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ANALYSIS OF OIL SPILL FIRES IN NUCLEAR POWER PLANTS

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Abstract: An analysis of a fire in a compartment of a nuclear power plant (NPP) needs deterministic and probabilistic models. The deterministic model aims at to estimate the time to damage of either the pumps or the cables in the compartment. A probabilistic model is also necessary because the fires can be of various sizes and at different locations in the fire room. Further, oil spill sizes were assumed to be equally probable and their locations were assumed to be independent. Calculations are made using the computer codes which use probabilistic as well as deterministic models as a tool for safety engineers to analyse the fire development in compartments.

Keywords: Oil spill fires, NPP, fire development, failure probability, safety engineering tool, compartment fires

Nükleer Santrallarda Petrol Sızıntısı Yangınlarının Analizi

Özet: Nükleer bir santralin, kapalı bir hacminde meydana gelecek bir yangının teorik analizi, deterministik ve probabilistik bir modele gereksinim gösterir. Deterministik model kapalı hacimdeki kablo veya pompalarda yangın sonucu meydana gelecek zarar zamanlamasını tahmin etmeyi amaçlar. Probabilistik modelin gereksinimi ise yangınların farklı büyüklükte ve ortamlarda meydana gelebilecek olmasından kaynaklanmaktadır. Ayrıca petrol sızıntısı miktarlarının muhtemelen eşit, ortamlarının ise birbirinden bağımsız oluşacağı kabul edilmiştir. Çalışmada nümerik analizler metinde belirtilen bilgisayar programları ile gerçekleştirilmiştir.

Anahtar kelimeler: Petrol sızıntısı yangınları, nükleer santral, yangın oluşumu, göçme ihtimali, güvenlik mühendisliği, tabii yangınlar

INTRODUCTION

The purpose of this paper is to facilitate a study to predict the probability of component failure, P_f, due to a fire in a nuclear power plant (NPP) compartment. Furthermore the assessment of temperature development and energy output in fire place as well as the temperature rise in the surrounding structural elements will be carried out. The components for fire induction are assumed to be pumps in the compartment or the cables which supply electricity to the pumps. It is assumed that the fire starts by means an oil spill from one of the pumps.

The development of fires in buildings can be divided into two periods of time separated by flashover. There is the growth, or pre-flashover stage and followed by some period of time the post-flashover stage where the fire has grown to fill the containment. An important application for calculation is to determine the post-flashover fire temperatures. Thus the fire resistance of building components exposed to fire can be predicted. These components include walls, floors, columns and beams, etc. and are generally designed as "*barriers*". A fundamental principle of fire safety design is that barriers must resist only a post-flashover fire. In the following literature review fire development and its consequences in NPP are discussed.

Literature review

Jee, M., et al. (2013), stated that the fire zones of nuclear power plants were classified into four types, that is, Special Zone, Red Zone, Yellow Zone, and White Zone. The research results present the most effective fire-fighting strategies suitable for each fire zone in nuclear power plants. **Jiaxu, Z., et al**. (2012), introduces a process of the *performance-based* fire protection method. In the method of the fire probabilistic safety assessment and the fire protection design in the nuclear power plants are described.

The paper from **Genebelin, V., et al**. (2009), contains a discussion of two models – the heat transfer and the IR "K-factor" models – to estimate the likelihood of fire-induced cable damage given a specified fire profile. The paper from **Nowlen, S**. (1992), provides a general discussion of the issue of nuclear power plant fire safety as it currently exists in the USA and included is a discussion of the past history of nuclear power plant fire events.

A new code, called VULCAN/STADIC-2, has been developed by **Frank et al**. (1986), to aid the probabilistic risk of the spread of fire damage within a large enclosure by combining simplified theoretical and empirical physical models (VULCAN) with the Monte Carlo simulation technique. This technique is also used in (Dobbernack, 1979). **Nicoletta, et al**. (1991), discuss the advantages and disadvantages of three basic types of fire models (zone, field, and control volume). It is shown that the type of fire model selected to solve a particular problem should be based on the information that is required.

The work from **Kazarians, et al**. (1978), is an investigation of fire as a potential threat to the safety of a nuclear power plant. A qualitative description of ignition mechanisms and factors affecting the growth of fire (detection mechanisms, extinguishing efforts, etc.) is presented and an estimate of the frequency of fires in nuclear power plants is given. **Schneider** (1991), indicates that the special "nuclear" boundary conditions e.g. the absolute confinement of radioactivity impose severe restrictions on the fire protection and fire-fighting measures.

S. Othumpangat, et al., and **Al-Majed, et al**. (2014), make it in their works evident that the challenge of managing oil spills around the world is increasing in complexity and magnitude. Oil spill prevention remains the only way to manage the transportation and exploration of this hazardous material as well as to deposit in a NPP.

Hosser, D et al (2009) presents a methodology to compare and evaluate numerical results with experimental data for NPP fires. The origin of this methodology is based on a global evaluation parameters, which by **Peacock et al**. (1999) is described in *"Least Square Method"*. On this basis, an evaluation comparing two complete time series is to be performed. Since local and global effects may occur simultaneously, the methodology for the comparison of the respective extreme values of a local evaluation parameter is expanded.

Consequences of a fire in a NPP

The literature review shows that the consequences of a fire in a single compartment of NPP involve assuming that all critical components, in the compartment to be investigated, fail. Such an analysis requires both the development of a deterministic as well as probabilistic models. On one hand numerical analyses by computer codes can be used to determine the temperature maxima in a containment which is given by its geometrical features. By applying parametric studies the influence of different parameters on the hot gas temperature development due to oil spill fires can be investigated in order to obtain information about the critical points as well. The objective of the deterministic model is to predict the time to damage of either the pumps or the cables. This critical time of damage must be compared with the fire duration in compartment. A probabilistic model is also necessary since the fires can develop in different intensity and locations.

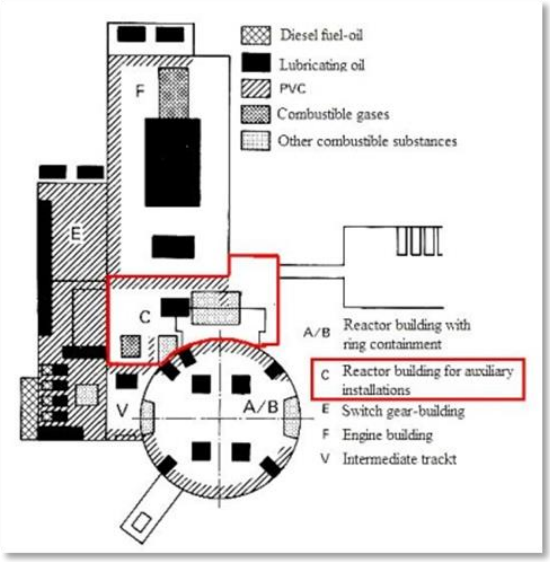

Figure 1: Plan view of a high pressure reactor building. (Hosser, D., et al.; 1982, in German)

Figure 1 shows the plan view of a power plant where a fire can develop in the pump and cable room due to oil spills. In the figure this area is shown with coloured outlines.

FIRE PROTECTION IN NPP

Conventional fire protection requirements are mainly governed by laws, regulations or directives. They must be modified in buildings of special nature and use under certain circumstances by the building authorities. The experience and knowledge gained on effective fire prevention measures can be transferred in part to NPP. However, there are number of fire safety nuclear specific difficulties in this area. Structural fire protection in NPP can best be reclined on the conventional structural fire protection. From the requirements of nuclear safety, however additional requirements must be provided. Where authorities cannot or can only perform limited structural fire protection measures for operational reasons, alternative measures are taken. They are;

- Reducing fire risk by limiting or specially constructing compartments for fuel
- Additional facilities and operational arrangements for fire detection
- Measures for mechanical smoke removal on non-vented plant areas

Fire protection requirements

Structural fire protection measurements are dealt with laws and regulations, recognized rules of civil engineering. Requirements for fire safety in NPP have to content:

- High grade regulations
- Accepted rules of civil engineering
- International rules and guidelines

The regulations were evaluated from the following point of views; *Design Concept* includes:

- Fire prevention
- Fire detection
- Fire-fighting
- Fire containment
- Fire extinguishing, escape and rescue measurements
- Organizational measures

Figure 2 shows fire protection design for NPP

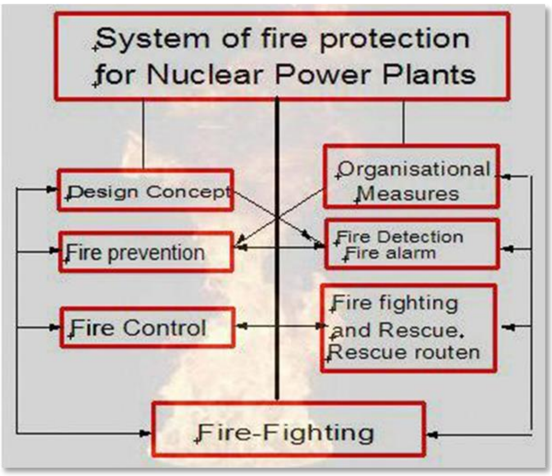

Figure 2: System of fire protection measures. (**Hosser, et al.** 1982, in German)

Fire detection

By a centralized automatic fire detection and alarm system all areas with fuels must be constantly monitored to detect a fire already in the development phase and fight the fire effectively. The rules to be monitored spaces are determined internationally more or less in details.

Fire-Fighting

For the effectively fire-fighting the present regulations deal with:

- Stationary extinguishers
- Facilities for manual fire fighting
- Water supply for fire fighting
- Smoke removal
- Fire-fighting troops, plant fire brigade, public fire brigades
- Access roads and paths for fire fighting

The individual components are documented in the national and international regulations with different importance.

Fire-containment

The locally limiting the effect of fire is achieved by following measures:

- Separation of the building by partitions
- Independent construction of fire compartments
- Foreclosure of major fuels by fire resistant structural elements
- Separation of redundant systems with sufficient distance
- Closure of ventilation ducts when passing through the partitions of fire compartments

Naturally the requirements differ in various countries. They can only be compared with the underlying test methods (DIN 4102, 1981). Except in the (IAEA-Directives, 1979) various rules are defined empirically.

HEAT BALANCE CALCULATION

The main equation is the first law of thermodynamics, or as it is known, the heat balance calculation for all the gas within the fire room. In Figure 3 such a fire room with its boundaries is illustrated. The chemical energy of fuel combustion is released and is lost by several routes. A major quantity of heat leaves through the window. Another fraction of the energy radiated out the window, while a ration of it goes to heating the walls. All these processes occur by means of convection and radiation. Therefore Eq. 1 can be used to describe the heat balance rates of the fire compartment:

$$\dot{H}_C = \dot{H}_L + \dot{H}_W + \dot{H}_R + \dot{H}_B \quad (1)$$

The corresponding mass balance equation Eq. 2 in the fire compartment is:

$$\dot{M}_B - (\dot{M}_L + \dot{R}) = 0 \quad (2)$$

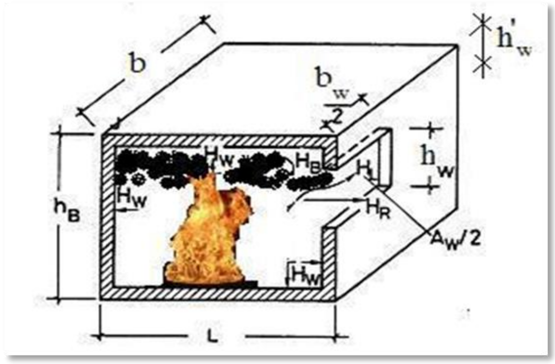

Figure 3: Fire room and the energy terms of the heat balance equation

All these energy rates are valid for a certain fire duration. The components are schematically illustrated in Figure 3.

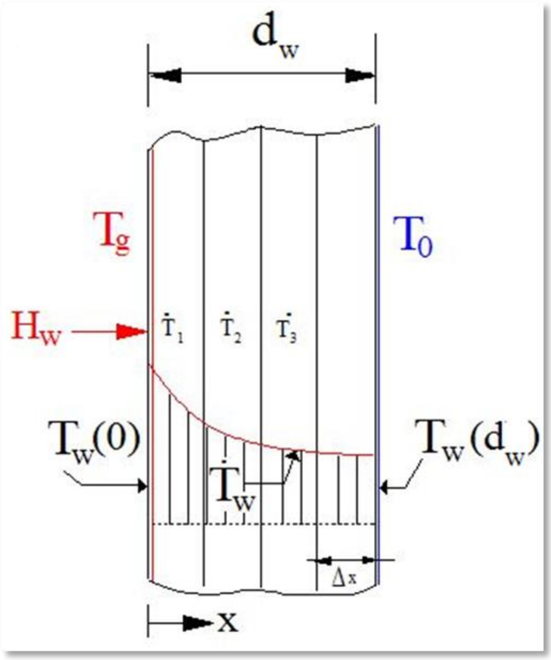

Figure 4: Compartment walls as section of an infinite slab

In this way solution of the heat balance problem is reduced into simultaneous equations (1) and (2). The solution of these equations give the fresh air inflow M_L and hot gas temperature T_g. To solve these equations an iterative method is necessary; this procedure and related equations are given in (**Haksever**, 1989&1990) in details.

The surface temperature of the surrounding walls on the exposed side has to be considered as an additional unknown parameter. The non-steady temperature distribution in the walls is evaluated under consideration of the appropriate boundary conditions, according to the ***Fourier Equation***. Since the temperature variations along the surface of the walls are assumed small, the walls can be represented as section of an infinite slab. Figure 4 shows the discretization of the compartment walls. A one dimensional problem to be solved for heat flow through the wall is expressed by Eq. 3:

$$\rho C_p \frac{\partial T_W}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T_W}{\partial x}\right) + \dot{q}_w \quad (3)$$

In Eq. 3, $\dot{q}_w$ is the heat generated within the wall if there is any heat source.

Several zone models with different complexity, have been developed to predict the compartment temperatures, fire gas productions and the endurance of the fire deterministically. All these programs give a time dependent solution of mass and temperature equations which describe fire development in a compartment (**Mittler**, 1985., **Haksever**., 1989). Due to the complexity of the problem and the equations to be solved at each time step require long time in terms of calculation times since in some time steps convergence problems can appear. In that case time steps must be reduced appropriately.

A fire in a NPP compartment must take into account of fires in several different intensity and locations. The popularly known method deriving of $\boldsymbol{P_f}$ is the *Monte Carlo Simulation Technique*. In the zone models is the calculation of P_f can be extremely time consuming for those several fire conditions to be investigated (**Dobbernack,** 1979). As a con-sequence an alternative methodology of evaluating the fire in a compartment was looked for and a deterministic and a probabilistic model were thus developed and combined in the computer code ***OSFIC*** (**Karlsson**, 1989) The computer code itself is described in a separate publication (**Karlsson**, 1988). The Program can thus predict the probability of component failure due to a fire. In this paper the effectiveness of the Code ***OSFIC*** and also the heat balance program ***AYSEN*** for oil spill fires by examples demonstrated. Both the computer prog-rams can be used together as a safety engineer's tool to investigate the probability of component failure (gas explosions are not considered).

NUMERICAL ANALYSES OF OIL SPILL FIRES IN NPP

The model ***OSFIC*** uses two different procedures to calculate the fire development in a compartment. The first is the case with sufficient amounts of oxygen as a *fuel bed controlled* fire and the second is the case of *ventilation controlled* fire. These cases appear in the fire development de-pending on the geometry, e.g. open doors and windows and closed openings of the fire room respectively. Model ***AYSEN*** takes into account these cases automatically and determines the type of *fire development* during the fire.

Both models uses a two zone models. When fire starts, hot gases rise from the burning oil towards the ceiling forming distinct layer of hot gases and finally after a certain time of fire duration the hot gases start flowing out of the openings. The time history of the fires in buildings can be divided into three periods of time separated by flashover. There is the growth, or pre-flashover, stage which is characterized by a localized zone of burning in a compartment, and following some period of time fully developed burning and decay. Calculation procedures can be found in the appropriate literature (**Karlsson,** 1989**., Haksever,** 1990). In the next section oil spill fires in a NPP are analysed by examples and the results of the both models are compared.

Heat release rate

Heat release rate is one of the most important parameter characterizing hazard from undesirable fires. It is an indicator for the rate of fire growth, size of the fire, human escape and fire suppression agents for fire control. Heat release rate is calculated in ***AYSEN*** for a fire from the following equation.

$$H_C = m.H_i.R_{sp}.F_b \quad (4)$$

In Eq. 4, H_C is total heat release (kW), H_i heat of combustion of the fuel (kJ/kg), R_{sp} mass loss rate of the fuel in combustion per unit fuel surface area (kg/m^{2}s), F_b fuel surface area (m^2) and *m* is a factor which defines not only the uncompleted burning but also the interaction with the fire room (ventilation conditions, fire source conditions, thermal properties. (s. DIN V18 230, part 1, 1989). m-Factor=1 can be taken for oil spill fires as an unfavorable condition.

Fire area

Eq. 4 indicates that the energy output during the fire rises in connection to the growing fire area. Both H_i and R_{sp} are variable quantities and depend strongly on the fuel and on the fire development. In ***AYSEN***, H_i and *Rsp* are calculated from a fire depending on the sort of fuels according the Table 1 (**Roitman**, 1972):

Table 1: Burning characteristics some fuels

Fuel	Mass loss rate of the fuel **kg/m^{2}h**	Heat of combustion of the fuel **kWh/kg**	Heat release per unit fuel surface area **kW/m^2**
Wood	30	4.65	139.56
Caoutchuc	24	11.63	279.12
Cotton bales	8.5	4.65	39.54
Polystyrene	30	11.63	348.90
Paper, loose	24	3.72	89.55
Petroleum	175	11.63	2035.25
Aceton	150	7.91	1186.26
Gasoline	160	11.83	1860.80
Oil	70	11.63	814.10

NUMERICAL EXAMPLES FOR FIRES IN NPP

Example 1; Fire in T-9916

Results obtained by the computer program OSFIC

This chapter presents an example case from compartments in the NPP Barsebäck. It is a NPP in the south Sweden. The compartments included in the oil spill study are:

1- Rooms T-9916 and T-9917 (condensate pump room)
2- Room T-0318 (feedwater pump room)
3- Room T-9915 (generator cellar)

Here will only the results of the investigation for **room T-9916** shown. A more detailed analysis of an oil spill fires for the rooms, reader can find in (**Karlsson**, 1988). Figure 5 illustrates the fire room with its dimensions and coordinate system.

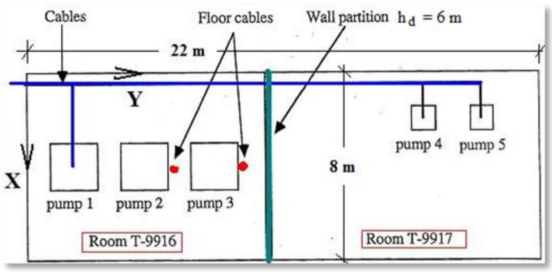

Figure 5: Plan view of rooms T9916 and T-8817. For further dimensions, see Figure 6

The fire compartment is l'=22.0 m long, b=8.0 m wide and h_B=6.0 m high. It is split into two rooms by a h_d= 2.0 m high wall partition. ***Room T-9916*** is l=10.0 m long, b=8.0 m wide and contains three condensate pumps. The cables enter through a wall at the height of 2.5 m. There are several scenarios to be taken into account in this case (s. **Karlsson** 1989); here it will be taken into account that the maximum amount of oil spilled from one of these pumps is 20.0 liters. The oil spill is assumed to be confined to room T-9916. The door is assumed to be open. The input data for the room T-9916 from (**Karlsson**, 1988) is given in Figure 6.

```
INPUT VARIABLES:

ROOM LENGTH, BREADTH AND HEIGHT = 22.00   8.00   6.00

DOOR HEIGHT AND BREADTH = 2.00   1.00

CRITICAL SURFACE TEMP. OF CABLE AND PUMP = 150.0   200.0

MAXIMUM AMOUNT OF OILSPILL (LITERS) = 20.0

A WALL SPLITS THE ROOM IN TWO PARTS.

WALL COORDINATES ARE:
 0.00  10.00
 8.00  10.00

X AND Y CABLE COORDINATES:
 0.20  0.00
 0.20  2.00
 4.00  2.00

HEIGHT FROM FLOOR TO CABLE = 2.00

X AND Y CORNER-COORDINATES OF PUMP:
 3.10  1.10
 4.90  2.90

PUMP HEIGHT = 1.90

DIFFERENTIAL NET SIZE DX AND DY : 0.50  0.50
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Figure 6: Input data for fire room T-9916. Surrounding walls are made of concrete

Figure 7 displays only a part of the long form for 10 liters oil spill size, for spill no 5. Calculated results show that for fire in *spill nr 5* due to an oil spill from 10 liters max. energy output is approximately 2414 kW and the max. fire room temperature is ~245 °C. However, fire extincts after ∼5 min. An information about the temperature development and the energy output is not presented in the results.

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SPILL NO 5          SPILL AMOUNT (LITERS) = 10.0

OILSPILL AREA = 2.00      FLAME HEIGHT = 3.56

ENERGY OUTPUT(KW) = 2413.8  MAX. GASTEMPERATURE (DEG C) = 242.9

TIME TO FLAME EXTINCTION (MINUTES) = 4.76

PROBABILITY OF DAMAGE FOR THIS OILSPILL % = 29.68
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Figure 7: Calculation results for *spill no 5* for 10 liters oil spill (420 MJ).

Results obtained by the computer program <u>AYSEN</u>

The input data for the calculation of a fire in T-9916 by means of ***AYSEN*** is given in Table 2. The walls of the compartment are out of normal concrete which include a humidity from 4%. In the following chapters results are presented for the temperature development, energy output and temperature distribution in the surrounding walls during the fire. Appropriate heat transfer correlations for different heat conditions can be found in literature (**Eckert**, 1959., **Schneider**, et al. 1977., **Hottel**, 1979., **VDI-Wärmeatlas**, 1983).

Table 2: Input data for the heat balance calculation *(AYSEN)* of fire room T-9916

DESCRIPTION OF THE FIRE ROOM T-9916 FOR *AYSEN*			
Thickness of the Walls [mm]		Window openings [m]	
d_w	300	b_w	6.0
d_r	300	h_w	0.5
d_c	300	h'_w	0.3
Fire room dimensions [m]		A_w	3.0 m^2
		Ventilation factor χ	χ[1] $= 0.04.\sqrt{h_w} \sim 0.03$ $m^{1/2}$
b	8.0	R_{sp} [kg/m^{2}h]	60
l	10.0	Total fuel size [MJ]	419
l`	22.0	Heat of combustion [MJ/kg]	41.9
h_d	6.0		
Molecular weight of hot gases and air [kg/mol]		Combustion enthalpy H_i/r [MJ /kg air]	741
w_g = 28.96	w_0 = 28.96	**Material of the walls:** **Normal concrete.** Humidity w=4%	

[1] $\chi = A_w \times h^{1/2}/A_t = 0.04$ $m^{1/2}$, **Magnusson**, S. Erik et al., Natural fires with different opening factors, Lund Institute of Technology, Sweden., (1970).

Temperature development in the fire room:

The interaction between the energy output and energy losses determines mainly the hot gas temperatures in the containment. Figure 8 shows a good agreement with results of ***OSFIC*** in the max. temperature level attained during the fire as well as to the time of flame extinction. Both computer programs calculate a max. hot gas temperature ~ 243 °C (***OSFIC***) and ~ 230. °C (***AYSEN***) respectively. The time of the flame extinction agrees also to the prediction from ***OSFIC*** as 5 min. In the picture the temperature development is also illustrated with a dotted line in the same scala of ISO-Fire-Curve by which the flash-over occurrence overlaps ISO834-fire curve. On the picture is also the equivalent fire duration is given. It is the time duration of the ISO-fire which coincides with the time to reach maximum temperature of a natural fire. (**Schneider et al.**, 1977). There are also some other criterias to determine the equivalent fire duration.

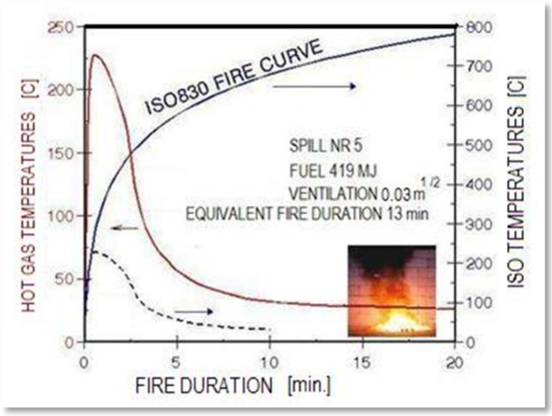

Figure 8: Temperature development in fire room T-9916 due to 10 liters oil spill *(AYSEN)*

Energy output into fire containment:

The energy output into the containment can occur in different ways, for example by the above mentioned oil spill fires or catching fire of the cables, or by heat transfer from hot structure materials, etc. Energy losses can mainly occur by heating up of solid structures and heat losses through the walls of the containment to the surroundings. In Figure 9 Energy output into the containment of the NPP is illustrated. ***AYSEN*** predicts a max. Energy output from 2808. kW versus OSFIC 2414 kW.

Heat flow into the walls of the containment:

The heat flow H_W into the walls of the containment can be calculated with the following equation (s. also Figure 4)

$$H_W = \alpha F_W\left(T_g - T_W(0)\right) \quad (5)$$

where T_g is the temperature of the containment atmosphere, $T_W(0)$ the temperature at the unheated surface, and F_W exposed surface area of the wall. The temperature distribution within the wall can be determined with respect to the Eq. 3.

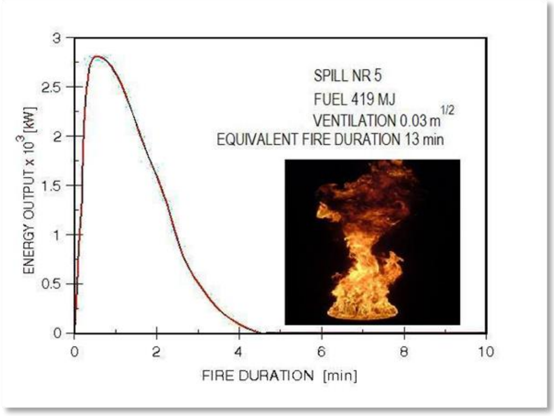

Figure 9: Energy output into the NPP containment during the fire (***AYSEN***)

The heat transfer coefficient α depends strongly on motion of the air mixture relative to the surface and the inclination of the wall surface (**Henderson**, C. I., 1969, **VDI-Wärmeatlas**, 1983). Figure 10 shows the max. temperature distribution within the surrounding walls together with the energy output into the containment during the fire. It can be seen that max. temperature on the fire induced surface of the wall attains approx. 40-43 °C and ambient temperature 20 °C in the wall in a distance from ~12 cm from the heated surface. The rest of the wall thickness remains with initial temperatures.

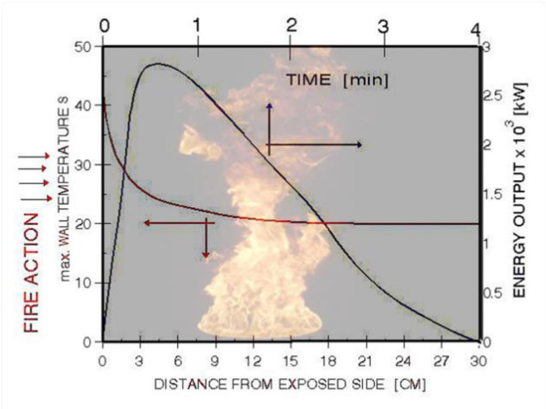

Figure 10: max. Temperature distribution within the surrounding walls and the energy output in the containment (***AYSEN***)

Remaining fuel and fuel-air interface in the containment during the fire:

Figure 11 below illustrates the pyrolysed fuel during the burning process. For example after one min. of ignition approx. 40% of fuel is pyrolysed. On the other hand picture shows the fuel-air interface defined with *∅-Value*.

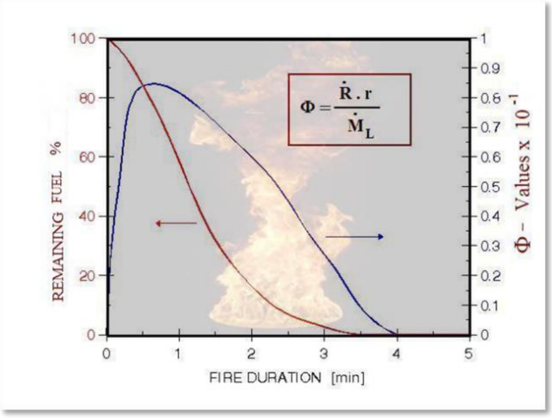

Figure 11: Development of the remaining fuel and fuel-air interface during the fire (***AYSEN***)

There are two basically different types of combustion reactions that can occur in a compartment fire. If there is insufficient oxygen in the compartment, however, exceedingly quanties of fuel, so fuel may also burn outside the doors or windows of compartment or in the compartment a *ventilation controlled* burning may occur. This type of combustion is indicated when Ø-Value[2] > 1.0 which means there is more fuel being pyrolysed in the compartment than can be burned inside it. The second is a gaseous reaction in the fire room above the fire source and within the compartment. This type of combustion is indicated when Ø-Value < 1.0 so there is excess fresh air in the compartment that can enable totally pyrolyse of the fuel. In this case a *fuel bed controlled* fire can occur within the fire room. Figure 11 shows that the combustion type within the compartment is *fuel bed controlled* and fire extincts due to the complete burning of the fuel in the fire room T-9916. The development of the Ø-Value is also similar to the energy output in the compartment.

Example 2; Fire in Room 1

Analysis of the fire in the room 1 using OSFIC

The Fire containment is l'=21.3 m long, b=10.0 m wide and h_B =4.50 m high. It is split into two rooms by a h_d=3.0 m high wall partition. The ***room 1***, is l=12.0 m long, b=10.0 m wide and contains two condensate pumps. The cables enter through a wall at the hight of 2.0 m. The maximum amount of oil spilled from one of these pumps is 10.0 liters.

The walls of the containment are 25 cm thick, made out of normal concrete and covered at the interior side with a 5 cm fire-brick (Figure 12).

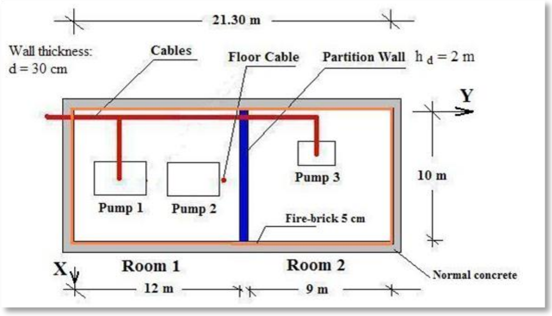

Figure 12: Plan view of the containment (*room 1*) in Example 2

The input data is given in Figure 13. There are several scenarios to be taken into account in this case (s. **Karlsson** 1989). Here it will be taken into account that the maximum amount of oil spilled from one of these pumps is assumed to be confined to *room 1***.** The door is assumed to be open. The following Table 3 shows only a part of the long form for 5 liters oil spill size, for spill no 5.

INPUT VARIABLES:

ROOM LENGTH, BREADTH AND HEIGHT = 21.3 10.0 4.5

DOOR HEIGHT AND BREADTH = 2.00 1.00

CRITICAL SURFACE TEMP. OF CABLE AND PUMP = 150.0 200.0

MAXIMUM AMOUNT OF OILSPILL (LITERS) = 10

A WALL SPLITS THE ROOM IN TWO PARTS.

WALL COORDINATES ARE:
0.0 12.0

10.0 12.0

X AND Y CABLE COORDINATES:
0.2 0.0
0.2 3.5
5.0 3.5
HEIGHT FROM FLOOR TO CABLE = 3.5

X AND Y CORNER-COORDINATES OF PUMP:
4.0 1.0

5.5 3.0
PUMP HEIGHT = 1.90

DIFFERENTIAL NET SIZE DX AND DY : 1.0 1.0

Figure 13: Input data for fire room in example 2.

Calculation results with OSFIC show that for fire in ***spill no 5*** due to an oil spill from 5 liters max. energy output is approximately 980 kW and the max. fire room temperature is ~147 °C. However, fire extincts after ~6 min (s. Figure 14).

[2] Φ=1 indicates a stohiometric burning case

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SPILL NO 5          SPILL AMOUNT (LITERS) = 5.0
OILSPILL AREA = 1.00        FLAME HEIGHT = 2.46
ENERGY OUTPUT(KW) = 979.7    MAX. GASTEMPERATURE (DEG C) = 146.7
TIME TO FLAME EXTINCTION (MINUTES) = 5.87
PROBABILITY OF DAMAGE FOR THIS OILSPILL % = 18.60
--------------------------------------------------
```

Figure 14: Calculation results for spill no 5 for 5 liters oil spill (220 MJ)

The room is divided into 1.0 x 1.0 m grids resulting in 212 oil spill positions. The final probability of damage for this oil spill size is 18.6%. The overall probability of damage is 22%. Displayed in Table 3 are the times to damage due to different modes of the heat transfer. Only results for 20 positions are displayed in the following table. The time to damage as a result of radiation from the flames depends on the position of the oil spill. These times are given in Table 3 for each oil spill position. Time to damage due to the heat transfer from the gas layer is not dependent on the position of the oil spill and is therefore given with a single number (22.7 min). The critical time to damage is the shortest time of these times. Here it is infinity; this expression is displayed when, the maximum gas temperature is lower than the critical cable temperature, consequently it takes an infinitely long time for the cable to reach its critical temperature (**Karlsson,** 1989).

Table 3: Times to damage due to different modes (***OSFIC***)

TIME TO CRITICAL DAMAGE AS A RESULT OF RADIATION FROM:

GAS LAYER TO CABLE (MINUTES) = ∞
GAS LAYER TO PUMP = ∞
PLUME TO CABLES = 22.68

POS. NO	FLAME TO PUMP	CRITICAL TIME	PROB.
1	2.11	2.11	0.17
2	1.26	1.26	0.17
3	0.66	0.66	0.17
4	0.32	0.32	0.17
5	0.21	0.21	0.17
6	0.21	0.21	0.17
7	0.24	0.24	0.17
8	0.46	0.46	0.17
9	0.93	0.93	0.17
10	1.65	1.65	0.17
11	2.64	2.64	0.17
12	1.99	1.99	0.17
13	1.14	1.14	0.17
14	0.55	0.55	0.17
15	0.21	0.21	0.17
16	0.11	0.11	0.17
17	0.11	0.11	0.17
18	0.11	0.11	0.17
19	0.35	0.35	0.17
20	0.81	0.81	0.17

The resulting probability of damage for each position is also given. If the time to extinction is shorter than the critical time to damage the probability of damage is defined to be zero. In this example there is a ~55% probability that the oil spill will be beyond the 1 m radius from any pump, so the probability to damage remains to be zero. All other positions divide between them, resulting in a probability of ~0.17 % to damage having a critical time of infinity. The first 75 positions give a time to damage less than two minutes, this is due to the fire plume being directly under the cables. In the next 20 or so positions the pump is in direct contact with the flame, giving the 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 gas layer which has a temperature of around 147-150 °C (s. Figure 14).

Results obtained by the computer program AYSEN

The input data for the **room 1** is given in Table 4. The walls of the compartment are out of normal concrete 25 cm which include a humidity from 4% and fire-brick 5 cm inside the fire compartment (s. Figure 12).

Table 4: Input data for the heat balance calculation of fire **room 1**

DESCRIPTION OF THE FIRE ROOM 1 FOR *AYSEN*			
Thickness of the Walls [cm]		Window openings [m]	
d_w	25+5=30	b_w	6.0
d_r	30	h_w	0.5
d_c	30	h'_w	0.3
Fire room dimensions [m]		A_w	3.0 m^2
		Ventilation Factor χ	$\chi = 0.04.\sqrt{h_w}$~0.03 $m^{1/2}$
b	10.0	R_{sp}[kg/m^2h]	60
l	12.0	Total fire load[MJ]	209.5
l`	21.30	Heat of combustion [MJ/kg]	41.9
h_d	4.50		
Molecular weight of hot gases and air [kg/mol]		Combustion enthalpy H_i/r [MJ/kg.air]	741
w_g = 28.96	w_0 = 28.96	**Material of the walls: Fire-Brick+Normal concrete.** Humidity 4%	

<u>Temperature development in fire room:</u>

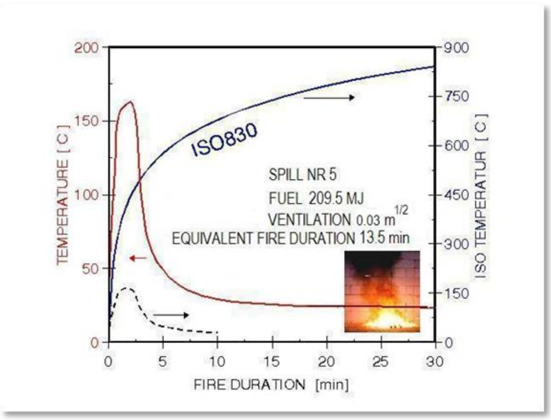

Figure 15: Temperature development in fire ***room 1*** predicted by ***AYSEN***

The interaction between the energy output and energy losses determines mainly the hot gas temperatures in the containment. Figure 15 shows an acceptable agreement with results of ***OSFIC*** in the max. temperature level attained during the fire as well as to the time flame extinction. Both computer programs calculate a max. hot gas temperature ~147 °C (OSFIC) and ~160 °C (***AYSEN***) respectively. The time of the flame extinction from ***AYSEN*** agrees also the prediction from OSFIC as ~6 min. ambient temperatures is attained approx. after 20 min. fire duration. In Figure 15, the temperature development is also illustrated with a dotted line in the same scale of ISO-Fire-Curve. For this fire the equivalent fire duration is determined as 13.5 min which shows the influence of the inner fire-brick layer of the containment walls.

A more detailed comparison of the results is given in the next section.

<u>Energy output into fire containment:</u>

The energy output into the containment (**fire *room 1***) can occur in different ways and energy losses by heating up of solid structures and heat losses through the walls and openings of the containment to the surroundings.

In Figure 16 Energy output into the containment of the NPP is illustrated. ***AYSEN*** predicts a max. Energy output from ~1390 kW and 980 kW of the **OSFIC** respectively. Figure 16 shows that the energy output into the containment remains approx. 1-2 min constant due to steady burning rate. From Figure 17 it can be seen that the fire is fuel bed controlled until the extinction of the fire.

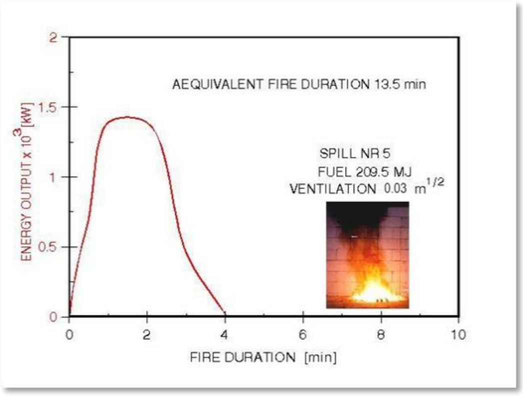

Figure 16: Energy output in fire room 1 due to 5 liters oil spill in in spill NR 5 predicted by ***AYSEN***

Figure 16 and 17 indicate that the energy output rate is not a fundamental property of the fuel, but is strongly dependent on environmental conditions. Energy output due to heat of combustion can be defined as the heat released per unit mass of fuel vapors produced. When all the fuel vapors burn completely H_i is defined as heat of complete combustion of the fuel which is the case in the fire. In ***OSFIC*** the energy released in the fire in both examples is assumed to be as if it were a fuel bed controlled fire. It is then considered to be constant at this value till the fire extincts.

<u>Remaining fuel and fuel-air interface in the containment during the fire:</u>

The Figure 17 illustrates the pyrolysed fuel during the burning process. For example after 1 min. of ignition approx. 30% of fuel is pyrolysed. On the other hand picture shows the fuel-air interface defined with Ø *-Value*. The type of combustion indicates that the Ø-Values << 1.0 so there is excess of fresh air in the compartment that can enable total pyrolysis of the fuel. In this case a *fuel bed controlled* fire is present within the fire room. The heat of combustion is a sum of *convective* and *radiative* components of combustion and both is de-fined as the ratio of respective heat release rate to mass loss rate of the fuel.

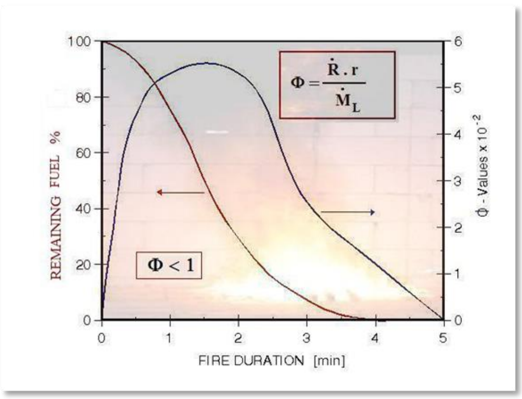

Figure 17: Development of the remaining fuel and fuel-air interface during the fire (***AYSEN***)

<u>PREDICTION OF THE FIRE DAMAGE IN THE CONTAINMENTS BY MEANS OF OSFIC</u>

Figure 18 shows the damage in % versus spill nr (or spilled oil in liter) for the open door case for fire room T-9916. Heat transfer from the gas layer occurs at a temperature of around ~ 243 °C (***AYSEN***; 227 °C., s. Figure 20). Figure 18 indicates that the probability of damage increases in accordance with the increasing energy output in the fire containment. In (**Karlsson**, 1989) it is stated that in room T-9916 there is 25% chance that pumps stop functioning. This chance remains approx. unchanged for spill fires from 10 liters oil on.

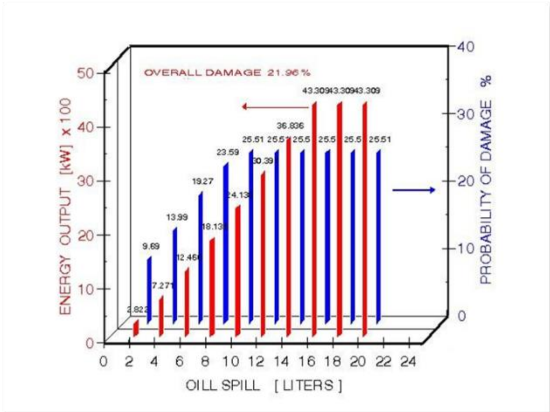

Figure 18: Energy output into the containment and the probability of damage in **example 1**, (T-9916, ***OSFIC***)

On the other hand in Figure 19 the fire damage in **Example 2** is illustrated. Figure 19 shows the damage in % versus spill nr (or spilled oil in liter) for the open door case. Heat transfer from the gas layer occurs a max. temperature of around ~147 °C (***AYSEN***; 163 °C., s. Figure 20). ***OSFIC*** predicts that in ***room 1*** for 10 liters oil spill there is ~32% chance that pumps stop functioning. Both fire room are approx. in same size in their dimensions. How-ever in Example 2, in the fire ***room 1*** there is more chance for the stopping of the pumps functioning. This is to the great extent due to less oil spill size (10 liters in fire room 1) in example 2 versus in example 1 (20 liters in fire room T-9916). However overall damage in both examples appears to be approx. equal (~22% versus ~20%).

Figure 20 shows comparatively the max. energy output and temperature level in the compartments predicted by ***OSFIC*** and ***AYSEN***. In both calculations the energy output with respect to ***AYSEN*** is higher than the values according to the ***OSFIC***.

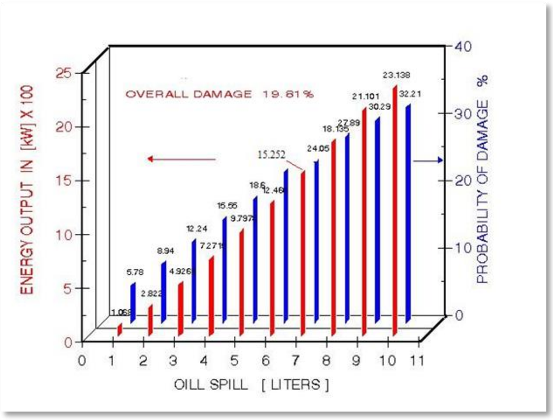

Figure 19: Energy output into the containment and the probability of damage in **Example 2** for fire *room 1*, (***OSFIC***)

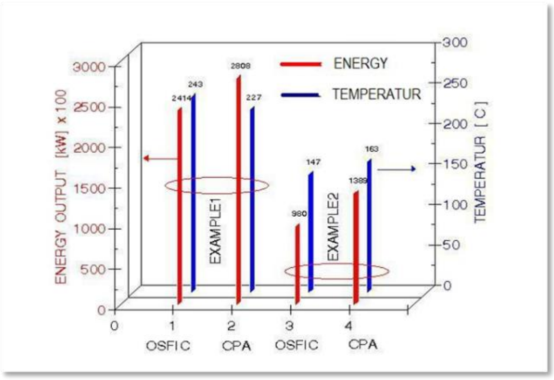

Figure 20: comparatively the max. energy output and temperature level in the compartments predicted by ***OSFIC*** and ***AYSEN*** ***(CPA;*** *calculation program AYSEN)*

From Table 5 below it can be seen that the mass loss rates of the computer programs are different and ***OSFIC*** uses a higher value though according **Table 5** the maximum value of the mass loss rate for oil is given as 70 kg/m^2/h (s. also **Table 1**). This difference depends mainly on the extinction conditions of fire predicted by ***OSFIC*** and on the burning area of the spilled oil. In ***AYSEN*** beside the oil spill size, also an increasing burning area with a certain fire propagation rate is applied (**Schneider, et al.**, 1990). In ***OSFIC*** this area is held constant in dimensions with a *1m radiu* (**Karlsson**, 1989).

Table 5: Pool mass loss rates

Pool mass loss rate [kg/m^2/h]	
OSFIC	***AYSEN***
140.4	70.0

The comparison of the maximum temperatures attained during the fire shows the influence of the wall construction as well as the combustion type especially in example 2, where a fire brick is used as interior layer for the compartment walls with high insulation capacity and fire develops as fuel-bed controlled.

SUMMARY

A more detailed summary for the ***Room T-9916*** in example 1, reader can find in (**Karlsson**, 1989). If fire starts in this room and the door is open, there are ~25% chances that pump 1 stops functioning (s. Figure 18). This conclusion is obtained for 20 liters oil spill (419 MJ) and open door case.

In example 2, for fire ***Room 1*** the overall probability of damage is ~20 % for open door case. This conclusion applies to 10 liters oil spill (209 MJ) and ~23% chances are present that pump 1 stops functioning (s. Figure 19).

Computer code ***OSFIC*** deals with many fire scenarios and is effective to determine the damage due to fire in compartment. However ***OSFIC*** does not present results for fire development with respect to time.

AYSEN is effective to give more information about the fire scenario in one room, concerning the temperature development, energy output, fuel-air interface to determine the fire type as well as the heat flow into the surrounding structural surface elements bound to time. However ***AYSEN*** run deal with a deterministic model and doesn't assume oil spill sizes and locations as conditional probabilities.

Both programs give approx. the same temperature maximas for relatively same boundary conditions. However this conclusion cannot be claimed for energy output into the fire room; ***OSFIC*** calculates less energy output than ***AYSEN***. The main reason is that ***OSFIC*** calculates the fuel-air interface greater than 1 ($\Phi>1$) and fire develops under exhausting condition. In contrary ***AYSEN*** has shown in both examples a *fuel bed controlled fire* ($\Phi<1$) and consequently it results in total burning of fuel without exhausting and a higher energy production.

Finally it can be stated that calculation programs are complying each other and can be used together as safety engineer's tool. By means of the programs the room configuration, pump and cable positions and wall partitioning in the compartment can be new designed in order to diminish the damage probabilities and to design an optimal construction.

NOTATIONS

A_W Total Area of the openings [m^2]

A_t Total Area of the surrounding walls of the compartment [m^2]

b_w Width of the window [m]

b Width of fire room [m]

l Length of fire room [m]

l' Total length of fire room [m]

Cp	Specific heat capacity of wall	[MJ/kgK]
d_w	Wall thickness	[mm]
d_f	Floor thickness	[mm]
d_c	Ceiling thickness	[mm]
F_b	Fuel surface area	[m^2]
F_w	Surface area of the wall	[m^2]
H_B	Energy rate stored by hot gas volume	[MJ/s]
h_B	Height of the fire room	[m]
H_C	Energy rate released in fire room	[MJ/s]
H_L	Energy rate leaving fire room	[MJ/s]
H_i	Heat of combustion of the fuel	[MJ/kg]
H_i /r	Combustion Enthalpy	[MJ/kg.air]
H_W	Energy rate absorbed by walls	[MJ/s]
h_d	Height of wall	[m]
h_w	Height of window	[m]
h'_w	Distance of upper edge of the window to ceiling	[m]
k	Coefficient of thermal conductivity	[W/mK]
M_B	Hot gas rate leaving the fire room	[kg/s]
M_L	Fresh air rate incoming the fire room	[kg/s]
m	Combustion efficiency factor	[1]
P_f	Damage probability	[%]
R	Burning rate	[kg/s]
R_{sp}	Specific mass loss rate of the fuel per unit fuel surface area	[kg/m^2h]
R	Mass ratio for stoichiometric combustion	[1]
T_g	Hot gas temperature	[K]
t_{eq}	Equivalent fire duration	[min]
T_0	Initial temperature	[K]
T_W	Wall temperature	[K]
$T_W(d_w)$	Surface temperature at the outside of the wall	[K]
$T_W(o)$	Surface temperature at the fire-side of the wall	[K]
q_w	Internal energy source rate	[W/m^3]
w_g	Molecular weight of hot gases	[kg/mol]
w_0	Molecular weight of air	[kg/mol]
w	Humidity of concrete	[%]
α	Heat transfer coefficient	[W/m^2K]
ρ	Density	[kg/m^3]
Φ	Fuel-air interface	[1]
DX, DY	Elements for discretization of fire room	[m]
X	Ventilation factor $(\Sigma A_w\sqrt{h_w})/A_t$	[$m^{1/2}$]
Δx	Infinite slab thickness in X direction	[mm]

The other notations are defined where they appear in the text.

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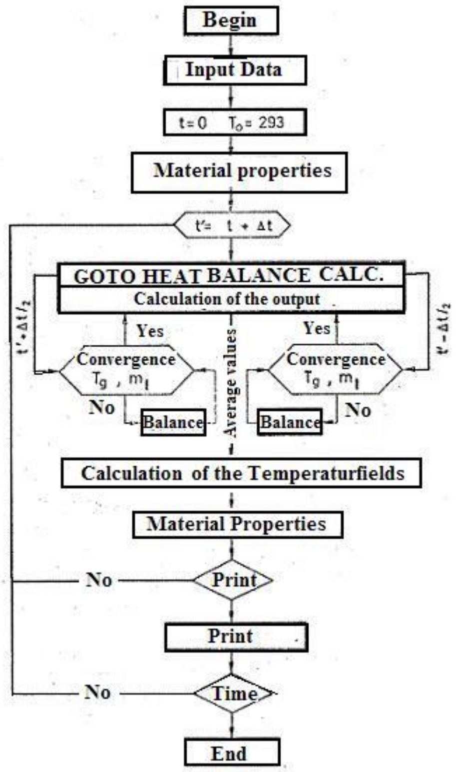
APPENDIX



Flow diagram of the calculation program (***AYSEN***) [17].