A Containment Analysis for SBLOCA without ECI in the Refurbished Wolsong-1 Nuclear Power Plant

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Abstract

A small break leading to loss of coolant accident (SBLOCA), being one of the topic accidents in the nuclear plant diagnosis in recent years, has been analyzed and evaluated for the refurbished Wolsong-1 Nuclear Power Plant (NPP). The industry standard toolset (IST) codes developed by CANDU Owners Group and updated models including design change parameters are applied to the event analyses. GOTHIC code [1] has been used for the containment analysis of Wolsong-1. Also, SMART-IST code [2] fitted in the Iodine Chemistry (IMOD-2) model has been used to predict nuclide behavior within the containment considering various aspects. IMOD-2 was incorporated into SMART-IST as a module dealing the chemical transformations and mass transfer of iodine species in containment. IMOD-2 model is very sensitive to paint and chemicals. The parameter studies for IMOD-2 model are performed to decide the analysis value set. The developed methodology and the results of SBLOCA without ECI are presented herein. Under the most heat-up conditions, the radionuclide release from the failed fuel into the containment and subsequently to the environment is such that the radioactive doses to the public are below the acceptable limits.

1. Introduction

Wolsong-1 NPP (W-1) has been under the long period of maintenance shutdown since the late 2009, and will be restarted in the late 2010. The major activities would be the replacement of all 380 fuel channels, calandria tube assemblies and the connecting feeder pipes. As a part of its refurbishment project, a full-scope safety analysis is jointly performed by Korean engineering companies. The Korean team is trying to apply IST codes, some design changes and some of Canadian Nuclear Safety Commission (CNSC) General Action Items (GAIs) to the refurbished Wolsong-1 NPP.

The main changes in containment analysis are the use of GOTHIC (Generation Of Thermal-hydraulic Information for Containments) and SMART-IST (Simple Model for Aerosol Removal and Transport – Industry Standard Toolset) codes for thermal-hydraulic behavior and nuclide behavior within the containment, respectively. The GOTHIC code is a general-purpose thermal-hydraulic code used to model multi-component and multi-phase flow systems. This code is suitable for safety analysis of nuclear power plant containment and other confinement buildings. The SMART-IST computer code models radionuclide in CANDU reactor containments during postulated accidents. SMART-IST models radioiodine in more detail than other nuclides using the IMOD-2 model developed at AECL. IMOD-2 model is very sensitive to paint and chemicals inside the containment. The sensitivity studies of some parameters for IMOD-2 model have been accomplished. In this paper, the containment analysis results of SBLOCA without Emergency Coolant Injection (ECI) event are explained. Also, the dose results from this event are presented and compared with the results of Wolsong-2, 3 & 4 NPP described in the Final Safety Analysis Reports (FSAR) issued in 1996.

2. Analysis methodology

2.1 Analysis method

The analysis process for SBLOCA without ECI event is shown in Figure 1. The thermal-hydraulic response of heat transport system has been analysed by the computer code CATHENA. The coolant discharge rate and enthalpy obtained from CATHENA are used as input data for the containment analysis by GOTHIC with the hydrogen release rate. The results of fuel analysis by ELESTRES are also used as input for the radionuclide release and distribution analysis in containment by SMART. The thermal-hydraulic information from GOTHIC and the radionuclide release amounts from SMART have been provided as input data for the ADDAM code to evaluate the public dose.

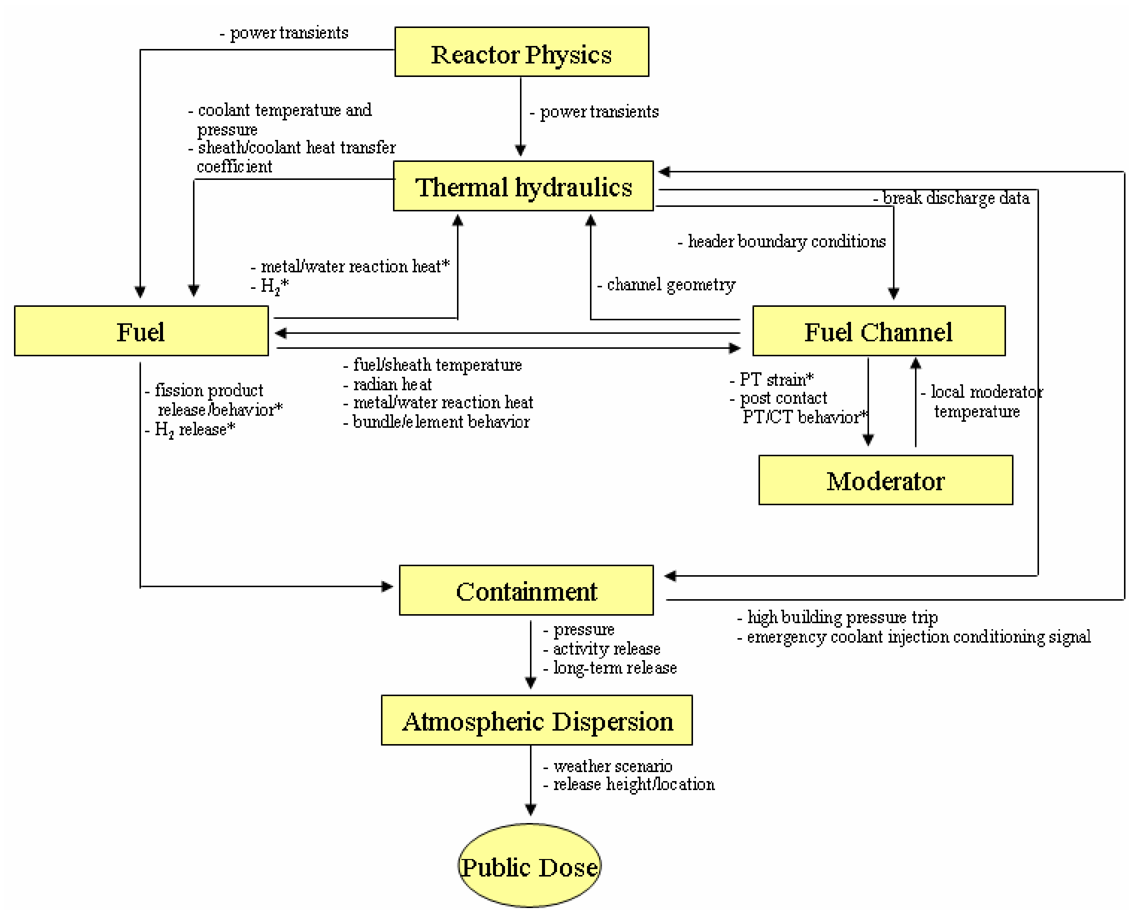


Figure 1 SBLOCA analysis process.

2.2 Analysis case

SBLOCA without ECI event is a relatively low frequency event occurring in nuclear plant. For all small LOCA cases, this event case gives the highest radionuclide release to the containment. Thus, 2.5% Reactor Inlet Header (RIH) break without ECI case is selected as the most limiting case in SBLOCA. The mass and energy discharge rates are depicted in Figures 2 and 3. Table 1 shows the total inventories and releases of 30 isotopes by ELESTRES from the broken loop.

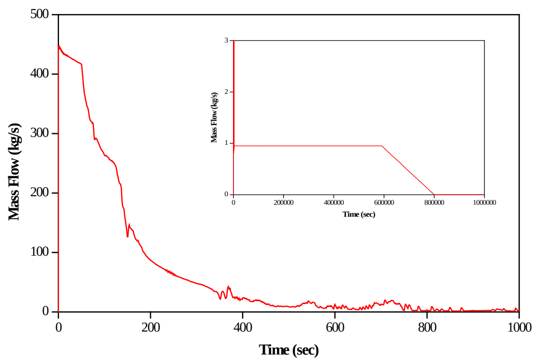


Figure 2 Mass discharge.

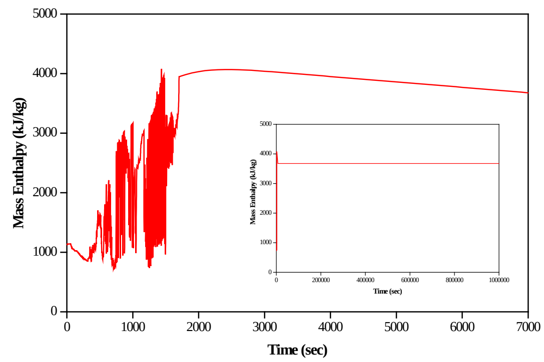


Figure 3 Enthalpy discharge.

Table 1 Total inventories and releases of 30 isotopes from the broken loop.

Isotope	Total inventory (TBq)	Free inventory (TBq)	Inventory released (TBq) (%)
CS-137	2.05E+04	8.69E+01	4.55E+02(1.80)*
CS-138	2.39E+06	6.70E+02	7.03E+04(2.91)
I-131	1.04E+06	9.05E+03	3.89E+04(2.89)
I-132	1.59E+06	1.86E+04	6.38E+04(2.88)
I-133	2.49E+06	7.70E+03	7.96E+04(2.90)
I-134	2.78E+06	1.84E+03	8.26E+04(2.91)
I-135	2.33E+06	4.16E+03	7.18E+04(2.90)
I-137	1.23E+06	7.24E+01	3.59E+04(2.91)
KR-83M	1.92E+05	7.08E+01	5.66E+03(2.91)
KR-85M	4.70E+05	2.69E+02	1.39E+04(2.91)
KR-85	2.45E+03	7.18E+00	5.16E+01(1.82)
KR-87	9.14E+05	2.79E+02	2.68E+04(2.91)
KR-88	1.29E+06	5.86E+02	3.81E+04(2.91)
KR-89	1.68E+06	1.05E+02	4.89E+04(2.91)
SR-89	1.05E+06	7.70E+03	7.70E+03(0.00)
SR-90	3.85E+04	1.29E+02	1.29E+02(0.00)
RU-103	1.37E+06	1.10E+04	1.10E+04(0.00)
RU-106	2.03E+04	6.27E+01	6.26E+01(0.00)
TE-131M	1.33E+05	9.49E+02	4.77E+03(2.89)
TE-131	9.44E+05	8.84E+02	2.83E+04(2.91)
TE-132	1.58E+06	1.69E+04	6.21E+04(2.88)
TE-133M	1.08E+06	1.49E+03	3.27E+04(2.90)
TE-133	1.44E+06	9.60E+02	4.29E+04(2.91)
TE-135	1.25E+06	1.34E+02	3.65E+04(2.91)
XE-133M	7.04E+04	1.36E+02	2.17E+03(2.90)
XE-133	2.30E+06	1.38E+04	7.99E+04(2.89)
XE-135M	4.00E+05	5.44E+01	1.17E+04(2.91)
XE-135	2.66E+05	6.89E+02	8.39E+03(2.90)
XE-137	2.26E+06	1.55E+02	6.61E+04(2.91)
XE-138	2.28E+06	3.02E+02	6.67E+04(2.91)

* The values in parenthesis are the percentage of bound inventory released.

2.3 Containment analysis model

2.3.1 Computer code

The containment thermal-hydraulic response has been simulated using the GOTHIC-IST Version_7.2a computer code. The GOTHIC-IST code simulates the thermal-hydraulic behavior of a CANDU containment resulting from design basis accidents and severe accident sequences. GOTHIC provides detailed thermal-hydraulic information for the analysis of radionuclide behavior, as well as information regarding pressures and temperatures in various containment areas.

2.3.2 Containment model

A lumped model composed of 13 nodes and 40 links for the containment and 2 nodes/9 links to represent the inlet and outlet lines of the ventilation system and the D_2O vapour recovery system purge lines as shown in Figure 4 is used.

The GOTHIC code includes sub-models for the dousing process, local air coolers, heat transfer to walls, instrument air flow, additional heat loads, containment isolation, blowout panels and break discharge flashing. The major assumptions are summarized in Table 2.

Table 2 Summary of containment assumptions.

System	Analysis Objectives (Radionuclide Release)
Containment Envelope	Intact
Containment Leakage	5.0% building volume per day at 124 kPa(g)
Mass and Surface Areas of Walls and Internal Structures	Lower estimate
Local Air Coolers and Fans on Class IV and Class III Power	8
Local Air Coolers and Fans on Class IV Power Only	0
Blowout Panels	Intact
Blowout Doors	Not modelled
Additional Heat Sources	Modelled
Containment Isolation	Activity signal
Dousing System	4 out of 6 headers
Instrument Air	Modelled
Initial Containment Pressure	0 kPa(g)

2.3.3 Break discharge model

The fluid from a pipe break is assumed to discharge into one of the fuelling machine rooms. Homogeneous equilibrium conditions between the discharging fluid and the accident node atmosphere are assumed. GOTHIC includes a drop break-up model that generates drops from the liquid flow from flashing of superheated water and due to hydrodynamic forces on the water. The advantage of using the drop break-up model is that the drop formation will automatically cease as the water temperature becomes sub-cooled.

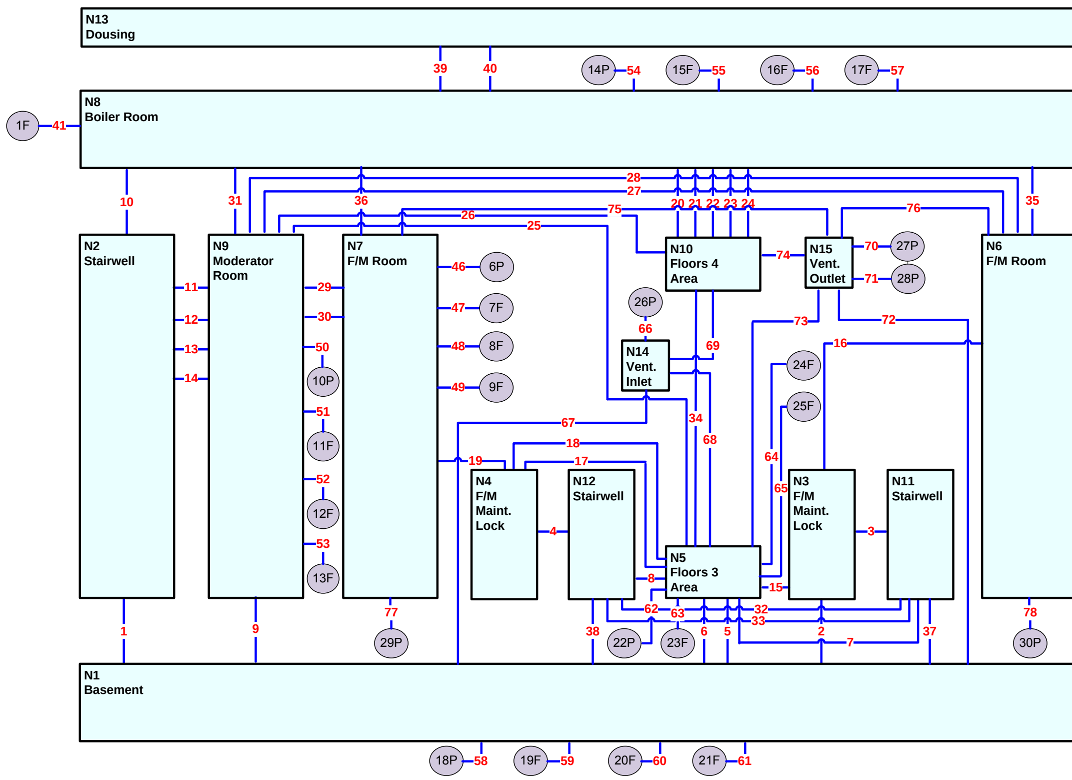


Figure 4 GOTHIC model for containment.

2.4 SMART model

The SMART-IST code is designed to predict nuclide behavior within containment considering various aspects such as releases of nuclides from the primary heat transport system, transport of nuclides among various rooms in the containment, removal of nuclides from the containment atmosphere through various removal mechanisms, changes in nuclides resulting from radioactive decay and build-up, and releases of nuclides to the outside atmosphere through containment escape paths. SMART-IST models radioiodine in more detail than other nuclides using the IMOD-2 model developed at AECL [3]. IMOD-2 has been incorporated into the overall mathematical framework of SMART-IST as a module modelling the chemical transformations between various iodine species and mass transfer of these species among gas, aqueous and adsorbed phases in the containment. IMOD-2 model is sensitive for paint and chemicals.

SMART-IST models transport of two forms of nuclides: a) contained in and carried by aerosols, and b) existing in the gaseous form. The following assumptions are made regarding aerosol and nuclide transport in containment:

- The transient thermal-hydraulic properties from GOTHIC are used as input data for calculation nuclides and aerosol transport.
- Gaseous nuclides and aerosols in a room are perfectly mixed, with uniform nodal properties.
- Nuclide and aerosol processes within a room do not contribute to mass, momentum or energy exchange with the gas present in the room.
- Airborne gaseous nuclides and aerosols are transported from one room to another by convection of the carrier gas through links.
- Gaseous nuclides and aerosols are transported from the free volume of a room to the external atmosphere by convection of the carrier gas through specified holes.
- Volumetric source or sink rates of nuclides and aerosols in a room are spatially uniform.

Also, SMART-IST uses a number of aerosol sub-models. The following are a brief description of these models.

2.4.1 Liquid aerosol agglomeration and gravitational settling

Agglomeration mechanism is physical process that results in the collision and adhesion of aerosol particles to form larger particles. Aerosol particles settle onto available horizontal areas due to the force exerted on them by gravity.

2.4.2 Impingement and Stefan flow

Experiments were conducted in the WALE (Wet Aerosol Leakage Experiment) facility, to study aerosol removal in a vessel, into which water jets were discharged under conditions typical to those of loss of coolant accident discharges [4]. SMART-IST uses an empirical model supported by experimental data for calculation of fractional removal of the jet aerosol mass. Near surfaces where condensation occurs, an aerodynamic flow may occur toward the surface. This flow is called Stefan flow.

2.4.3 Turbulent deposition and thermophoresis

SMART-IST calculates turbulent deposition using a combination of the Liu-Agarwal model [5] for turbulent-inertial deposition, and the Davies model for turbulent-diffusion deposition [6]. When a temperature gradient occurs in a gas (e.g., due to heat transfer to a surface), the aerosol particles suspended in the gas experience a force in the direction of decreasing temperature [7]. The motion of the aerosol particle that results from this force is called thermophoresis.

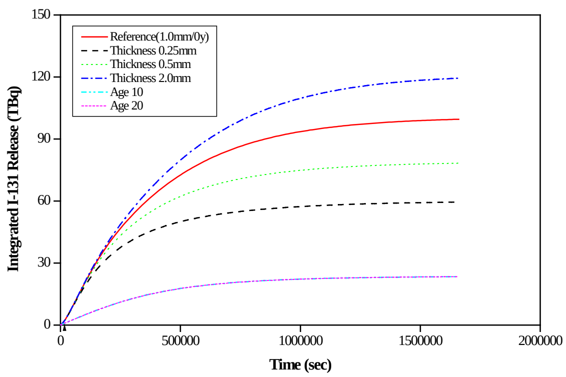
2.4.4 Containment iodine chemistry model (IMOD-2)

SMART-IST uses a containment iodine chemistry model, IMOD-2. This model has been developed by Wren, et al. [3]. The main processes modelled in IMOD-2 are the chemical transformations between non-volatile iodine species and volatile iodine species in the aqueous phase, and the partitioning of volatile iodine species among the gas, aqueous and adsorbed phases. For the purpose of implementing IMOD-2 in SMART-IST, it is assumed that the aqueous phase in each node consists of two parts: The first part is the bulk liquid pool on the floor formed by the removal of liquid aerosols from the free volume; the second part is the airborne liquid aerosols in the node. The concentration of an iodine isotope in liquid aerosols and in the gaseous state of a node may change depending on the result of the IMOD-2 calculations

3. Analysis results and discussion

3.1 Sensitivity study

Since IMOD-2 model of SMART is sensitive to containment building paint and chemicals, the selected parameters which can affect the aerosol behavior and used in code are paint thickness, paint age, dousing water pH, primary heat transport (PHT) coolant pH and pool pH. For sensitivity study, 2.5% RIH break without ECI and I-131 nuclide which is considered as a reference nuclide in aerosol behavior are selected. In Figures 5 and 6, the reference case has 1.0 mm paint thickness, paint age of 0.0 year, dousing and PHT water pH of 9.0 and pool water pH of 7.0.



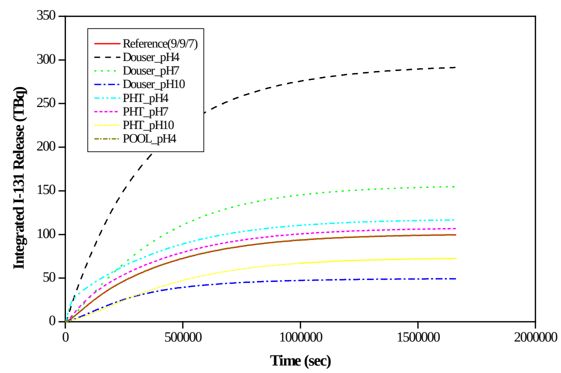


Figure 5 Comparisons of I-131 release for paint. Figure 6 Comparisons of I-131 release for pH

The sensitivity study shows that paint thickness and dousing water pH are very sensitive in creating organic iodine. I-131 release amount increases as the thickness of the building paint increases. Figure 6 shows that dousing water pH is more sensitive than PHT and pool pH in iodine creation. Table 3 shows the comparison of I-131 release amounts through leakage after SBLOCA. Based on design data, analysis values are selected (marked value) for Wolsong-1 refurbishment. This analysis set has been applied to SBLOCA analysis.

Table 3 Comparison of I-131 release amounts.

	Analysis value/I-131 Release (TBq)			
Paint thickness (mm)	0.25/59.5	0.5*/78.3	1.0/99.5	2.0/119.4
Paint age (yr)	0/99.5	0.2*/57.6	1.0/24.2	10/23.3
Dousing pH	4/291.4	7/154.8	9*/99.5	10/49.3
PHT pH	4/116.7	7/106.7	9*/99.5	10/72.6
Pool pH	4/99.80	7*/99.5	10/98.8	-

* Marked values are analysis values for Wolsong-1

3.2 Results of containment assessment

Table 4 gives the containment event sequence for radionuclide release analysis. Figure 7 shows the containment pressure transients. Containment isolation on pressure occurs at 8 seconds which includes 3 seconds to close the isolation dampers on receipt of the isolation signal. Dousing from 6 headers has been initiated when the containment pressure exceeds 8.8 kPa(g). The peak pressure is 19.8 kPa(g) which occurs in the accident node at 50 seconds. The dousing starts at 38 seconds and stops at 300 seconds. After the dousing stops, the containment pressure increases again, making the second peak of 7.3 kPa(g) at 17000 seconds (4.72 hrs). Thereafter, the containment pressure decreases gradually due to the effect of local air coolers and building leakage. After the termination of instrument air ingress at 16840 seconds (4.68 hrs) the containment pressure decreases at a faster rate, reaching atmospheric in about 9.8 days. Figure 8 show the containment temperature transients. The peak temperature is 94℃ which occurs in the accident fuelling machine room at 46 seconds.

Table 4 Containment event sequence for a 2.5% RIH break without ECI.

Sequence of Event	Time
Break occurs at reactor outlet header in the fuelling machine room (R1-107)	0 second
Containment isolation on high pressure	8 seconds
Start of dousing	38 seconds
Peak pressure and reaching time	19.8 kPa(g) at 50 sec
Stop of dousing	300 seconds
Radionuclide release to the accident fuelling machine room	523 seconds
Ingress of normal instrument air terminates	16840 seconds (4.68 hours)
Pressure in the steam generator room reaches atmospheric and containment analysis ends	8.48E05 seconds (9.8 days)

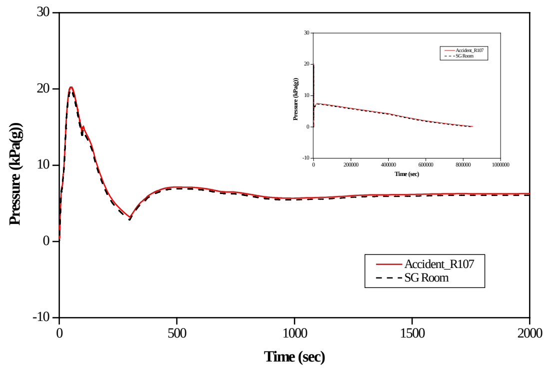


Figure 7 Pressure transient.

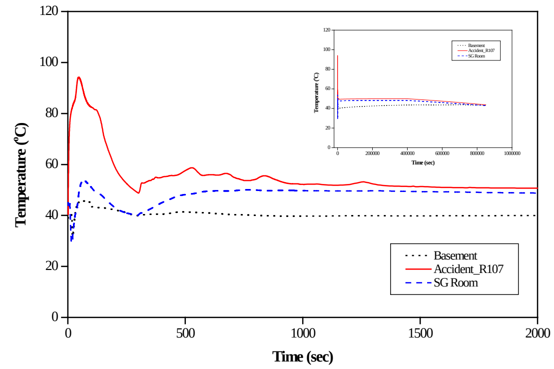


Figure 8 Temperature transient.

The amounts of I-131 and Xe-133 in the containment rooms after break are shown in Figures 9 and 10, respectively. Figures 11 and 12 show the releases of I-131 and Xe-133 from containment to the environment, respectively. The total amounts of I-131 and Xe-133 released to the environment are 38 TBq and 10345 TBq respectively. For a 2.5% RIH break with LOECI, the detailed release predictions for all fission products from containment are given in Table 5. Usually, iodine nuclides have an effect on the thyroid dose, whereas noble gases on the whole body dose

Table 5 Radioactivity releases (TBq) via various release paths for a 2.5% RIH break without ECI.

Nuclide Name	Stack	Inlet	Leakage
H-3	1.2130255E-03	7.2668216E-21	2.9995550E+01
I-131	0.0000000E+00	0.0000000E+00	3.7728330E+01
I-132	0.0000000E+00	0.0000000E+00	4.7397066E+01
I-133	0.0000000E+00	0.0000000E+00	5.0698491E+01
I-134	0.0000000E+00	0.0000000E+00	1.3627974E+01
I-135	0.0000000E+00	0.0000000E+00	3.2381986E+01
Kr-87	0.0000000E+00	0.0000000E+00	4.3518929E+01
Kr-88	0.0000000E+00	0.0000000E+00	1.6260841E+02
Kr-89	0.0000000E+00	0.0000000E+00	2.0131548E-02
Xe-133M	0.0000000E+00	0.0000000E+00	2.1011338E+02
Xe-133	0.0000000E+00	0.0000000E+00	1.0314347E+04
Xe-135M	0.0000000E+00	0.0000000E+00	1.3112455E+02
Xe-135	0.0000000E+00	0.0000000E+00	9.2364828E+02
Xe-137	0.0000000E+00	0.0000000E+00	8.0255638E-02
Xe-138	0.0000000E+00	0.0000000E+00	6.5204878E+00
MIXTURE-I	6.7256578E-06	4.0306934E-23	8.9913151E-03
MIXTU-N.G	1.9838654E-04	1.1964139E-21	6.3655676E+00

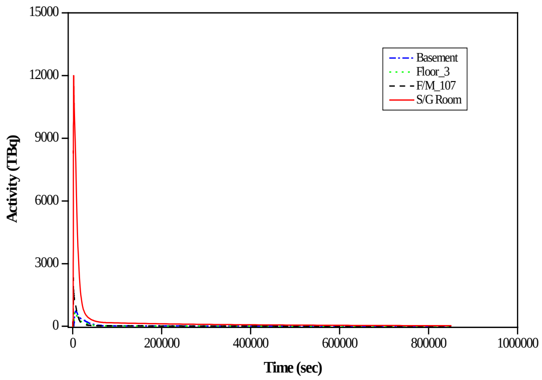


Figure 9 I-131 amounts in containment rooms.

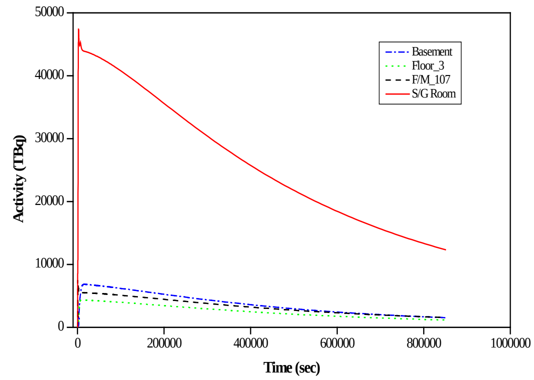


Figure 10 Xe-133 amounts in containment rooms.

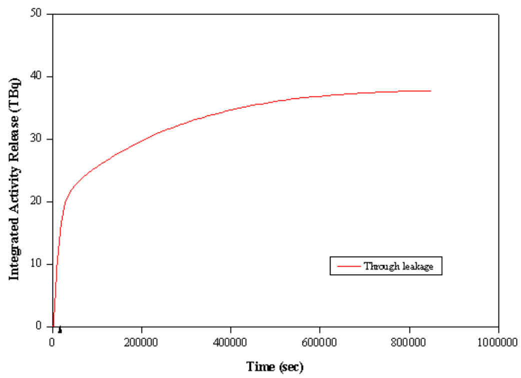


Figure 11 Integral I-131 release.

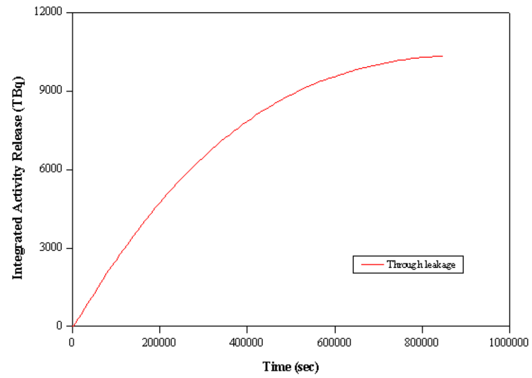


Figure 12 Integral Xe-133 release.

Table 6 shows the comparison of public dose between W-1 and W-2, 3&4. The dose limits for dual failure are used as acceptance criteria for this analysis, as listed in Table 6.

Table 6 Comparison of public doses for 2.5% RIH break without ECI.

Release Source	Individual Doses*	
	Whole Body (mSv)	Thyroid (mSv)
W 2,3&4 FSAR	5.6	26.0
W1-RF	22.9	117.5
Dose Limit	250	2500

* These doses are the values at the 99.5th percentile for W-1 and 90th percentile for W-2, 3&4.

4. Conclusion

The radionuclide releases and dose to the public have been analysed for a case of SBLOCA without ECI which causes the highest radionuclide releases to the containment.

This paper presents the result of parameter study of IMOD-2 model to decide analysis value for Wolsong-1 refurbishment. SMART-IST models radioiodine in more detail than other nuclides using the IMOD-2 model. The radioiodine release has been assessed by using the SMART-IST code for various parameters. IMOD-2 model is very sensitive to paint thickness and dousing water pH. The selected analysis value set has been used to predict nuclide behavior within the containment.

It has also been confirmed that the developed model and the newly introduced computer codes have successfully tested SBLOCA in the refurbished Wolsong-1. Under the most heat-up conditions, the release of radionuclide from the failed fuel into the containment and subsequently to the environment is such that the radioactive doses to the public are far below the acceptable limits.

5. References

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