USING MAGIC CODE FOR CANDU-6 EPS FIRE SCENARIOS SIMULATION

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This paper presents a fire ignition and evolution scenarios within the emergency power supply building for a CANDU-6 nuclear power plant, due to off-site power system unavailability following an earthquake. The fire evolution and propagation in the two EPS building compartments will be analyzed using MAGIC code, which is a two zones model, based on homogenous thermo-physical properties afferent to each layer. The thermal characteristics of the two compartment layers (as time function) are obtained by solving the mass and energy conservation equations, the ideal gas law and some fire plume correlations.

Keywords: fire simulation, MAGIC, CANDU-6, lube oil fire, diesel oil fire, cable fire

1. Introduction

Nuclear power plant operation experience over the past three decades indicates that fires occurred during NPPs (nuclear power plant) operation may constitute a real and significant threat to nuclear safety in addition to the conventional fire hazards to life and property. It is widely acknowledged that in many cases, the risk posed by fires can be comparable to or even exceed the risk from internal events [1], [2], [3].

Therefore, international efforts have been made to fully understand and analyze the phenomenon of fire and its consequences at NPPs on one hand and to improve NPP design and regulatory requirements to fire safety as well as fire protection technology on the other hand.

From a technical point of view it is known that all nuclear facilities are design taking into account accidental fires; even so, after service experience shows that fire scenarios are still among the main contributors to the overall vulnerability of nuclear facilities and also are confirmed by the high frequency and high importance of the events in this area.

In safety assessment of nuclear facilities against fire scenarios, modeling has improved significantly in recent years. However, this phenomenon is still lack

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of data with the highest contribution to the overall uncertainty about the vulnerability of SSCs (systems, structures and components). In fact, failure modes and thresholds of several components are not fully understood in terms of the effects of temperature, smoke, aerosols, lack of oxygen, etc.

Moreover, recent interest shown for more complex scenarios related to large fires (i.e., fires initiated over large areas at a time) makes it more difficult to assess. Explosions, mechanical impact and spread of fire effects in large areas, combined with thermal effects, can lead to possible damage of the separation barriers. In these cases, simplistic assumptions of damage to all fire equipment in the affected area become too conservative and unacceptable, requiring accurate qualification procedures.

In this study we analyze the evolution and the effects of a fire scenario involving the compartments of an emergency power supply system building of a CANDU-6 NPP (CANada Deuterium Uranium Nuclear Power Plant).

Fire simulation and validation of analytical procedures have become increasingly important over time, especially in the context of fire safety analysis for nuclear power plants. Fire simulation models have been developed as analytical instruments to support the risk assessments from the point of view of fire safety [4], [5], [6], [7].

Using the calculated predictions can be considered, on one hand to improve and upgrade fire predictions by licensees and, on the other hand, as a tool for reproducible and clearly understood estimations from the available assessments and/or from the set of fire protection measures by the authorities and their experts.

As a tool to simulate the evolution of the fire spread in a multi-compartmental building, as a result of natural ventilation and/or the interaction with artificial ventilation networks is used MAGIC code.

2. Theoretical basis of MAGIC models

MAGIC Software (Modeling with Aspen of Gasification Integrated with a Combined cycle) is a Aspen Plus model using Fortran subroutines, created in 1985 by EDF Research & Development in order to develop a tool for numerical simulation adapted to the EDF (Électricité de France) needs to perform nuclear power plants fire safety studies [8], [9], [10].

MAGIC code calculates the concentration of oxygen and combustion gases for different gaseous areas. Also, major fires can cause secondary fires: a threshold induction is activated with a time delay depending on the temperatures reached by the fuel (secondary fire).

From the geometrical point of view, MAGIC operates on a set of rectangular rooms, the edges of which are parallel to the coordinate system axis.

These rooms communicate with each other and with the outside through horizontal or vertical openings.

As a result of the geometrical and thermal compartments and openings characteristics, gas flow and thermal conditions evolutions of the plant are obtained for one or more fires, the following parameters: temperatures for hot and cold gas layers, the concentrations of oxygen and combustion gases, the smoke gases in each room, mass flow rates of air and smoke through openings and vents, pressure at the floor level in each room, the surface temperature of the wall, thermal fluxes (radiative and total) changed by targets.

Also are available specific outcomes: plume temperature, unburned fuel mass, gas temperatures passing through the vents, smoke and thermic detectors temperatures, etc.

Initially, a fire compartment can be treated as a free burning, as an unlimited fire. This approach is valid until lack of oxygen or thermal effects become significant. In many ventilated areas, the ventilation system stops automatically under fire, either by closing the ventilation system or by closing doors or fire dampers. However, there are areas where ventilation openings can continue to work or unprotected openings may remain open. The evolution of fire in a compartment, and the conditions results depend on the following variables (among others) [11] ÷ [23]: HRR (heat release rate of combustible materials), size of the enclosure, construction materials and geometry and compartment ventilation.

2.1 Pool fire heat release rate

Fire development is generally characterized in terms of heat release rate (HRR) vs. time. Thus, determining the HRR (or burning rate) is an essential aspect in a fire hazard evaluation.

A common method of assessing HRR is to measure the burning rate, which is also known as the mass loss rate. Estimating the HRR based on the mass loss rate requires knowledge of the fire effective heat on combustion. For many materials, the burning rate is reported per horizontal burning area in units of kg/m^{2}s. Thus, HRR is calculated using the following equation:

$$\dot{Q} = \dot{m}'' \Delta H_{c,eff} A_f \left(1 - e^{-k\beta D}\right) \qquad (1)$$

where: $\dot{m}''$ is burning or mass loss rate per unit area per unit time, in kg/m^{2}s; A_f - horizontal burning area of the fuel, in m^2; kβ - empirical constant, in m^{-1}; D - diameter of burning pool fire, in m.

2.2 Flame height calculations

The flame height is important quantitative characteristic for NPP fire scenarios whose targets are located near to ignition sources. Some of these scenarios subject target take into account the flame temperature because the distance between the target and the source of ignition is lower than the expected flame height. A typical example is a cable tray located above an electrical panel. MAGIC code predicts the flame height using closed form semi-empirical correlations. Thus, the formula used by MAGIC is that evaluated by Heskestad, which is based on numerous experiments for low or high fire power with different types of fuels (gas, liquid, solid) [9]:

$$H_f = 0{,}235\dot{Q}^{\,2/5} - 1{,}02 \cdot D \tag{2}$$

where: H_f is flame height, in m; $\dot{Q}$ - heat release rate of the fire, in kW; D - pool fire diameter, in m.

The pool fire flame height estimation according to Thomas method is made about the following formula:

$$H_f = 42 \cdot D \cdot \left(\frac{m''}{\rho_a\sqrt{gD}}\right)^{0.61} \tag{3}$$

where, H_f - pool flame height, in m; D - pool fire diameter, in m; m'' - mass burning rate of fuel per unit surface area, in kg/m^2s; ρ_a - ambient air density, in kg/m^3; g - gravitational acceleration, in m/s^2.

2.3 Estimating hot gas layer temperature

Hot gas layer temperature has a particular importance in fire scenarios because it can be an indicator of the degree of target failure at a distance from the ignition source. The model predicts the ambient temperature rises due to energy released by a fire in an enclosure. However, the volume is set differently from one model to another. Thus, the output values of the temperature of the hot gas layer for the two zones model is a uniform temperature in the upper volume control (which is considered the hot gas layer, because the accumulated hot gases are transported to the upper part of the compartment by the plume).

Foote, Pagni, and Alvares (FPA) (1985) (also reported by Walton and Thomas, 1995 and 2002) developed another method, which follows the basic correlations of the MQH method (McCaffrey, Quintiere and Harkleroad for natural ventilation compartments), but adds components for forced-ventilation fires.

The upper-layer gas temperature increase above ambient is given as a function of the fire HRR, the compartment ventilation flow rate, the gas-specific heat capacity, the compartment surface area, and an effective heat transfer coefficient. The nondimensional form of the resulting temperature correlation is as follows:

$$\frac{\Delta T_g}{T_a} = 0{,}63\left(\frac{\dot{Q}}{\dot{m}c_pT_a}\right)^{0{,}72}\left(\frac{h_kA_T}{\dot{m}c_a}\right)^{-0{,}36} \tag{4}$$

where: ΔT_g - hot gas layer temperature rise above ambient (T_g - T_a), in K; T_a - ambient air temperature, in K; $\dot{Q}$ - heat release rate of the fire, in kW;

$\dot{m}$ - compartment mass ventilation flow rate, in kg/sec; c_p - specific heat of air, in kJ/kg·K; h_k - heat transfer coefficient, in kW/m^{2}K.

Where, h_k, heat transfer coefficient is calculated according the following formula:

$$h_k = \sqrt{\frac{k\rho c}{t}} \tag{5}$$

where, k - thermal conductivity of the interior lining, in kW/mK; ρ - density of the interior lining, in kg/m^3; c - thermal capacity of the interior lining, in kJ/kgK; t - exposure time, in s.

A_T total area of compartment enclosing surfaces, in m^2, is calculated according the following formula:

$$A_T = 2(w_c \cdot l_c) + 2(h_c \cdot w_c) + 2(h_c \cdot l_c) \tag{6}$$

where: w_c - compartment width, in m; l_c - compartment length, in m; h_c - compartment height, in m.

The above correlation for forced-ventilation fires can be used for different construction materials by summing the A_T values for the various wall, ceiling, and floor elements.

Deal and Beyler (1990) (also reported by Walton and Thomas, 2002) developed a simple model of forced ventilated compartment fires. The model is based on a quasi-steady simplified energy equation with a simple wall heat loss model. The model is only valid for times up to 2000 seconds. The approximate compartment hot gas layer temperature increase, ΔT_g, above ambient (T_g - T_a) is given by the following equation:

$$\Delta T_g = T_g - T_a = \frac{\dot{Q}}{\dot{m}c_p + h_k A_T} \tag{7}$$

where: ΔT_g - hot gas layer temperature rise above ambient (T_g - T_a), in K; T_a - ambient air temperature, in K; $\dot{Q}$ - heat release rate of the fire, in kW; $\dot{m}$ - compartment mass ventilation flow rate, in kg/sec; c_p - specific heat of air, in kJ/kg·K; h_k - heat transfer coefficient, in kW/m^2·K;

where h_k is:

$$h_k = 0.4\, max\left(\sqrt{\frac{k\rho c}{t}}, \frac{k}{\delta}\right) \tag{8}$$

where: k - thermal conductivity of the interior lining, in kW/mK; ρ - density of the interior lining, in kg/m^3; c - thermal capacity of the interior lining, in kJ/kgK; t - exposure time, in s; δ - thickness of the interior lining, in m.

where: A_T total area of compartment enclosing surfaces, in m^2, calculated according to the formula (6).

3. Lubricating Oil Fire Scenario

3.1 Fire scenario description and model input parameters

According to the events reports, most of the emergency diesel generators area fires are caused by fuel lines or lubricating oil lines rupture. Thus, a possible scenario can be the subsequent ignition of lubricating oil issuing from a rupture line (for example, a 0.15 m rupture diameter), in the form of an atomized spray. As ignition source is considered the hot diesel exhaust ducting (exhaust temperature 577 °C). Obviously, this scenario occurs during diesel generators operation, following a loss of offsite power initiating event.

For this case will be analyzed various situations: for the first scenario we will consider closed the door between the compartment, another scenario considered will be the one with opened door between the two compartment; in both cases taking into account the assumption with or without operative sprinklers and available sprinkler system.

The diesel generators building consist of two compartments separated by a 3 hours fire resistive wall. The walls are made of glass fiber reinforced concrete, and the separation wall between the two rooms is from glass fiber reinforced gypsum. The door on the separation wall is also defined as a 3 hours fire resistant.

The two diesel generators compartments are mechanically ventilated through a ventilation system with an exhaust flow of 34.337 m^3/s and an injection flow of 34.92 m^3/s for fire room, and an exhaust flow of 34.27 m^3/s and an injection flow of 34.93 m^3/s for the fire adjacent room.

In the evolution of this fire scenario are considered two stages of fire development: the first stage involves the initial fire development by ignition of lubricating oil that comes in contact with a diesel generators heat exhaust duct, and the second stage of development of fire implies the involvement of the entire inventory of combustible materials, diesel oil day tank (100 kg) and lubricating oil tank (808 kg) considering as source of ignition the radiative transfer causing the combustible materials ignition. The first involvement of the diesel oil stored in the day tank is through radiative heat transfer from the initiating fire to the day tank surfaces. In the next stage of development it is considered that all burnable materials and fuel inventory are suddenly and readily available and burns under ventilation-limited conditions.

Fire protection features considered in this case, for each room, includes two intelligent ionization smoke detector, an automatic sprinkler system consisting of six sprinkler heads and a 3 hours wall fire resistance barrier between the two compartments. The sprinkler characteristics considered in this case are: response time index of 42 $(m/s)^{0.5}$ and a leakage rate represented by a k factor = 250. The initial temperature of the water for fire-fighting network water is 20 °C, at a pressure on sprinkler heads of about 4 bar and an activation temperature of 68 ° C.

The tanks, cylindrical in shape, are assumed to be located at a 2 m distance for the lubricating oil tank, respectively a 3 m distance for the diesel oil tank, form the radiative initiating flame.

The thermal characteristics of combustible materials considered are listed in the next table.

Table 1

Thermal characteristics of combustible materials

combustible materials	Pyrolysis rate (g/s)	Heat of combustion (kJ/kg)	Burning rate $\dot{m}''$ (kg/m^2·s)	Stoichiometry (O_2 mss/fuel mass)	Density (kg/m^3)	Empitical constant kβ (m^{-1})
lube oil	39	46000	0,039	4,6	760	0,7
diesel oil	34,3	44700	0,048	2,88	740	3,6
Cable type						
PE/PVC	31.4-108	25100	0.0044	1.28	-	-

*Values from NUREG-1805 (U.S. Nuclear Regulatory Commission)

Ignition temperature of combustible materials is defined to be: 130 °C for lubricating oil, 100 °C for diesel oil and 130 °C for PE/PVC cables.

3.2 Results and discussions

3.2.1 Model validation

For model validation we consider only the initiating fire, for which we state that the combustible materials of this fire source are limitless, with a room rate ventilation system of about 0.583 m^3/s or 0.7 kg/s, and with no sprinkler system available**.**

Pool fire heat release rate calculation

The heat release rate of the initiating lube oil pool fire will be calculated according to (1):

$$A_f = \frac{\pi D^2}{4} \rightarrow A_f = 0.785\ m^2 \qquad (9)$$

where, D = 1 m -pool fire diameter. So,

$$\dot{Q} = 708.95\ kW$$

Estimation of the pool fire flame height

The pool fire flame height estimation for the initiating fire is calculating according to methods, one is the Heskestad method, which is the same method used by MAGIC code simulations, and the second one is the Thomas method.

According to Heskestad [see (2)],

from the empirical calculations, the pool flame height is of about $H_f = 2.23$ m.

From the empirical calculations of the Thomas method [see (3)]:

the pool fire flame height is resulted to be of about 2.59 m.

According to MAGIC simulation, the maximum flame height is 3.46 m. These results are acceptable, because in these calculations the admitted errors are about 50%.

Hot gas layer temperature evolution

For model validation we consider only the initiating fire, for which we state that the combustible materials of this fire source are limitless, with a room rate ventilation system of about 0.583 m^3/s or 0.7 kg/s, and with no sprinkler system available.

According to Foote, Pagni and Alvares method [see (4)],

we obtain a temperature evolution like that in the Fig. 1, blue line. The graphic submitted in Fig. 1, green line, represent the MAGIC layout for the hot gas layer temperature.

From the FPA Method calculation, we obtain a maximum temperature of about 206.83 °C. The maximum value for the hot gas temperature stated by the MAGIC calculation in of about 215.62 °C.

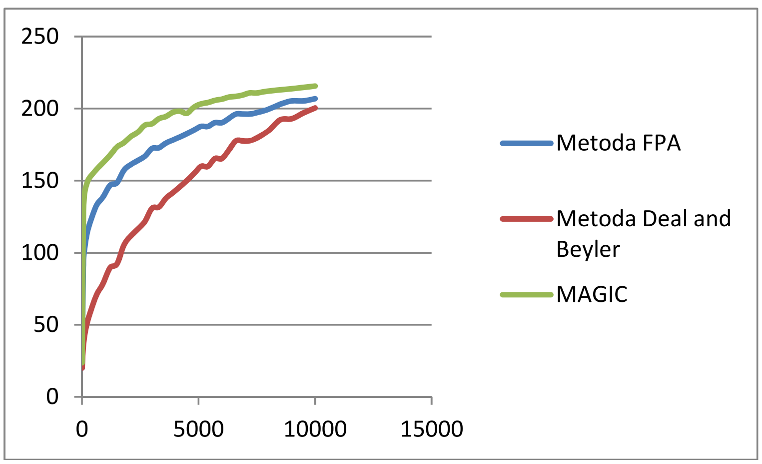

Fig. 1 Hot gas layer temperature prediction according to Foote, Pagni and Alvares Method, Deal and Beyler Method and MAGIC Method

According to Deal and Beyler method [see (7)],

we obtain a hot gas layer temperature evolution according to Fig. 1, red line. From the empirical calculation we obtain for this method a maximum value for the hot gas layer temperature of about 200.5 °C, which is comparable with the result stated by MAGIC simulation (Fig. 1, green line) that is of about 215.62 °C.

3.2.2 Parametric study for the defined scenario

First scenario - Closed door between compartments and available sprinkler and ventilation system

Taking into account the defined scenario characteristics, after MAGIC simulation for the case for the initial fire ignition, Fig. 2, we can state that the maximum hot gas layer temperature as a result of the initial fire source burning from the ignition room is about 113.652°C for the upper layer.

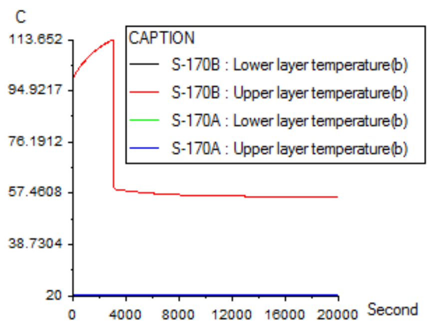

Fig. 2 Upper and lower room layers temperatures after the lube oil pool fire initiation

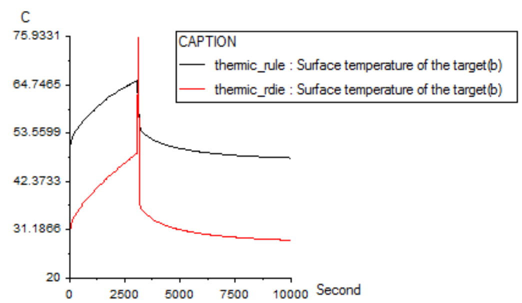

Fig. 3 Surface temperature of thermic targets placed on the lube oil and diesel tanks surfaces

According to MAGIC calculation for the thermic target mounted on the lube oil tank surface, the maximum temperature of the lube oil tank surface is of about 66 °C and 76 °C for the diesel oil tank. Because the lube oil, respective diesel oil, ignition temperature is defined to be at t = 130 °C and 100 °C, form Fig. 3 we can state that the this critically values are not reached.

The conclusion of this fire scenario is that it would not be extended to the lube oil and diesel tanks, and the fire will be extinguished by the available automatic sprinkler system. So, this fire would not have safety implication on the safe running of the EPS System, because this fire scenario will not affect the second EPS system that must start immediately after fire ignition.

Second scenario - Closed door between compartments and unavailable automatic sprinkler system and ventilation system

For this fire scenario, after MAGIC simulation, we state that, as we can observe in Fig. 4, the temperature reached 197.5 °C for the hot gas layer (upper layer) and 40 °C for the cold one (lower layer). Also, at this point, and taking into account the east wall temperature represented in Fig. 5, we can see that the wall temperature for the adjacent room record a increase of 48.9 °C for the upper layer. This wall temperature increase for the fire adjacent room does not jeopardize the separation safety function between the two diesel.

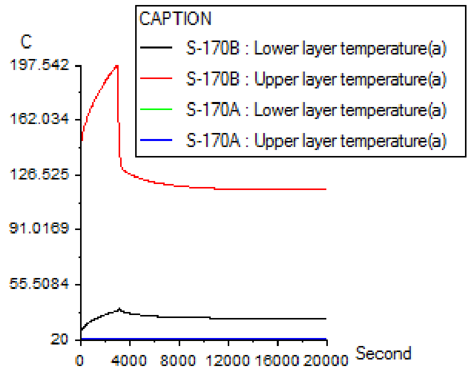

Fig. 4 Upper and lower room layers temperatures after the lube oil pool fire initiation within unavailable sprinkler system and ventilation system conditions

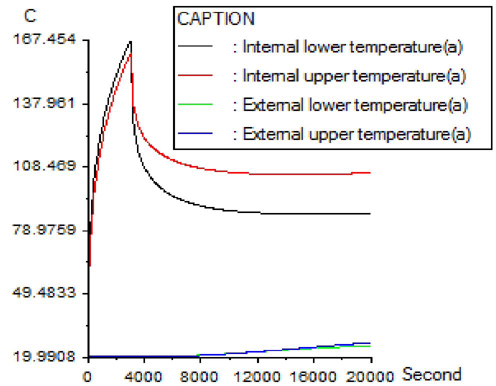

Fig. 5 Internal and external temperatures registered at the east wall surfaces

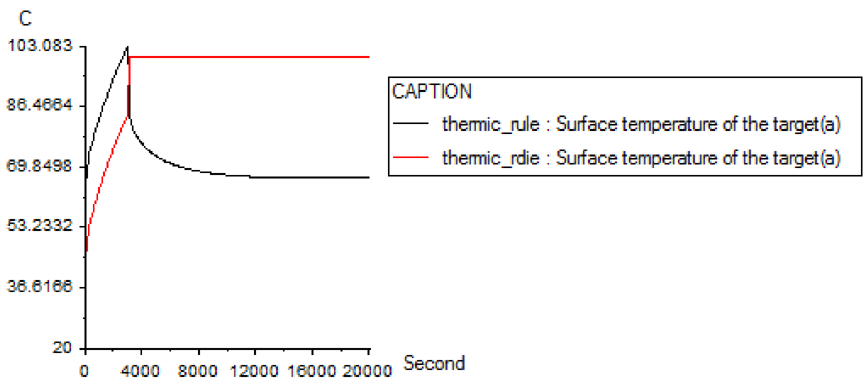

Fig. 6 Surface temperature for lube oil tank and for diesel oil tank in the case of unavailable automatic sprinkler system and ventilation system

From Fig. 6 we observe that according MAGIC thermic detectors the ignition moment for the diesel oil tank, the secondary fire, which is define to be at 100 °C will be at 3000 s.

After the secondary fire ignition, at the diesel oil tank, the hot gas layer temperature of the fire source room increase up to 229.5 °C, respectively up to 48.9 °C for the cold gas layer temperature (Fig. 7). For the adjacent diesel room, the temperature does not register any modification towards the previous situation (Fig. 8).

The last stage of fire development consists on lubricating oil tank and cable tray fire spread. According to the input parameters their ignition temperature is defined at 130 °C. After MAGIC calculation, the ignition time for the lube oil tank ignition resulted to be at 3077 °C from the start of the initiating fire (Fig. 9).

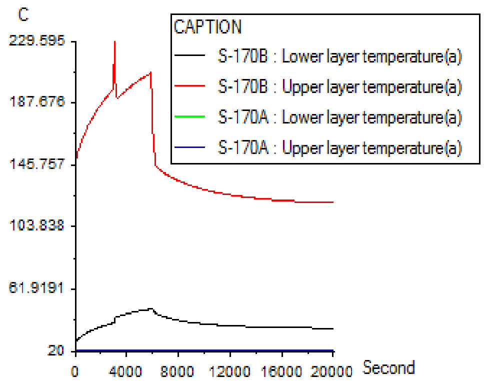

Fig. 7 Layer temperatures for the two diesel rooms after the ignition of the diesel oil tank fire (secondary fire)

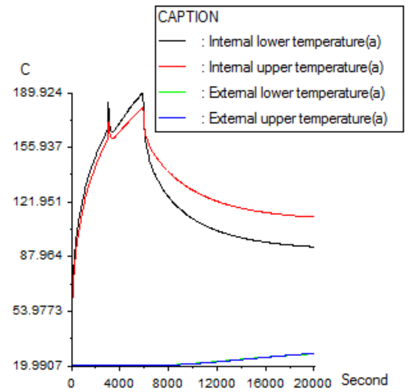

Fig. 8 Internal and external east wall temperature

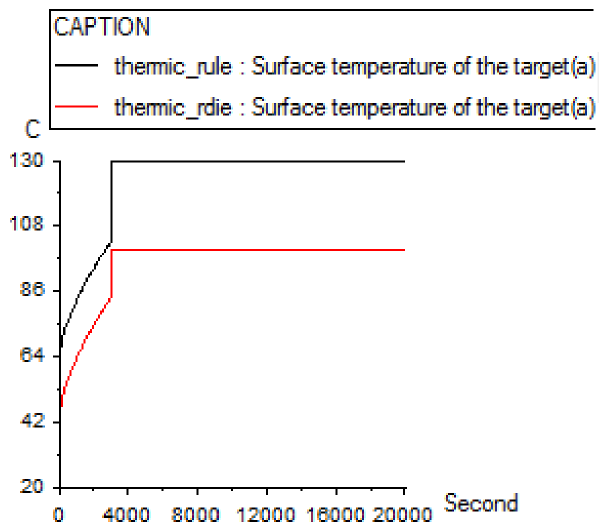

Fig. 9 Surface temperature al the two thermic targets of the lube oil and diesel tanks

Being defined all these steps, we can state that the evolution of temperatures for the two gas layers, upper layer and lower layer, for the both diesel rooms, is as according to Fig. 10.

As we can observe in Fig. 11 the wall fire barrier has maintained its integrity against fire so, the second diesel generator the room stated a temperature increase of about maximum 31 °C.

So that, we concluded that the second diesel room will not be affected by the fire from the adjacent room and the separation barrier safety function will be maintained.

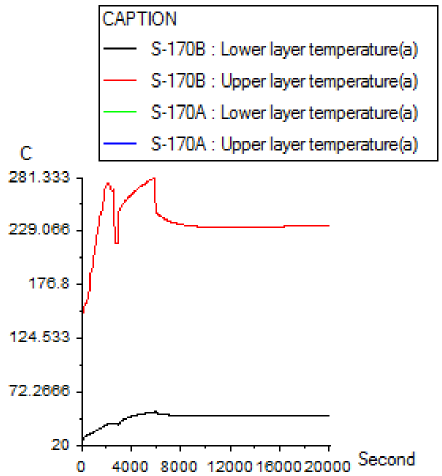

Fig. 10 Upper and lower layers temperature as a result of the spread of fire to the two tanks and to the cable tray, for both diesel rooms

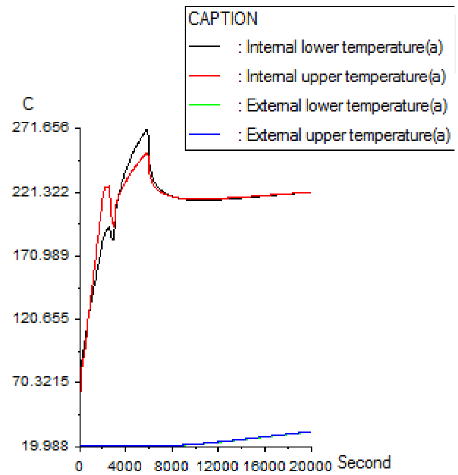

Fig. 11 Indoor and outdoor fire resistive wall temperature

Third scenario - Open door between compartments and unavailable automatic sprinkler system and ventilation system

For this scenario we define sprinkler and ventilation systems inoperability and we assume that the separation door between the diesel generators compartments was forgotten open.

After MAGIC simulation, according to Fig. 13 we can see that the temperature level does not reach the temperature required to fire development.

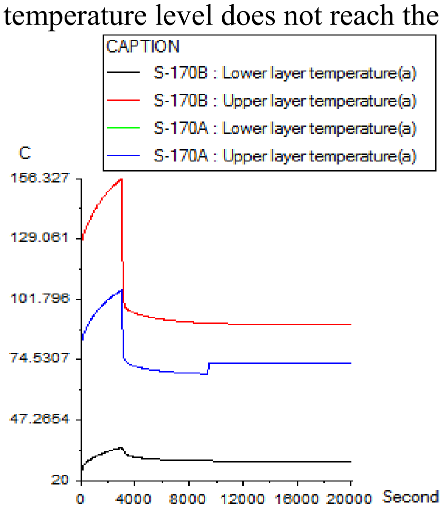

Fig. 12 Layers temperatures for the two rooms

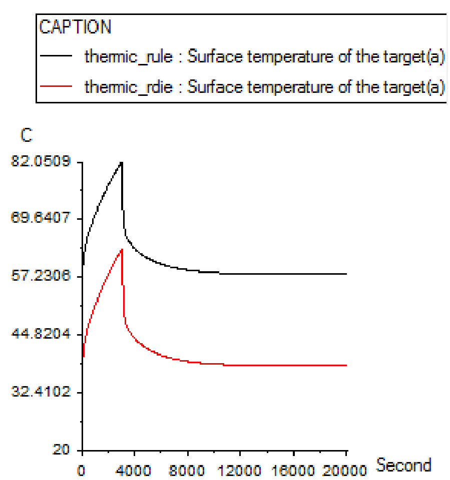

Fig. 13 Lube oil and Diesel oil tanks targets surface temperatures

Thus, even if the maximum temperature of the hot gas layer associated to the fire room will be about 156° (see Fig. 12), the fire will not spread to the other possible combustible materials.

4. Conclusions

As a conclusion of these three assumptions, we can state that the only critical scenario is the second one, the one for the closed door between the two compartments and with the unavailable sprinkler and ventilation systems.

Such analysis are useful to determine the interest parameters evolution for fire safety analysis, by determining the implications that a fire may have on safety function or safety related function equipments.

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[18] Rates of Fire Events at U.S. Nuclear Power Plants, 1987-2007; This report updates the Office for Analysis and Evaluation of Operational Data (AEOD) report AEOD/S97-03, “Special Study, Fire Events – Feedback of U.S. Operating Experience,” June 1997, updating data, frequency estimates, trends, and figures.

[19] Rates of Fire Events at U.S. Nuclear Power Plants, 1987-2008; This report updates the Office for Analysis and Evaluation of Operational Data (AEOD) report AEOD/S97-03, “Special Study, Fire Events – Feedback of U.S. Operating Experience,” June 1997, updating data, frequency estimates, trends, and figures

[20] Rates of Fire Events at U.S. Nuclear Power Plants, 1987-2009; This report updates the Office for Analysis and Evaluation of Operational Data (AEOD) report AEOD/S97-03, “Special Study, Fire Events – Feedback of U.S. Operating Experience,” June 1997, updating data, frequency estimates, trends, and figures

[21] Rates of Fire Events at U.S. Nuclear Power Plants, 1987-2010; This report updates the Office for Analysis and Evaluation of Operational Data (AEOD) report AEOD/S97-03, “Special Study, Fire Events – Feedback of U.S. Operating Experience,” June 1997, updating data, frequency estimates, trends, and figures

[22] Rates of Fire Events at U.S. Nuclear Power Plants, 1987-2011; This report updates the Office for Analysis and Evaluation of Operational Data (AEOD) report AEOD/S97-03, “Special Study, Fire Events – Feedback of U.S. Operating Experience,” June 1997, updating data, frequency estimates, trends, and figures

[23] Rates of Fire Events at U.S. Nuclear Power Plants, 1987-2012; This report updates the Office for Analysis and Evaluation of Operational Data (AEOD) report AEOD/S97-03, “Special Study, Fire Events – Feedback of U.S. Operating Experience,” June 1997, updating data, frequency estimates, trends, and figures

[24] *J.R. Houghton, D.M. Rasmuson*, RES/OERAB/S01-01, Fire Events - Update of U.S. Operating Experience, 1986-1999, Commercial Power Reactors, U.S. NRC, December 2001

[25] NUREG/CR-4230, Probability-Based Evaluation of Selected fire Protection Features in Nuclear Power Plants, M.A. Azarm, J.L. Boccio, Brookhaven National Laboratory, prepared for U.S. Nuclear Regulatory Commission, 1985

[26] MAGIC Version (4.1.3) Mathematical Model, Laurent Gay, Erisc Wizenne EDF Septen, March 2012