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OIL POOL FIRE IN AN EPR-TYPE CONTAINMENT

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ABSTRACT

Simulation of oil fire in a containment of an EPR-type nuclear power plant has been carried out using the CFD (computational fluid dynamics) code FLUENT. The oil leak forms an oil pool below one of the main cooling pumps. The goal was to evaluate the temperature field near the steam generators during the different phases of fire. The concern is that water in the level measurement impulse pipelines, used to measure the water level in steam generators, may warm up and evaporate due to elevated temperature and cause spurious protection signals and false information.

The initial state was estimated with a steady state simulation, which took into account the cooling system in the steam generator rooms and the pressure control systems of the containment. The systems were in operation until containment isolation took place. Two different predefined fire profiles were used with maximum heat output of 46 MW and 7.5 MW. The simulations were performed using 110 l and 880 l of lubrication oil.

The rupture foils and hydrogen damper doors controlling the connection between the steam generator room and the dome area are described as well. These have influence in the flow field especially after the cooling system has stopped due to containment isolation signal.

According to the simulations temperature near the steam generators on the fire side of the steam generator room may be so high that evaporation in the pipelines is possible in the case of 46 MW and 880 l of oil. With lower amount of oil and/or lower heat release rate of 7.5 MW the evaporation in the pipelines is unlikely. In all cases the steam generators on the other side of the steam generator room should maintain acceptable operating conditions.

FIRE PROFILE AND OIL POOL

The selected maximum heat release rate was chosen to be the same used in the earlier simulations by AREVA NP, of which some information, except the results, were available when doing this work. It has to be recognized that the upper heat release rate is exceptionally high. After the simulation it has been clarified that the floor of the steam generator room is formed to drive the possible liquid spills to floor drains, which should prevent forming of large oil pools. Additionally, the recirculation pump motors have been protected by using oil collecting pans limiting the active oil surface area. In both fire profiles it is assumed that the heat release rate (or the corresponding oil supply) will reach the nominal value within two minutes.

THE MODELS AND COMPUTATIONAL GRID

The code used for the containment analysis is FLUENT, Version 6.3.26. The standard models provided with the code are used, such as the k-ε turbulence model, species transport and heat transfer. Gas mixture is composed of oxygen, water vapour, carbon dioxide and nitrogen. The initial state is the normal air with 30 % relative humidity. The initial temperature in the containment is set to 25 °C (298 K) in the dome and annular sections. In the SG (steam generator)-room the temperature is calculated in the initial simulation for the normal state when heat loads and cooling system are active. The initial pressure in the environment outside the containment is assumed to be 1.013 bar.

Both wall and bulk condensations are described by using user defined functions, a standard feature in FLUENT to provide own source terms and boundary conditions.

The steam generator room is connected to the IRWST room below by four shafts. In the case the hydrogen damper doors are opened, air flows from the annular section to the IRWST room and further through floor openings to the SG room.

Oil pool is formed below the reactor coolant pump 4. It is assumed that the oil pool below the pump is 25 m^2 in the case of a 46 MW fire and 4 m^2 in the case of a7.5 MW fire.

The rupture foils (or hatches) are located above the steam generators on level + 31.55 m. The temperature hatches were placed between the steam generators (near coordinate y = 0 in Figure 1). The area of the temperature hatches (opened by both pressure difference and temperature rise) is about 40 m^2 altogether divided on both sides. The area of rupture foils (opened by pressure difference only) is about 36 m^2. The location of the oil pool is below pump 4 shown in Figure 1.

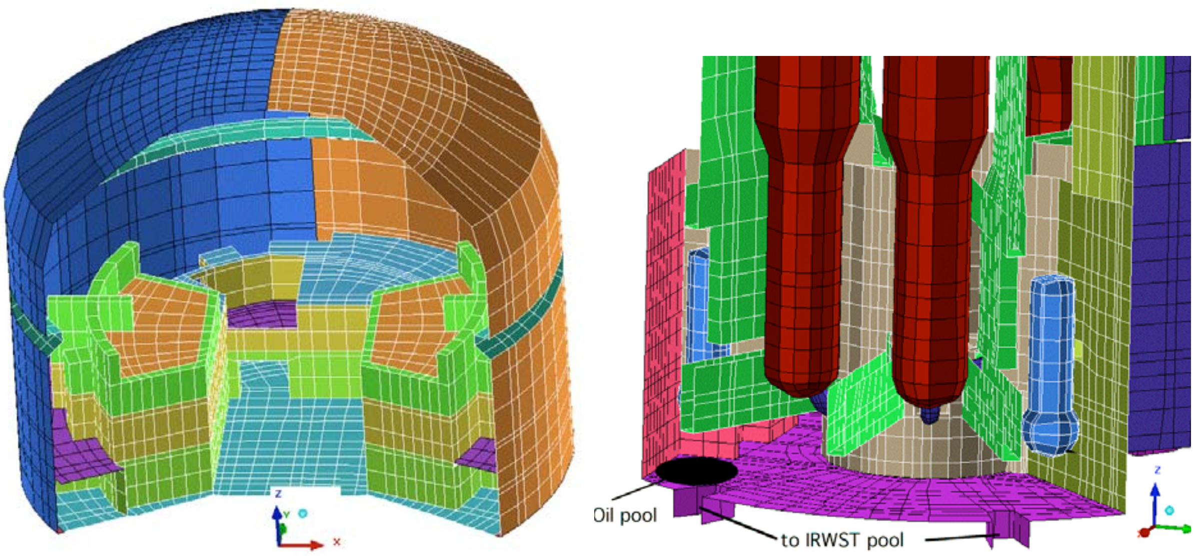

Figure 1 Grid of the dome area (left); the rupture foils are located on the top of the SG-room towers; steam generators SG3 and SG4 and pumps (right); the oil pool is formed below pump 4

The computational grid consists of four parts including the steam generator room, dome area, annular domain and IRWST room and core melt spreading room. The number of computational cells has been kept as low as possible due to the long time transient. The total modelled volume is 73704 m^3. The number of computational cells is 101729. A view to the computational grid in the steam generator room is shown in Figure 2.

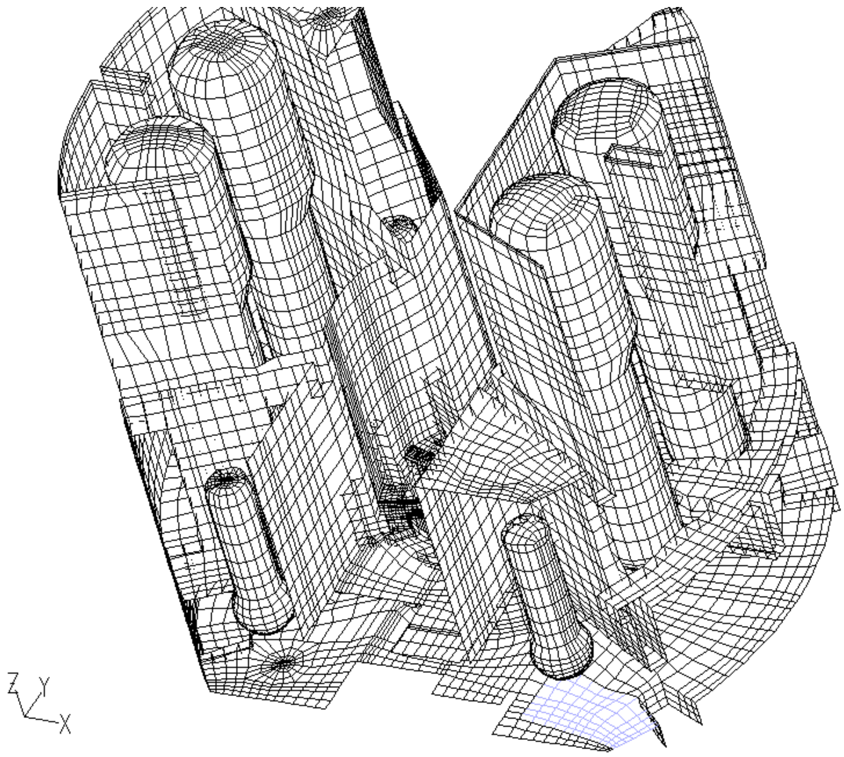

Figure 2 View of the computational grid; steam generator room, steam generators and pumps are shown; the oil pool is shown below pump 4 (25 m^2 for 46 MW case); some walls are omitted for clarity; the ceiling above pump 4 is on level + 19 m and above pump 3 on + 28 m

VENTILATION, PRESSURE CONTROL AND CONTAINMENT MIXING

The HVAC-system description gives the principal values for ventilation, cooling and pressure control systems, [1] and [2]. The more detailed information for the dynamics of the control systems is not included in these documents. A schematic view of the SG room cooling KLA6 in normal conditions is shown in Figure 3. It is assumed that the cooling systems on both sides of the SG room are independent of each other. In the case of fire the heat load on the fire side (SGs 3-4) will rise. That will change the temperature flowing into the cooling unit. The change to the cooling rate was estimated by using the effectiveness ε estimated according to the normal conditions. The temperature of air T_{cool} after the heat exchanger is estimated from

$$T_{cool} = T_{hot} - \varepsilon\left(T_{hot} - T_{water}\right),$$

where T_{hot} is the intake temperature and T_{water} is the cooling water temperature (22 °C). The minimum cool temperature is 28 °C (301 K).

KLA10 system leads air to the dome and annular domains. The air flow is regulated so that pressure in this domain is 200 Pa lower than in the environment outside the containment. It is assumed that the system reduces inflow in the case of rising pressure in the containment. The maximum capacity of the system is 5450 m^3/h.

KLA20 air suction system takes air from the SG room and maintains the pressure difference 100 Pa between the dome (high pressure) and SG room (low pressure). The suction is changed according to the pressure difference. The maximum capacity of the system is 5450 m^3/h. There are fire damper fuses in the KLA20 outlets operating at temperature 70 °C, but in this case the temperature does not rise to that value until the system stops for other reasons.

There are undocumented leaks between the dome and the SG room. In the model two leaks have been defined for pressure control, one at the top of the SG room and one at level +13 m. The area of the leaks is such that the nominal volume flow (about 4500 m^3/h) is reached with the normal pressure differences. This pressure control system in the model is running until the containment isolation takes place.

The containment isolation takes place when pressure difference between the containment and the environment is more than 30 mbar. If it is assumed the environment pressure to be the standard 1013 mbar this means containment threshold pressure 1043 mbar in the model.

Due to containment isolation the following systems are stopped or isolated and affecting the boundary conditions in the model:

- Cooling water for KLA6 system
- Electricity supply for KLA6 fans
- KLA10 and KLA20 pressure control
- Fire extinguishing water supply

In the case of isolation the fans are stopped. The fire extinguishing system has not been modelled in the simulation. It is only noted that the fire water supply may be isolated even in the case of fire.

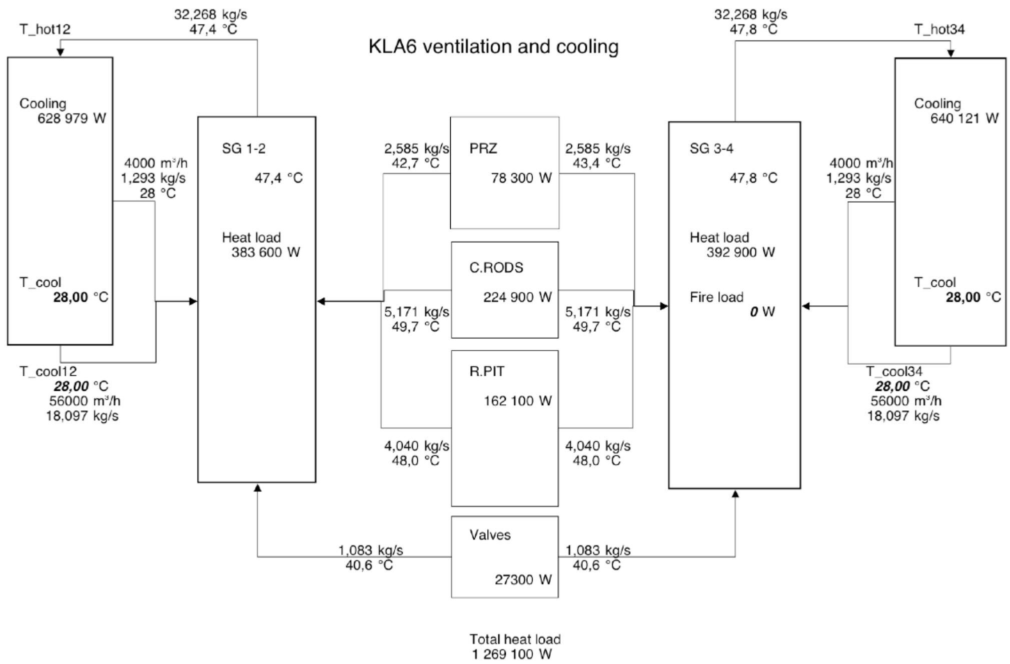

Figure 3 Scheme of the KLA6 cooling system of the power plant; heat loads of different parts have been taken from the description of the HVAC-system

The rupture foils between SG room and the dome area on level + 31.55 m open at pressure difference 50 mbar (pressure hatches) between the SG room and the dome. Part of the foils will also open when temperature is about 85 °C (pressure / temperature hatches). In the simulation it is assumed that the temperature hatch has got some thermal inertia and it opens after temperature has been 30 s higher than the threshold value. In case of elevated pressure the opening is imminent. In the simulation only one cell face of the grid is allowed to open at each time step. The parameters of foils and doors have been taken from the system description [3].

There are eight hydrogen damper doors on the level - 2.30 m between the annular part and the IRWST tank room, with a total cross section of 5 m^2. The doors open when pressure difference between the SG room and the dome is higher that 35 mbar or when pressure exceeds the environment pressure by 0.2 bar. Opening takes place after a 60 s delay. These openings enhance the natural convection in the containment.

RESULTS FOR HIGH FIRE RATE 46 MW

FLUENT is used first to simulate the normal pressure and temperature conditions in the containment where normal pressure control and ventilation systems are operating. In the state when all systems are running steadily, the oil leak starts. The actual fire simulation is started from that moment. Simulation is calculated as time dependent with a 0.5 s time step.

All the cases are simulated until the defined amount of oil is consumed. After that the simulation is continued some time to follow up of the cooling phase. The fire growth time to the nominal maximum rate is two minutes in all cases. The total burning time in the 46 MW fire with 110 l of oil is only 140 s. After the whole amount of oil is consumed the cooling phase is estimated by continuing simulation to 360 s. Oil is burnt according to the EBU-model taking into account the mixing rate of fuel and oxidant and the local oxygen and fuel concentrations.

The pressure development during the simulation is shown in Figure 4. Temperature development at selected points is shown in Figure 5. The temperature field is shown in Figure 6 where constant temperature iso-surface is coloured by velocity. This shows that high temperature prevails around both steam generators on the fire side of the SG room. Due to the natural convection the other side (steam generators SG 1 and SG 2) stays relatively cool.

Events during the simulation with 110 l of oil are:

Time [s]	Event
0...120	Fire grows to nominal output 46 MW
55...66	Temperature to threshold value below hatches above the fire (SG 3-4)
68	Pressure difference > 30 mbar between dome and SG room, hydrogen dampers to be opened after 60 s delay
70	Pressure in SG room exceeds 1043 mbar, causing containment isolation
72...73	Some rupture foils opened due to pressure, areas 1.8 m^2 (SG 1-2) and 2.35 m^2 (SG 3-4)
85...106	Temperature hatches above fire (SG 3-4) opened after 30 s delay
128...133	Hydrogen damper doors opened, area 5 m^2
140	110 l oil consumed, fire dies out
140...360	Natural convection cooling and mixing
290...320	Temperature hatches above SGs 1-2 opened
360	Simulation ends

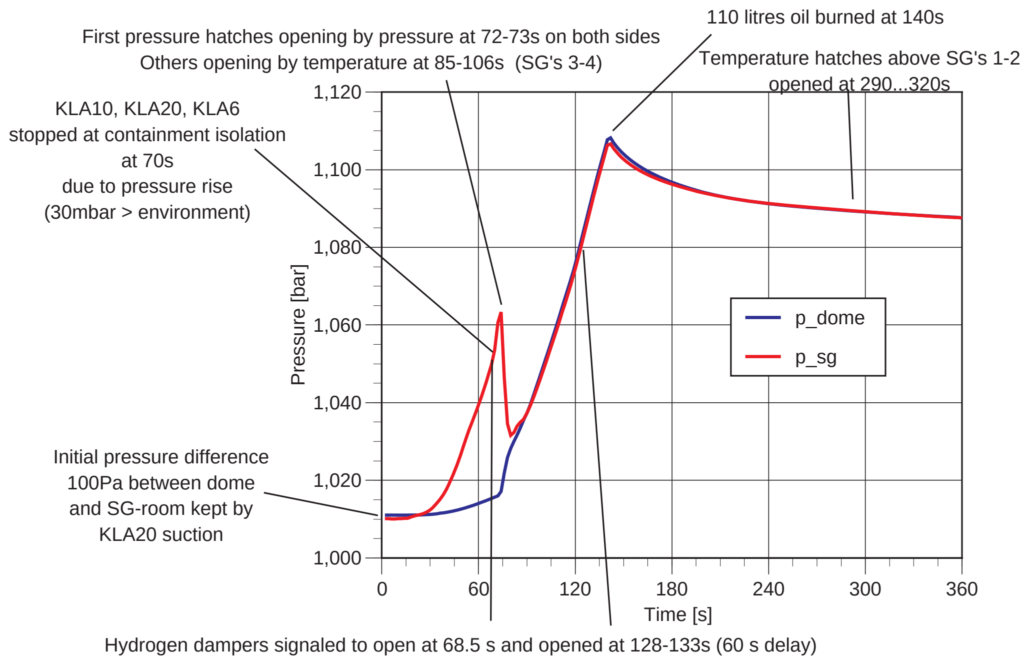

Figure 4 Pressure development in the steam generator room and dome during a 46 MW fire with 110 l of oil; important events are noted in the figure

The figures of temperature field show that hot burning products fill the upper part of the fire side SG room above a certain level. There is no significant structural separation between the steam generators 3 and 4. The other side with SG's 1-2 will not be filled with hot products.

The time of temperature getting above 200 °C near the SG's is about 100 s in this fire case as shown in Figure 5. This is quite short time period when considering the possibility of water heating up considerably or boiling in the level measurement impulse pipelines.

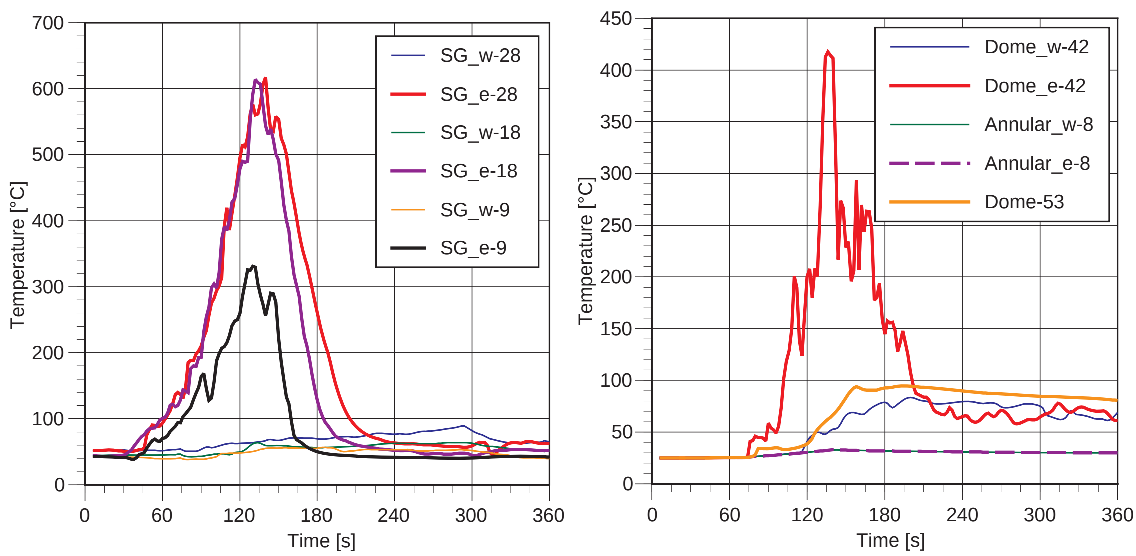

Figure 5 Temperature at selected monitor points near the steam generators and dome area at various elevations during the 46 MW fire with 110 l of oil; the number refers to the plant elevation coordinate; w(est) refers to SGs 1-2 and e(ast) to SGs 3-4

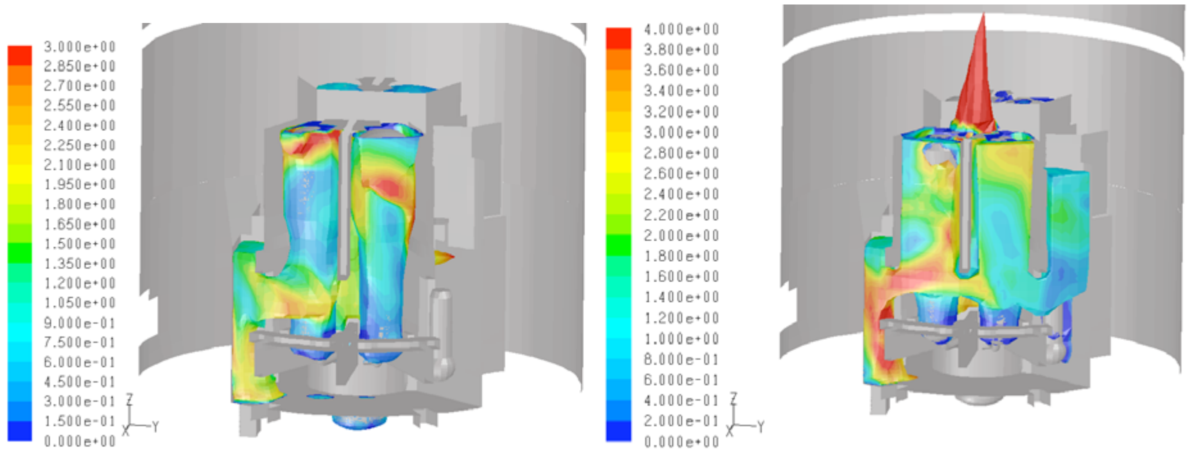

Figure 6 Iso-surface of temperature 100 °C at time 60 s (left); iso-surface of temperature 250 °C at time 140 s (right); the surface is coloured by velocity [m/s]

RESULTS FOR LOWER FIRE RATE 7.5 MW

Events during the simulation with maximum heat release rate of 7.5 MW and 110 l of oil are:

Time [s]	Event
0...120	Fire grows to nominal output 7.5 MW
84...95	Temperature to threshold value below hatches above the fire (SGs 3-4)
114...138	Temperature hatches opened after 30s delay above the fire side (SGs 3-4), pressure balanced between dome and SG room, opening about 20 m^2
480	Pressure in SG room/dome exceeds 1043 mbar, causing containment isolation, pressure control and cooling stopped
552	110 l oil consumed, fire dies out
566...600	Temperature hatches on the other side (SGs 1-2) opened by temperature, opening about 20 m^2
552...1200	Natural convection cooling and mixing
1200	Simulation ends

In this case the pressure rise due to the fire is smaller compared to the 46 MW fire rate and neither pressure operated hatches nor hydrogen damper doors will be opened. This leads to weaker natural convection and mixing of atmosphere inside the containment. The hatches above the fire are opened after 114 s balancing the pressure between the SG room and the dome area. At this stage fresh air is entering the SG room mainly through the opened foils, the same route where hot plume is rising. The containment isolation pressure difference between dome and SG room is reached slightly before the amount of oil is consumed. Stopping the pressure control and cooling has a clear effect in the pressure rise. The temperature operated hatches above the other side SGs are opened after the oil has been consumed. At this stage the natural convection and mixing is improved. The pressure in the containment does not drop very much after extinguishing of fire, because the hot primary circuit and reactor vessel still release heat to the SG room. The pressure development is shown in Figure 7.

Temperature values, shown in Figure 8, are lower than in the previous cases due to lower heat release rate. Temperature history at the monitor locations is very turbulent due to the flow field. The hatch opening above SGs 3-4 lets the hot plume flow up to the dome. The same opening occasionally lets cold air to the SG-room, which can be seen as temperature variations at the monitor points. The opening above SGs 1 2 keeps closed up to 566 s when it is opened due to elevated temperature. In this case the trigger time of the hatch opening has been at 536 s, i.e. before the end of the fire. The changes in sensitivity of opening of the temperature or pressure hatches might have influence on the natural convection and mixing of the atmosphere of the containment.

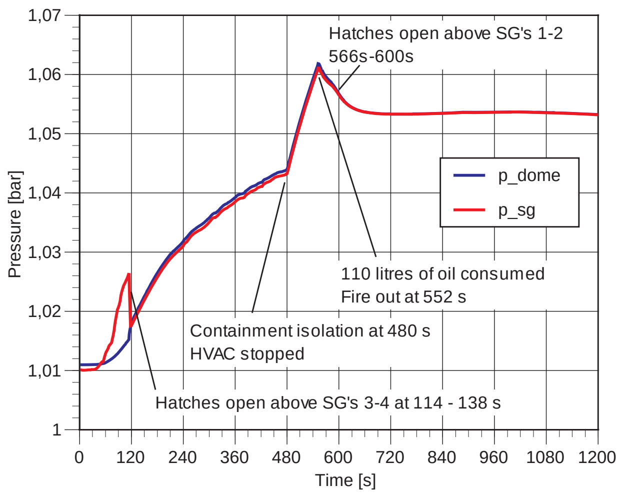

Figure 7 Pressure development during a 7.5 MW fire with 110 l of oil

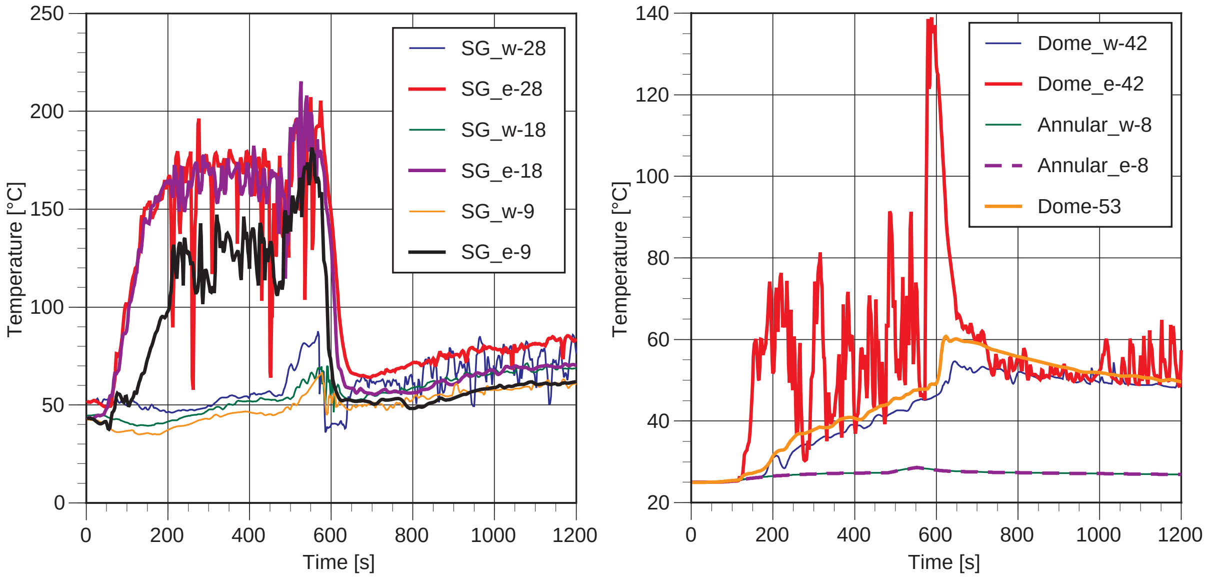

Figure 8 Temperature at selected monitor points during the 7.5 MW fire with 110 l of oil

CONCLUSIONS

Fire simulation of an oil pool fire in the EPR-type containment of a nuclear power plant has been performed. In the simulation it is assumed that the oil pool is formed under reactor coolant pump 4. The halves of the steam generator room are quite well separated from each other, even though there is a connection on the floor level + 1.50 m. Each pair of steam generators is encountering equal general thermal conditions, because there is no essential separation between the units in the same halve of the steam generator room.

The basic case is 46 MW heat release rate with 110 liters of oil. With this heat release rate and oil amount the burning time is only 140 seconds. Fire is able to increase temperature near the steam generators 3 and 4 up to 600 °C. (The temperature near the flame is essentially higher and is able to make local damage, but the location of interest is further from the origin of the fire.) However, the influence time of high temperature is limited (temperature is about two minutes more than 200 °C) due to the short burning time. Temperature near the steam generators 1 and 2 is not very much elevated during this fire case.

The assumed heat release rate of 46 MW represents a very intense fire load. For this reason it was investigated what were the results with lower heat release rate and longer burning time. The optional case has 7.5 MW heat release rate and 110 liters of oil leading to 552 s burning time. The lower heat release rate leads to essentially lower temperature near the steam generators. Temperature does not increase 240 °C and temperature increases 200 °C only for a short time near the steam generators during the simulations. Thus there should not be danger of evaporation of water in the impulse pipelines.

In all the simulations it was assumed that pressure control and cooling systems were operating until the containment isolation takes place. It should be noted that the cooling capacity of the KLA6 system would increase substantially under elevated temperature conditions. Another matter is if the electric motors of the fans are able to operate under those conditions. In all cases the cooling system was shut down at the time of containment isolation.

These simulations show that the pressure / temperature hatches above the steam generators and hydrogen damper doors have an essential influence in natural convection, mixing and cooling in the containment. With heat release rate of 46 MW the pressure difference between the steam generator room and dome / annular compartments gets so high that the hydrogen damper doors at level - 2.30 m are opened and enhance natural convection. With the lower heat release rate 7.5 MW this pressure difference is not gained and the doors keep closed and the mixing of the atmosphere is weaker.

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[2] Zipprian J., H.-G. Stahl, "Database of Different Pressures", Assignment Flow Chart, Rev. B 2006-10-23, AREVA NP, Siemens AG, NESB-G/2006/en/1019, 2006
[3] Losch, N., and J. Hector, "System Description Combustible Gas Control – JMT, Rev. D", 24 November 2006, AREVA NP, Siemens AG, Sofinel, (EZS-100031), 2006