The stationary pressure balance for each room.
- Back-mixing through horizontal vents, cf. Cooper (1989).
- The heat balance for the hot gas layer in each room, cf. Quintiere (1989) equation (40).
- The mass balance for the hot gas layer in each room, cf. Quintiere (1989) equation (30a).

1.6 Pressure balance

When stating the stationary pressure balance, it is assumed that the time derivative of the pressure, dP/dt, can be neglected. Quintiere (1989) p. 112-13 has by means of example calculations verified this assumption for typical fire scenarios. However, if the stationary pressure balances are used for simulation of explosions in large rooms with small openings, then the increase in pressure will be overestimated.

The stationary pressure balance leads to the following algebraic equation for each room:

$$\sum_{\substack{j \\ \text{(net inlet)}}} v_j + \sum_{\substack{j \\ \text{(net inlet)}}} \frac{q_j \cdot R}{P_0 \cdot M_w \cdot C_p} = 0$$

where:

q_j is the direct heat input (positive or negative) in [kW] from a building component or from the fire (q_c = 0.65·),

R = 0.0820562 atm·m^3/(kmole·K) is the ideal gas constant,

P_0 = 1 atm,

M_w = 28.965 g/mole is the average molecular weight of air,

C_p = 1.00464 kW·s/(kg·K) is the heat capacity of air and

v_j is the volumetric flow (positive or negative) in [m^3/s] through an opening into the room.

The volumetric flow is determined by integration of the Bernoulli equation across the opening in question, see e.g. Quintiere (1989) equations (25) and (26), i.e.:

$$v = C_B \cdot w \cdot \int_{h_0}^{h+h_0} \sqrt{\frac{2}{\rho_j} \cdot [P_j(z) - P_i(z)]} \cdot dz$$

where:

P_i, P_j is pressure in room i and j in [Pa] at height z,

z is the height above the floor in [m],

w is the width of the opening in question in [m],

h is the height of the opening in question in [m],

h_0 is the height from the floor to the opening in question in [m]

C_B = 0.7 is the Bernoulli flow coefficient, cf. e.g. Quintiere (1989),

ρ_j = $\rho_0 \cdot (T_0/T_j)$ is the density of the gas in question,

T_j is the temperature in [K] of the gas in question,

T_0 = 293.15 K and

ρ_0 = 1.199 kg/m^3 is the density of air at 293.15 K.

The pressure in a given room at height z is determined by the equation:

$$P(z) = P(0) - \int_0^z \rho_0 \cdot g \cdot \frac{T_0}{T} \cdot dz$$

where:

T_0 = 293.15 K,

T = is the temperature in [K] in the room at the given height above the floor and

g = 9.81 m/s^2 is the acceleration due to gravity.

It is possible to specify a wind speed, u_w, for outside each room, so the model includes a corresponding wind pressure, $\Delta p_w = \rho_0 \cdot (u_w)^2/2$, for all vertical openings (for example doors and windows) from the room to the surroundings. The default value is u_w = 0 m/s for all rooms.

Note:

In the DOS version of Argos, the default values are u_w = 5 m/s outside the fire room (towards opening), and u_w=0 elsewhere. Setting u_w = 0 m/s is a more conservative assumption.

1.7 Back-mixing

When the pressure difference Δp in [N/m^2], across a horizontal vent is smaller than a certain limit, Δp_{flood} in [N/m^2], then some back-mixing will take place. Application of Cooper's equations (16), (19), (20) and (21) for circular vents leads to the following expression for back-mixing, v_{back} in [m^3/s]:

$$v_{back} = N_v \cdot \frac{1}{10} \cdot \sqrt{2 \cdot g \cdot (A_v)^{\frac{5}{2}} \cdot \frac{\Delta\rho}{(\rho_1 + \rho_2)}} \cdot \left(1 - \frac{|\Delta p|}{\Delta p_{flood}}\right)$$

where:

$$\Delta p_{flood} = \frac{2^{11}}{15^2 \cdot \pi^{5/2}} \cdot g \cdot \Delta\rho \cdot \sqrt{A_v} \ ,$$

N_v is the number of horizontal vents,

A_v is the area of each vent in [m^2],

$\rho_{1\&2}$ is the gas density on each side of the vent in [kg/m^3] and

$\Delta\rho$ $= |\rho_1 - \rho_2|$

For smoke vents only, the total venting area, A_{tot} in [m^2], is specified in ARGOS. In this case N_v and A_v are determined as:

N_v = Min{ N | $A_{tot}/N < 2$ m^2 } and

$A_v = A_{tot}/N_v$.

The back-mixing flow appears in the heat and mass balances but it has no direct influence on the pressure balance.

1.8 Heat balance

The following assumptions are made when stating the heat transport equations for the building:

- All building components facing the hot gas layer in a given room are identical with the ceiling base in that room.
- The rear side of the exposed building component is always facing the surroundings.
- A subarea of an exposed building component immediately assumes the same temperature profile as the ceiling, as soon as it is reached by the hot gas layer. The corresponding immediate heat transfer from the hot gas layer is not accounted for.
- If there is no hot gas layer in the room in question and the criterion for formation of a hot gas layer is not satisfied, then the incoming heat is assumed to be lost. The corresponding gas contraction is accounted for in the pressure balance, as described above in chapter 1.6.

The heat balance for the gases in each room leads to the following differential equation:

$$\frac{dQ}{dt} = \sum_{\substack{j \\ (net\ inlet)}} C_p \cdot \left(T_j - T_0 \right) \cdot \rho_0 \cdot \frac{T_0}{T_j} \cdot v_j + \sum_{\substack{j \\ (net\ inlet)}} q_j$$

where:

Q is the heat content in the hot gas layer in [kWs],

t is the time in [s] from ignition,

C_p = 1.00464 kW·s/(kg·K) is the heat capacity of air,

T_j is the temperature in [K] of the gas in question,

T_0 = 293.15 K,

ρ_0 = 1.199 kg/m^3 is the density of air at 293.15 K,

v_j is the volumetric flow (positive or negative) in [m^3/s] through an opening into the room and

q_j is the heat input (positive or negative) in [kW] from a building component or from the fire (q_c = 0.65·).

The heat loss, $-q_j$, from a gas to a building component is determined by the following heat balance for the surface of the building component:

$$-q_j = A \cdot [h_c \cdot (T - T_s) + \varepsilon_e \cdot \sigma_{SB} \cdot (T^4 - T_s^4)]$$

where:

A is the exposed surface area in [m^2] of the building component in question,

T is the temperature in [K] of the gas in question,

T_s is the temperature in [K] of the exposed surface,

σ_{SB} = 5.67·10^{-11} kW/(m^2·K^4) is the Stefan-Boltzmann constant,

ε_e = 0.9 is the effective emissivity for radiative heat transfer between the exposed building surface and room gas or surrounding air and

h_c is the film coefficient for convective heat transfer.

The following assumptions are made:

h_c = 0.0115 kW/(m^2·K) for surfaces exposed to room gases and

h_c = 0.0077 kW/(m^2·K) for surfaces exposed to the surrounding air.

The value h_c = 0.00115 kW/(m^2·K) is the maximum value obtainable for $T_s \geq 293.15$ K from the following practically constant function given by Jones & Peacock (1989):

$$h_c = \frac{\kappa}{l} \cdot C_0 \cdot (Gr \cdot Pr)^{1/3}$$

where:

$$Gr = g \cdot l^3 \cdot \frac{|T - T_s|}{\nu^2 \cdot T} \quad \textit{is the Grashof number}$$

$$\kappa = 2.72 \cdot 10^{-4} \cdot \left(\frac{T + T_s}{2} \right)^{4/5} \frac{W}{m \cdot °K} \quad \textit{is the thermal conductivity of the gas}$$

Pr = 0.72 is the Prandtl number,

L is an arbitrary length scale in [m],

$\nu = 7.18 \cdot 10^{-10} \cdot \left(\frac{T + T_s}{2} \right)^{7/4} m^2/s$ is the kinematic viscosity of the gas and

C_0 = 0.21, corresponding to heat transfer from the hot gas to the cold horizontal surface.

The heat transfer through a building component is determined by the following partial differential equation

$$\rho(T_m)\cdot C_p(T_m)\cdot\frac{\delta T_m}{\delta t}=\frac{\delta}{\delta x}\left(\lambda(T_m)\cdot\frac{\delta T_m}{\delta x}\right)$$

where:

T_m is the temperature in [K] of the solid material at the given position in the building component,

t is the time in [s] from ignition,

$\rho(T_m)$ is the density in [kg/m^3] of the solid material,

$C_p(T_m)$ is the heat capacity in [kJ/(kg·K)] of the solid material and

$\lambda(T_m)$ is the thermal conductivity in [kW/(m·K)] of the solid material.

All the parameters (ρ, C_p and λ) are functions of the temperature of the solid material.

1.9 Mass balance

The following assumptions are made when stating the mass balance for the hot gas layer in each room:

- All hot gas or cold gas flowing into a hot gas layer is mixed with the hot gas in the hot gas layer.
- Hot gas flowing into a cold gas layer rises towards the hot gas layer (or the ceiling) and at the same time cold gas is entrained.
- If an opening includes a hot gas layer boundary, or if the flow direction changes within an opening, then the opening is divided into sub-openings.

The entrainment of cold air into the plume is determined by application of McCaffrey's empirical expressions. For each individual sub-opening a virtual heat source is determined. The distance from floor to the virtual heat source is determined, so that the mass flow and the plume temperature at the vertical position corresponding to the centre of the sub-opening (i.e.: z = h° + h/2) is the same as the mass flow through the sub-opening and the temperature of the hot gas flowing through the sub-opening. Thus the mass input to the hot gas layer is determined as if it came from the virtual heat source.

The mass balance for the hot gas layer in each room leads to the following differential equation:

$$\frac{dM}{dt} = \sum_{\substack{j \\ (net\ inlet)}} \rho_0 \cdot \frac{T_0}{T_j} \cdot v_j$$

where:

M is the mass content in the hot gas layer in [kg],

t is the time in [s] from ignition,

T_j is the temperature in [K] of the gas in question,

T_0 = 293.15 K,

ρ_0 = 1.199 kg/m^3 is the density of air at 293.15 K and

v_j is the volumetric flow (positive or negative) in [m^3/s] into the hot gas layer.

1.10 Oxygen balance

It is assumed that all combustion products from the fire enter the hot gas layer in the fire room. If no hot gas layer exists, then the combustion products enter the cold gas in the fire room.

The oxygen balance for the gas layers in each room leads to the following differential equation:

$$\frac{dM_{O_2}}{dt} = -\frac{\dot{Q}}{\Delta H_{air} \cdot \rho_0} \cdot (C_{O_2})_{ref} + \sum_{\substack{j \\ (net\ inlet)}} (C_{O_2})_j \cdot v_j$$

where:

M_{O2} is the oxygen content in [kmole] in the gas layer in question,

t is the time in [s] from ignition,

$\dot{Q}$ is the total rate of heat release in [kW] from the fire,

ΔH_{air} = 3000 kJ/kg air is the lower heat of combustion per kg air,

ρ_0 = 1.199 kg/m^3 is the density of air at 1 atm and 293.15 K,

$(C_{O2})_{ref}$ is the oxygen concentration in [kmole/m^3] in ambient air at 1 atm and 293.15 K,

$(C_{O2})_j$ is the oxygen concentration in [kmole/m^3] in the gas in question and

v_j is the volumetric flow (positive or negative) in [m^3/s] into the gas layer in question.

1.11 Smoke balance

It is assumed that all smoke from the fire enters the hot gas layer in the fire room. If no hot gas layer exists, then the smoke enters the cold gas in the fire room.

The smoke balance for the gas layers in each room leads to the following differential equation:

$$\frac{dS_{tot}}{dt} = \frac{\dot{Q}}{\Delta H_{air} \cdot \rho_0} \cdot S_0 + \sum_{j \text{ (net inlet)}} S_j \cdot v_j$$

where:

S_{tot} is the smoke content in [dB·m^2] or [ob·m^3] in the gas layer in question. Thus, S_{tot} = N dB·m^2 is the amount of smoke,which will be able to fill a volume of N m^3 with a smoke obscuration of 1 dB/m.

t is the time in [s] from ignition,

$\dot{Q}$ is the total rate of heat release in [kW] from the fire,

ΔH_{air} = 3000 kJ/kg air is the lower heat of combustion per kg air and

ρ_0 = 1.199 kg/m^3 is the density of air at 1 atm and 293.15 K,

S_0 is the optical smoke potential in [dB/m] for the burning material. S_0 is defined as the amount of smoke produced per volume of air (at 1 atm and 293.15 K) consumed by combustion with 100% oxygen conversion. S_0 relates to the smoke obscuration potential, D_0 in [dB·m^2/kg], of Rasbash & Phillips (1978) by the following equation:

$$S_0 = D_0 \cdot \frac{\Delta H_{air}}{\Delta H_{mat}} \cdot \rho_0$$

where:

ΔH_{mat} is the lower heat of combustion in [kJ/kg material] for the material in question.

S_j is the smoke density in [dB/m] or [ob] in the gas in question and

v_j is the volumetric flow (positive or negative) in [m^3] into the gas layer in question.

1.12 Heat radiation from hot gas layer

The heat radiation, q_{floor} in [kW/m^2], from the hot gas layer to the floor is calculated as

$$q_{floor} = \Phi \cdot \varepsilon_\varepsilon \cdot \sigma_{SB} \cdot T^4$$

where:

T is the hot gas layer temperature in [K],

σ_{SB} = 5.67·10^{-11} kW/(m^2·K^4) is the Stefan-Boltzman constant,

ε_e = 0.9 is the effective emissivity of the hot gas layer. (The value of the effective emissivity is debatable; Magnusson et al. (1974) suggest ε_e = 0.85, whereas Drysdale (1985) suggests ε_e = 1) and

Φ is the configuration factor.

The configuration factor corresponds to a point at floor level in the middle of a rectangular room. If the actual room is not rectangular, then the calculations are performed for an equivalent rectangular room with the same perimeter and area as the actual room. From the formula given by DiNenno (1988), we get the following expression for the configuration factor:

$$\Phi = \frac{\frac{2}{\pi}\cdot\frac{L}{2\cdot Z}}{\sqrt{1+\left(\frac{L}{2\cdot Z}\right)^2}}\cdot \mathrm{Arctan}\left(\frac{\frac{W}{2\cdot Z}}{\sqrt{1+\left(\frac{L}{2\cdot Z}\right)^2}}\right)$$

$$+ \frac{\frac{2}{\pi}\cdot\frac{W}{2\cdot Z}}{\sqrt{1+\left(\frac{W}{2\cdot Z}\right)^2}}\cdot \mathrm{Arctan}\left(\frac{\frac{L}{2\cdot Z}}{\sqrt{1+\left(\frac{W}{2\cdot Z}\right)^2}}\right),$$

where:

W is the width of the rectangular room in [m],

L is the length of the rectangular room in [m] and

Z is the distance from the floor to the hot gas layer in [m].

1.13 Heat detectors

The performance of heat detectors is simulated in accordance with Alpert (1972).

The temperature, T_{bulb} in [C] of the sensitive element in a heat detector is determined by the following differential equation:

$$\frac{d(\Delta T_{bulb})}{dt} = \frac{\sqrt{U}}{RTI}\left(\Delta T_{jet} - \left(1 + \frac{C}{\sqrt{u}}\right)\Delta T_{bulb}\right)$$

$$\Delta T_{jet} = T_{jet} - T_{amb}$$

$$\Delta T_{bulb} = T_{bulb} - T_{amb}$$

where:

T_{jet} is the temperature of the hot gas jet in [K],

T_{bulb} is the temperature of the sprinkler bulb,

T_{amb} is the ambient temperature

u is the linear velocity of the hot gas jet in [m/s],

t is the time in seconds

RTI is the response time index in $(m \cdot s)^{1/2}$ and

C is the heat conduction loss to sprinkler fittings in $(m/s)^{1/2}$

The parameter C is the heat conduction loss to the sprinkler fittings. A low value of C means that energy loss to the sprinkler fittings is low and a high value means a high loss of energy.

There is no energy loss to the sprinkler fittings when the value of C is 0 and the two-parameter response model is reduced to the one parameter response model, used in the previous version of Argos (this model is also the most widespread). The default value for C is 1.

This model is also used for the calculation of activation of standard heat detectors. Heat detectors do not have a heat loss to other components, such as cold pipes, so for a heat detector, the value of C should be set to 0. A typical RTI value for a heat detector is 1, as they are mainly characterised by their activation temperature.

A typical RTI value for a sprinkler lies in the range from 20 to 200 $(m \cdot s)^{½}$. See figure 4 below. This figure also shows limits on the value of C.

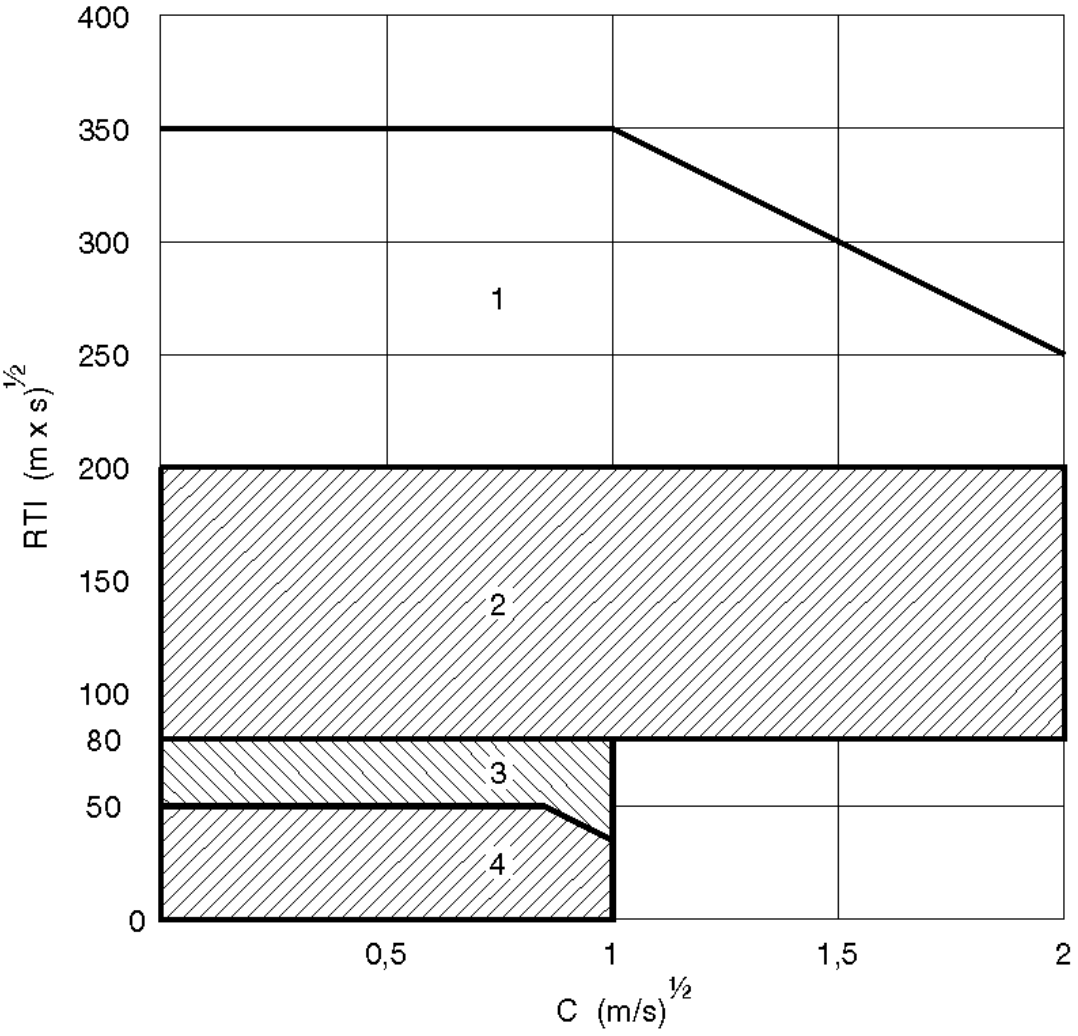

Figure 4 Relationship between C and RTI for different sprinkler types

1. Standard B (Old type of sprinkler bulb - fat bulbs)
2. Standard A
3. Special response
4. Quick response

When calculating T_{jet} and U, it is assumed that the net convective heat input to the room from fire and from other rooms enters the room at floor level. Thus, the response time will be overestimated if the heat actually enters the room near the ceiling. The calculated response time can be reduced by specifying a very short horizontal distance from the source of heat to the detector.

The jet stream temperature is calculated according to the empirical formula:

$$T_{jet} = T_0 + \frac{16.9}{h} \cdot \left(\frac{q_c}{(1-\chi_{rad}) \cdot h} \right)^{\frac{2}{3}} \quad \text{for } \frac{r}{h} \leq 0.18 \text{ and}$$

$$T_{jet} = T_0 + \frac{5.38}{h} \cdot \left(\frac{q_c}{(1-\chi_{rad}) \cdot r} \right)^{\frac{2}{3}} \quad \text{for } \frac{r}{h} > 0.18$$

where:

T_0 = 293.15 K is the initial room temperature,

q_c is the net rate of convective heat input to the room from fire and from other rooms in [kW],

r is the horizontal distance in [m] from the source of heat to the detector

h is the height of the room in [m].

χ_{rad} is the fraction of RHR radiated by the fire [-] ($0.01 < \chi_{rad} < 0.99$)
a typical value is 0.35, which means 35 % of the rate of heat release is released as radiation and the remaining 65% as convective heat.
Therefore $(1-\chi_{rad})$ is the convective fraction of RHR.

If the calculated value of T_{jet} is lower than the temperature T of the hot gas layer in the room in question, then T_{jet} is set equal to T.

The jet stream linear velocity is calculated according to the empirical formula:

$$U = 0.947 \cdot \left(\frac{q_c}{(1-\chi_{rad}) \cdot h} \right)^{1/3} \quad \text{for } \frac{r}{h} \leq 0.15 \text{ and}$$

$$U = 0.197 \cdot \left(\frac{q_c}{(1-\chi_{rad})} \right)^{1/3} \cdot \frac{\sqrt{h}}{r^{5/6}} \quad \text{for} \frac{r}{h} > 0.15$$

If the calculated value of U is less than 0.1 m/s, then U is set equal to 0.1 m/s.

In the calculations, it is assumed that the source of hot gas is situated in the centre of a square with a detector in each corner. Thus the horizontal distance from the source of hot gas to the detector, r, is set equal to the specified distance between detectors divided by √2.

1.14 Response time for fire department

The time from receiving the alarm to leaving the fire station is assumed to be 2 minutes for stations with 24-hour attendance (service) and otherwise 5 minutes.

The driving speed is assumed to be 0.7 km/min in city areas and otherwise 1 km/min.

It is assumed that after arriving at the fire, the fire brigade needs 1 minute for preparation before extinguishing is started.

1.15 Extinguishing

Extinguishing by automatic water sprinklers and by the fire brigade is simulated by use of the same simple empirical model. The rate of heat release after extinguishing which has started at the time t_e in [s] is calculated as follows:

$$\dot{Q}(t) = \dot{Q}(t_e) \qquad t_e < t < (t_e + 30s)$$

$$\dot{Q}(t) = \dot{Q}(t_e) - \frac{t - t_e - 30s}{0.03\ \frac{s}{kW}} \qquad (t_e + 30s) \leq t < (t_e + 30s + q_{fire}(t_e) \cdot 0.03\ \tfrac{s}{kW})$$

where

$\dot{Q}\ (t_e)$ is the rate of heat release at the time, when extinguishing is started.

2 Fire graphs

Graphs for rate of heat release (RHR), accumulative energy release, fire area, flame height, safety distance and plume mass flow can be viewed in the database for fires by using the “Show fire graphs” button. These graphs are for free-burning fires.

It should be noted that for the Energy Formula Fire and the Data Point Fire, the rate of heat release per area is taken from the parameters menu. This is done in order to calculate the area of the fire. The default value for this parameter is 500 kW/m^2 but it can be changed in the parameters menu (See the Argos User’ Guide for details).

Setting the rate of heat release per area to a higher value, for example the value for hexane (3.45 MW/m^2), makes the calculations more conservative, since the flame from a hexane fire (high energy release pr. m^2) is slim and tall and thus more radiant.

2.1 Calculation of flame height

Flame height is calculated from the following equation.

$$L = 0{,}235\dot{Q}^{2/5} - 1.02D \text{ [m]}$$

where

$\dot{Q}$: Rate of heat release (RHR) [kW] and

$D = \sqrt{\frac{4 \cdot Fire\ Area}{\Pi}}$: Diameter of the fire [m]

2.2 Calculation of safety distance

Safety distance is the distance from the edge of the flaming zone in meters at which radiation levels are either 1, 2.5, 5, 10 or 15 kW/m^2. These levels have been chosen for determining the risk of injury to persons and the risk of flame spread to an nearby object, as explained below. See also page 153 in the Argos User's Guide for more information.

Exposure of humans

- 1 kW/m^2 for indefinite skin exposure
- 2.5 kW/m^2 for a maximum of 5 minutes.
- 5 kW/m^2 is a typical upper limit for short-term exposure (maximum 10s exposure).
- 10 kW/m^2 is a typical upper limit for fire fighters in protective clothing.

Risk of flame spread

- 15 kW/m^2 is a typical lower limit for pilot ignition of combustible materials.

Radiation from flames can be calculated in different ways, thereby giving different results. A comparison with a point method is made at the end of this section.

When the height and the diameter of the flame has been calculated, the results are used to calculate the safety distance graph.

In Argos, the flame is approximated by a vertical rectangle ($L \cdot D$), and the net radiation of one face of this rectangle equals

$$E = \frac{Q_{radiation}}{Area} = \frac{1}{4} \cdot \frac{\chi_{rad} \cdot RHR}{L \cdot D} \quad [kW/m^2J$$

χ_{rad}: Fraction of RHR radiated by the fire (default is 0.35)

The radiant flux at a given distance and at a height of $0.5 \cdot flame\,height\ (L)$ can be obtained from

$$q_r = 4 \cdot E \cdot \Phi \text{ [kW/m}^2\text{]}$$

where

$\Phi = f\left(\frac{l}{2}, \frac{D}{2}, R\right)$: configuration factor and

R : Distance from centre of fire to target

The safety distance is calculated from the edge of the fire to the radiant flux of interest and is obtained from

Safety distance = $R - \frac{D}{2}$ [m]

2.3 Uncertainty in radiation calculations

Radiation from a flame varies with the amount of soot in the flame at different heights. Furthermore, flames are not square. This makes it very difficult to make precise predictions of radiation levels close to a flame.

A method of estimating the radiant flux at a given distance is to assume that $Q_{radiation}$ originates from a point source on the flame axis at a height $0.5 \cdot flame\,height$ above the fuel surface. The radiant flux at distance *R* is determined by

$$q_r = \frac{\alpha \cdot RHR}{4 \cdot \pi \cdot R^2}$$

If more accuracy is required, multiple point sources are defined and the radiant flux at $0.5 \cdot flame\,height$ and distance R - D/2 (from the edge of the fire) is calculated. To illustrate the different values obtained with these methods, the results from a pool fire of 10 MW and a diameter of 2 meters are shown in the following table.

Radiant flux [kW/m^2]	Safety distance, R-D/2 [m]			
	Configuration factor ϕ (Argos)	20 points	5 points	1 point
1.0	15.40	15.57	15.61	15.69
2.5	9.12	9.36	9.37	9.56
5.0	5.85	6.20	6.21	6.46
10.0	3.43	3.91	3.92	4.28
15.0	2.28	2.88	2.89	3.31

It can be seen from the table that the further away from the fire, the smaller the difference in the results, i.e. it is of minor importance which method is being used for the calculation. Closer to the fire, there is a larger variation in the results.

In the methods used to calculate the radiant flux, there are several simplified assumptions, as noted in the beginning of this section. This will lead to an overestimation of the radiant flux, in particular for the point method.

Therefore the configuration factor method is used in Argos, though caution is required when calculating radiation close to the flame.

There are five graphs available for each of the different fire types, except for the smouldering fire. A smouldering fire will not have flames and therefore only graphs for rate of heat release (RHR) and accumulative energy release are available.

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