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EFFECT OF SUPPRESSION POOL SWELL ON CONTAINMENT PRESSURE TRANSIENTS DURING LOCA

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ABSTRACT

In suppression pool type containments, the dry well (V1 Volume) and wet well (V2 Volume) are connected through suppression pool via vent pipes. In case of LOCA, the steam flashes into dry well and gets pressurised and causes the steam-air mixture to bubbles through suppression pool and finally escapes to wet well. During the flow, the suppression pool swells and it oscillates due to bubble formation, growth and migration through the pool water medium. The oscillation of pool surface affects the V1 and V2 pressure, structural wall and other systems/equipments provided nearby suppression pool. A mathematical modelling of pool swell phenomenon was developed earlier and is plugged into in-house containment thermal hydraulic code CONTRAN and an analysis was performed for postulated LOCA scenario. The suppression pool swell modelling consists of vent clearance transient, bubble formation at vent pipe exit, bubble growth in pool medium, bubble migration and its break up at pool surface. Effects of pool swell on suppression pool level variations, dry well and wet well pressure transients are evaluated.

INTRODUCTION

In Indian Pressurised Heavy Water Reactor (IPHWR), Boiling Water Reactor (BWR) and proposed Advanced Heavy Water Reactor (AHWR), the reactor core and other safety systems/equipments are housed in primary containment. The primary containment is considered as the ultimate safety barrier and designed to withstand the effects of the Loss-Of-Coolant Accident (LOCA) during which high enthalpy steam is released into the containment. The primary containment is logically divided into high enthalpy V1 volume called dry well and a low enthalpy V2 volume called wet well. The wet well contains a large mass of water called suppression pool. The dry well is connected to wet well by means of vent system via suppression pool. The vent system consists of vent shafts, distribution headers and vent pipe. The suppression pool system is an entirely passive system and does not perform any function during operational states. However, during loss of coolant accident conditions, the high enthalpy steam released into drywell and causes rapid pressure build-up and forces the steam-air mixture to suppression pool through vent system. The steam-air mixture bubbles through the suppression pool and undergo heat and mass transfer with the pool before escaping into wet well. During the heat and mass transfer with suppression pool, the steam is condensed and air is cooled. In this way, suppression pool helps in mitigating the pressure and temperature build-up in the containment due to LOCA.

During the flow of steam-air mixture through suppression pool, the containment and pool internal structures need to withstand the hydrodynamic loads due to jet impingement and general motion of pool water during vent clearing phase from vents, loads associated with the pool swell in the subsequent air clearing phase and those due to chugging (oscillatory condensation steam) apart from the general thermodynamic loading due to mass and energy released due to LOCA. Earlier a simplified model was developed by A.K. Ghosh [1] for pool swell and it was tested for constant drywell pressure considering air. Wet well pressure transients were calculated and it was compared with the values of reported experiments conducted at MIT and JAERI [1] for simplified geometry.

In the present analysis, modeling of pool swell was carried out for the proposed AHWR containment and it is incorporated in the in-house containment thermal hydraulic code called CONTRAN, which evaluates containment pressure temperature transients as a result of LOCA. At the outset, the analysis considers only air flowing through suppression pool instead of steam-air mixture and heat transfer between the air and pool water is assumed in a simplified way that air enters into wet well space at pool temperature.

BRIEF DESCRPTION OF AHWR CONTAINMENT SYSTEMS

AHWR uses a double containment envelope viz, a primary and a secondary containment (see Fig.1) along with a number of containment Engineered Safety Features (ESFs). The primary containment is completely surrounded by the secondary containment. The primary containment is constructed of pre-stressed concrete and the secondary containment is of reinforced concrete. The primary containment is divided into two volumes called V1 (drywell) and V2 (wetwell), for efficient accident management. The arrangement is such that volume–V2 completely surrounds the volume–V1 [2]. These two volumes are interconnected by a vent system via the Gravity Driven Water Pool (GDWP) or suppression pool. The volume V1 houses all the high enthalpy systems like the reactor core, steam generator and other associated systems and it is inaccessible during normal operation due to high radiation fields. The volume V2 contains low enthalpy systems like GDWP and is generally accessible during reactor operation. The two volumes are sealed from each other, except under accident conditions, during which flow may be established between the two volumes via the vent pipes submerged in GDWP. The GDWP is located in the dome region of reactor building and contains approximately 6000 m^3 of water inventory. During LOCA, high enthalpy fluid is discharged into the volume V1, causing its pressurization. The pressure differential between volumes V1 and V2 causes the water column in the vents to recede (vent clearing). Once the vents are cleared, it establishes the steam-air mixture flow from V1 to V2. The steam-air mixture bubbles through the GDWP, where the steam gets condensed completely and the hot air is cooled before passing to V2 [3].

The GDWP performs the important function of energy as well as radionuclide management. GDWP as an energy management feature is required to limit the peak pressure and temperature in the containment following a LOCA by completely condensing the incoming steam. By limiting the peak pressure, the driving force for leakage of fission products to environment is reduced. Radionuclide management which is a secondary function involves effective fission product removal by dissolving, trapping, entraining or scrubbing away part of the fission products that reach the pool. All PHWRs in India, with the exception of Rajasthan Atomic Power Station, use a vapor suppression pool type of containment system for this purpose. This essentially consists of a pool of water located at the lowest floor in the reactor building. Unlike the suppression pool of Indian PHWRs, the GDWP of AHWR is located at a higher elevation. Besides performing the conventional functions of a suppression pool like removal of decay heat from reactor core following a LOCA, it performs additional duties. It serves as a heat sink for residual heat removal from other sources and also acts as a source of cooling water to concrete structure.

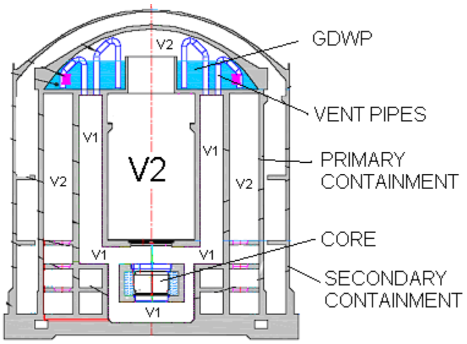

Fig.1: Schematic diagram of AHWR containment

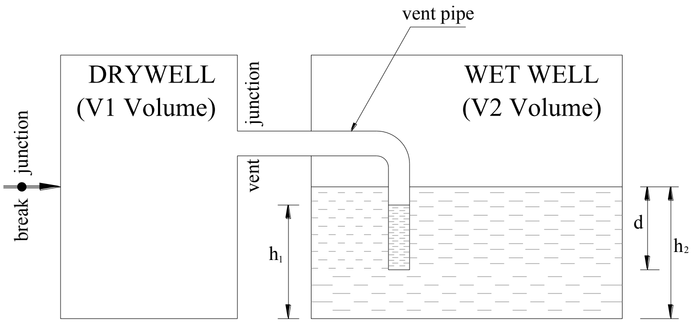

Fig.2: Volume connectivity & nodalisation of AHWR containment

In order to avoid excessive local pressure buildup and high differential pressure across internal structures during LOCA, Blow out Panels (BOP‟s) are provided. The BOP installed on the tail pipe towers (part of volume V1) is required to communicate to V2 by rupturing when the differential pressure between these volumes exceeds a predetermined value. The BOPs thus provide additional interconnection between volumes V1 and V2 and help in internal pressure equalization during accident conditions. Apart from the above features, the containment system includes other ESFs like building coolers and other filtration and ventilation systems provide additional energy/radionuclide management.

POOL SWELL MODEL

Dry well is connected to wet well through several number of vent pipes via suppression pool. Therefore, the model is developed for a simplified geometry of a single vent pipe inside a pool and the effects such as pool level change, mass flow rate etc are multiplied with number of vent pipes. The Fig.2 shows the volume connectivity of the AHWR containment for pool swell model. The modeling involves vent clearance transient, followed by bubble formation, bubble growth and translation through pool medium till it breaks up into wet well.

Vent clearing transient

As the drywell pressure builds up, the water column in the vent pipe starts moving downwards at a velocity (V_1) and the mass flow rate is $G_1 = \rho_w A_1 V_1$ and for „N‟ number of vent pipes submerged into the suppression pool, the mass flow rate G_1 would be $G_1 = N\rho_w A_1 V_1$. The suppression pool level starts moving upwards with a velocity (V_2) and the mass flow rate is $G_2 = \rho_w A_2 V_2$. Where A_1 and A_2 are cross flow area of vent pipe and suppression pool. The transient level in vent pipe and suppression pool is obtained by solving the one-dimensional momentum equation for the incompressible flow [3].

$$\frac{dG_1}{dt} = \frac{\rho_w A_2}{(h_2 + h_1 r)}\left\{\left(\frac{P_1 - P_2}{\rho_w}\right) + g(h_1 - h_2) - \frac{G_2|G_2|}{2(\rho_w A_2)^2}\left[K + (1 - r^2)\right]\right\} \tag{1}$$

$$\frac{dh_1}{dt} = \frac{-G_1}{\rho_w A_1 N} \text{ and } \frac{dh_2}{dt} = \frac{G_2}{\rho_w A_2} \tag{2}$$

$$V_1 = \frac{dh_1}{dt} \text{ and } V_2 = \frac{dh_2}{dt} \tag{3}$$

Where $r=A_2/A_1$. The flow rate of water through vent pipe (G_1) is calculated from equation-1, based on the initial drywell pressure (P_1), wet well pressure (P_2), water level in vent pipe (h_1) and suppression pool level (h_2). Based on the flow rate, the water level change in vent pipe and suppression pool can be calculated using equation (2) and the calculations were performed till the vent gets cleared. The rise in suppression pool level (x_c) due to vent clearance is calculated from the initial pool level and pool level at the end of vent clearance transient.

Pool Swell Phenomenon [1]

After the vent pipe cleared of water an air bubble is assumed to form at the end of the vent pipe and detach when its diameter is twice the vent pipe diameter [4]. At the moment of detachment the bubble pressure is assumed to be same as that of the drywell. Penetration of bubble down into the pool is ignored. The growth of bubble is assumed to be spherical and migrates vertically. Effects of pool boundary and the free surface on the bubble growth are not accounted for. The bubble initially expands when the internal pressure is more than the external pressure due to the air-space and the hydrostatic pressure and then the former undershoots the latter due to inertia. Subsequently, the bubble starts contracting and the cycle continues. In the meanwhile the bubble rises continuously vertically due to buoyancy. The bubble expansion causes a transient pool swell leading to the compression of the air-space in the wet well above which tends to retard the bubble growth. While the first free bubble undergoes the motion described above, a second bubble is formed at the end of the vent pipe and detaches according to the previously mentioned criterion. It is assumed that this bubble coalesce with the existing bubble without any further delay and the process of bubble formation, coalescing with the existing bubble and the movement of the free bubble will continue till, eventually, the rising bubble breaks through the pool surface and escapes into the wet well air-space. The suppression pool level oscillation takes place due to the following reasons, (i) due to bubble formation and its growth at the end of vent pipe (x_1), (ii) due to the presence of free bubble and its growth in the suppression pool (x_2) and (iii) due to the displacement/movement of free bubble (x_3). Bubble formation and its growth takes place at the end of vent pipe (inside suppression pool) and the bubble mass variation can be calculated as

$$\frac{dm_{bub}}{dt} = \dot{m} \tag{4}$$

where $\dot{m} = C_d A_1 \rho_a V$, (ρ_a) is the density of flowing air from dry well and volume of bubble can be calculated from

$$\frac{d\overline{V}_{bub}}{dt} = C_d A_1 V \tag{5}$$

$$V = \sqrt{\frac{2\Delta P}{K\rho_a}} \text{ and } \Delta P = P_1 - (P_2 + g\rho_w \delta) \tag{6}$$

V is the velocity of air flowing through the vent pipe and it depends on the dry well pressure (P_1), wet well pressure (P_2), submergence depth (δ) and density of suppression pool water (ρ_w). The rise in suppression pool level due to formation of bubble (x_1) is calculated from bubble volume. $x_1' = V_{bub} / A_{sp}$ and for the „*N*" number of vent pipes, the total rise in the suppression pool level is

$$x_1 = Nx_1' \tag{7}$$

Once the diameter of the bubble growing at the vent pipe end becomes twice of the vent pipe diameter then the bubble gets detached at drywell pressure and starts growing. The bubble growth is calculated in the following way by considering the bubble in spherical nature. The one-dimensional equation of continuity in spherical co-ordinates is [5]

$$\frac{\partial \rho_w}{\partial t} + \rho_w \frac{\partial u}{\partial r} + u \frac{\partial \rho_w}{\partial r} + \frac{2\rho_w u}{r} = 0 \tag{8}$$

where ρ_w is the density of water and u is the radial velocity at radius r. Since it is constant, the equation becomes

$$\frac{\partial u}{\partial r} = -\frac{2u}{r} \tag{9}$$

Upon integrating the above equation and assuming $u=u_1$ at $r=1.0$. then

$$u = \frac{u_1}{r^2} \tag{10}$$

The one-dimensional transient momentum equation in spherical co-ordinates considering only radial direction and neglecting the effect of gravity is given below.

$$\rho_w \frac{\partial u}{\partial t} + \rho_w u \frac{\partial u}{\partial r} = -\frac{\partial P}{\partial r} \tag{11}$$

Substituting equation () in equation (), we get

$$\frac{\rho_w}{r^2}\frac{\partial u_1}{\partial t} - \frac{2\rho_w u_1^2}{r^5} = -\frac{\partial P}{\partial r} \tag{12}$$

If the bubble migrates vertically with a velocity „U" then the radial velocity of the bubble on the surface of sphere is [5]

$$u = \frac{dr}{dt} + U\cos\theta \tag{13}$$

Substitute equation () in above equation

$$u_1 = r^2 \frac{dr}{dt} + Ur^2 \cos\theta \tag{14}$$

Substitute above equation in momentum equation and integrating it from $r=R$ to $r=\infty$ (i.e. infinite medium) by allowing $U \neq 0$ and considering vertical direction i.e. $\theta=0$, then we get

$$R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 - \frac{U^2}{4} + \left(\frac{P_2 - P_{bub}}{\rho_w}\right) = 0 \tag{15}$$

The equation () is solved by Euler method and bubble radius and volume can be evaluated. Suppression pool level rise can be evaluated from the bubble volume.

$$x_2 = \frac{N}{A_{sp}}\frac{4\pi R^3}{3} \tag{16}$$

Pressure inside the gas bubble is obtained for an isothermal process. Therefore pressure at each time step can be calculated from previous time step and the equation is

$$P_{bub,i} = P_{bub,i-1}\left(\frac{R_{i-1}}{R_i}\right)^3 \tag{17}$$

Calculation of bubble vertical velocity ‘U’

The moving water‟s effective inertia as regards translation was that of a mass ($2\pi\rho R/3$) with velocity U. The vertical momentum acquired by the water should be ($2\pi\rho RU/3$) and is the result of buoyant force on the gas sphere equal to ($4\pi\rho gR^3/3$) by Archimedes‟s principle. Equating the impulse of this force to the momentum acquired by Newton‟s 2nd law gives [5].

$$\int_0^t F dt = \frac{4\pi\rho g}{3}\int_0^t R^3 dt = \frac{2\pi}{3}\rho R^3 U \tag{18}$$

Then $$U = \frac{2g}{R^3}\int_0^t R^3 dt \tag{19}$$

The level change in suppression pool due to translation of free bubble (x_3) can be calculated by the following equation.

$$\frac{dx_3}{dt} = \left(\frac{\pi R^2}{A_{sp}}\right)U \tag{20}$$

The total change in pool level at any instant of time is calculated as

$$x = x_c + x_1 + x_2 + x_3 \tag{21}$$

As the suppression pool level changes the wet well volume also changes and it affects the pressure. The change in wetwell pressure affects the bubble pressure, bubble growth and vice versa.

Coalescing of bubbles [1]

Once the bubble forming at the end of vent pipe detaches, then it is assumed that the bubble will coalesce with existing free bubble immediately. The pressure and volume after two bubbles have coalesced are calculated by conservation of mass and energy and the final pressure (P'_{bub}) is calculated from the following equation.

$$P'_{bub} = \left(P_{bub}^{m1/m2} P_1\right)^{1/(1+(m1/m2))} \tag{22}$$

where m_1 and m_2 are the number of moles in the existing and gravity and the newly generated bubble and new bubble radius is evaluated from final pressure new.

METHOD OF ANALYSIS

The steam-air mixture in drywell, due to LOCA, is allowed to flow through suppression pool for limiting pressure and temperature buildup in containment building. During the flow, the suppression pool level oscillates due to bubble dynamics which affects the drywell and wet well pressure. Therefore, mathematical modeling of flow of steam-air mixture through suppression pool was developed using FORTRAN code in a subroutine form and it was integrated with containment thermal hydraulic code CONTRAN, which evaluates the containment pressure and temperature transients due to LOCA [6,7]. Mass and energy blowdown data of steam, for a given break size of LOCA, were the main inputs for CONTRAN code for evaluating pressure and temp transients in dry well and wet well.

The drywell and wet well pressures at each time step, for a given break size of LOCA, were given as input to the subroutine. Initially vent clearing transient calculations were carried out by solving equations 1 and 2 using fourth order Runge-Kutta method and level transients in vent pipe and suppression pool were evaluated. After vent clearance, pool swell calculations were performed. Bubble formation and its growth at the exit of vent pipe and the change in suppression pool level due to bubble growth are calculated from the equations 4, 5, 6 & 7. After the bubble gets detached it becomes free bubble and it is assumed that its initial pressure is same as the dry well pressure. The free bubble size variation was calculated by solving 1-D transient momentum equation. Effects of bubble size over suppression pool level and bubble pressure are evaluated. The bubble is assumed to migrate vertically and its migration velocity is calculated using equation 19. The suppression pool level change due to bubble formation/growth at vent pipe exit, free bubble and bubble translation are summed up to get the total change in suppression pool for each time step. Based on the change in suppression pool level, the wet well volume and its pressure were calculated by the CONTRAN code. The suppression pool level and wet well pressure affects the flow through suppression pool and bubble size and vice versa. The flow through suppression pool takes place till the dry well pressure exceeds summation of wet well pressure and pressure head equivalent to submergence depth.

RESULTS AND DISCUSSION

Transient mass flow rate of steam discharged and energy discharged, for 200% break at RIH with SDS 1&2 failure (but Emergency Core Cooling System (ECCS) is available), were used as input for the present study. The blow down mass and cumulative energy discharge data, as shown in Fig.3 and 4, were generated separately using RELAP5/Mod3.2 for the above break case. Fig.5 shows the containment pressure transients in drywell (V1 volume) and wet well (V2 volume) for with and without considering pool swell model. When pool swell model is not considered, the CONTRAN code calculates the flow rate of steam-air mixture through suppression pool based on the drywell, wet well pressure and constant submergence depth. Therefore, the flow rate is governed by the drywell and wet well pressure. When pool swell model is considered, the flow rate through suppression pool is governed by drywell, wet well and submergence depth. The submergence depth is affected by the presence of bubbles in suppression pool and its variation affects the wet well pressure as well as drywell pressure. Since drywell volume is smaller than wet well volume, the pressure oscillation in drywell is higher than wet well. The peak pressure obtained, for without considering pool swell, is less compared to the peak pressure obtained when pool swell model is considered and the reason being is due to more flow through suppression pool when pool swell model is not considered.

Fig.6 shows the variation of drywell, wet well and bubble pressure in suppression pool from 1s to 5 s. The bubble pressure is assumed to be equal to drywell pressure when it gets detached from the vent pipe exit. Thereafter, the bubble pressure starts reducing and goes below the wet well pressure and then it rises. In this way, the bubble pressure oscillates till the bubble breaks into wet well area. The bubble size variation is shown in Fig.7 and it expansion and contraction is depending upon the bubble pressure and wet well pressure. Whenever the bubble pressure is higher than wet well pressure then bubble expands and as the bubble expands, its pressure starts coming down. If bubble pressure becomes lesser than wet well pressure, then bubble contracts and bubble pressure starts rising.

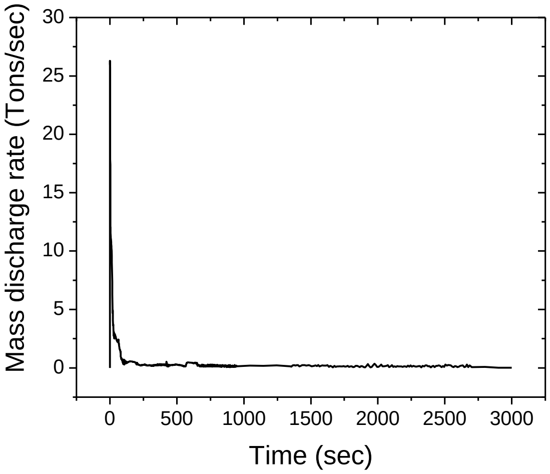

Fig.3: Blowdown discharge rate Vs time.

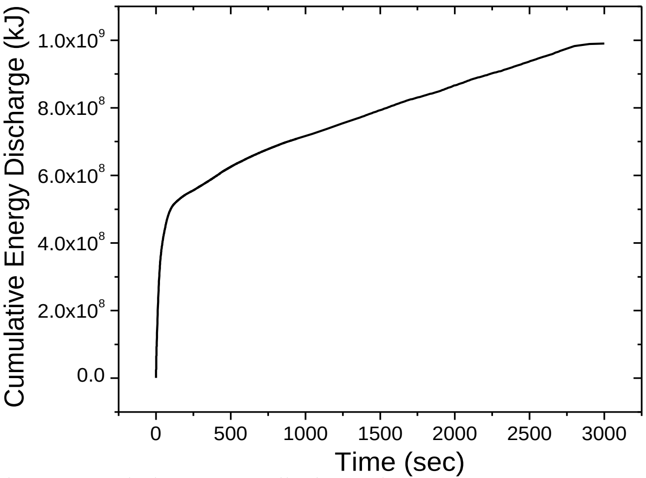

Fig.4: Cumulative energy discharged.

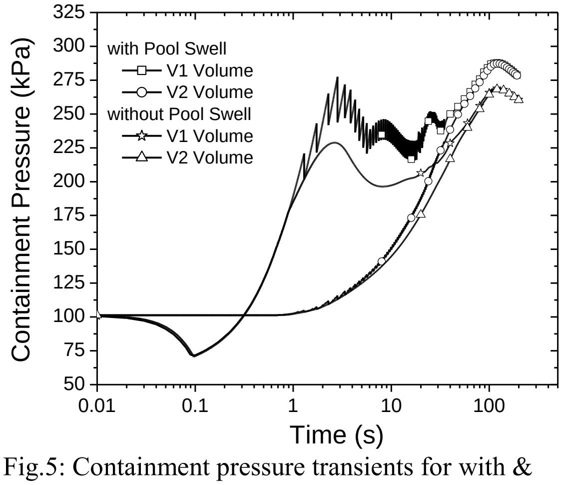

Fig.5: Containment pressure transients for with & without pool swell model.

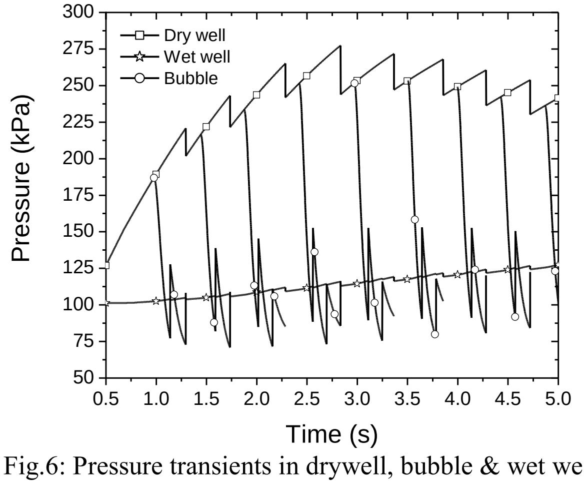

Fig.6: Pressure transients in drywell, bubble & wet well.

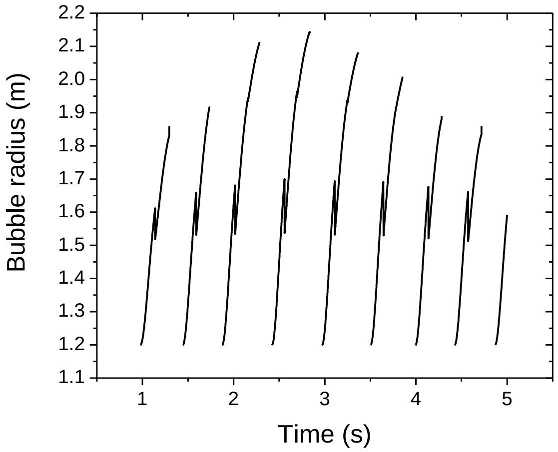

Fig.7: Variation of free bubble radius from detachment to break up at pool surface.

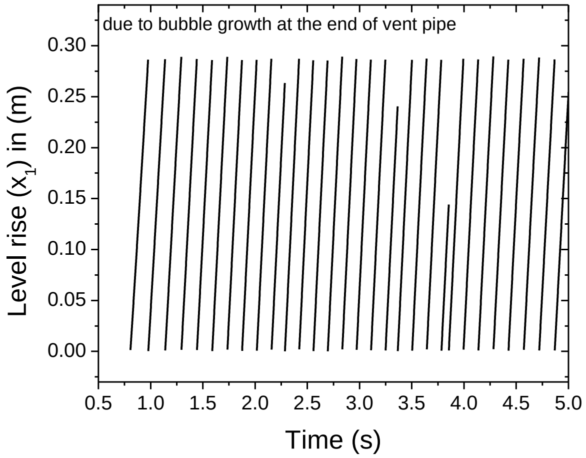

Fig.8: Variation of pool level due to bubble growth.

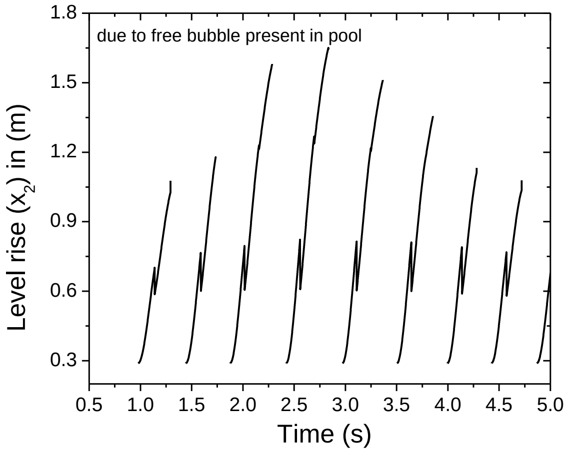

Fig.9: Variation of pool level due to free bubble growth in pool medium.

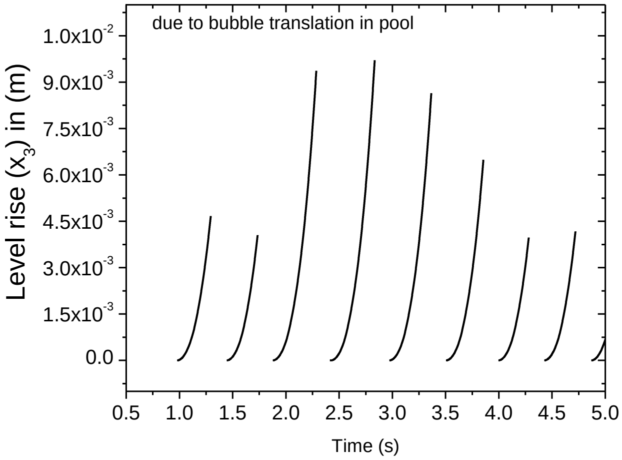

Fig.10: Variation of pool level due to bubble migration in pool medium.

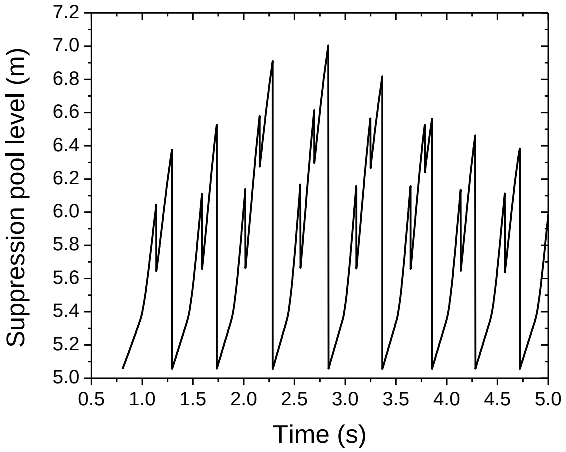

Fig.11: Variation of supression pool level during the transient.

Initial suppression pool level is 5m and it rised to 5.5m at the end of vent clearance transient. The level is further rised due to the bubble formation at the vent pipe exit and its variation is shown in Fig.8. Maximum level rise due to bubble formation at vent pipe exit is around 0.28m and the rate of rise in level depends upon the drywell, wet well and submergence depth. After the bubble gets detached from vent pipe exit, either it expands or contracts. The expansion and contraction of bubble affects the suppression pool level and its change is shown in Fig.9. Initially the free bubble size is twice the vent pipe‟s diameter and it expands because of its pressure is being higher than wet well pressure and the bubble radius goes almost four times of vent pipe diameter. Therefore, the presence of free bubbles can displace more suppression pool water volume and the maximum rise in level is around 1.65m. The rise in suppression pool level is also takes place due to the bubble vertical translation and its variation is shown in Fig.10. The overall suppression pool level variation considering the level rise due to bubble formation, growth and translation is shown in Fig.11. From the Fig.11 it is observed that the maximum rise in pool level is 7.1m. The pressure load on the systems and equipments submerged inside the suppression pool can be calculated from the pool height and wet well pressure.

Though steam-air mixture is flowing from dry well to wet well through suppression pool, but in the analysis, only air is assumed to flow through pool water medium to get conservative results. However by considering the steam-air mixture and heat & mass transfer between the bubbles and pool water, the peak containment pressure and peak rise in pool water level would be reduced.

CONCLUSION

Steam released into V1 volume of the AHWR containment building due to postulated LOCA causes its pressure to rise and it is limited by diverting the steam-air mixture to V2 volume through suppression pool. Therefore mathematical modeling of flow of steam-air mixture through suppression pool is carried out and it was integrated with containment thermal hydraulic code CONTRAN. Thermal hydraulic analysis of containment have been carried out and the drywell and wet well pressure and temperature transients following LOCA were calculated using CONTRAN code for with and without considering pool swell model. The containment peak pressure calculated by considering pool swell model is higher than the peak pressure calculated if pool swell model is not considered. The oscillation of suppression pool level and maximum rise in pool level during the transient were calculated. Since the pool swell calculations are performed for air and the peak pressure and suppression pool level oscillations are high. However, the peak pressure, pool level oscillations may reduce by considering the heat and mass transfer steam-air mixture with suppression pool water.

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