A deterministic and probabilistic model for oilspill fires in nuclear power plants: a final report to the Swedish Atomic Energy Board

Karlsson, Björn

1989

LUND UNIVERSITY · SWEDEN
INSTITUTE OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF FIRE SAFETY ENGINEERING
CODEN: SE-LUTVDG/TVBB-3049
ISSN 0284-933X

BJÖRN KARLSSON

A DETERMINISTIC AND PROBABILISTIC MODEL FOR OILSPILL FIRES IN NUCLEAR POWER PLANTS

A final report to the Swedish Atomic Energy Board.

LUND 1989

Table of contents

2

Abstract

A deterministic and probabilistic model for oilspill fires in nuclear power plant compartments has been developed. It's objective is to predict whether certain components in the compartment will cease to function as a result of the fire and to give the probability of failure. Results are presented for several scenarios in two compartments. The model has been implemented in the computer code OSFIC, a tool for safety engineers to compare various component configurations in different compartments.

List of symbols

A	=	Area
C_p	=	Heat capacity (of air unless otherwise stated)
D	=	Diameter
d	=	Thickness
F	=	Configuration factor
g	=	Gravitational acceleration
H	=	Height
ΔH	=	Heat of combustion
h_k	=	Convection coefficient
k	=	Thermal conductivity
kß	=	Product og flame extinction-absorption coefficient and mean beam length corrector
$k\rho c$	=	Thermal inertia
L	=	Length
m''	=	Mass burning rate per area
m_{air}	=	Mass flow rate of air
M	=	Mass
Δp	=	Pressure rise
q''	=	Radiative heat transfer per area
Q	=	Energy release rate
Q*	=	Nondimentionalized energy release rate
Q_c	=	Convective energy release rate
S	=	Floor surface area
t	=	Time
T	=	Temperature
T_p	=	Plume temperature
y	=	Ratio of room height to gaslayer height
α	=	Thermal diffusivity (also a factor in equation [8])
χ	=	Combustion efficiency factor
ρ	=	Density (of air unless otherwise stated)
τ	=	Nondimentionalized time
σ	=	Stefan-Boltzmann constant
ε	=	Emissivity

Other subscripts:

b	=	Burn-out	ox	=	oxygen
f	=	fire	s	=	surface
g	=	gas	0	=	ambient
o	=	opening	∞	=	infinity
core	=	core of cable	w	=	wall

1.0 Introduction

Barsebäck is a nuclear power plant in the south of Sweden owned by the power company Sydkraft. This project was sponsored by the Swedish Atomic Energy Board as a part of an effort to evaluate the risk of core melt resulting from a compartment fire in Barsebäck.

A systematic method of evaluating the consequences of a fire in a single compartment in Barsebäck has been developed by Kluge (1). The method involves assuming that all critical components, in the compartment in question, fail. If this assumption leads to an unacceptable core melt frequency a more detailed study into a possible fire in the compartment is required in order to re-examine the assumption.

The purpose of this project was to facilitate such a study, to develop a method of analysis to predict the probability of component failure, P_f, due to a fire in a compartment. The components are in this study assumed to be the pumps in the compartment or the cables supplying the electricity to the pumps. The source of the fire is assumed to be an oilspill from one of the pumps.

Such an analysis requires both the development of deterministic and probabilistic models. The objective of the deterministic model would be to estimate the time to damage of either the pumps or the cables and comparing this time to the durability of the fire. A probabilistic model is also required since the fires can be of various magnitudes and at different locations in the compartment.

Several zone models, varying in their degree of sophistication, have been developed to predict deterministically the environmental conditions in a compartment fire. One of the more sophisticated models is FIRST (2), a computer program developed at the CFR. The program gives a time dependent solution of simplified mass and energy transfer equations which describe fire development in a compartment. For nuclear reactor safety studies the zone-model COMPBURN (3) has been developed. Mitler (4) has compared the two models. The physical limitations of these models are mainly in the areas of fire growth and spread, burning in the upper layer and effects of oxygen depletion.

Due to the complexity of the problem and the large amount of equations to be solved at each time step these models require a relatively long time with regard to setting up input data and in terms of calculation times. An assessment of the consequences of a fire in a nuclear power plant compartment has to take account of fires of several different levels of intensity and at different locations in the compartment. The straight forward procedure of deriving P_f is using the Monte

Carlo simulation technique. A very real and practical problem when basing the simulation on the above mentioned zone-models is that the calculation of P_f would be extremely time consuming for each scenario and component to be investigated.

As a consequence an alternative methodology of evaluating the environmental conditions due to a fire in a compartment was sought, replacing a complete zone-model with a set of simpler, interconnected equations. The main fire environment factor to be evaluated is the hot layer temperature. Earlier a complete zone-model would have been required to evaluate this but now there exist regression formulae for the gastemperatures in both naturally and mechanically ventilated enclosures. Similarily the gastemperature in a nearly closed compartment can be calculated. Simple expressions also exist for the burning rate, plume radius and temperature, flameheights, flame radiation, hot gas layer radiation, overpressure, smoke filling, oxygen concentration, etc. (5). In addition, classical heat transfer provides expressions for quantities such as view factors and temperature fields in systems with concentrated mass or in semi-infinite bodies.

A preliminary study by Magnusson (6) indicated that a deterministic model for oilspill fires could be developed using simple hand-calculation methods to evaluate the fire characteristics and the heat transfer to the components.

A deterministic and a probabilistic model were thus developed and combined in the computer code OSFIC (OilSpill Fires In Compartments).The computer code itself is described in a separate publication (Karlsson (7)). Chapter 2 of this paper describes the theoretical background for the deterministic model, Chapter 3 describes the probabilistic model. Chapter 4 gives examples of the program results for certain compartments in Barsebäck.

The computer program can thus predict the probability of component failure due to a fire. But more importantly it can be used as a safety engineers tool, to change the room configuration, the pump and cable positions, insert a protecting wall in the compartment and see if these measures would lessen the probability of component failure.

2. Deterministic model for oilspill fires.

The proposed model uses two different procedures to calculate the fire characteristics depending on the type of compartment. The first is the case of open doors, where the fire has access to sufficient amounts of oxygen to ensure continuous burning. The second is the case of closed doors where the fire may suffocate due to lack of oxygen.

2.1 Open compartment

For a fire in a compartment with open doors a two zone model is used. When it starts, hot gases rise from the burning oil towards the ceiling and spread across it, forming a distinct layer of hot gases near the ceiling. This layer gradually becomes thicker and finally reaches the top of the opening where the hot gases start flowing out, stabilizing the thickness of the layer.

For the compartment sizes and energy outputs considered in this study the time this takes is relatively short (in the order of seconds) and the conservative assumption is made that at the start of the fire the layer is already stabilized at the top of the opening.

2.1.1 Energy release rate

The rate at which energy is released in a fire is the single most important factor characterizing its behavior. It is a key factor for calculating other fire characteristics associated with fire growth, such as gastemperatures, flame heights and time to burn-out.

For many fuels it is difficult to estimate this growth rate. Furnishings, piles of wood and other materials can show a very varying burning rate. In this study we are however only concerned with oilspill fires, showing a much more consistent burning rate.

Once an oilspill has ignited, the time history of the fire can be divided into the periods of growth, fully developed burning and decay.

In the growth period the fire spreads over the oilspill in a comparatively short time. This period is neglected in the current study, the fire is assumed to exhibit fully developed burning at ignition.

The second period is characterized by a burning rate where the fire is either limited by available ventilation or by fuel surface area. Accordingly, the fire is then said to be ventilation controlled or fuel bed controlled.

For fuel bed controlled fires the energy release rate can be given by an expression of the form (Drysdale (8)):

$$\dot{Q} = \chi \dot{m}'' A_f \Delta H \qquad [1]$$

Babrauskas (9) has recommended that the burning rate for pool fires with diameter larger than 0.2 m be given by the expression:

$$\dot{m}'' = \dot{m}''_{\infty} \left(1 - e^{-k\beta D}\right) \qquad [2]$$

He also gave experimentally determined values for the above quantities for different liquid fuels. His data on hydrocarbon transformer oil is used in this study.

For ventilation controlled fires the burning rate is limited by the amount of oxygen available, 1kg oxygen used in combustion releases approximately 13.2 MJ. Kawagoe (10) gave an expression for estimating the mass of air entering through the opening:

$$\dot{m}_{air} = 0.5\, A_o \sqrt{H_o} \qquad [3]$$

This gives an upper limit to the mass rate of inflowing air and assumes that the fuel mass loss rate is small compared with the incoming air flow rate. A more accurate result can be achieved by combining plume equations with equations describing the flow at the opening. However, simple hand-calculations have shown that equation [3] gives reasonable results for the range of ventilation openings and mass loss rates considered in this paper.

The energy release rate can thus be estimated from the expression (for example see Lawson and Quintiere (5)):

$$\dot{Q} = 0.232\, \dot{m}_{air} \Delta H_{ox} \qquad [4]$$

This again is a maximum value, assuming maximum flow and complete mixing.

2.1.2 Time to burn-out

If one knows the total amount of oil spilled and it's mass loss rate it is a simple matter to calculate how long time it takes to evaporate all of the available oil. The following expression gives the time to burn-out:

$$t_b = \frac{M_f}{\dot{m}'' \chi A_f} \qquad [5]$$

2.1.3 Gastemperatures

McCaffrey et al. (11) suggested that the upper layer temperature rise could be approximated from the regression formula:

$$\frac{\Delta T}{T_0} = 1.63 \left(\frac{\dot{Q}}{\sqrt{g}\, c_p \rho_o T_o A_o \sqrt{H_o}} \right)^{2/3} \left(\frac{h_c A_w}{\sqrt{g}\, c_p \rho_o A_o \sqrt{H_o}} \right)^{-1/3} \qquad [6]$$

The effective enclosure conductance, h_c, is assumed to be 30 W/m^2 °C.

Alvares et al. (12) have presented a similar correlation for force-ventilated compartments, following the methods used by McCaffrey et al.

The gastemperature is here dependent on how long the fire has been burning in the enclosure, increasing very slightly with time. In the current study the gastemperature is evaluated at the time of burn-out and the conservative assumption is made that it remains constant at this value from the start of the fire till burn-out.

2.2 Closed compartment

The rate of pressure rise in a closed compartment is often kept small by gas leakage through cracks around windows and doors. Zukosky (13) developed a procedure to calculate the fire characteristics in compartments where the time to reach a steady state pressure is small compared with the time it takes to fill the compartment with smoke.

The procedure proposed in this paper builds on Zukoski's approach. When a fire starts the hot gases rise to the ceiling and as long as the oil burns the ceiling layer continues to grow both in depth and temperature. It is assumed that there is a relatively sharp interface between the hot upper layer and the ambient air in the lower part of the room. While the upper layer grows, ambient air is pushed out through the leakage at the floor level due to the expansion of the heated gases. The fire is assumed to go out when the hot layer reaches the floor.

If the steady state pressure rise is very high the door to the compartment might fail. The computer program presented here calculates the pressure rise and if it is above a certain value the computations are aborted with the message that the model is not valid for such a large energy effect. However, for most of the cases considered in this study the steady state pressure rise is not very high.

Zukoski (13) gives an expression to calculate the steady state pressure rise:

$$\Delta p = \left(\frac{\dot{Q}}{c_p T_0 A_0}\right)^2 \frac{1}{2\rho_0} \qquad [7]$$

2.2.1 Energy release

The energy released in the fire is assumed to be as if it were a fuel bed controlled fire, that is, calculated according to equation [1]. It is then considered to be constant at this value till the fire suffocates due to lack of oxygen.

This would look a bit different in reality. As the oxygen concentration decreases, the burning rate slows down. Instead of getting a fire with a high, constant energy output for a short time one would get a fire with a high energy output, decreasing with the decrease in oxygen concentration and finally suffocating.

2.2.2 Gastemperatures

Zukoski (13) applied the first law of thermodynamics to determine the time required to fill a room with products of combustion from a fire. The room was assumed to have a small leakage opening at the floor level. He suggested that the process was governed by the differential equation:

$$\frac{dy}{d\tau} + Q^* + k_1 (Q^*)^{1/3} (y)^{5/3} = 0 \qquad [8]$$

where $$\tau = t \sqrt{\frac{g}{H}} \left(\frac{H^2}{S}\right) \qquad [9]$$

and $$Q^* = \frac{\dot{Q}}{c_p \rho_o T_o \sqrt{gH}\, H^2}$$ [10]

and k_1 is a collection of constants, approximately equal to 0.21.

Zukoski (13) also gave an expression for the ceiling layer density:

$$\frac{\rho}{\rho_0} = 1 - \frac{Q^* \tau}{1 - y}$$ [11]

This can easily be rearranged to give the temperature of the hot gases for some specific layer height. We are interested in the gastemperature and the time it takes for the layer to reach the floor. Having substituted temperatures for densities, equation [11] reduces to (for y = 0):

$$T = \frac{T_0}{1 - Q^* \tau_{floor}}$$ [12]

Q^* can be found from equation [10] but a knowledge of τ_{floor} requires the solution of the differential equation [8] which has to be solved numerically. To avoid this in the computer program the equation was solved for y = 0 with the simulation language SIMNON (18). τ_{floor} was plotted versus Q^* and a logarithmic curve was fitted to the results, see figure 1. This gives τ_{floor} as a function of Q^*:

$$\tau_{floor} = 1.045\ (Q^*)^{-0.85}$$ [13]

Thus it is possible to calculate the time it takes for the layer to reach floor level by rearranging equation [9]. The gastemperature at this time can be found from equation [12].

2.2.3 Time to burn-out

The time to burn-out is calculated according to the process described above, that is, from equations [9] and [13]. The term burn-out is here ambiguous and can mean both the cessation of combustion due to lack of fuel and the suffocation of the fire due to lack of oxygen.

Like explained above, in reality the fire does not have a constant, high energy output but decreases as the oxygen concentration falls. This has the effect that the fire may go on for a longer period than calculated from above, but with a steadily decreasing intensity. The total energy release will however remain basically the same.

Zukoski's theoretical model was compared with experimental results, showing a good agreement (see Appendix B).

2.3 Heat transfer

Once the size of the oilspill has been defined, the energy output and the resulting gastemperature, flameheight and time to burn-out can be calculated from the procedure given above. Knowing the gastemperature one can calculate the heat transfer from the hot layer to the cable and pump and the time it takes to heat the surface of these components up to a certain critical surface temperature at which the component is assumed to fail.

If the position of the fire in the compartment is also known the heat transfer from the flames to the components can similarly be calculated. As a result, the time it takes to heat the component up to the critical surface temperature can be found.

A typical compartment in Barsebäck has two or three pumps in it which are defined to be the critical components, along with the cables supplying the electricity to them. The procedure suggested here considers each of these pumps in turn, and the cable supplying it, and defines the five following modes in which these components may become damaged and cease to function:

1) The radiation from the hot layer to the cable causes the cable to reach a predefined critical surface temperature, resulting in function failure.
2) Similarly, the hot layer radiates to the pump causing elevated surface temperatures and function failure.
3) If the fire is directly under the cable the plume temperature can cause cable failure.
4) The flame radiates to the pump, causing elevated surface temperatures and failure.
5) In some cases the electrical supply is from a cable emerging from the floor, entering the pump at around the height of one meter from the floor. This cable can be subjected to radiation from the flame, resulting in cable failure.

The combined heat transfer of two modes is not taken into account. For example, the gaslayer radiates mainly to the top of the pump and comparatively little to the sides. Similarly, the flame radiates mainly to the sides of the pump and comparatively little to the top of it. This is therefore assumed to be a reasonable assumption considering the purposes of the model.

Having calculated the time to failure for each of the modes, the smallest of the times is the critical time to failure, t_{crit}.

2.3.1 Heat transfer from gaslayer to cables.

There are generally two ways to connect a cable to a pump in the compartments at Barsebäck; either it enters the room through a wall at some height which is equal to or higher than the door; or it enters through the floor. In the latter case the cable may be subjected to radiation from the flame, this case is treated in a later section. The cables entering through the wall are considered to be emerged in the hot layer whether the door is open or not. In this case the lumped thermal capacity method is used to calculate the heat transfer to the cables.

Since the cables are made of various materials in different layers a problem arises when trying to determine their overall density, heat capacity and thermal conductivity. The cables considered here consist of three materials; a thick aluminum core surrounded by PVC, a thin copper layer and finally a coat of PVC. The overall cable diameter is around 8 cm and it is not contained in a cable tray.

The problem is solved in a similar way in which on would solve the problem of heat transfer to an insulated steel column. The PVC is considered to be the insulator and not to have any heat capacity. The core is assumed to consist of the combined copper and aluminum. The temperature gradients within the core are neglected, it is considered to be of a uniform temperature throughout.

The solution of the differential equation governing this type of heat conduction is (Holman (14)):

$$\frac{T_s - T_g}{T_0 - T_g} = e^{-t/t_c} \qquad [14]$$

where

$$t_c = \frac{c_p V \rho d_{pvc}}{A k_{pvc}} \qquad [15]$$

The c_p, V, ρ refer to the core of the cable.

Equation [14] can be rearranged to give the time required for the cable to reach a certain critical temperature:

$$t = - t_c \, Ln\left(1 - \frac{T_s - T_g}{T_0 - T_g}\right) \qquad [16]$$

2.3.2 Heat transfer from gaslayer to pump

To analyse this case the pump is assumed to be a semi-infinite solid and convective heat losses are taken into account. The solution of the differential equation governing this, solved for the temperature at the surface is (Holman (14)):

$$T_s - T_0 = \frac{\dot{q}''}{h_k}\left(1 - e^{z^2} \text{erfc}\,(z)\right) \qquad [17]$$

where $$z = h_k \sqrt{\frac{t}{k\rho c}} \qquad [18]$$

The error function can be approximated from (Claesson et al. (15)):

$$e^{z^2} \text{erfc}\,(z) = \frac{2 + z}{2 + \left(1 + 4/\pi\right) z + \sqrt{\pi}\, z^2} \qquad [19]$$

The rate of heat transfer can be written as:

$$\dot{q}'' = \left(T_g^4 - T_0^4\right) \sigma \, \varepsilon \, F \qquad [20]$$

The configuration factor from the gaslayer to the pump is calculated in a standard manner, see Appendix A.

The above equations can be combined and solved by the Newton-Raphson method to give the time to reach the critical surface temperature. The convection heat transfer coefficient is again set to be constant at 30 W/m^2 °C for all cases. The material constants are assumed to be those of steel.

This method of analyses is only valid for a certain combination of a minimum thickness of material and for a maximum time. This minimum thickness or maximum time can be evaluated from:

$$L > 2\sqrt{\alpha t} \qquad [21]$$

The thermal diffusivity of steel is relatively high but we are only concerned with very short periods of time which gives an acceptable thickness of material.

One of the five modes of heat transfer mentioned above will have caused a critical surface temperature on a component within a few minutes. In some cases it takes a very long time for the gaslayer to heat the surface of the pump up to the critical temperature, resulting in an unacceptable minimum thickness of material. The resulting time from these calculations is therefore not valid but one of the other modes of heat transfer has already supplied a much shorter time and it is this short time we are interested in.

This method of analyses is therefore considered to be valid when this mode supplies the shortest time and therefore an acceptable minimum thickness. Furthermore, the pumps studied in this paper are relatively solid constructions resulting in an acceptable thickness.

2.3.3 Heat transfer from plume to cable

To calculate the heat transfer from the plume to the cable one must know the position of the plume and the cable, the height of the cables, the plume radius and the plume temperature at this height. The height and position of the cable is supplied as input to the program, the position of the plume will be dealt with in the next chapter.

Heskestad (16) has given the plume radius at a certain height to be:

$$b_{\Delta T} = 0.12\left(T_P/T_0\right)^{1/2}(z - z_0) \qquad [22]$$

where

$$z_0 = -1.02\,D + 0.083\,\dot{Q}^{2/5} \qquad [23]$$

He expressed the temperature rise in the plume at this height to be:

$$\Delta T_p = 9.1\left(\frac{T_0}{g\,c_p^2\,\rho_0^2}\right)^{1/3}\dot{Q}_c^{2/3}(z - z_0)^{-5/3} \qquad [24]$$

ΔT was defined as the centerline temperature rise and $b_{\Delta T}$ was the radius at which this temperature had declined to half of ΔT. In the proposed model the cable is assumed to be subjected to the centerline temperature if it is within the plume radius, if it is outside this radius it is assumed to be subjected to the gastemperature.

The time to damage is calculated from equation [16] as in section 2.3.1 with plume temperature substituted for gastemperature.

2.3.4 Heat transfer from the flame to the pump

The heat transfer from the flame to the pump can be calculated using the same type of analyses as in section 2.3.2, equations [17], [18], [19] and [20]. In this case however one needs to know a number of additional parameters such as the height and shape of the flame, it's temperature and emissivity and the configuration factor from the flame to the pump.

Here, the flame is considered to be of a cylindrical shape. Heskestad (16) gave the following approximate relation for the flame height:

$$L = -1.02\,D + 0.23\,\dot{Q}^{2/5} \qquad [25]$$

In order to calculate the configuration factor one must know where on the pump the most critical point is to be able to find the distance from the flame to this point. In this study the point is assumed to be the one closest to the flame, at any height on the pump. Whether it is on a corner of the pump or on one of the sides is assumed immaterial.

The formula for calculating the configuration factor is given in Appendix A. This expression gives the configuration factor from a cylinder to a parallel surface element at the height of the cylinder top. To find the configuration factor from the center of the flame to the pump it is first evaluated for half the cylinder height and then doubled.

The radiation from the flame to the pump can be evaluated from equation [20]. Due to the fourth power dependence of the flame temperature, the radiation is sensitive to its choice. Modak (17) reports the effective radiation temperature for most heights above the fuel surface to be around 1300° K and this value is used here. The emissivity factor is conservatively taken to be 0,95. The convective cooling coefficient is assumed to be constant for all cases at 30 $W/m^2\,°C$.

2.3.5 Heat transfer from the flame to the cable.

The calculation of the time to critical cable surface temperature due to radiation from the flame is based on the lumped thermal capacity method of analyses. The solution of the differential equation governing this process is slightly different from the one presented in section 2.3.1 since the cable is not immersed in the gaslayer but subjected to radiation from a distant flame.

Here, convection heat losses are taken into account as well as the PVC insulator. Thus there are two time constants involved in the analyses, one taking account of the insulator and another of the convection heat losses. The derivation is given in Appendix C. The resulting equation is:

$$T_{core} = T_0 + \frac{\dot{q}''}{h_k}\left(1 - e^{-t/(t_{C1} t_{C2})}\right) \qquad [26]$$

where $$t_{C1} = \frac{\rho \, c_p V}{A \, h_k} \qquad [27]$$

and $$t_{C2} = 1 + \frac{h_k \, d_{pvc}}{k_{pvc}} \qquad [28]$$

The c_p, V, ρ and A refer to the core of the cable.

The configuration factor is calculated in the same way as in section 2.3.4, the flame temperature, emissivity and material constants are also from that section.

2.4 Results from the deterministic model.

Firstly, the procedure described above gives fire characteristics such as energy output, gastemperature, flame height and time to burn-out as a function of oilspill size. Secondly, it gives the critical time to failure as a function of oilspill size and oilspill position, $t_{crit}(s,p)$.

If the time to burn-out is shorter than the time needed to reach the critical surface temperature, $t_{crit}(s,p)$, the component is assumed not to cease functioning for this specific size and position of oilspill fire.

How the above methodology used to arrive at a probabilistic result is described in the next chapter.

3. Probabilistic model

To be able to use the deterministic model presented above two more variables need to be determined; the size of the oilspill and it's position in the compartment. These variables are non-deterministic and must be expressed in probabilistic terms.

3.1 Oilspill position

Oilspills can arise from several different sources. The most probable source is considered to be a leakage from a pump. Also, the pipes supplying the oil to the pump can fail in some way, causing a leak reasonably close to the pipes or an oil spray resulting in an oilspill at any point in the room. Similarly, an employee can accidentally spill oil from a container causing an oilspill at some point in the room.

The spill is assumed to be circular and since it's position can be anywhere, the compartment is split into a net of coordinates where the fires are positioned. The time to critical damage is calculated at one position and the fire is moved to the next, etc. This is illustrated in Figure 1.

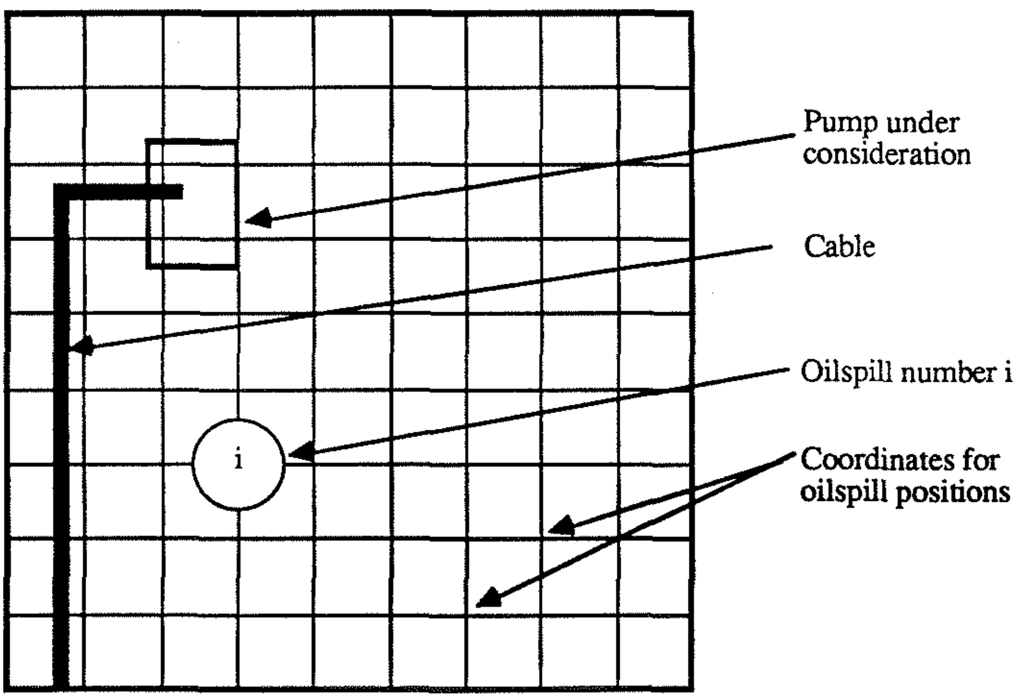


Figure 1. Room configuration and oilspill positions

The oilspill size and location are quantities which have to be based on their relative frequency distribution curves. The location could be at any point in the room, but it is more likely to be in the vicinity of the pump or the supply pipe. Therefore, certain areas or points in the compartment are give certain probabilities.

We now consider one certain oilspill size, s, and position it at, say, 100 locations in the room. The critical time to damage, $t_{crit}(s,p)$, and the time to burn-out, $t_b(s)$, are calculated and compared at each position. At certain positions $t_{crit}(s,p)$ is greater than $t_b(s)$ and the probability of component failure is assumed to be zero for an oilspill of size s at point p. The results are then weighted up, taking into account the frequency distribution curve for the oilspill location. The result is therefore the probability of component failure for one certain oilspill size, P_{fs}, evaluated from the equation

$$P_{fs} = \sum_{j=1}^{100} P_{fj} * \lambda_j \qquad [29]$$

where λ_j is the value at the j[th] point of the relative frequency distribution curve for the location of the oilspill.

3.2. Oilspill size

The pumps in the rooms relevant to this study contain a certain maximum amount of oil. The largest oilspill that can occur in the room is defined to be the maximum amount of oil in one of the pumps. This amount of oil is then divided into ten oilspill sizes, the first being the smallest and the last being the maximum amount of spill.

The results from the procedure outlined above are 10 different probabilities of component failure, P_1, P_2,...,P_{10}, as a function of the oilspill size. The overall component failure probability is evaluated from the equation

$$P_f = \sum_{s=1}^{10} P_{fs} * \lambda_s \qquad [30]$$

where λ_s is the value at the s[th] point of the relative frequency distribution curve for the oilspill size.

4.0 Results from the computer program OSFIC.

This chapter presents some example cases from compartments in the nuclear power plant at Barsebäck. Note that the results presented here are mainly to demonstrate how the methodology, presented in the previous chapters, works. Reliable statistical data on the shape of the frequency distribution curves, for both the oilspill size and the oilspill position, is scarce. It was not considered to be within the scope of this paper to gather and investigate the necessary statistical data. For the purpose of demonstrating the methodology the following assumptions on the frequency distributions are made:

- 60% of the oilspills are located within 1 m radius of the perimeter of any pump in the compartment. The remaining 40% of the spills can occur anywhere else in the room.
- all oilspill sizes are considered to be equally probable

As a consequence, the results are not conclusive and the numbers quoted below are most profitably used for comparing relative results from different compartment and design configurations.

The compartments included in the oilspill study are:

1) Rooms T-9916 and T-9917 (Condensate- and auxiliary condensate pump room)
2) Room T-0316 (Auxiliary feedwater pump room)
3) Room T-9915 (a part of the Generator cellar)

4.1 Rooms T-9916 and T-9917.

This compartment is 22 m long, 8 m wide and 6 m high. It is split into two rooms by a 2 m high wall partition. A diagrammatic sketch of the compartment is shown in Figure 3.

Room T-9916 is 10 m long by 8 m wide and contains three condensate pumps. The cables to one of these enter through a wall at the hight of 2.5 m, the other pumps get electricity by cables emerging from the floor. The maximum amount of oil spilled from one of these pumps is 20 liters.

Room T-9917 is 12 m long by 8 m wide and contains two auxiliary condensate pumps. The cables to both pumps enter through a wall at the hight of 2.5 m. The maximum amount of oil spilled from one of these pumps is 5 liters.

We examine an oilspill which can be positioned at any single point in one of these rooms. There are several scenarios to be considered in this case. Results are presented for the following ones:

A) An oilspill of maximum 20 liters is assumed to be confined to room T-9916. The time to damage of pump 1 (see Figure 3) or the cable supplying it is examined. The door is assumed to be open.

B) Same scenario as A except the door is assumed closed.

C) An oilspill of maximum 20 liters is assumed to be confined to room T-9916. Pump 2 is examined.

D) Same scenario as C except the door is assumed closed.

E) An oilspill of maximum 20 liters is confined to room T-9916. Pump 4 (in room T-9917) is examined. Here, the flames do not radiate towards the pump since a wall separates them. The gaslayer transfers heat towards pump and cable and the plume temperature can also damage the cable. The door is assumed open.

F) Same as scenario E except door is assumed closed.

G) An oilspill of maximum 5 liters is confined to room T-9917. Pump 4 is examined. The door is assumed to be open.

H) Same as scenario G except door is assumed closed.

4.1.1 Scenario A and B

As an example of results from a certain size oilspill, Figure 4 shows the critical times to damage for a 10 liter oilspill in scenario A. The room is divided into a 0.5 x 0.5 m grid resulting in 357 oilspill positions. Each point on the graph represents the shortest time to damage from the five possible heat transfer modes mentioned in Chapter 2. The thick, vertical line shows the time to burn-out, which is around 4.7 minutes. All cases on the left of this line result in component damage.

The first 25 positions give a time to damage under two minutes, this is due to the fire plume being directly under the cables. In the next 50 or so positions the pump is in direct contact with the flame, giving the time to damage as just over two minutes. Another 10 positions give a time to damage between two and four minutes, this is due to the flame being quite close to the pump.

The last two hundred or so positions give a time to cable damage of around 13 minutes. This is as a result of heat transfer from the gaslayer which has a temperature of around 250 °C.

There are therefore 85 positions out of 357 that do cause damage for this size oilspill, or ≈ 24%. However, the final probability of damage for this oilspill size is ≈ 30% (see Figure 5) since many of the positions resulting in damage are close to the pump and are considered to have a higher frequency than other positions in the compartment.

The overall probability of damage is 28.7% for scenario A and 25.7% for scenario B. One would expect a greater difference between the open- and closed door case. The reader is therefore reminded that in the closed door case adiabatic gas-temperatures are assumed (no account is taken of heat loss to the compartment boundaries), resulting in a relatively high probability of damage.

4.1.2 Scenarios C and D

Figure 6 shows the results from these scenarios. Here the cable enters through the floor so the plume and gaslayer do not affect the cables as much as in scenario A and B. The flame does, however, radiate to the floor cable so the overall probability of failure is 28.3% for scenario C and 22.4% for scenario D.

4.1.3 Scenarios E and F

Figure 7 shows the results from this scenario. The pump under consideration is seperated from the oilspill by a wall partition so the flames do not radiate towards the pump. Component damage can only be achieved when the cable is within the plume radius and the plume temperature causes damage to the cable. Alternatively the gaslayer can transfer heat towards the cables and the pump, but even for a 20 liter spill this heat transfer takes a longer time than the time to burn-out. The overall probability of damage to components is therefore very small, 5.8% for scenario E and 5.1% for scenario F.

4.1.4 Scenarios G and H

Here, the maximum oilspill is so small that there is no differance between the open- and closed door case. Damage to the components is only caused by the flame radiating to the the pump and only in cases where the spills are very close to the pump. The overall probability of damage is 16.1% for both scenarios.

4.2 Room T-0316

This compartment is 6.6 m long by 4.4 m wide and 4 m high. It contains two auxiliary feedwater pumps. The cables to one of these enters through a wall at the height of 2.5 m, the other pump gets electricity by a cable emerging from the floor. The maximum amount of oil spilled from one of these pumps is 100 liters. A diagrammatic sketch of the room is shown in Figure 9.

Results from the following scenarios are shown:

I) The time to damage of pump 1 (see Figure 9) or the cable supplying it is examined for an oilspill of maximum 100 liters. The door is assumed open.

J) Same as scenario I but the door is assumed closed.

K) Pump 2 is examined for an oilspill of maximum 100 liters. The door is assumed open.

L) Same as scenario K but the door is assumed closed.

4.2.1 Scenarios I and J

Figure 10 shows that the probabilities of damage for these scenarios are much higher than in the compartment considered earlier. This is due to a much larger maximum oilspill and a much smaller room. For the open door case, the fire becomes ventilation controlled at a spill size of ≈ 20 liters and the time to burn-out increases linearly with increasing spill size. In the closed room case no account is taken of energy losses to the compartment boundaries, so for large oilspills the gastemperatures cause failure at all oilspill positions. The rate of pressure rise is too high for the Zukoski model (described in chapter 2) to be valid. Under these circumstances incomplete burning may result in pockets of unburnt fuel, causing a risk of explosions. The components are therefore considered to get damaged for spill amounts greater than 20 liters. The model gives the resulting overall probability of failure as 90.1% for scenario I and 82.9% for scenario J.

4.2.2 Scenario K and L

Figure 11 shows very similar results as in the two previous scenarios. The same comments are valid, the differance here is that the cable does not enter through the floor and is therefore more vulnerable to the plume and the gaslayer and less so to radiation from the flame. The resulting overall damage probabilities are however quite similar, 92.0% for scenario K and 82.8% for scenario L.

4.3 Room T-9915

This room has an opening through a stairway to the large generator cellar. The critical components in this room are the cables to the pumps in rooms T-9916 and T-9917. The scenario considered for this room is a very large oilspillage from the turbine, which contains 43000 liters of oil. Because of the large amount of oil the fire is assumed to last for a long time and the probability of damage assumed to be 100%.

4.4 Summary of results

Room T-9916 showed reasonable results for the scenarios examined here. If a fire starts in this room and the door is open, there is a 28% chance that pump 1 stops functioning and a similar probability that pump 2 and 3 stop functioning. If the door is closed there is 22% - 25% chance that pumps 1, 2 and 3 will stop functioning. These pumps were also examined for a 5 liter spill in room T-9917. The result was a zero probability of damage to the three pumps.

Room T-9917 shows good results, there is only ≈16% chance that pumps 4 and 5 will stop functioning if an oilspill fire starts in this room. This is mainly due to the small amount of maximum spill. Pumps 4 and 5 were also examined for a 20 liter spill in room T-9916, the results were ≈ 5% probability of damage.

Room T-0316 showed poor results. If the door is open, there is a 90% - 92% chance that pumps 1 and 2 will stop functioning. If the door is closed there is an 82% chance that both pumps will stop functioning. This is mainly due to the large maximum oilspill. However, smaller oilspills may be more probable than very large ones and account should be taken of this to get a more realistic result.

5. Summary

In the example runs above, all oilspill sizes were assumed to be equally probable. Further, oilspill sizes and locations were assumed to be unrelated. Conditional probabilities can of course easily be incorporated into a Monte Carlo simulation calculation.

The results quoted above as a consequence are most profitably used for comparing relative results from different compartment and design configurations. The final paper will discuss problems of validation and calibration with real fire experiments.

A typical program run deals with very many fire scenarios in one compartment and takes only a few minutes to run on an IBM PC AT computer. The computer program is being used as a safety engineers tool, to change the room configuration, the pump and cable positions, inserting a protecting wall in the compartment and see if these measures would lessen the probability of component failure, as defined in the model.

Summing up, a methodology for calculating the probability of component failure has been developed, based on a set of simplified regression expressions and physical laws. Calculating times are drastically reduced, opening the way for a more comprehensive use of fire exposure models in probabilistic safety analyses.

Bibliography:

(1) Kluge, J., "BRAND/BVT - Metod för analys av konsekvens av brand i enskild brandcell". Sydkraft, PM ÅK-8509-07, Malmö; 1985.

(2) Mitler, H.E., Rockett, J.A., Users' Guide to FIRST, A Comprehensive Single-Room Fire Model, NBSIR 87-3595, National Bureau of Standards, Gaithersburg, MD 20899, September 1985.

(3) Siu, N.O., COMPBRN - A Computer Code for Modeling Compartment Fires, US Nuclear Regulatory Commission, NUREG/CR-3239, UCLA-ENG-8257, May 1983.

(4) Mitler, H.E., Comparison of Several Compartment Fire Models: An Interim Report, NBSIR 85-3233, National Bureau of Standards, Gaithersburg, MD 20899, Oct 1985.

(5) Lawson, J., Quintiere, J. Q., "Slide Rule Estimates of Fire Growth", Fire Technology, Vol. 21, No. 4; November 1985.

(6) Magnusson, S.E., "Brandscenario i kärnkraftverk. Exempel på preliminär analys.", Internal memorandum, Dept. of Fire Safety Science, Lund Inst. of Technology; April 1987.

(7) Karlsson, B., "Users Guide to OSFIC". Dept. of Fire Safety Science, Lund Inst. of Technology; March 1988.

(8) Drysdale, D., "An Introduction to Fire Dynamics". John Wiley and Sons, Chichester; 1985.

(9) Babrauskas, V., "Estimating Large Pool Fire Burning Rates". Fire Technology, Vol. 19, No. 4, pp 251-261; November 1983.

(10) Kawagoe, K., "Fire Behaviour in Rooms". Report No. 27, Building Research Institute, Tokyo; 1958.

(11) McCaffrey, B. J., Quintiere, J. Q., Harkleroad, M.F., "Estimating Room Temperatures and the Likelyhood of Flashover Using Fire Test Data Correlations". Fire Technology, Vol. 17, pp 98-119; 1981.

(12) Alvares, N. J., "A Temperature Correlation for *Forced-Ventilated*

Compartment Fires". Fire Safety Science - Proceedings of the First International Symposium, pp 139-148; 1985.

(13) Zukoski, E. E., "Development of a Stratified Ceiling Layer in the Early Stages of a Closed-Room Fire". Fire and Materials, Vol. 2, No.2; 1978.

(14) Holman, J. P., "Heat Transfer", 6th Ed. McGraw-Hill, New York; 1986.

(15) Claesson, J., Nevander, L. E., Sandin, K.," Värme". Husbyygnadsteknik, Lund Inst. of Technology, Lund; 1984.

(16) Heskestad, G., "Engineering Relations for Fire Plumes". Scociety of Fire Protection Engineers, Technology Report 82-8; 1982.

(17) Modak, A. T., "The Burning of Large Pool Fires". Fire Safety Journal, 3, p.177; 1980/1981.

(18) Åström, K.J., "A SIMNON Tutorial", Dept. of Automatic Crontrol, Lund Inst. of Technology, Lund 1982.

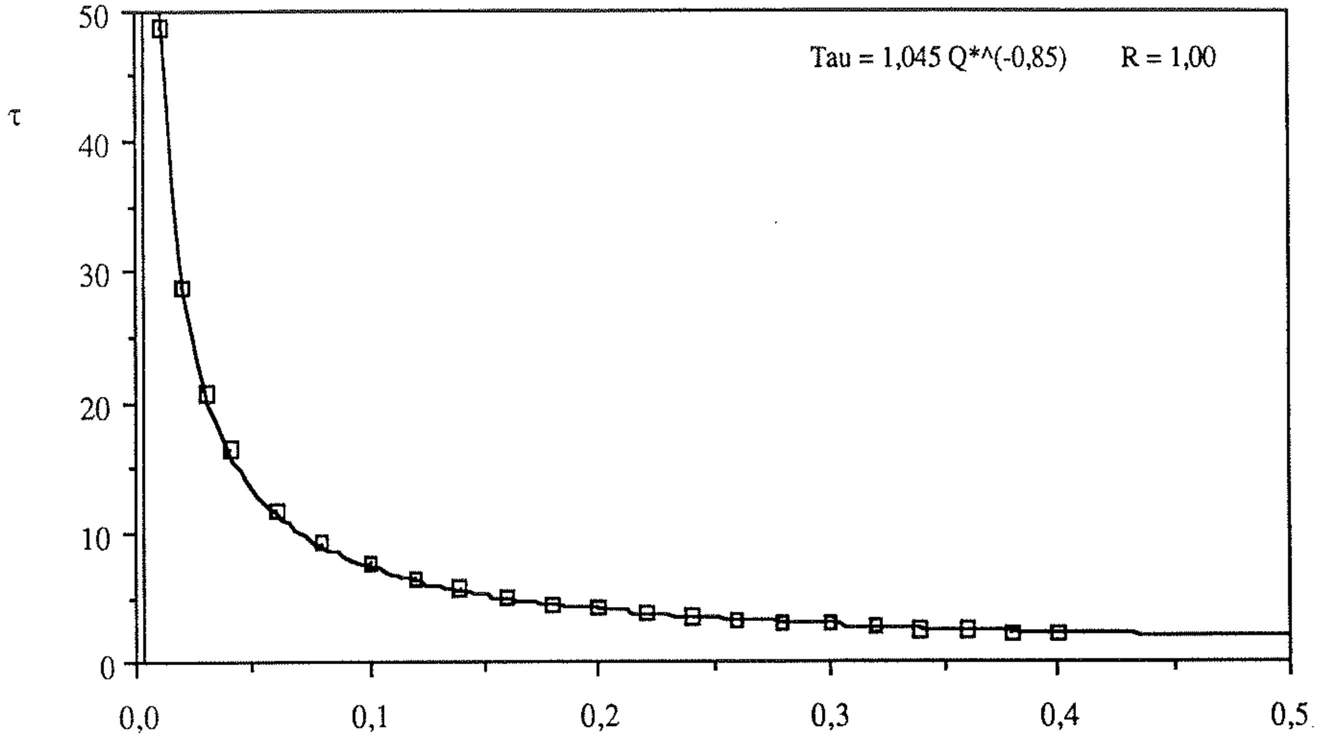


Fig.2. τ versus Q* for y = 0

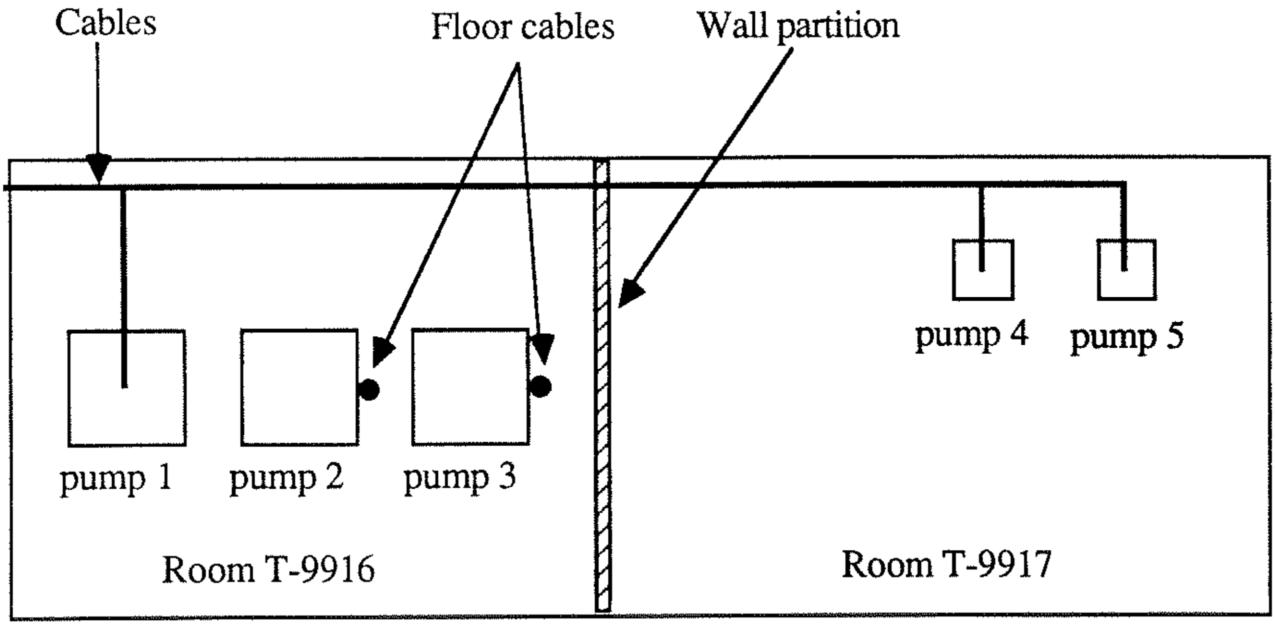


Fig.3. Plan view of rooms T-9916 and T9917.

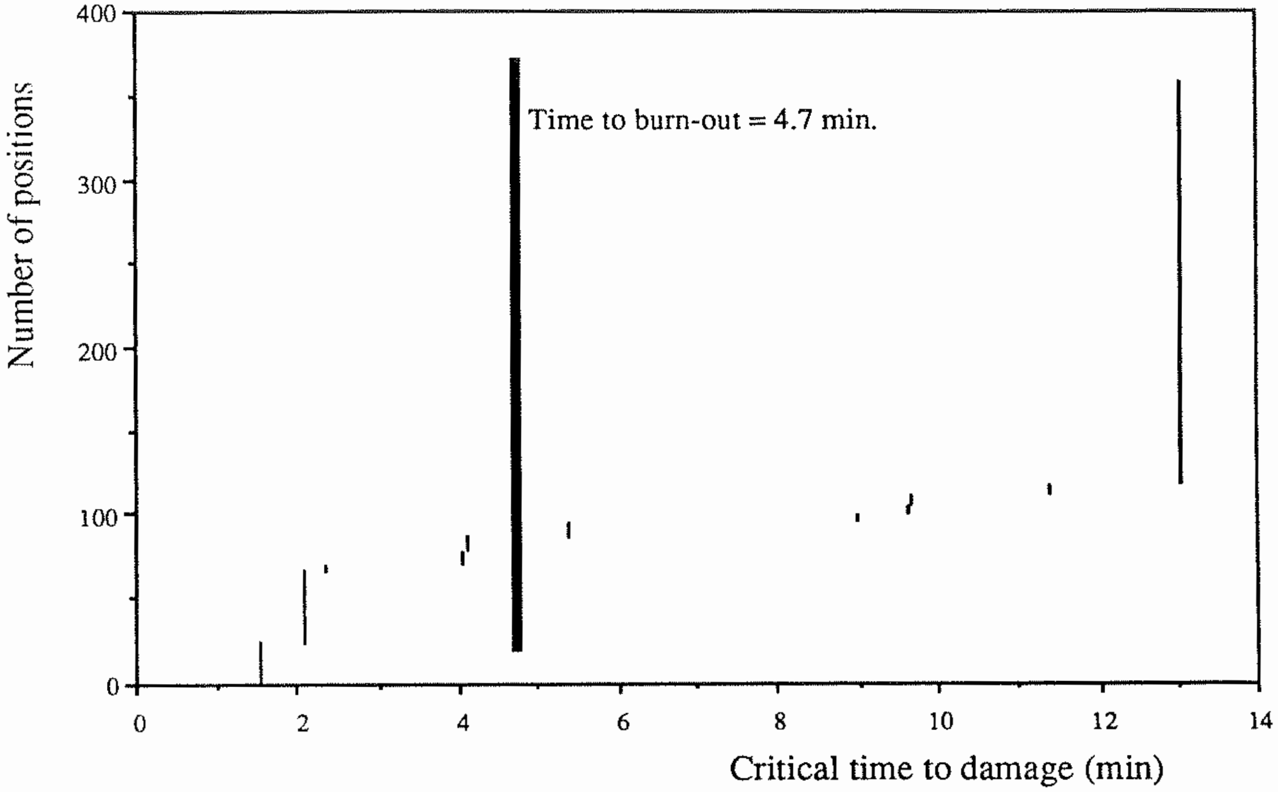


Fig.4. Scenario A. Critical time to damage for a 10 liter oilspill

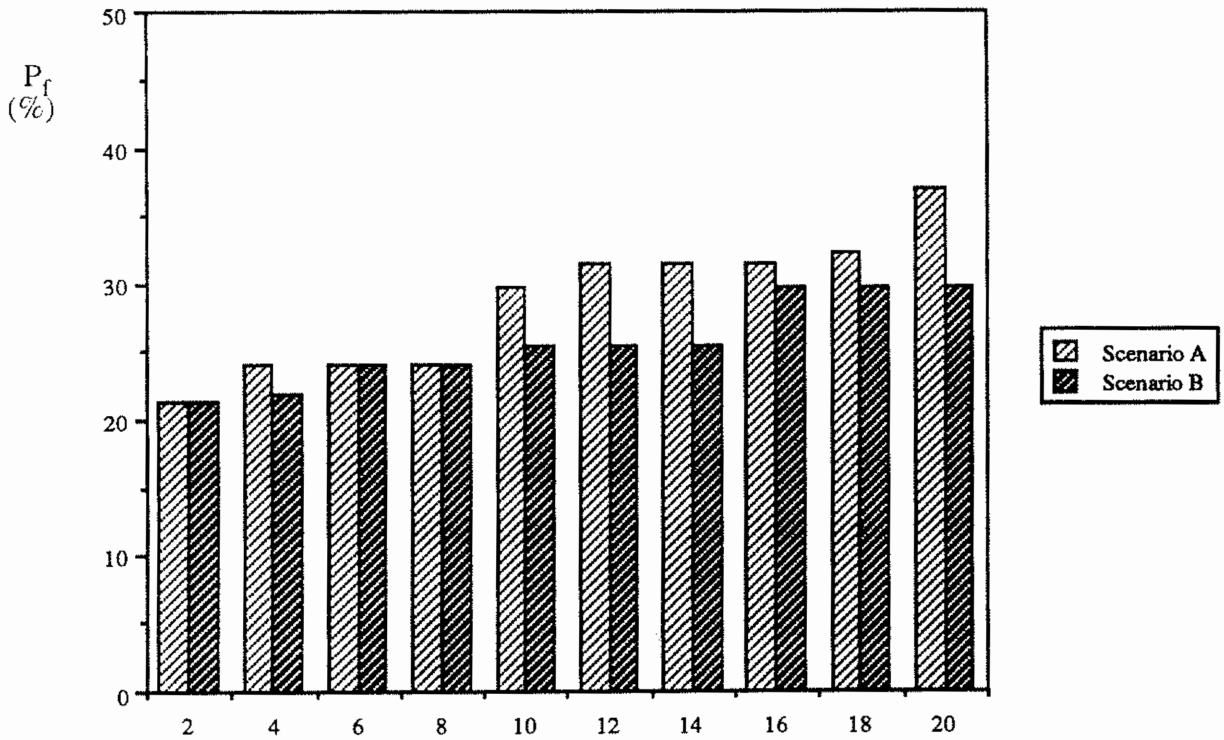


Fig.5. Scenario A and B. Liters

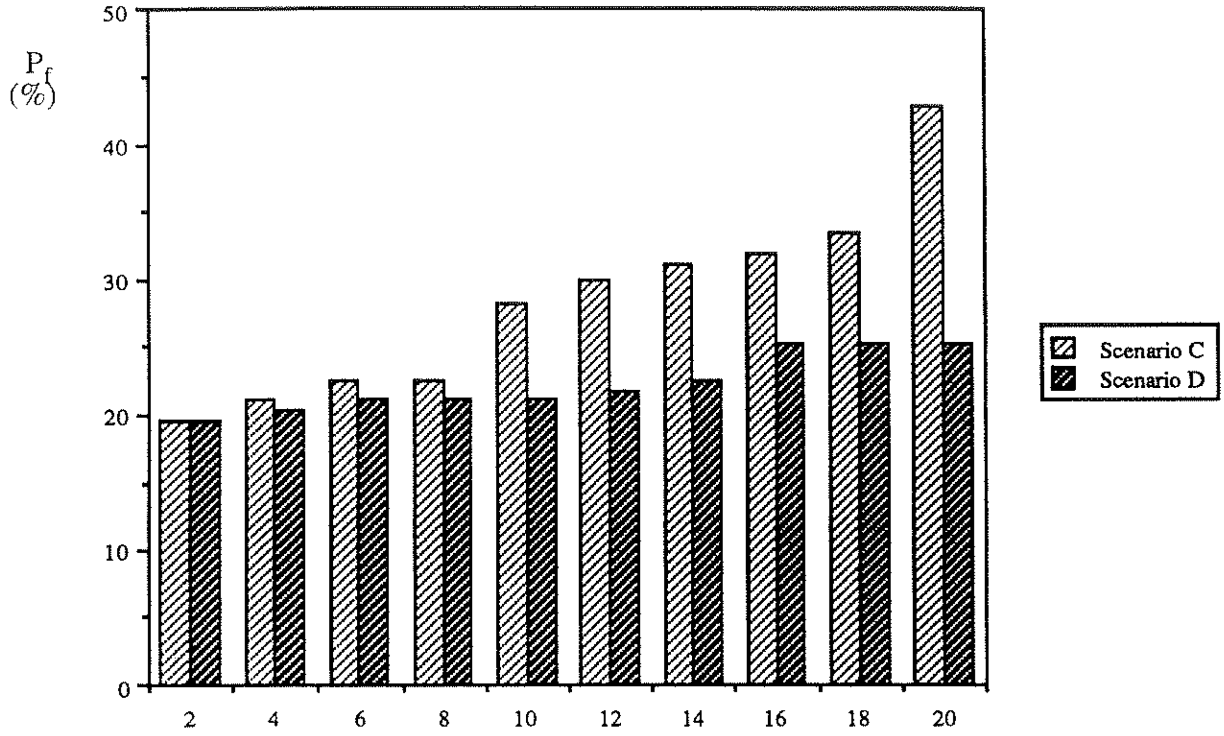


Fig.6. Scenario C and D. Liters

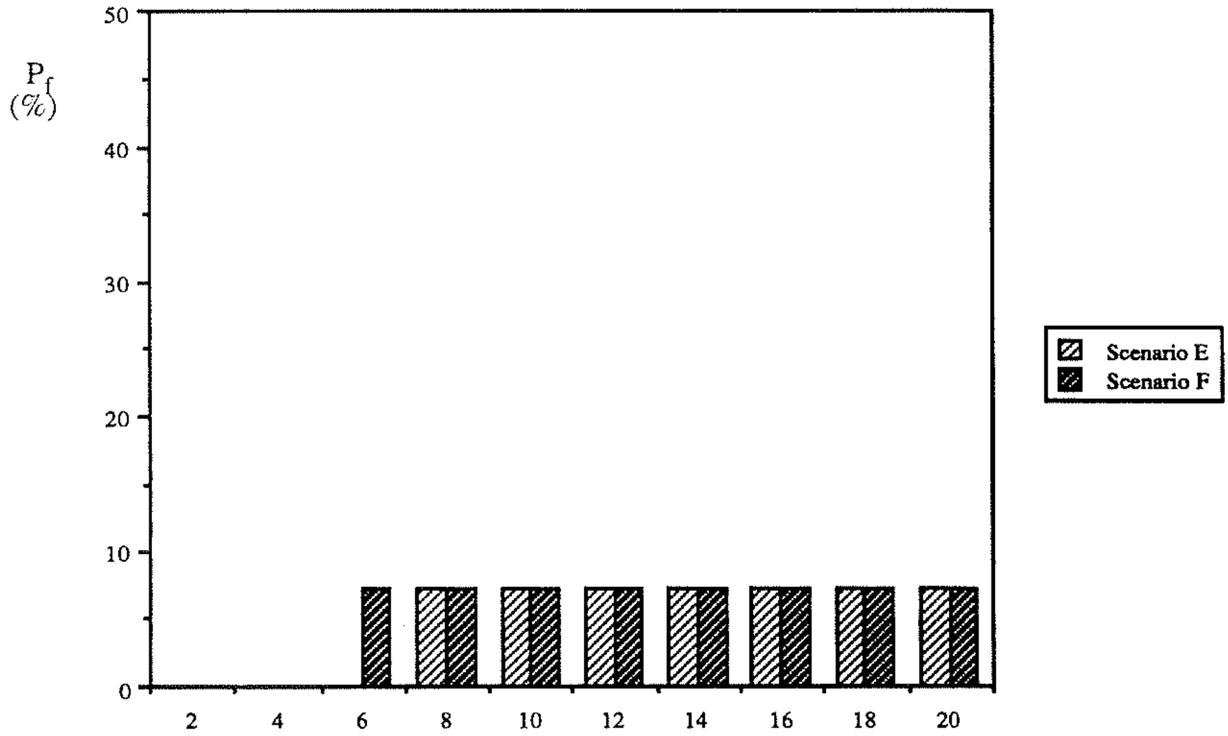


Fig.7. Scenario E and F. Liters

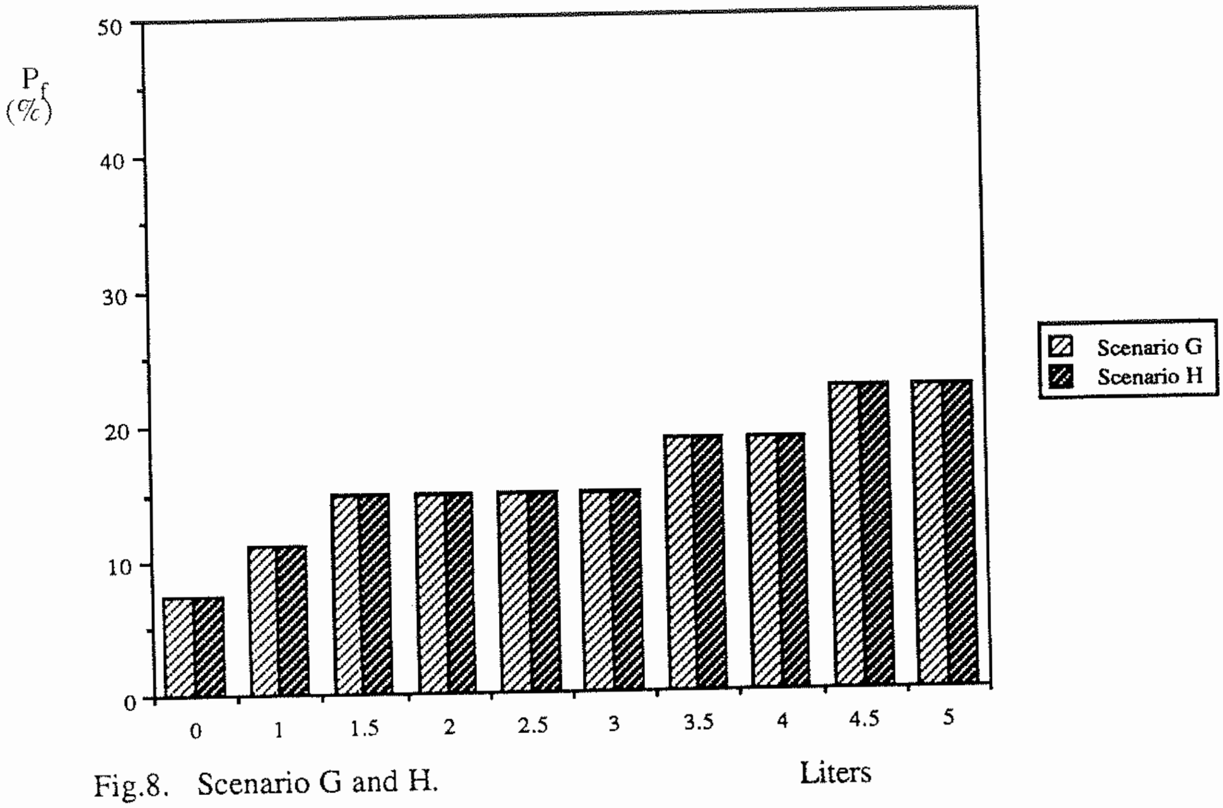


Fig.8. Scenario G and H.

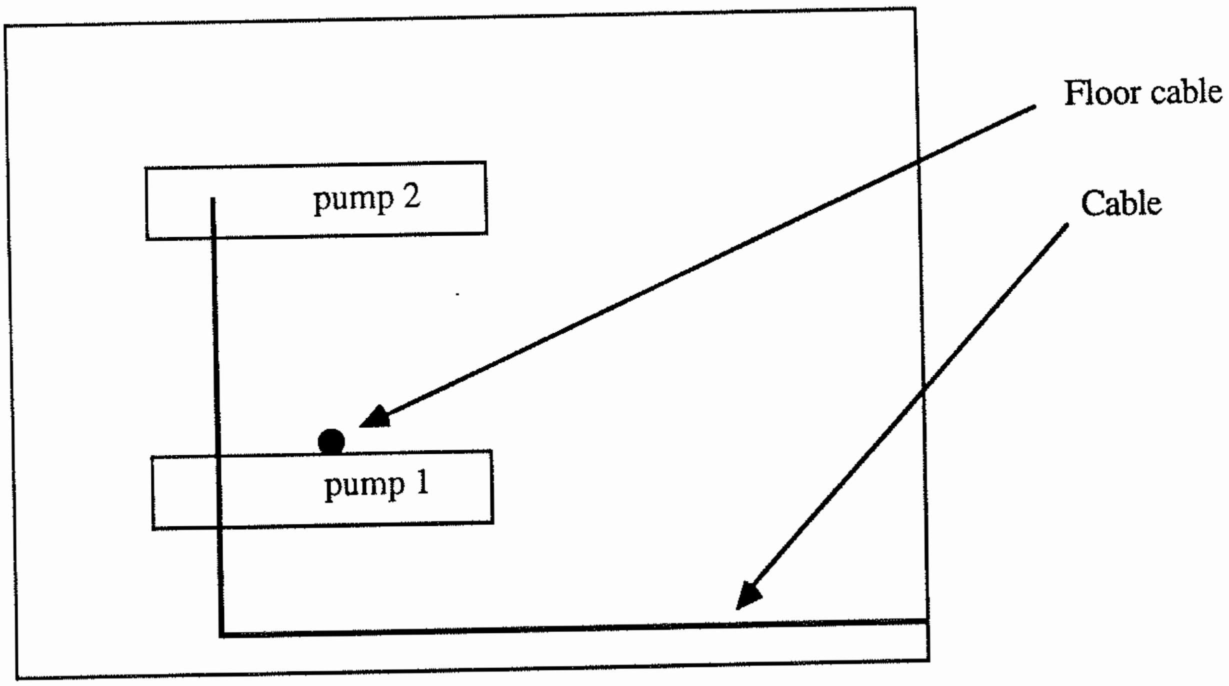


Fig.9. Plan view of room T-0316.

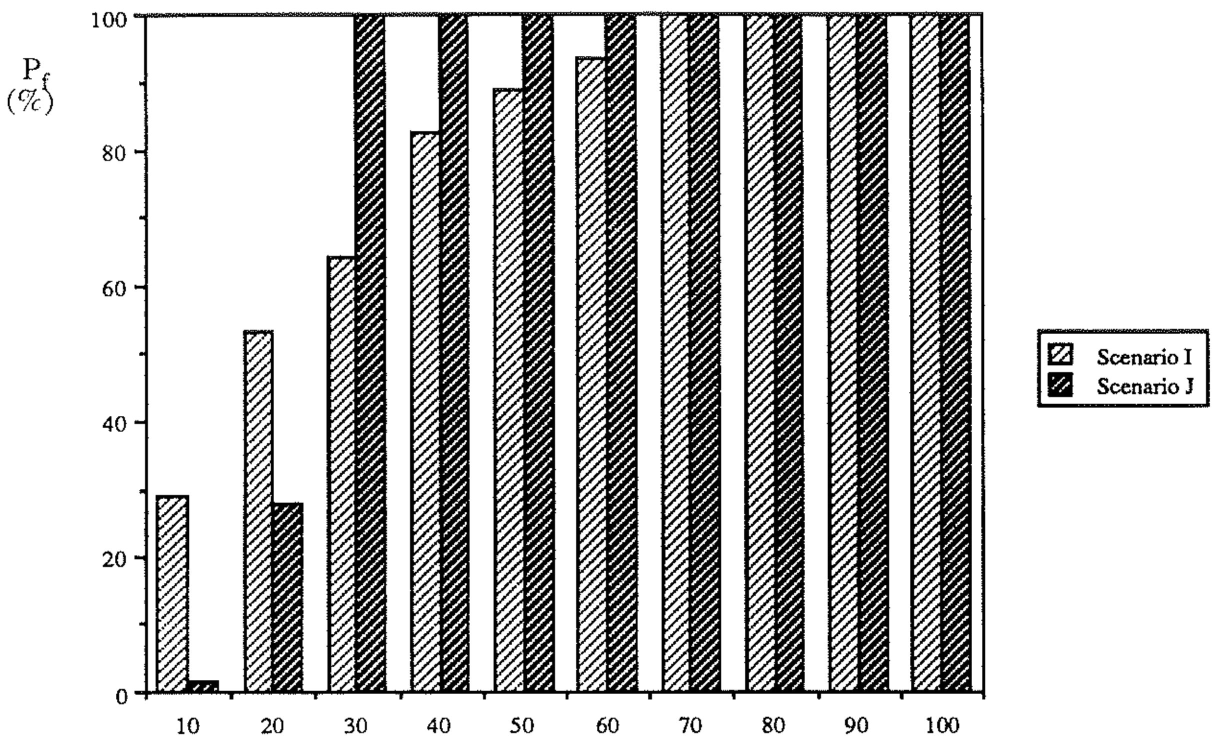


Fig.10. Scenario I and J.

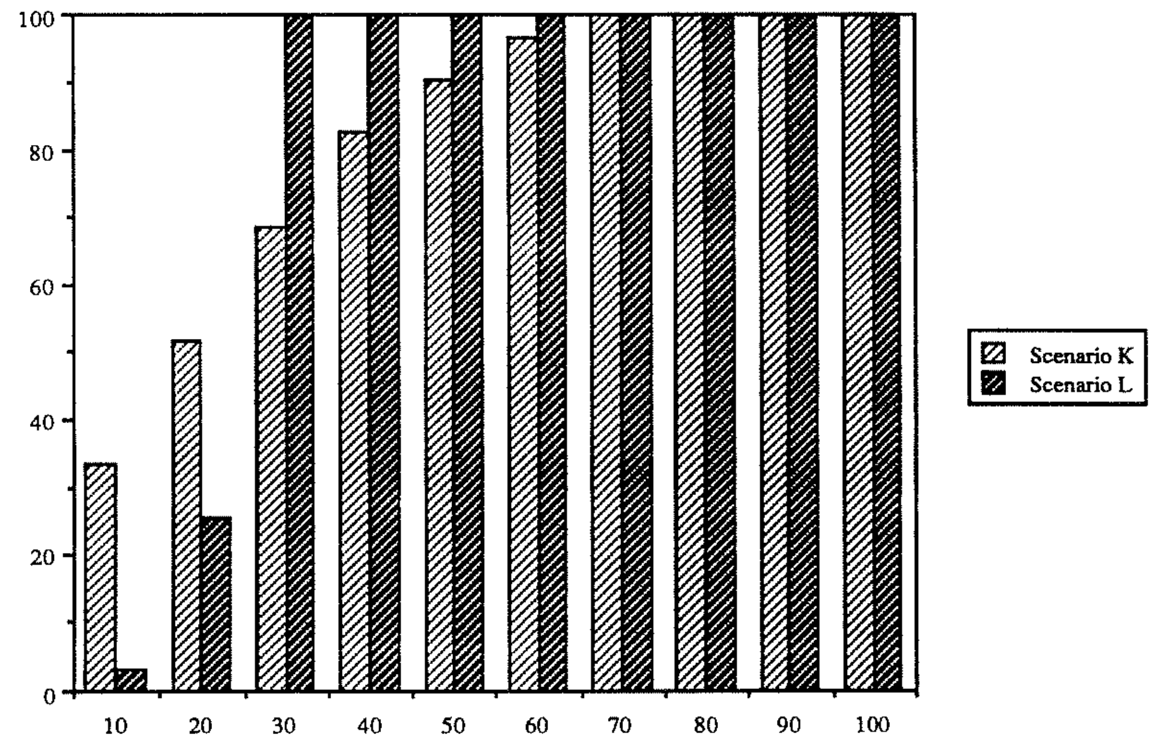


Fig.11. Scenario K and L.

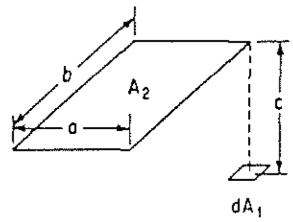
Appendix A

Configuration Factors

Reference:

Siegel, R., Howell, J. R., "Thermal Radiation Heat Transfer", second edition. McGraw-Hill, New York; 1981.

4

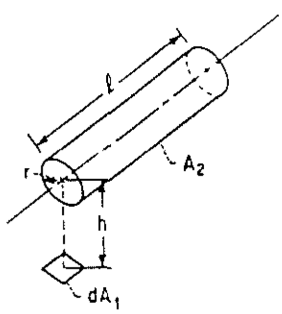


Plane element dA_1 to plane parallel rectangle; normal to element passes through corner of rectangle.

$X = \frac{a}{c} \qquad Y = \frac{b}{c}$

$$F_{d1-2} = \frac{1}{2\pi}\left(\frac{X}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\frac{X}{\sqrt{1+Y^2}}\right)$$

24



Plane element dA_1 to right circular cylinder of finite length l and radius r; normal to element passes through one end of cylinder and is perpendicular to cylinder axis.

$L = \frac{l}{r} \qquad H = \frac{h}{r}$

$X = (1 + H)^2 + L^2$

$Y = (1 - H)^2 + L^2$

$$F_{d1-2} = \frac{1}{\pi H}\tan^{-1}\frac{L}{\sqrt{H^2-1}} + \frac{L}{\pi}\left[\frac{X-2H}{H\sqrt{XY}}\tan^{-1}\sqrt{\frac{X(H-1)}{Y(H+1)}} - \frac{1}{H}\tan^{-1}\sqrt{\frac{H-1}{H+1}}\right]$$

Appendix B

Smoke Filling

Comparison of Zukoski's differential equation and experiments.

Zukoski's differential equation for leakage at floor level:

$$\frac{dy}{d\tau} + Q^* + k_1 (Q^*)^{1/3} (y)^{5/3} = 0$$

Two fullscale experiments are considered:

1) FOA- experiments (ref. 1) Smoke filling times were studied in a room with floor area 5.62*5.62m^2 and height 6.15m. The fuel was kerosine with three different fuel areas; 0.25 m^2, 0.5 m^2 and 0.75 m^2. Figures 1-3 show observed smoke filling time and the solution to the above equation.
2) Japanese experiments (ref. 2) Smoke filling times were observed in a room with floor area 720 m^2 and height 26.3 m. The fuel used was methanol with a fuel area of 1.8*1.8 m^2. Figures 5 and 6 show the observed smoke filling time and the solution of a differential equation from ref. 2. Figure 4 shows the differance in this equation and Zukoski's. The differance is minimal.

References:

1) Hägglund et al. "Smoke filling experiments in a 6x6x6 meter enclosure". FOA report no C 20585-D6. Stockholm 1985.
2) Tanaka, Yamana. "Smoke Control in Large Spaces". Fire Science and Technology, Vol 5, No 1, 1985.

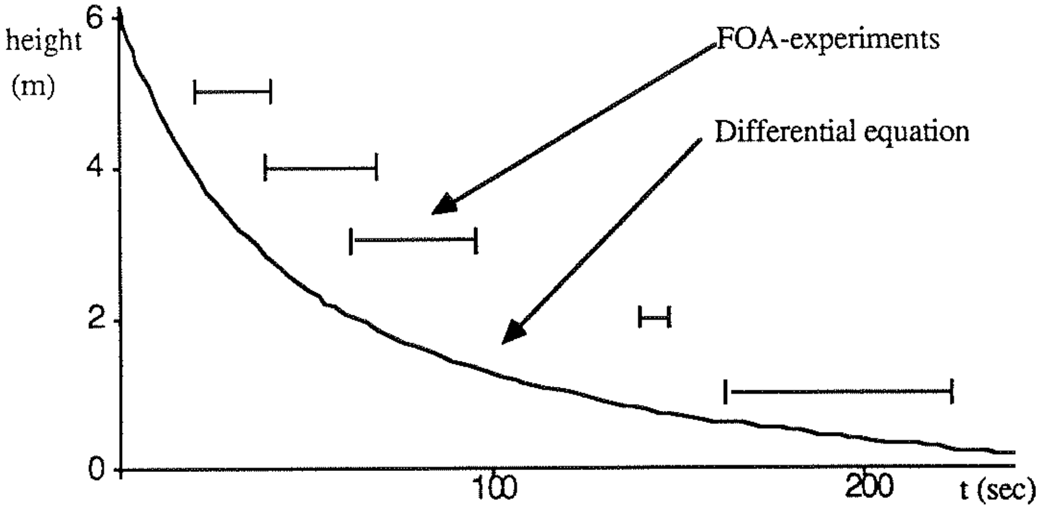


Figure 1 Spill size = 0.25 m^2

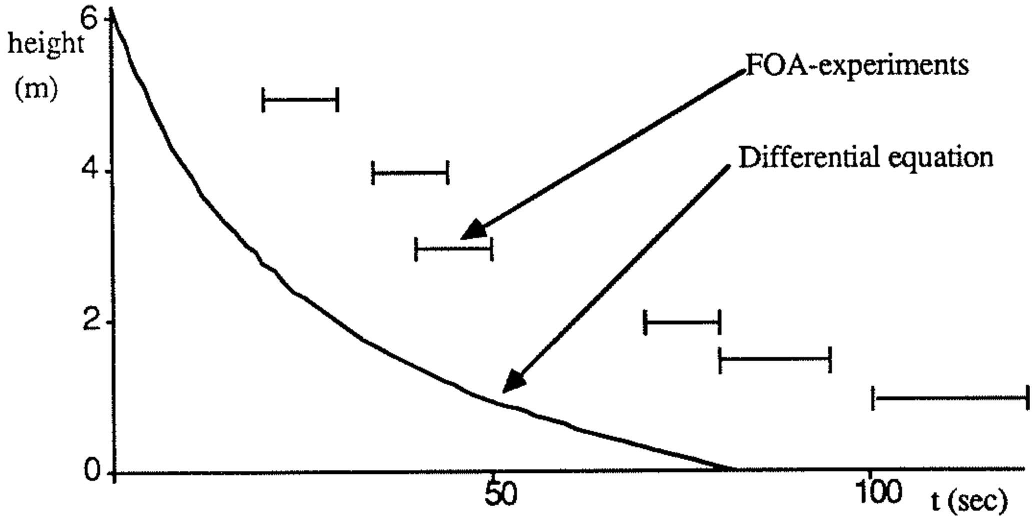


Figure 2 Spill size = 0.5 m^2

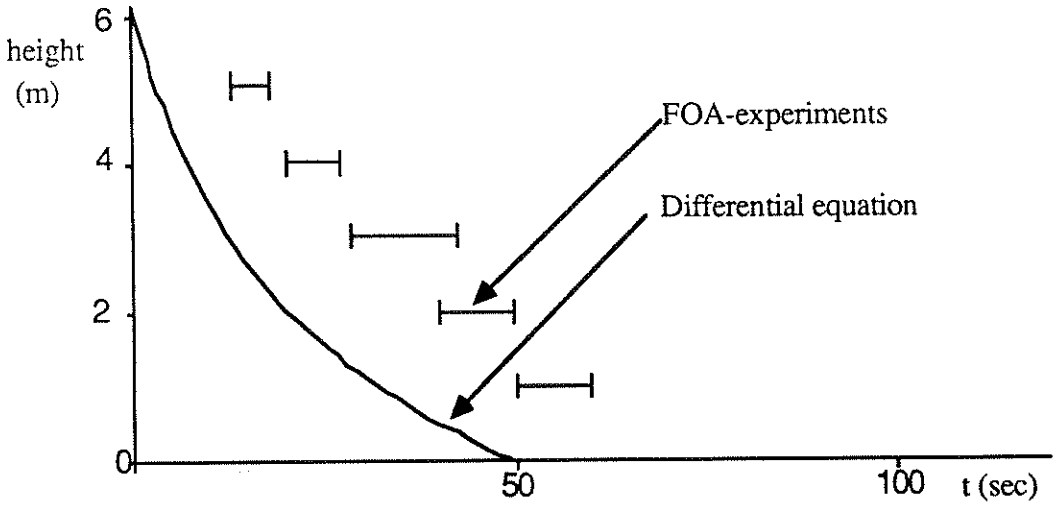


Figure 3 Spill size = 0.75 m^2

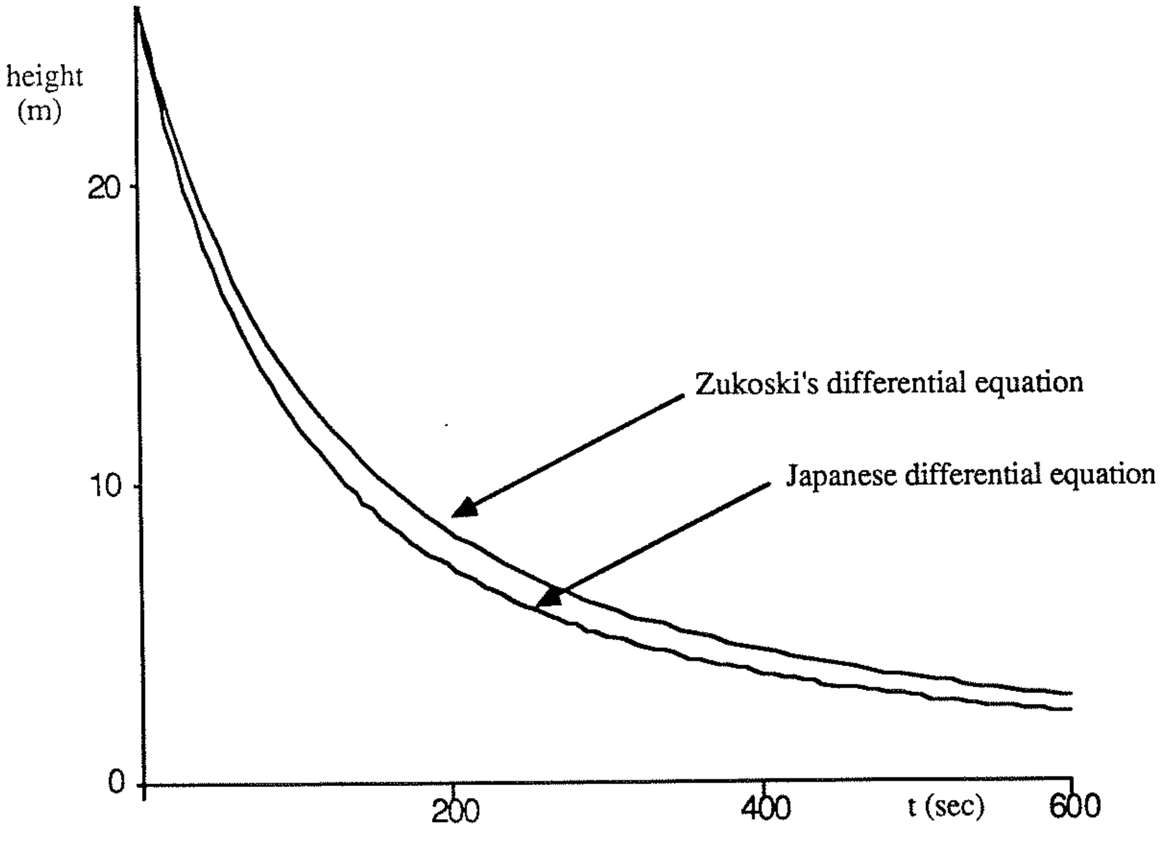


Figure 4 Japanese experiment

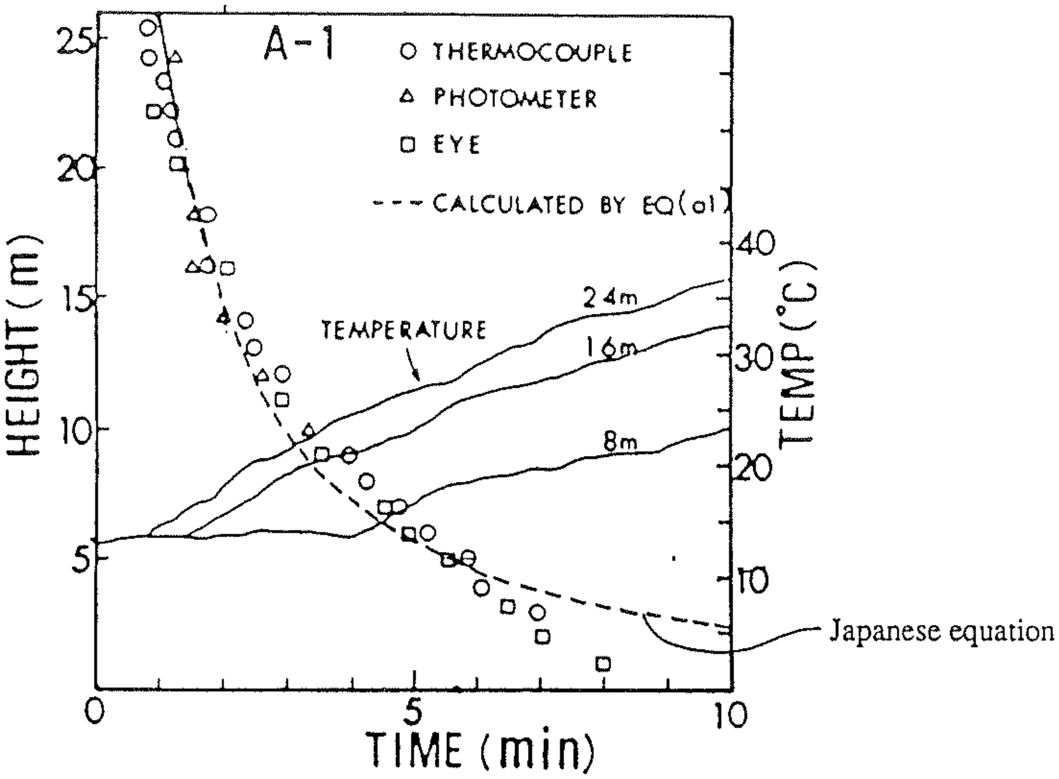


Figure 5 Smoke filling with time (A－1 : natural filling)

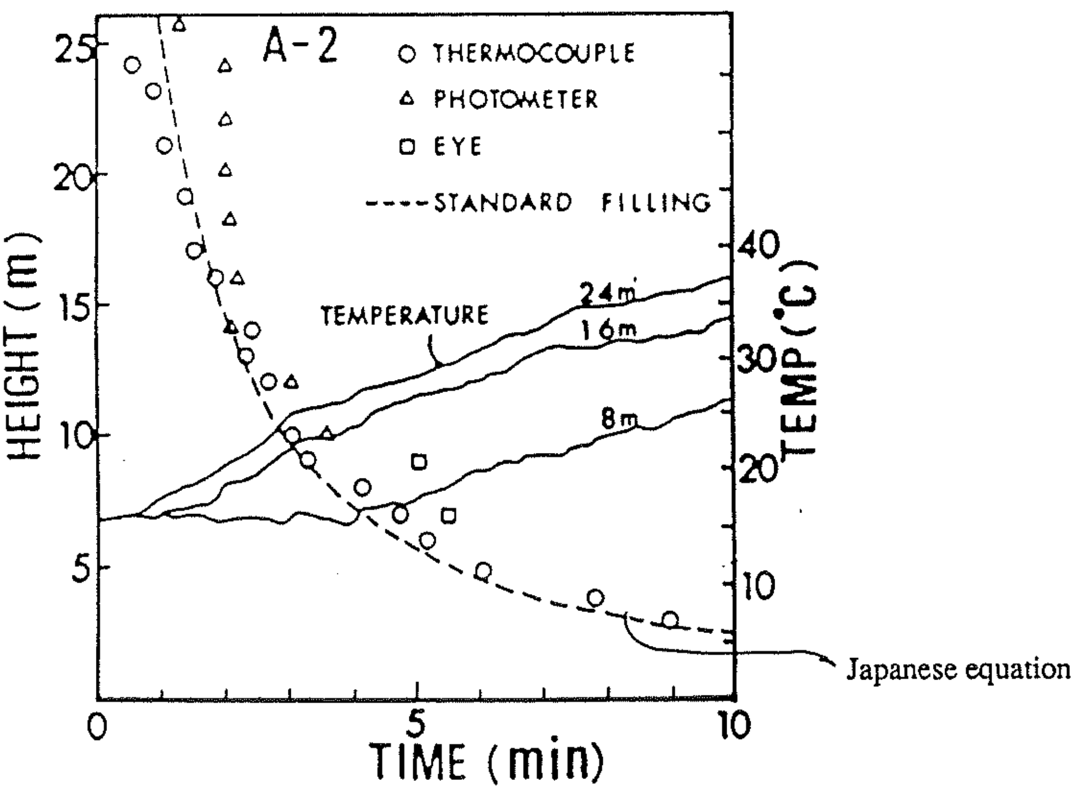


Figure 6 Smoke filling with time (A－2 : natural filling under pressurized condition)

Appendix C

Lumped thermal capacity model, including insulation and convection

Consider a composite object of surface area A_s, subjected to external radiation q". Material 1 has a relatively low density and heat capacity, material 2 a relatively high density and heat capacity (see Figure 1).

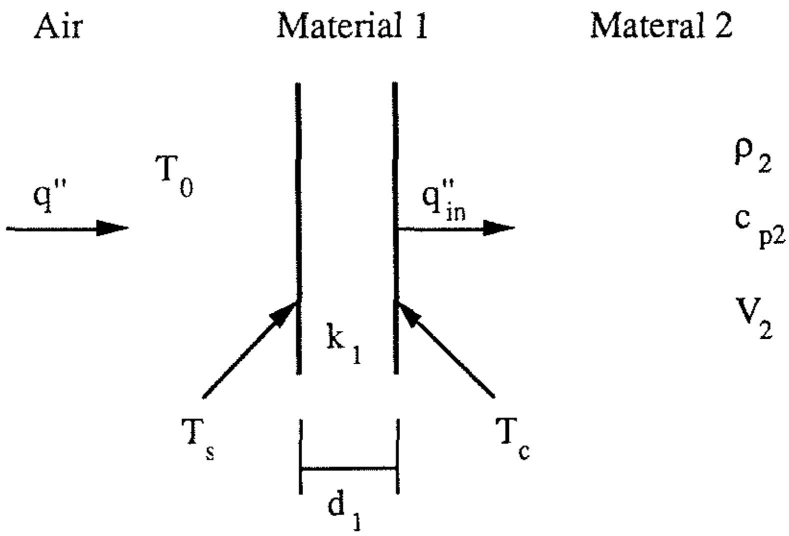


Figure 1

Assuming a constant convective cooling coefficient, steady state conditions for the heat flux through material 1 and that material 2 behaves as a lumped mass, the three following equations for heat flux can be written :

$$q''_{in} A_s = (q'' - h_k(T_s - T_0))\ A_s \qquad [1]$$

$$q''_{in} A_s = (k_1/d_1)(T_s - T_c)\ A_s \qquad [2]$$

$$q''_{in} A_s = \rho_2 V_2 c_2\ (dT_c/dt) \qquad [3]$$

Equating [1] and [2] and solving for T_s one gets:

$$T_s = \frac{\dot{q}'' + h_k T_0 + \frac{k_1}{d_1} T_c}{\frac{k_1}{d_1} + h_k} \qquad [4]$$

Substituting [4] in [1] one gets an expression for q''_{in}

$$\dot{q}''_{in} = \frac{\dot{q}''\frac{k_1}{d_1} - h_k\frac{k_1}{d_1}(T_c - T_0)}{\frac{k_1}{d_1} + h_k} \qquad [5]$$

Substituting [5] into [3] results in the differential equation

$$\frac{dT_c}{dt} + \frac{1}{t_{C1}t_{C2}}T_c = \frac{1}{t_{C1}t_{C2}}\frac{\dot{q}''}{h_k} + \frac{1}{t_{C1}t_{C2}}T_0 \qquad [6]$$

where

$$t_{C1} = \frac{\rho_2 c_{p2} V_2}{A_s h_k}$$

and

$$t_{C2} = 1 + \frac{h_k d_1}{k_1}$$

Solving this ordinary differential equation with the boundary condition $T_c(0) = T_0$ gives:

$$T_C = T_0 + \frac{\dot{q}''}{h_k}\left(1 - e^{-t/(t_{C1}t_{C2})}\right) \qquad [7]$$