Evaluation of Containment Response for Fire Load due to Aircraft Fuel Spillage

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1 ABSTRACT

Nuclear containment is an important safety related structure which acts as an ultimate barrier against release of radioactivity. In the recent past, safety assessment for Indian PHWR nuclear containment has been carried out for aircraft impact. However, during this assessment, the thermal load generated due to the fuel spillage was not taken into consideration. Recent studies have pointed out that the fire involved during the aircraft impact on WTC (World Trade Centre) towers had a significant effect on their collapse. This has therefore necessitated a study on the behavior of the containment under fire due to the spillage of aircraft fuel. An analytical study has been carried out on the containment behavior under thermal load due to the spillage of the aircraft fuel. The thermal load due to fuel spillage has been carried out using typical aviation turbine fuel properties. A detailed finite element model of the containment has been prepared. A parametric study for the evaluation of containment response has been carried out by varying heat input and duration of fire ball. The effect of radiation due to ground fire on the containment is also analyzed. Transient thermal analysis has been carried out to obtain the temperature distribution at various locations at different time intervals. These results are discussed in the present paper.

2 INTRODUCTION

Nuclear containment is an important safety related structure which acts as an ultimate barrier against release of radioactivity. Indian PHWR (Pressurized Heavy Water Reactor) contains a primary inner containment of pre-stressed concrete construction and a secondary containment of reinforced concrete construction. The inner containment is designed for Design Basis Accidents (DBA) due to postulated loss of coolant accident (LOCA) and main steam line break (MSLB) along with seismic load. The double containment also serves to resist the external and internal missile impact loads effectively. The site selection for Indian Pressurized Heavy Water Reactor (PHWR) has been based on the principle of screening distance value (SDV) and hence the accident due to aircraft impact has a very low probability ~1E-07. It may be noted that larger aircrafts cannot be maneuvered with high velocities near the containment structure, which have typical heights up to a maximum of 50 m. However, as part of the safety evaluation program, Indian nuclear containment structures have been also assessed for Beyond Design Basis Accidents (BDBA) such as aircraft impact load. In the year 2003, a study was carried out by Kukreja (2005) in the Reactor Safety Division, BARC on the structural behaviour of the Indian 500 MWe PHWR containment under the aircraft impact. The study illustrates that the overall structural integrity of the containment will not be affected due to aircraft impact. However, in that particular study, the effects on the containment by fire induced thermal load due to spillage of Aviation Turbine Fuel (ATF) from the aircraft are not considered. The effect of the thermal load on any structure observes high importance especially after witnessing the World Trade Centre (WTC) collapse due to aircraft impact. The collapse of the WTC was initially reported due to the impact collision caused by the aircraft. However, various subsequent studies by Bazant (2002), Quintiere (2002) and Usmani (2003) revealed that the main cause for WTC collapse is the loss of structural strength of the steel columns, due to prolonged heating to high temperatures (upto 800-900 ºC) because of burning ATF. This necessitates a study on the behavior of the containment under fire due to the spillage of aircraft fuel. The present paper contains an analytical study to evaluate containment response under fire due to aircraft fuel spillage.

3 DETAILS OF THE ANALYSIS

3.1 FE model details

The cross sectional elevation of Indian 500 MWe PHWR containment building is as shown in Figure. 1. It contains a primary inner containment of pre-stressed concrete construction and a secondary containment of reinforced concrete construction. The thickness of Outer Containment Wall (OCW) is 610 mm and the Inner Containment Wall (ICW) is 750 mm. The outer diameter of the OCW is 55.54 m and its height from the ground level is 40.93m. Figure. 2 shows the Finite Element model of the containment. Concrete Portion has been modeled using 3-D Solid conduction elements and rebars with one dimensional conduction elements. Convective and radiative boundary conditions have been applied to the model. There are total 7320 solid conduction elements, 7320 bar conduction elements. Due to symmetry of the containment, only one half of it is modeled.

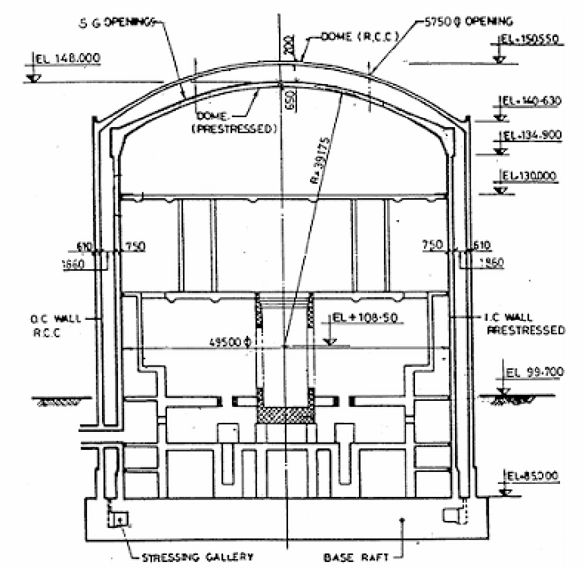

Figure 1. Cross Section of OCW and ICW of 500MWe PHWR

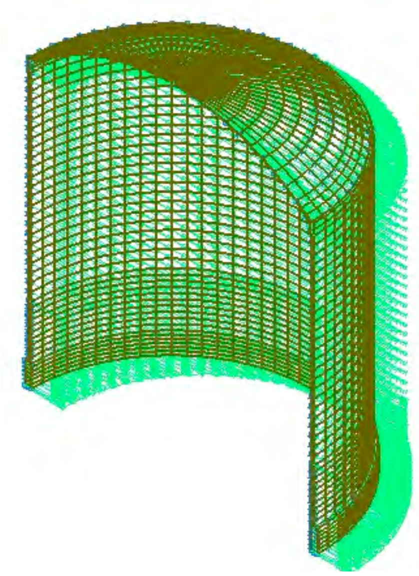

Figure 2. FE model of the outer containment

3.2 Evaluation of containment response under thermal load due to fuel spillage

Containment response for thermal load due to fuel spillage has been obtained by performing a transient thermal analysis. Kukreja (2005) has assumed that a commercial aircraft collides horizontally at the dome wall junction of the containment just below ring beam. The same assumption has been used in the present study to calculate thermal load due to fuel spillage. Quintiere (2002) stated, "It is estimated that about 29000 kg of jet fuel was in aircraft and about 9400 kg of jet fuel was expended in the fireballs of the initial impacts, and the remaining jet fuel may have burned for several minutes more on a floor during an investigation on WTC collapse". In the present study the same estimation has been used for heat flux calculation i.e. 9400 kg of jet fuel is expended in the fire balls during impact and the balance amount has spilled on ground. Some part of fire ball energy goes as heat input to containment and the remaining portion will be dissipated to atmosphere by convection and radiation. The containment will be subjected to a part of thermal energy of fire ball. A parametric study for the evaluation of thermal response of containment has been carried out by varying heat input and duration of fire ball. The effect of radiation due to ground fire on to the OCW is also analyzed.

3.2.1 Heat flux calculations

The total heat flux (Q) acting on the containment wall has two components.

(a) Heat flux (Q_1) due to fireballs after the initial impact.

$$Q_1 = \frac{mCV}{tA} \tag{1}$$

Where, m is mass of fuel, CV is Calorific Value (42.8 MJ/kg) [Heywood (1988)], t is the time of burning and A is the area on which burning takes place. The heat flux values for mass of 9400kg and varying time duration of time duration of 1, 5 & 10 s are shown in Table 1.

Table 1. Heat flux values for mass of 9400kg.

S. No	Mass of fuel, m (kg)	Time, t (s)	Heat Flux, Q_1 (MW/m^2)
1	9400	1	112.5
2	9400	5	22.5
3	9400	10	11.25

(b) Heat flux (Q_2) due to radiation exchange between the ground fire (i.e. fire caused due to fuel spillage on ground near the containment) and the outer containment wall (OCW).

Figure. 3 shows the schematic of projected area of OCW (A_2) and ground (A_1). The heat flux due to radiation heat exchange between these two areas is given by,

$$Q_2 = \sigma_b \left[\left(A_1 F_{12} T_1^4 \right) - \left(A_2 F_{21} T_2^4 \right) \right] \tag{2}$$

Where, σ_b is Stefan-Boltzmann constant (5.67 X 10^{-8} $W/m^2 . K^4$) and F is shape factor.

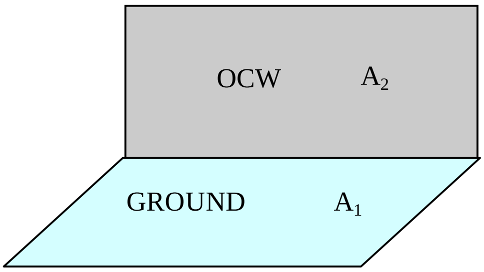

Figure 3. Schematic diagram of projected area of OCW and ground

After the aircraft impact, some amount of fuel will be expended in the initial fire ball whereas the balance amount will be spilled on the ground along with the aircraft debris in some irregular pattern. Flame area A_f would be difficult to predict and therefore for simplification of calculations, it is assumed that the fuel is spread near the OCW in a rectangular pattern (width is fixed to be equal to diameter of OCW i.e. 55.54 m and two cases of length (i.e 10 m and 50 m) are taken. The fuel burning velocity (S) of the unburnt fuel is 30 cm/s approximately for liquid phase and density (ρ) is 800 kg/m^3 [Heywood (1988)]. Fuel burning velocity is given by

$$S = \frac{m}{A_f \rho t} \tag{3}$$

This in turn gives the time of burning of the fuel (t) on ground as,

$$t = \frac{m}{A_f \rho S} \tag{4}$$

From the above equation, the time of burning of the fuel (t) on ground has been calculated and tabulated in Table 2.

Table 1. Time of burning of fuel on ground.

S. No	Mass of fuel, m (kg)	Flame Area, A_f (m^2)	Time of burning, t (s)
1	19,600	555.4 (i.e. 55.54 x 10)	0.1437
2	19,600	2777 (i.e. 55.54 x 50)	0.0286

It can be seen that as A_f increases, 't' decreases. It is therefore seen that the fuel spread on the ground burns off quickly (within 0.1 to 0.2 s) compared to that of fire ball (more than 1 s). Therefore, heat flux Q_2 due to radiation exchange between ground fire onto the OCW can be considered as negligible. However, the above time periods are valid, provided the complete mass of 19600 kg fuel is spread over the above areas uniformly and is ignited simultaneously. However, in reality, the aircraft disintegrates and its wreckage viz. wings, tailfin, fuselage portion, engines etc will be scattered around and spillage of fuel takes place in irregular pattern. Pockets of fire takes place near the containment site for much longer durations and is difficult to analyze the amount of heat flux generated and the radiation effect on to the OCW. A time-dependent computational crash analysis, followed by a computational fluid dynamics analysis of the fire interfaced with the material properties of aircraft wreckage could offer a predictive tool to analyze the total heat flux generated. This however is an extremely demanding computational effort. For the present study, it is assumed that the radiation effect on to the OCW due to ground fire is approximately 1% of the heat flux generated due to the fire ball.

In view of the above, transient thermal analysis has been carried out with two cases taken into consideration i.e., one case with heat flux due to fire ball and the second case with heat flux due to fire ball as well as radiation effect.

3.2.2 Effect of heat flux from fire ball on containment response

The containment response has been studied by varying the heat flux from fire ball. Ten different cases have been studied. 10% of fire ball energy has been applied as heat flux to FE model in case 1. The heat flux (Q) is applied on the finite element model to the nodes corresponding to the wall portion between ring beam and ground. Due to symmetry, the flux has been applied to quarter portion only. The initial and ambient temperature is taken as 300K. Temperature distribution has been obtained at four typical locations: outer concrete cover (OC), outer rebar (OR), inner rebar (IR) and inner concrete cover (IC) portions as shown in Figure. 4. Heat flux (Q_1) of 2.25 MW/m^2 (10% of fire ball energy) has been applied for 5 s and transient thermal analysis has been carried out for a total time of 3.3 hours. Similar analyses have been carried out for 20% (case 2), 30% (case 3), 40% (case 4), 50% (case 5), 60% (case 6), 70% (case 7), 80% (case 8), 90% (case 9) and 100% (case 10) of fire ball energy. The temperature distributions at different locations are shown in Fig 5 to Fig. 9. The outer concrete cover portion has reached a peak temperature of 393K, 486 K, 579 K, 673 K, 766 K, 859 K, 952 K, 1046 K, 1139 K and 1232 K for case 1 to case 10 respectively. The outer rebar has reached a peak temperature of 304 K, 308 K, 312 K, 315 K, 318 K, 321 K, 324 K, 327 K, 330 K and 332 K for case 1 to case 10 respectively. Negligible rise in temperature is observed for inner rebar and inner concrete portions. From the experimental studies by Arioz (2007) on concrete specimens at high temperature, it was noticed that the surface cracks became visible when the temperature reached 600^o C. The cracks were very pronounced at 800^o C and increased extremely when the temperature increased to 1000^o C. It can be correlated that surface cracks will be visible on outer concrete cover if the OCW is subjected to 70% of fire ball energy. The cracks will be very pronounced if OCW is subjected to more than 90% of fire ball energy.

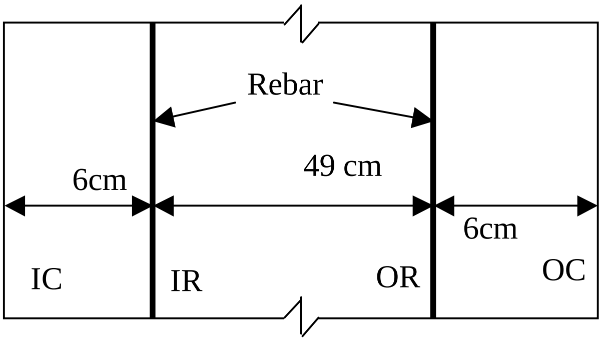

Figure 4. Schematic of locations in the outer containment wall

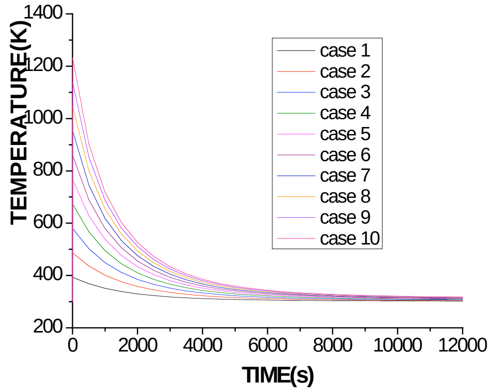

Figure 5. Temperature vs time for outer concrete cover

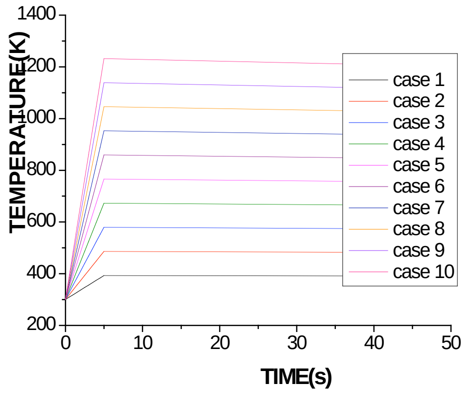

Figure 6. Temperature vs time for outer concrete cover (upto 50s)

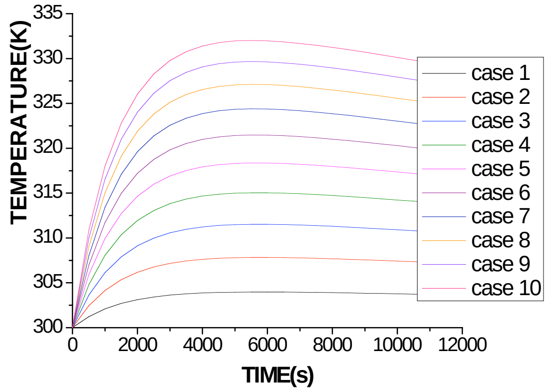

Figure 7. Temperature vs time for outer rebar

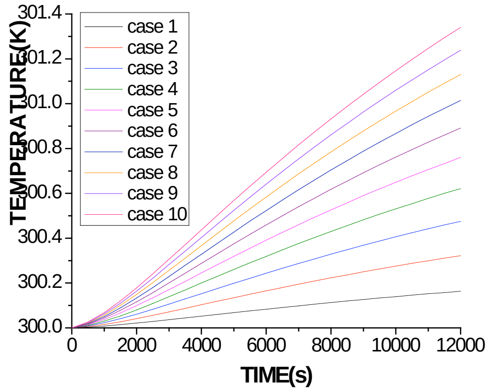

Figure 8. Temperature vs time for inner rebar

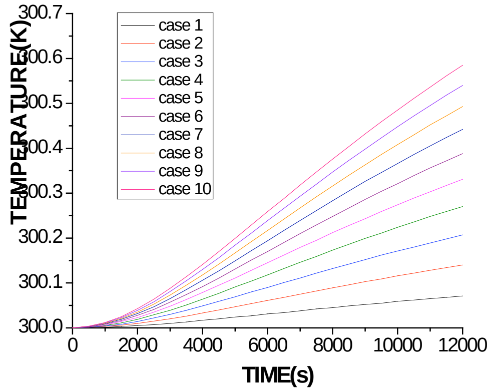

Figure 9. Temperature vs time for inner concrete cover

3.2.3 Efffect of fire ball duration on containment response

Containment response has been evaluated by varying the fire ball duration and keeping the heat input (100% of fire ball energy) as constant. It takes around 3s for the fire ball to reach ground from ring beam in case of free fall. The fire ball duration is varied in that range (1, 5 and 10s). Table 3 gives the temperatures for various locations with fire ball duration of 1 s. Similarly, Tables 4 and 5 give the temperatures with fire ball duration of 5s and 10s respectively. It can be shown that the variation in temperature due to change in fire ball duration is negligible.

Table 3. Temperature at various locations (Fire ball duration of 1s)

Location	Peak temperature (K)	Temperature at 3.3 hours (K)
OC	1238.8	317.4
OR	332.12	329
IR	300.88	300.88
IC	300.58	300.58

Table 4. Temperature at various locations (Fire ball duration of 5s)

Location	Peak temperature (K)	Temperature at 3.3 hours (K)
OC	1232	317.4
OR	332.12	329
IR	300.8	300.8
IC	300.5	300.5

Table 5. Temperature at various locations (Fire ball duration of 10s)

Location	Peak temperature (K)	Temperature at 3.3 hours (K)
OC	1231	317.4
OR	332.09	329
IR	300.8	300.8
IC	300.5	300.5

3.2.4 Efffect of radiation due to ground fire on containment response

In the study on WTC collapse by Quintiere (2002), the fire duration per floor was taken as about 80–100 min. The upper limit of 100 min has been taken as ground fire duration and as mentioned earlier, a heat flux of 1% of that of fire ball is taken to study the effect of radiation due to ground fire on OCW. This heat flux of 0.225 MW/ m^2 (i.e.1% of 22.5 MW/ m^2) has been applied on OCW for a period of 100 min. Transient thermal analysis has been carried out due to heat flux due to fire ball (22.5 MW/ m^2) and radiation effect (0.225 MW/ m^2). The temperature distributions at different locations are shown in Figure 10 to Figure 13. The outer concrete cover portion has reached a peak temperature of 1332.4 K (at 5505 s) and a temperature of around 409 K after 3.3 hours. The outer rebar has reached a peak temperature of 497.2 (at 7505 s) and a temperature of 483 K after 3.3 hrs. Negligible rise in temperature is observed for inner rebar and inner concrete portions. It can be observed that radiation due to ground fire results in sustained exposure of concrete surface to higher temperatures.

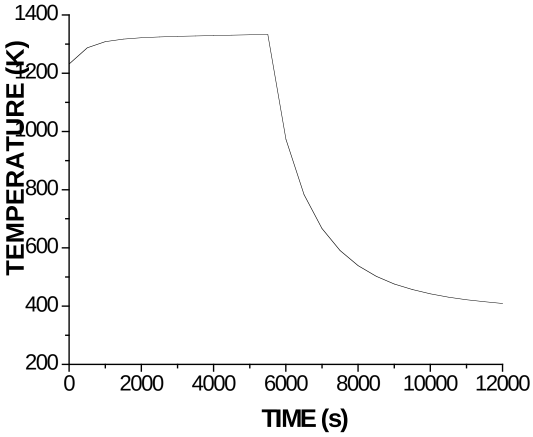

Figure 10. Temperature vs time for outer concrete cover

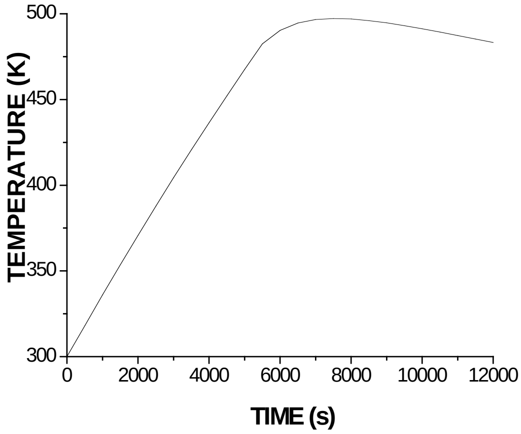

Figure 11. Temperature vs time for outer re bar

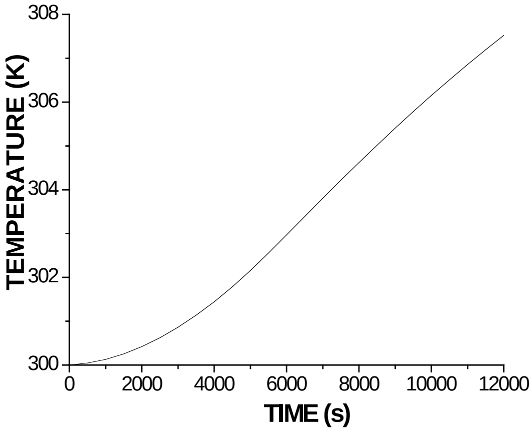

Figure 12. Temperature vs time for inner rebar

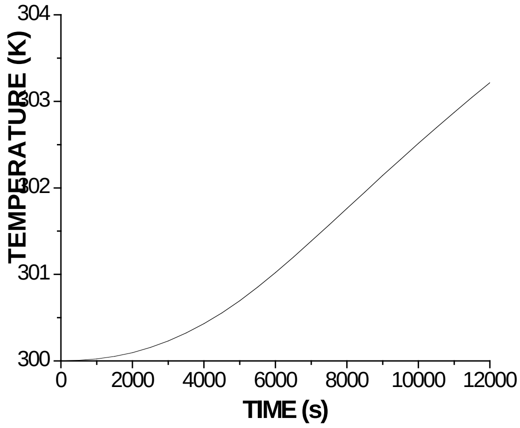

Figure 13. Temperature vs time for inner concrete cover

4 CONCLUSIONS

An analytical study on thermal behavior of the outer containment under fire due to the spillage of the aircraft fuel has been carried out. The heat flux calculations have been carried out using typical aviation turbine fuel properties. Transient thermal analysis has been carried out and temperature distributions at different locations have been obtained. A parametric study for the evaluation of containment response has been carried out by varying heat input and duration of fire ball. It is observed that the outer concrete cover portion of the OCW will be affected much under thermal load due to fuel spillage. Temperature rise in the inner concrete cover portion and rebars is negligible. These results have been correlated with experimental studies available in literature and concluded that the outer concrete cover will be subjected to decomposition due to thermal damage under fire due to fuel spillage. However, the central concrete portion will remain intact under such loading. It is also observed that fire ball duration has a negligible effect on containment response.

Symbols

A	Area	m^2
CV	calorific value	J/kg
ρ	density	kg/m^3

S	fuel burning velocity	m/s
F	shape factor	-
Q_1	heat flux due to fireballs	W/m^2
Q_2	heat flux due to radiation exchange between the ground fire and OCW	W/m^2
m	mass of the fuel	kg
σ_b	Stefan-Boltzmann constant	$W/m^2. K^4$
t	time	s

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