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Impact of Engineered Safety Features on AHWR Containment

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1 ABSTRACT

The proposed AHWR employs double containment envelope along with many Engineered Safety Features (ESFs) to mitigate the consequences of LOCA with safety system failure, during which high enthalpy steam and radioactive fission products will be discharged into containment. In such conditions, the pressurized containment will be the source of activity release to the environment by way of leakage. It is required to study the effect of ESFs on flows and leakages from the AHWR containment. For this purpose, an in-house thermal hydraulic code CONTRAN was used. Modules for simulating the engineered safety features were incorporated with this code. The AHWR containment is divided into three nodal volumes interconnected by junctions. The blow down mass, energy discharge data and activity released into the containment from reactor core, for a postulated LOCA case of 200% RIH break with failure of shutdown systems (1 & 2), are inputs to CONTRAN code. Since the interest of the paper is to study the impact of ESFs on leakages, all the activity released into the containment were assumed to be in gaseous form. Analysis was carried out for a number of cases, postulated based on availability/unavailability of ESFs. CONTRAN evaluates the pressure, temperature and activity concentration transients, for 72hrs, in the subdivided volumes along with the activity released out of the containment through leakages and stack discharges for all the cases. This paper highlights the importance of operation of ESF in reducing the activity release to the environment.

2 INTRODUCTION

The proposed Advanced Heavy Water Reactor (AHWR) is a 300MW(e), vertical pressure tube type, heavy water moderated, boiling light water cooled natural circulation reactor [Sinha,R.K. et al (2006)]. There are 452 vertical channels are present in reactor core and each channel contains fuel bundle consists of (Th–^{233}U)O_2 pins and (Th–Pu)O_2 pins and total fuel inventory is 64.25Tons. The AHWR employs a double containment philosophy with a Gravity Driven Water Pool (GDWP) to house the reactor and other safety related equipments. The Primary Containment (PC) is surrounded by the outer Secondary Containment (SC). The containment is designed to withstand the effects of the Loss-Of-Coolant Accident (LOCA) during which high enthalpy steam and radioactivity is released into the containment. The primary containment is proposed to provide with many containment Engineered Safety Features (ESFs) such as Containment coolers, Primary Containment Filtration and Pump Back (PCFPB) system, Secondary Containment Filtration, Recirculation and Purge (SCFRP) system and Primary Containment Controlled Discharge (PCCD) system.

The main objectives of ESFs are (i) to control the release of radioactivity, within permissible limits, to the environment during normal and accident conditions, (ii) to remove the heat generated due to running equipments and others during normal operation, (iii) to provide a long term heat removal from containment atmosphere during an accident and thereby assist in bringing down the containment pressure and temperature and (iv) to clean the containment atmosphere during accident conditions.

The release to the environment is reduced by (i) limiting the pressure and temperature in the containment by GDWP and containment coolers (i.e. minimizing the time integrated over pressure), (ii) removal of the air borne fission products from the containment atmosphere by employing suitable clean up, filtration, ventilation systems and by GDWP also and (iii) retention of radioactivity within containment by maintaining the integrity of containment (by providing high degree of leak tightness).

As part of the PSA studies for the proposed Advanced Heavy Water Reactor (AHWR) project, it was required to perform studies pertaining to effect of ESFs on containment pressure, temperature and source terms. Therefore, a postulated LOCA case of 200% break size of Reactor Inlet Header (RIH) with the failure of Shutdown systems 1 & 2 (but Emergency Core Cooling System is available) was taken up for the analysis. The considered fuel burn up at the initial time of accident is 24000MWd/t. The mass of Th232, Pu239 and U233 in each channel are 127.926kg, 4.62kg and 9.6kg and the core melt is around 6.8%.

The effect of the accident is to release high enthalpy steam and radioactivity into the containment. The transient analysis was carried using in-house containment thermal hydraulics computer code 'CONTRAN'. The blow-down mass, energy discharge data and activity released into the containment, from reactor core, are inputs to the CONTRAN code.

For the analysis, the AHWR containment was divided into three nodal volumes along with GDWP. CONTRAN evaluates the pressure and temperature transients along with the radioactivity concentration transients in the nodal/subdivided volumes and also calculates the release of radioactivity at the ground level as well as through the stack. The aim of this analysis to find the impact of containment ESFs on containment pressure, temperature, flow between compartments, leakages, activity concentration and its releases. The evaluation of activity releases are preliminary, therefore the activity is assumed to be released into containment in gaseous form only and it does not consider the chemistry between the fission products and retention by way of agglomeration, deposition etc.

3 BRIEF DESCRPTION OF AHWR CONTAINMENT SYSTEMS

The containment system of a nuclear reactor performs the important function of serving as one of the barriers to any release of radioactivity during normal and postulated accident conditions. For the confinement and removal of radioactivity and to minimise the leakage to the environment during LOCA conditions, 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 prestressed 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. These two volumes are interconnected by a vent system via the GDWP. The volume V1 houses all the high enthalpy systems like the reactor core, fuelling machine vaults etc and 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 [Ghosh,A.K. et al (1984)]. The fig. 1 shows the simplified AHWR containment system.

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 pressurized heavy water reactors (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.

In order to avoid excessive local pressure buildup and high differential pressure across internal structures during LOCA, adequate connections for flow between various rooms are provided in both the volumes. As opposed to this, it is essential that during normal operation, certain barriers exist between rooms having different levels of activity. These conflicting requirements necessitate the use of Blow Out Panels (BOP's), which operate at a predetermined differential pressure. A typical 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 presssure equalisation during accident conditions. Apart from the above features, the containment system includes other ESFs like building coolers, primary containment controlled discharge, filteration and ventilation systems etc, which provide additional energy/radionuclide management. In this study, data such as recirculation, purge and vent flow rate that are required for various containment engineered safety systems are assumed to be same as of standardisied Indian PHWR.

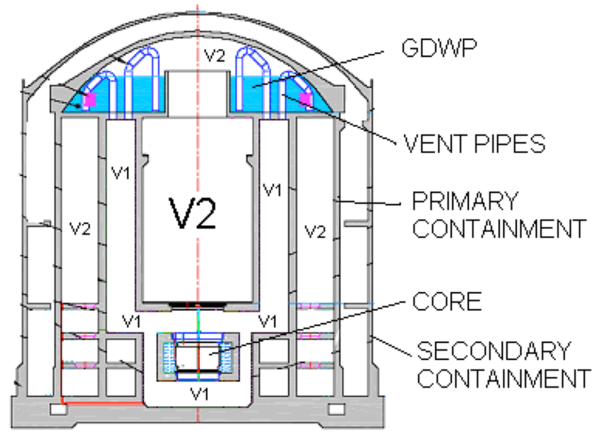

Figure 1. AHWR containment system

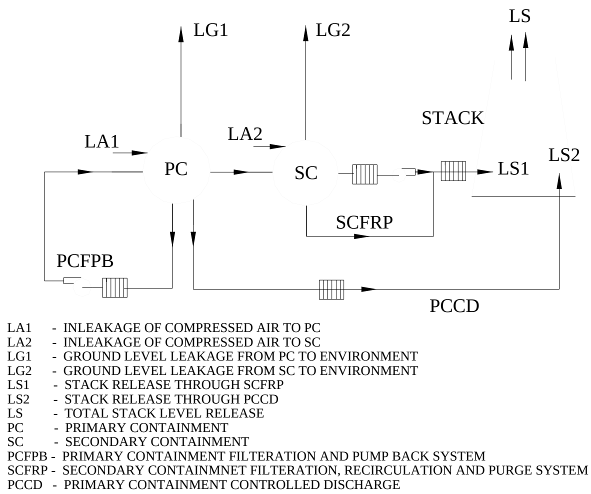

Figure 2. AHWR Containment activity release model.

3.1 Containment coolers (NPCIL, 1999)

The containment coolers are provided to remove the heat generated due to running equipments and by other means during normal operation and they also provide a long term heat removal from the containment during accident conditions. The containment coolers are provided at the top of primary containment and remove the heat to GDWP in a passive manner. Following an accident such as LOCA leakage from the primary containment will continue as long as it is under pressurized condition and leakages contribute to release of radioactivity at ground level. Therefore, the coolers depressurize the containment by condensing the steam and cool down the containment atmosphere and thereby limit the release of radioactivity at ground level.

3.2 Primary containment controlled discharge (PCCD) (NPCIL, 73140)

In order to depressurize the primary containment below 104.7kPa, which may be difficult to achieve by cooling alone, there is a provision of dicharging the containment atmosphere to environment in a controlled manner through filters and stack. This is carried out by the PCCD system. The option of controlled discharge can be delayed by 48 hours or more by that time the primary containment cleanup system (PCFBP) would have reduced activity in the primary containment atmosphere considerably. However, operation of PCCD system depends upon containment pressure, meteorological condition and activity levels in the primary containment.

3.3 Primary Containment Filtration and Pump Back system (PCFPB) (NPCIL, 73150)

This system helps to remove radionuclide Caesium and Iodine from containment atmosphere. In this system about 13600 m3/hr air flow is recirculated (V1 to V2 volume) within the primary containment through charcoal filters in combination with HEPA filter. The system is designed to perform containment atmosphere cleanup operation on a long term basis after an accident and it is intended to start manually with a nominal delay of three hours following the accident. Due to radioactive Iodine absorption charcoal filter temperature rises and when filter temperature reaches 80°C flow from V1 to V2 will be isolated and filter cooling will be by air circulation from V2 volume to limit the temperature rise.

3.4 Secondary Containment Filtration, Recirculation and Purge system (SCFRP) (NPCIL, 73160)

This system provides multipass filtration and mixing by recirculation within the secondary containment space and also maintains negative pressure within the secondary containment space. To achieve these functions, about 1700 m3/hr of air from the secondary containment space is passed through charcoal and HEPA filters by a centrifugal fan, after which 76% flow is re-circulated back to the secondary containment, while the remaining fraction is purged out to atmosphere via stack, through additional filters, to maintain a negative pressure (about 12 mm of WG) in the secondary containment. Iodine filters and fans have 100% standby. If –ve pressure higher than 24 mm of WC purge line closes automatically & reopens automatically when –ve pressure falls below 12 mm of WC.

Fig. 2 shows containment activity release model for AHWR which has been incorporated in the CONTRAN code. The activity is released from the containment at ground and stack levels. Ground level releases consists of release of activity from the PC and SC to the environment by leakage and these are designated as LG1 and LG2 respectively, shown in fig. 2. Stack level release is through filter and stack and this consists of the release by SCFRP (LS1) and PCCD system (LS2). The activity leakage depends upon following parameters

(i) Activity concentration in the containment atmosphere following an accident.

(ii) Containment ambient pressure following an accident. (Leakage rate depend upon the pressure difference between containment and atmosphere)

4 COMPUTER CODE CONTRAN

The in-house computer code CONTRAN (CONtainment TRansient ANalysis) used for the present analysis has the following salient features [Haware,S.K et al (2005)]:

1. It is a multicompartment containment transient analysis code which solves the mass and energy conservation equations within each of the compartments to predict the thermal hydraulic transients.
2. The code can accomodate any number of compartments and at present each compartment can have six junctions which may act as inlet or outlet depending on the pressure gradient.
3. Each compartment can have upto three heat slabs of different materials which act as heat sink.
4. A number of condensation heat transfer coefficient models are available to evaluate heat transfer to containment structures.
5. One dimensional transient heat conduction model, to represent containment wall, with an option of using uniform as well as non-uniform grid sizes is available.
6. Contains a model to evaluate vent clearing transients in the suppression pool.
7. Option of using variable time step for computation.
8. Capable of predicting the post accident long term containment pressure and temperature transients.
9. The blowdown mass and energy discharge rates for any given break size can be given as input to the code.
10. It has been extensively validated against experimental data [Haware,S.K et al (1994, 1989)].
11. Containment Engineered safety systems such as Containment Coolers, PCFPB, SCFRP and PCCD can be modelled.
12. Time dependent activity release into the containment can be given as input and ground and stack level release from the containment can be evaluated.

4.1 Assumptions for thermal hydraulic Analysis

i) The assumed steam condensation efficiency of GDWP is 50%.
ii) The assumed air cooling efficiency of GDWP is 50 %.
iii) Uchida model [Almenas,K. (1982)] was employed for condensation heat transfer coefficient calculation.
iv) Structural heat transfer calculations were carried out assuming one-dimensional transient heat conduction through heat slabs.
v) The details of containment coolers provided in standardised Indian PHWR 220MW(e) is used for the analysis. Effect of passive containment coolers is not considered.

4.2 Assumptions for activity release analysis

i) Volumetric flow rate of all the pumps for containment engineered safety systems are constant with time and assumed to be same as that of Indian PHWR.
ii) The efficiency of Charcoal filter and HEPA filter is taken as 90 %.
iii) Leakage rate from containment has been assumed which is given in table 3.
iv) SCFRP system will be available immediately after the blowdown.
v) PCFPB system will be switched 'ON' after 4 hours of initiation of the accident.
vi) PCCD system is assumed to be switched 'ON' after 24 hours of accident if containment pressure is lower then 106 kPa (0.05 kg/cm2-g).
vii) The details of PCFPB, PCCD and SCFRP systems provided in standardised Indian PHWR 220MW(e) are used for the analysis.
viii) Instrument/Compressed air leakage into Primary and Secondary containment is not considered.

4.3 Equations used in CONTRAN

The containment is divided into many compartments or volumes and the mass and energy conservation equations were solved for each compartment. The flows between two compartments were calculated using momentum equations. The mass and energy conservation equations are

$$\frac{dm_i}{dt} = \sum \dot{m}_{i,in} - \sum \dot{m}_{i,out} \qquad (1)$$

where $\sum \dot{m}_{i,in}$ is the sum of incoming flow rates of air and steam into i^{th} volume, which consists of flow through openings, leakages etc. $\sum \dot{m}_{i,out}$ is the summation of outgoing flow rates of air and steam from the ith volume, which consists of flow through openings, leakages, flow to PCFPB, PCCD and SCFRP systems and due to steam condensation over walls and containment coolers.

$$\frac{dH_i}{dt} = \left(\sum \dot{m}_{i,in}\bar{h}_{i,in} - \sum \dot{m}_{i,out}\bar{h}_{i,out}\right) - \left(Q_{cond} + Q_{cool}\right) + V_i\frac{dP_i}{dt} \qquad (2)$$

The first term and second term are the energy of incoming and outgoing air and steam through openings, leakages, PCFPB etc. Q_{cond} is the condensation heat transfer for containment wall and Q_{cool} is the condensation heat transfer on containment coolers, which are given below. Heat addition due to decay of fission products has not been considered. For calculating the flow between the two compartments, a model based on the isentropic flow of a mixture of steam, non-condensable gases and water through an orifice is used.

In this analysis four radioactive species Iodine, Caesium, Krypton and Xenon have been considered for activity transport. The conservation equations for Iodine is as follows,

$$\frac{dm_{I,i}}{dt} = \left(\sum \dot{m}_{I,i,in} - \sum \dot{m}_{I,i,out}\right) - m_{I,i}\lambda_I \qquad (3)$$

The $m_{I,i}$ is the mass of Iodine present in i^{th} volume and $\sum \dot{m}_{I,i,in}$ is the summation of incoming iodine, to ith volume. $\sum \dot{m}_{I,i,out}$ is the summation of outgoing iodine, from i^{th} volume and the last term is due to decay of Iodine. The conservation equation for other fission product species is similar to equation-3. All the three equations represent a compartment and similar equations are to be solved for other compartments.

The condensation heat transfer and condensation rate to walls can be calculated from the following equations.

$$Q_{cond} = h_{cont}\, A\left(T_{sat} - T_{wall}\right) \qquad (4)$$

$$\dot{m}_{cond} = \frac{Q_{cond}}{\bar{h}_{fg}} \qquad (5)$$

where Q_{cond} is the condensation heat transfer, $\dot{m}_{cond}$ is the condensation rate and h_{cont} is the condensation heat transfer coefficient calculated using Uchida correlation [11]. The heat transfer and condensation rate on containment coolers can be calculated using following relations

$$Q_{cool} = h_{cool}\ A\left(T_{sat} - T_{cw}\right) \tag{6}$$

$$\dot{m}_{cool} = \frac{Q_{cool}}{\bar{h}_{fg}} \tag{7}$$

where Q_{cool} is the heat transfer to the cooling water, $\dot{m}_{cool}$ is the steam condensation rate on coolers and h_{cool} is the overall heat transfer coefficient for coolers. Leakages from the compartment can be calculated using following relations

$$\overline{Q} = K\left(\Delta P\right)^{0.8} \tag{8}$$

where $\overline{Q}$ is the leakage in m^3/sec that leaks out of a compartment/volume to other volume or atmosphere is related to pressure difference (ΔP in Pascal) between respective volumes and K is the flow resistance. The PCFPB, PCCD and SCFRP systems are provided with a combination of charcoal filters and HEPA filters for removing the radioactive nuclides.

5 METHOD OF ANALYSIS

The transient analysis was carried out using in-house containment thermal hydraulics code ‘CONTRAN’ which is incorporated with subroutines for simulating the engineered safety features. For the purpose of analysis, a three volume configuration, which is shown in fig. 3, of entire AHWR containment with GDWP is considered. The primary containment is divided into two volumes. The primary containment volume V1 is considered as first nodal volume and the primary containment volume V2 is considered as second nodal volume. The region between primary and secondary containment is considered as third nodal volume. Volume connectivity between each volume and various engineered safety features provided in each volume are shown in fig. 3.

Geometrical data such as volume details, heat transfer area, junction flow area, number & type of heat slabs per volume and thermophysical properties of containment materials were given as inputs for the CONTRAN code. Blowdown mass and energy discharge data for a break size along with activity released into the containment from the reactor core were given as input to CONTRAN. The code evaulates the pressure-temperature transient, activity concentration transient in each volume. The code also evaluates the activity released out of the containment through stack level and ground level release. Stack release is from containment atmosphere to environment by SCFRP and PCCD systems through filters and stack. Stack release is evaulated based on activity concentration, flow rate and filter efficiency. The ground release is due to the leakage from the pressurisied containment atmosphere. The ground release is calculated based on the activity concentration and leakage rate which in turn is a function of containment pressure.

Four different ESFs will be provided in AHWR containment. To study the effect of each ESF on source term, 16 cases have been postulated based on availability and unavailability of each ESF, which are shown in table 1. The analysis was carried upto 72hrs and results such as ground level and stack level releases are calculated up to 72hrs only.

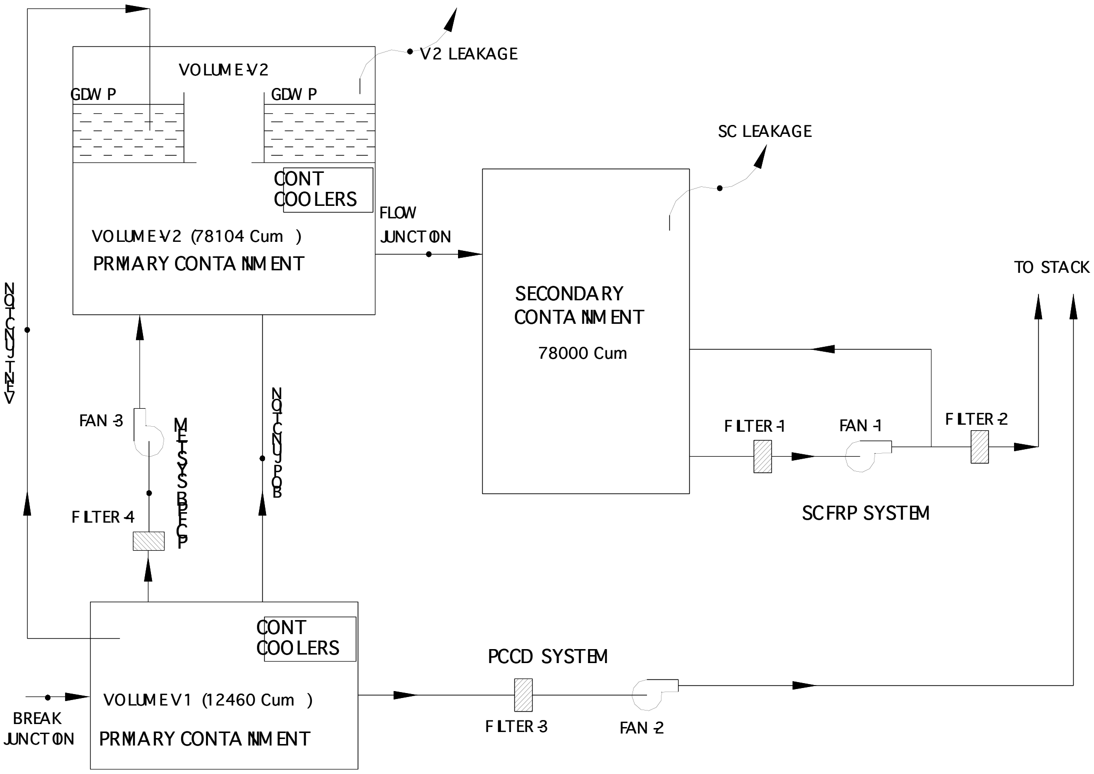

Figure 3. Volume connectivity for AHWR containment with Engineered Safety Features

Table 1. Cases considered for the present analysis.

	Containment Coolers	PCFPB	SCFRP	PCCD
CASE-1	ON	ON	ON	ON
CASE-2	ON	ON	ON	OFF
CASE-3	ON	ON	OFF	ON
CASE-4	ON	ON	OFF	OFF
CASE-5	ON	OFF	ON	ON
CASE-6	ON	OFF	ON	OFF
CASE-7	ON	OFF	OFF	ON
CASE-8	ON	OFF	OFF	OFF
CASE-9	OFF	ON	ON	ON
CASE-10	OFF	ON	ON	OFF
CASE-11	OFF	ON	OFF	ON
CASE-12	OFF	ON	OFF	OFF
CASE-13	OFF	OFF	ON	ON
CASE-14	OFF	OFF	ON	OFF
CASE-15	OFF	OFF	OFF	ON
CASE-16	OFF	OFF	OFF	OFF

Table 2. Initial conditions in the containment.

Pressure in all volumes		101.3 kPa
Temperature in all volumes		32°C
Relative Humidity	First nodal volume (i.e. primary containment volume V1)	0 %
	Second nodal volume (i.e. primary containment Volume V2)	60 %
	Third nodal volume (i.e. annulus region between primary and secondary containment)	0 %

6 RESULTS AND DISCUSSION

Blowdown mass, energy and activity release data 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 energy discharge data were generated seperately using RELAP5/Mod3.2 for the above break case. The activity released into the containment from reactor core is calculated using an in-house code called PHTACT. Fig. 4 and fig. 5 show the blowdown mass and energy discharge data. Fig. 6 shows the cumulative activity release data for Caesium and Xenon and fig. 7 shows the cumulative activity release data for Iodine and Krypton into the containment with respect to time. Initial conditions for various containment volumes are shown in table 2. Leakage rates assumed for the containment for radiological calculations are shown in table 3.

The table 4 shows the integrated mass and energy discharged into the containment. Table 5 shows the core inventory of fission product considered and amount of fission product released into the containment. Release of other fission products such as Te, Sb, Ag, Mo Ru etc were not considered as its radiological consequences are insignificant. For all the 16 cases (refer table 1), pressure, temperature and activity concentration transients and activity release have been evaluated. Table 6 shows the effect of containment coolers on containment peak pressure, which shows that the peak pressure is reduced by 30kPa in both V1 and V2 volumes and temperature is decreased about 10K in volume V1 and 37K in V2. Fig. 8 and 9 show the comparison of pressure and temperature transients when coolers are under operation and not under operation for case-1 and case-16.

Table 3. Leakage rate assumptions for long term thermal hydraulic and activity release calculation.

S.No		Leakage
1	Primary containment to Secondary containment	0.3% of Primary Containment volume per hour at maximum containment pressure (i.e. 282.75 kPa) in case of LOCA
2	Primary containment to environment	10% of leakage from primary containment to secondary containment is assumed to bypass directly from primary containment to environment.
3	Secondary containment to environment	0.6% of total containment volume (primary and secondary containment) per hour at 103.3kPa (200 mm of water column).
4	V1 volume to V2 volume of primary containment	Area equivalent to $0.0929 m^2$ ($1 ft^2$)
5	BOP area	$5.946\ m^2$

The containment coolers reduce the time integrated V1 and V2 volume pressure for a period of time. Therefore, the operation of containment coolers is necessary to reduce the containment over pressure with respect to time. Fig. 9 shows the temperature in volumes V1 and V2 for case-1 and case-16 with respect to time. It is thus apparent from the fig. 9 that the temperature in volumes reduces significantly when coolers are under operation and it can be observed that after the steam blowdown the temperature in both volumes starts reducing quickly. Thus the coolers prevent the containment structures from heating and reduce the development of thermal stresses which occurs due to temperature gradient across the wall. If the tensile thermal stress exceeds the permissible value then cracks may initiate on the containment structures and results in higher leakage. The fig. 10 & 11 show the Caesium concentration variation with respect to time for several cases in volume V1 and V2 respectively and it can be observed that for case-1, all ESFs are ON, the concentration reaches high and decreases after 4hrs because of operation of PCFPB (comes into operation after 4hrs). For case-8, only coolers ON, the concentration in the both volumes remains unchanged after blowdown. Due to condensation of steam on coolers, the pressure difference between volume V1 and V2 is less for case-1 & 8 and results in low flowrate between V1 and V2. Therefore, the concentration in volume V1 is higher than volume V2. For case-12, only PCFPB is ON, the concentration in both V1 and V2 volumes decreases and for other case-14, only SCFRP is ON, the concentration in both the volumes attains almost equilibrium and similar trends are observed for other cases 15 and 16. Iodine concentration variations are not shown as its variations are similar to Caesium variations.

Fig. 12 and 13 show the Xenon concentration variation with respect to time for some cases in Volume V1 and V2 respectively. For case-8 the concentration in volume V1 is higher than volume V2 and in all other cases the xenon concentrations attains equilibrium value. Concentration variation of Krypton is also not shown as its variations are similar to Xenon variations. Xenon and Krypton are noble gases so it cannot be filtered using HEPA/charcoal filters hence its concentration inside the containment volume attains an equilibrium value.

Fig. 14 is the bar chart showing the Caesium release to the environment through ground and stack release for various cases. Total release is the summation of both ground level release and stack level release. From case-1 to 8, the coolers are ON and therefore the ground releases are less compared to case-9 to 16. From cases-1 to 4 the releases are still lesser than cases-5 to 8 and the reason being operation of PCFPB system. In case-5 and 7 the stack releases are contributed by PCCD system. The fig. 15 shows the Iodine release to environment for various cases and the bar chart shows the similar nature of Caesium bar charts.

Fig. 16 and 17 show the bar chart for Krypton and Xenon release to environment for various cases. It can be observed from the figures that the major part of release is by stack release and it is due to operation of PCCD system. Ground level releases are less when coolers are under operation.

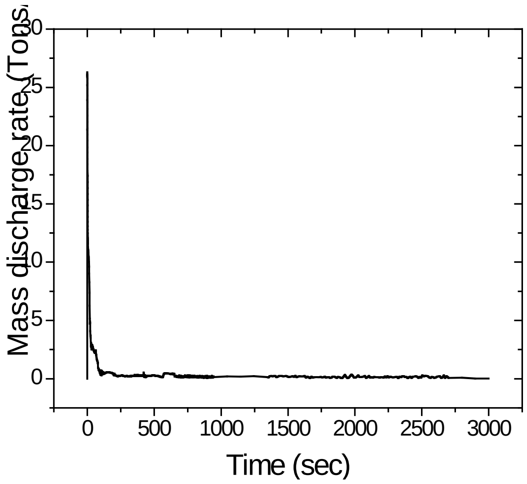

Figure 4. Blowdown discharge rate Vs time.

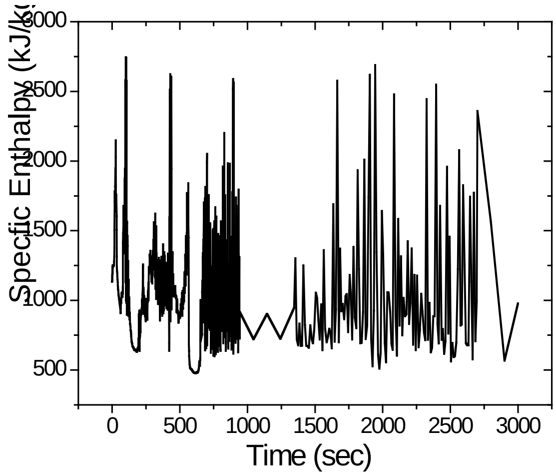

Figure 5. Blowdown specific enthalpy Vs time.

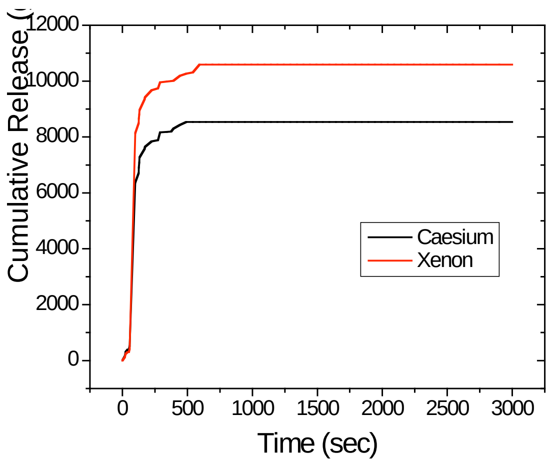

Figure 6. Cumulative Caesium and Xenon release into the containment Vs time.

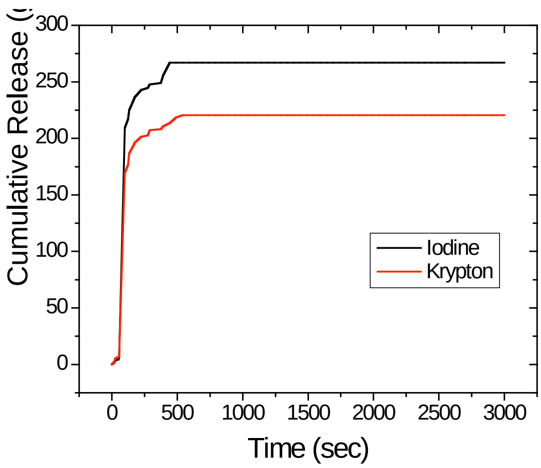

Figure 7. Cumulative Iodine and Krypton release into the containment Vs time.

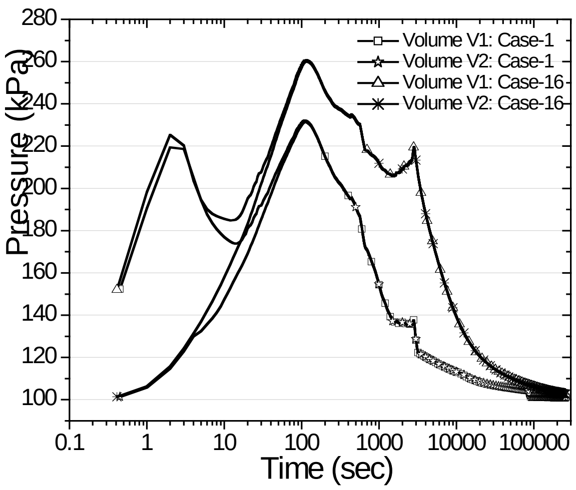

Figure 8. Pressure Vs time in V1 and V2 volumes for case-1 and 16.

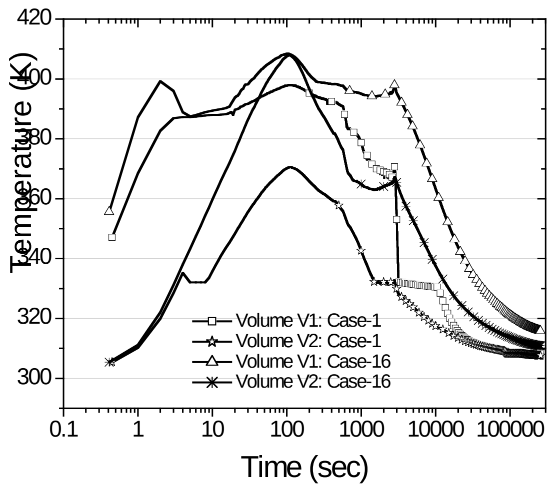

Fig-9: Temperature Vs time in V1 and V2 volumes for case-1 and 16.

Table 4. Integrated mass and energy discharge

Table 5. Core inventory and activity released into containment.

Break Size (%)	Blowdown duration (sec)	Integrated Mass discharge (Tons)	Integrated energy discharge (Million kJ)
200	3000	916.935	990.044

	Core inventory used for analysis (kg)	Activity Released into containment from core (kg)	Activity Released into containment from core (Bq)
Caesium	127.49	10.24	3.3973×10^{16}
Iodine	4.26	0.265	1.2625×10^{18}
Krypton	3.42	0.234	3.5×10^{15}
Xenon	164.45	11.227	7.8382×10^{19}

Table 6. Peak pressure and peak temperature with their time of occurrence in V1 and V2 volumes.

	Peak Pressure (kPa)	Time of occurrence of peak pressure (sec)	Peak Temperature (K)	Time of occurrence of peak temperature (sec)
Case-1: Vol V1	260.69	115.29	408.52	101.47
Case-1: Vol V2	260.04	115.69	407.93	108.05
Case-16: Vol V1	232.28	107.47	398.06	105.39
Case-16: Vol V2	231.45	111.56	370.63	113.71

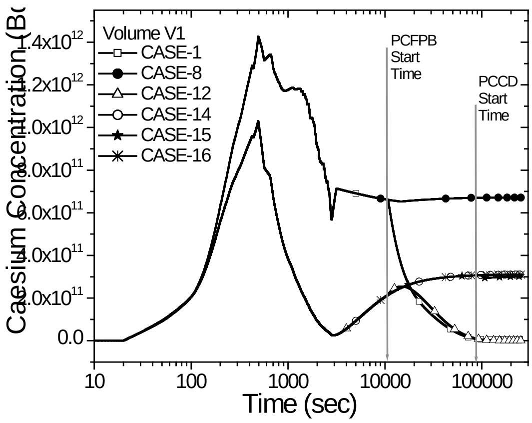

Figure 10. Caesium concentration variations with respect to time for various cases in volume V1.

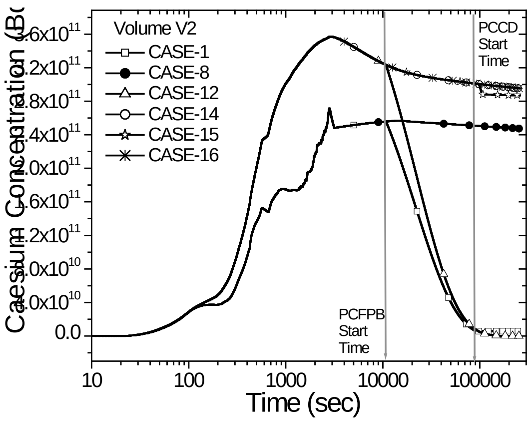

Figure 11. Caesium concentration variations with respect to time for various cases in volume V2.

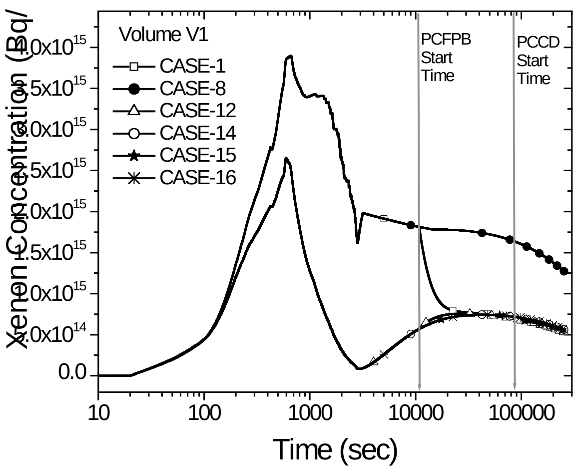

Figure 12. Xenon concentration variations with respect to time for various cases in volume V1.

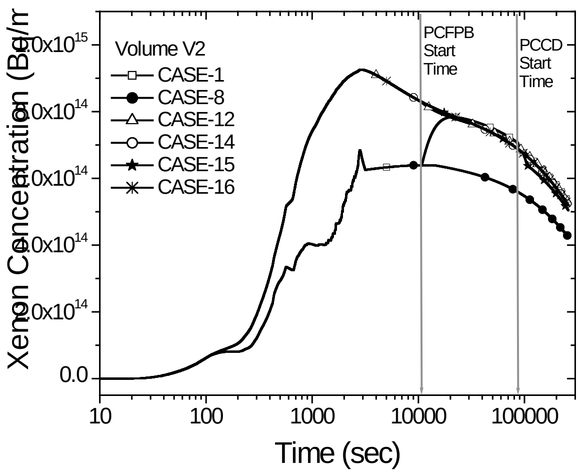

Figure 13. Xenon concentration variations with respect to time for various cases in volume V2.

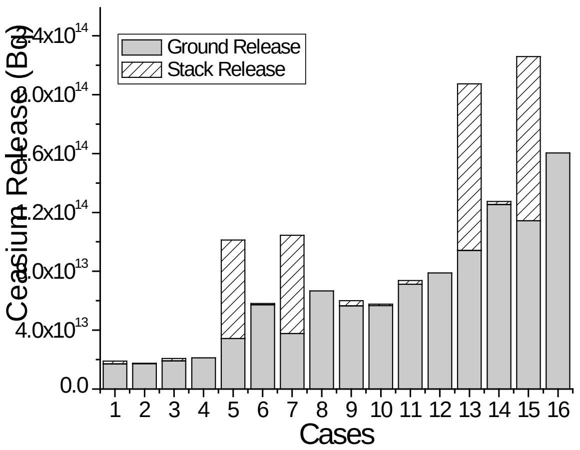

Figure 14. Caesium released out of containment by way of ground and stack for various cases.

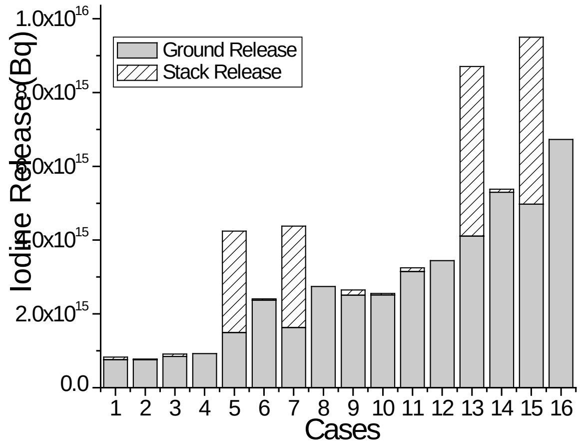

Figure 15. Iodine released out of containment by way of ground and stack for various cases.

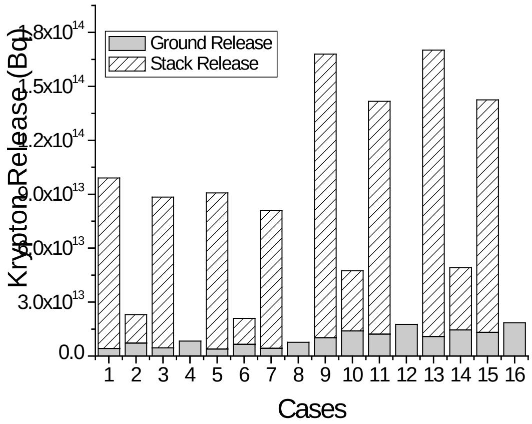

Figure 16. Krypton released out of containment by way of ground and stack for various cases.

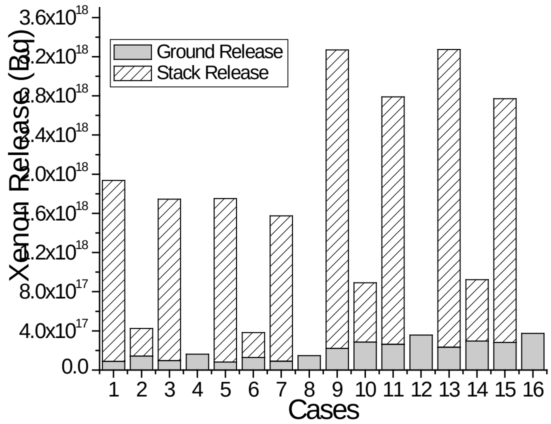

Figure 17. Xenon released out of containment by way of ground and stack for various cases.

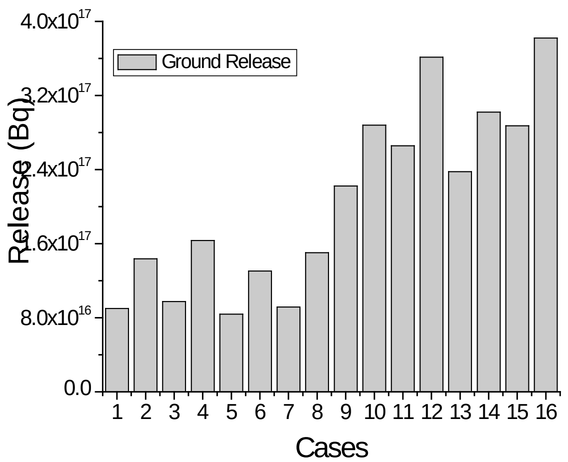

Figure 18. Total activity (summation of Cs, I, Kr & Xe) released out of containment by way of leakage (Ground release) for various cases.

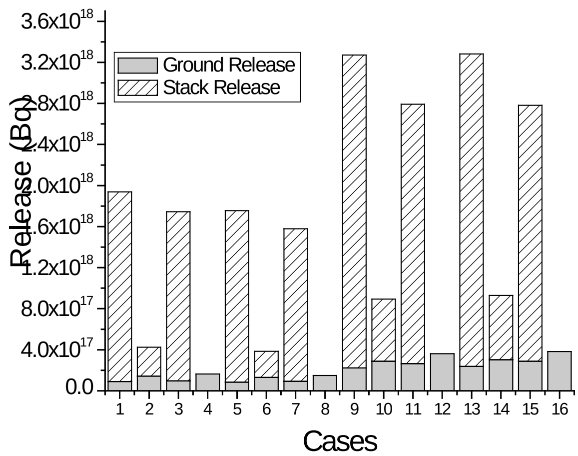

Figure 19. Total activity (summation of Cs, I, Kr & Xe) released out of containment by way of ground and stack for various cases.

Fig. 18 shows the total activity (summation of Cs, I, Kr & Xe) released out of containment by way of ground release alone (i.e. leakage) and fig. 19 shows the total activity released out of containment by way of ground and stack for various cases. From these two barcharts it can be observed that the cases from 9 to 16 (when coolers are not in operation) gives more release to environment through ground and stack as well. Among the cases from 1 to 8, the case 4 and 8 have low total release (refer fig. 19). In these two cases PCCD and

SCFRP are not in operation hence the total release is contributed mainly by ground release. But from the fig.18, it can be observed that in case 4 and 8, the ground release is higher among the cases from 1 to 8. Generally ground releases are crucial because the release is taking place at lower elevation and near the plant and it can give more dose, so it has to be averted to the extent possible. In case of stack release, the activity is released at higher elevation so it gets dispersed to maximum area. The ground release is governed by pressure difference but the stack release is by operation of PCCD and SCFRP systems and it can be interfered manually. In this context, we can observe that the case-5, except PCFPB all other ESFs are in operation, has lowest ground release and case-1, all ESFs are in operation, has somewhat higher ground release than case-5. In AHWR, V1 volume is surrounded by V2 volume (refer fig.1) and PCFPB pumps the V1 atmosphere to V2 volume through filters for removing Caesium and Iodine. But noble gases are not filtered out by PCFPB filters and the concentration of noble gases in volume V2 is higher and this contributes somewhat higher ground release for case-1 compared to case-5. But operation of PCFPB is necessary for removing Caesium and Iodine. Therefore, the operation of coolers are essential in bringing down the activity release by means of leakage.

Ground release is of the order of 0.1% (of activity released into the containment from reactor core) when all the ESFs are under operation i.e. for case-1. For case-16, no ESFs are under operation, the ground release raises to 0.5%. Stack level release is due to the operation of PCCD and SCFRP system. Stack level release of noble gases are of the order of 4% but the percentage of Caesium and Iodine release through stack is less because of provision of filters in PCCD and SCFRP systems. There is no stack level release when PCCD and SCFRP systems are not under operation but it increases the ground level releases.

7 CONCLUSION

Effect of ESFs on flows and leakages between compartments of AHWR containment have been carried out for a postulated LOCA case. Operation of coolers reduces the containment peak pressure significantly and also reduces time integrated containment pressure and thereby reduces the ground level release to the environment by way of leakage. PCFPB removes the airborne radioactivity such as Iodine and Caesium present in the containment atmosphere and thus reduces the stack level and ground level radioactivity release contributed by Caesium and Iodine. Therefore, for containing the radioactivity within the containment, the operation of containment coolers and PCFPB are essential. However, if the coolers cannot able to reduce the containment pressure below 104.7kPa then operation of PCCD is required based on meteorological conditions. From this analysis, it can be observed that the operation of containment coolers reduce the activity release to a great extent and other ESFs operation are also necessary to minimise the activity release to environment. Since the analysis aims at the impact of ESFs on flows and leakages in AHWR containment, it does not consider the chemistry between the fission products and retention by way of agglomeration, deposition etc. Therefore the obtained release values are conservative estimate.

Symbols

A	Heat transfer area (m^2)
H	Total enthalpy (J)
h	Heat transfer co-efficient (W/m^2-K)
$\bar{h}$	specific enthalpy (J/kg)
m	Mass (kg)
$\dot{m}$	Mass flow rate or condensation rate (kg/sec)
P	Pressure (Pa)
Q	Heat transfer (W)
$\bar{Q}$	Volumetric flow rate (m^3/sec)
t	Time (s)

Subscripts

cond	condensation
cont	containment
cool	cooler
cw	cooling water
fg	latent
I	Iodine
i	compartment /volume number
in	incoming
out	outgoing
sat	saturation

T	Temperature (K)	*stm*	steam
V	Volume (m^3)	*tub*	tube
	Decay constant	*wall*	Wall

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