Source Term Sensitivity Evaluation under SBO Induced Severe Core Damage Using MAAP-ISAAC in Wolsong Unit 2 Plants

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1. Introduction

The main objective of this paper is to evaluate a station blackout (SBO) accident resulting in hypothetical severe core damage using MAAP-ISAAC (Integrated Severe Accident Analysis code for CANDU plants; 'ISAAC' is used from here) 4.03 version [1]. Specifically, fission product (FP) behavior inside the containment is analyzed at Wolsong (WS) Unit 2. These include fission product behavior like (1) the release from fuel, (2) the transport among atmosphere, heat sinks and pool (including a deposition by natural/non-engineering mechanisms and a phase change between the gas and aerosol), and (3) the removal by engineering safety systems such as sprays. This work is done for providing code comparison basis with CAISER code [2]. CAISER (CANDU Advanced Integrated SEveRe) code [3] is an up-to-date PHWR severe accident code developed and being improved at KAERI (Korea Atomic Energy Research Institute) following a demand for an accurate and detailed code in a CANDU society.

This study shows the analysis results for the PHWR SBO scenarios with ISAAC in terms of the severe core damage progression, mainly about the fission product behavior, from an SBO induced severe core damage resulting in the fuel channel failure. According to the WS Level-1 PSA analysis, SBO is the initiating event of a loss of Class IV and Class III power resulting in the plant damage state (PDS) with high occurrence frequency and significant radiological consequence. In the SBO event, the accident hypothetically progresses to severe core damage and disassembly only when any active safety systems are not available. Current study basically uses ISAAC version 4.03 which has used in the development of WS severe accident management guidance. It is constructed in modules covering individual regions in the plant: primary heat transport system (PHTS), steam generator (S/G), calandria vessel (CV), Reactor Vault (RV) and the reactor building (R/B). The code provides an integrated tool for evaluating in-plant effects of postulated accidents, for which a wide spectrum of phenomena including fuel channel (pressure tube (PT), calandria tube (CT)) failure, R/B temperature/pressure change and FP behavior.

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(1) MAAP[4] is an Electric Power Institute (EPRI) software program that performs severe accident analysis for nuclear power plants including assessments of core damage and radiological transport. A valid license to MAAP4 and/or MAAP5 from EPRI is required.

2. SBO Sequence and ISAAC Configuration

In this paper, SBO induced severe core damage is analyzed using ISAAC in an R/B nodalization scheme (as demonstrated in Fig.1) of Wolsong unit 2/3/4 plants which have a typical CANDU6 PHTS configuration [5]. The containment compartments are simply grouped by 12 representative regions with 22 flow junctions between them in which containment failure is assumed at the upper dome (height = 43.28 m) region of R/B [6].

ISAAC Configuration for Reactor Building (R/B)

Node	Compartment
1	Basement
2	Reactor vault
3, 4	Fueling machine room
5	Moderator room
6	Access area
7	Boiler room
8, 13	Upper dome
9	Dousing tank
10	Degasser condenser tank
11, 12	End Shield

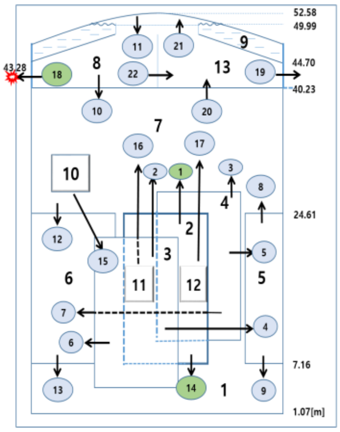

Fig. 1. CANDU6 R/B Nodalization (with R/B rupture failure) Scheme in ISAAC

The reference (SBO-N) and sensitivity (SBO-Y) cases, differentiated by R/B failure (as shown in Table I), are representative high pressure accidents defined as a transient initiated by a loss of off-site AC (Class IV) power, with the subsequent loss of all on-site standby and emergency electric power supplies. If extreme event is assumed when any of the high/medium/low-pressure emergency core cooling system, SG main/ auxiliary feed water systems, moderator cooling system and end-shield cooling system are not available, the accident sequence would progress to a severe core damage accident. In the high pressure accident scenario, the primary loops are not automatically isolated from each other.

Table I: Status of Major Safety System or Function in SBO

Cases	Rx Trip	PHTS loop Isolation	MFW or AFW	ECCS	MCS	ESC	R/B Failure	Comments
SBO-N	O	X	X	X	X	X	X	no AC power
SBO-Y	O	X	X	X	X	X	O	

2. ISAAC Fission Product Models

The models related to vapor fission product analysis is like the followings:

- The ISAAC model employs temperature dependent vapor pressure correlations and the ideal gas law to calculate the driving force for a condensation or an evaporation
- Aerosol formation from the supersaturated vapor allows us to calculate the vapor diffusion rate to the walls; if the mass of the vapor is supersaturated in a time step, the excess mass is assumed to form aerosols
- Vapor deposition removal rate is

$$\lambda = D_f \frac{Sh}{h_c}$$

- Diffusion coefficient near the heat sinks is

$$D_f = 4.7 \cdot 10^{-3} \; T_m^{1.5} \,/\, \left[10 \cdot P_{gas}\left(1 + 829 / T_m\right)\right]$$

Where,
Sh = Sherwood number
h_c = Characteristic length of condensation
P_{gas} = Gas pressure, $T_m = 0.5\,(T_g + T_{WALL})$

The ISAAC models for FP transport and distribution is demonstrated in Fig.2.

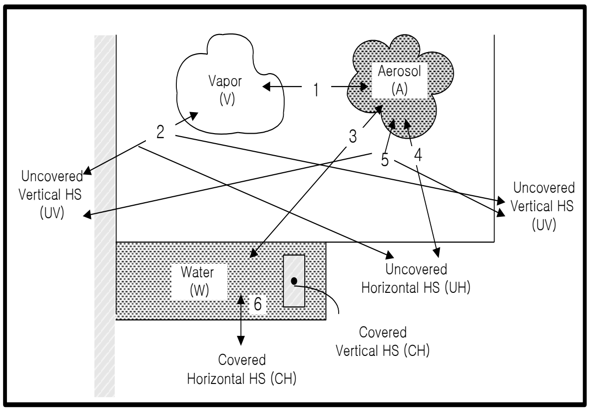

Fig. 2. ISAAC FP Transport Model for Distribution Analysis

The models related to aerosol fission product analysis is like the followings:

1. Gas-Aerosol equilibrium
2. Aerosol deposition on water by diffusiophoresis (= stephan flow)
3. Aerosol deposition on the walls
   - Step1: by thermophoresis
   - Step2: by impaction and gravitational settling (= sedimentation)
4. Plus summations for total deposition
   - Step1: assume steady-state aerosol, no nodalization
   - Step2: replace with decay aerosol, no nodalization
   - Step3: replace with hygroscopic aerosol, no nodalization
   - Step4: replace with nodalization

3. SBO Main Events in ISAAC4.03

SBO main events showing accident progression in ISAAC4.03 is presented in Table II for 2 cases (SBO-Y and SBO-N). In SBO-N case, R/B failure by any means is not assumed because no R/B failure is conservative from a viewpoint of in-containment source term (ST). In SBO-Y case, as a more realistic scenario, R/B failure by steam overpressurization is assumed at 4.26 bar(a) (=426 kPa(a)) about 1 day (~81,000 seconds) after SBO starts in which 0.1 m^2 rupture size of breakage is presumed.

Table II: SBO Main Event Progress in ISAAC4.03

Event Timing (4x4 checker: local balloon)	MAPP-ISAAC [sec]	
	SBO-Y	SBO-N
SBO start	0	
Dousing spray operation	10,494~11,531 (Δt: ~1,000)	
(first) Channel (PT/CT) failure	14,029/21,758(Loop 1/2)	
100% fuel channel relocation	36,569	
Moderator dryout / Corium debris melt	40,054 / 48,313	
RV water saturation /	58,720 /	
RV water dryout	162,057	166,690
R/B rupture failure	**81,025**	**N/A**
CV creep failure	148,559	157,163
RV floor MCCI start	171,307	175,730
RV floor peak ablation rate	224,542	224,736
Zr 100% oxidation	232,822	240,591
RV BMT failure	39,6386	425,736
Calculation end	500,000	

4. R/B PT Analysis

For the estimation of possible ST into the environment via the R/B breakage, the PT (pressure and temperature) analysis inside R/B which predicts the R/B failure is needed.

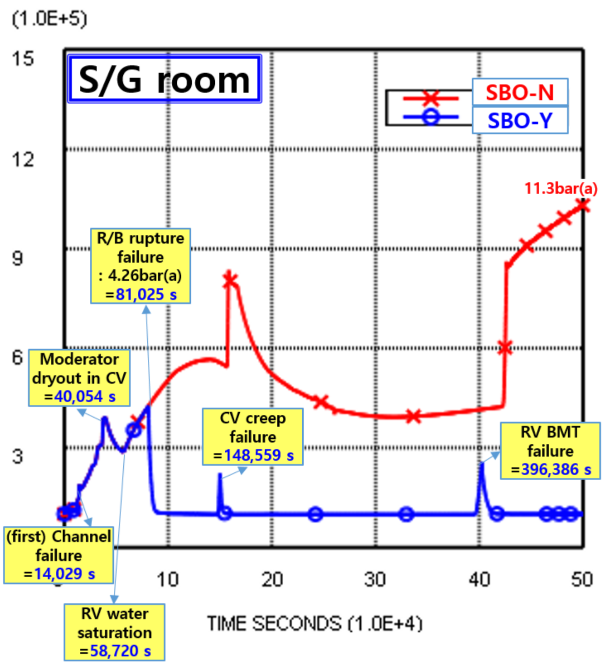

Fig. 3. R/B Pressure Prediction in ISAAC

Fig. 3 shows the pressure behavior of the boiler room (S/G room), which is the largest room (about 20,000 m^3 by free volume) in the R/B, simulated by ISAAC 4.03. At the start of the accident, the pressure in the R/B is atmospheric, and the pressure gradually increases as steam is released into the R/B from PHTS through the valves (= liquid relief valves). On the other hand, the heat removal function of the calandria vessel (CV) has been lost due to the loss of the moderator cooling system. Consequently, the pressure and temperature of the CV increase continuously due to continuous heat transfer from the horizontal fuel channels. At 14,029 seconds, a rupture occurs in the horizontal fuel channel due to creep, causing the high-temperature fuel inside the horizontal fuel channels to be released into the CV. This leads to rapid steam generation, causing the pressure in the CV to rise quickly. When the pressure difference between the CV and R/B reaches 20 psi(d), the burst panel ruptures. The water from the CV is released as steam to the R/B causing the pressure in the R/B to rise quickly (and resulting in the gradual depletion of 217 tons of water in the CV). After the CV water is completely depleted at 40,054 seconds, there is no steam supply source until 58,720 seconds, when the RV water (outside the CV) reaches the saturation temperature and begins to boil (the boiling effect of the cooling water inside the R/B enclosure (End Shield Cooling) is not observed because the amount of cooling water is very small compared to the RV). The steam generated in the RV is introduced into the R/B. The introduced steam further increases the R/B pressure until it reaches 426 kPa(a) at 81,025 seconds, at which point the R/B fails. In contrast to the SBO-N case (red line), R/B pressure drops rapidly to the atmospheric pressure just after R/B rupture failure in SBO-Y case (blue line). Subsequently, when the CV fails at 148,559 seconds, the molten core is relocated to the RV, causing a peak pressure (= first steam spike) at this point. After the cooling water in the RV is depleted, the molten core-concrete interaction (MCCI) starts at the bottom of the RV, and by 396,386 seconds, the bottom of the RV is penetrated. Another peak pressure (= second steam spike) occurs at the point when the molten core is relocated to the basement of the R/B. Fig. 4, which is the temperature behavior of the R/B, shows a similar trend to the pressure behavior.

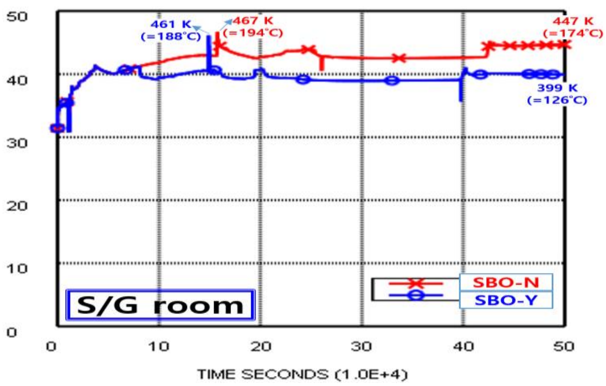

Fig. 4. R/B Temperature Prediction in ISAAC

5. Ex-containment Source Term Evaluation

As ex-containment (= environmental release) source term evaluation for the R/B failure case, fission product behavior is assessed in detail under SBO induced severe core damage. Specifically, the proportions are estimated such as (1) cumulative in-/ex-containment source term of the Cesium(Cs) elements, (2) release fraction size for main FP species (including Cs and I(Iodine)), and (3) comparison with reference standards such as domestic ST (= Accident Management Program (AMP) Cs reference ST [7] in Korea). Fig. 5 shows in-containment and ex-containment ST evaluation for Cs as a representative species while Fig. 6 shows the ex-containment ST for 12 FP groups in ISAAC. According to these, the following three findings are highlighted:

1. In intact R/B scenario (SBO-N), the tiny radiation leakage is calculated from the R/B (= containment) design leakage which is a background/basis leakage (= 0.01% (3.6g) of Cs initial inventory until 500,000 seconds). This is approximately 2% compared to the case of R/B rupture failure (SBO-Y).
2. In failed R/B scenario (SBO-Y), when R/B failure occurs at approximately 81,000 seconds (~1 day), in-core FPs released to the R/B atmosphere (almost of aerosol form [8]) are mostly deposited. Nevertheless both the suspended aerosols (left in the atmosphere (=0.144%)) and the resuspended aerosols (which are agitated from the deposited by pressure difference) have chances to become ex-containment ST. At approximately 200,000 seconds (~2.3 days when CV already failed and MCCI has started), the cumulative ex-containment ST becomes saturated at 0.537% (= 165g) for Cs elements. This is about 5 times (using 93.5% conversion factor of Cs into Cs-137) higher than the domestic AMP standard (= 100 TBq of Cs-137).
3. The release fraction order among 12 FP groups (including Cs and I) in ISAAC code is as follows.
    - noble>CsOH/CsI>Sb>TeO_2>Te_2>MoO_2>SrO >BaO>CeO_2>La_2O_3>UO_2

6. Results

The PHWR SBO induced severe accident progress for ex-containment source term was simulated and analyzed using the ISAAC code. The ISAAC analysis results of this study (unlike previous studies) provide both very precise results for fission product behavior in the reactor building with or without containment failure, and detailed and specific sensitivity results at the required level from CAISER verification.

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REFERENCES

[1] KAERI (Korea Atomic Energy Research Institute), ISAAC Computer Code User's Manual, KAERI/TR-3645/2008 (2008).

[2] J.Y. Kang et. al., Preliminary Analysis about SBO-induced Severe Accident at CANDU-6 Using M-CAISER Code, Transactions of the Korean Nuclear Society spring Meeting, JeJu, Korea, July 9-10 (2020).

[3] Jun Ho Bae, Jun Young Kang, Sang Ho Kim, Yong Mann Song, Ki Hyun Kim, Dong Gun Son, Jong Yeob Jeong, Numerical simulation of CS28-1 experiment by using CANDU severe accident analysis code, CAISER, Annals of Nuclear Energy, September (2020).

[4] Modular Accident Analysis Program (MAAP) for CANDU Reactors, ANS (1992).

[5] Y.M. Song et. al., Detailed Core Response Evaluation of SBO Induced Severe Core Damage Using ISAAC for M-CAISER Comparison Basis in Wolsong Plants, Transactions of the Korean Nuclear Society Virtual Autumn Meeting, December 17-18 (2020).

[6] KHNP, ISAAC Modeling for PSA-based Severe Accidents (Wolsong NPP), 59RF-03500-AR-068, Revision 2 (2011).

[7] Nuclear Safety and Security Commission, NUCLEAR SAFETY ACT (2022. 6. 10).

[8] Y.M. Song et. al., In-Containment Source Term Evaluation under SBO Induced Severe Core Damage Using MAAP-ISAAC in Wolsong Unit 2 Plants, Transactions of the Korean Nuclear Society spring Meeting, JeJu, Korea, May 22-23 (2025).

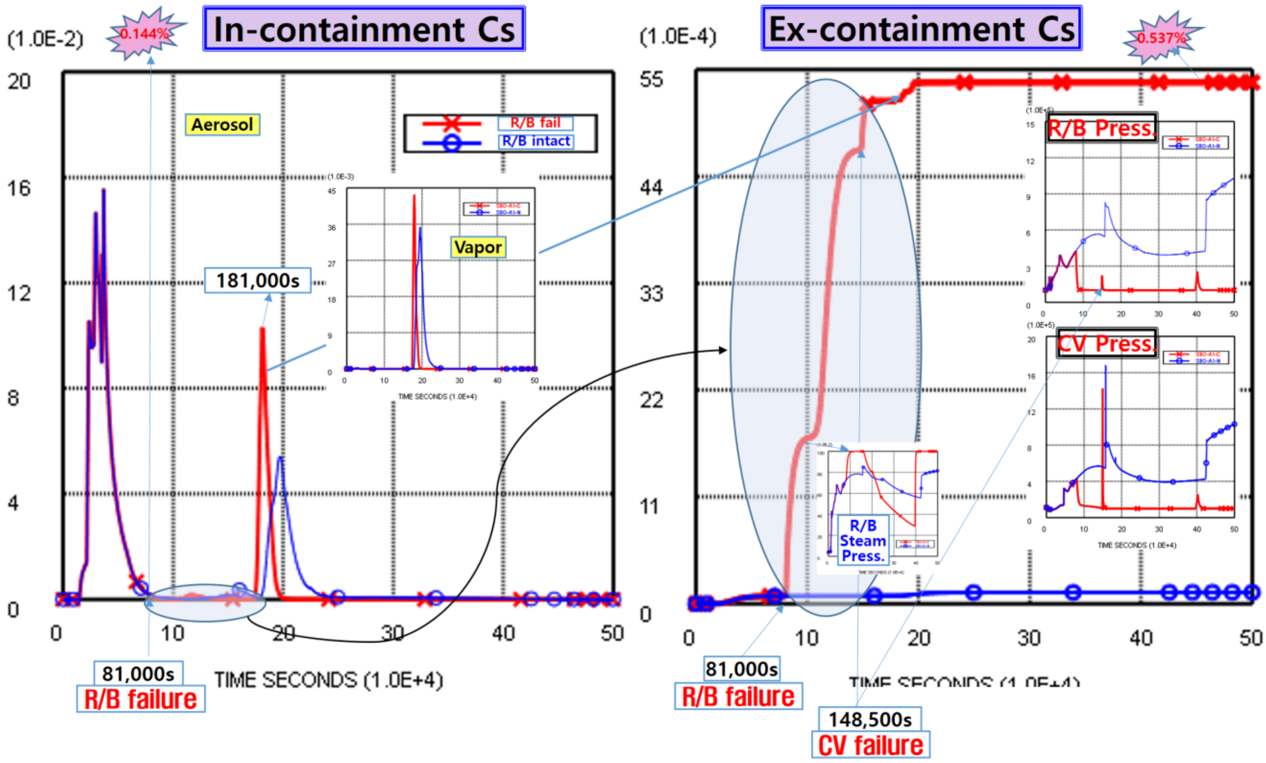

Fig. 5. In-Containment and Out-Containment Source Term Evaluation for Cs Using ISAAC

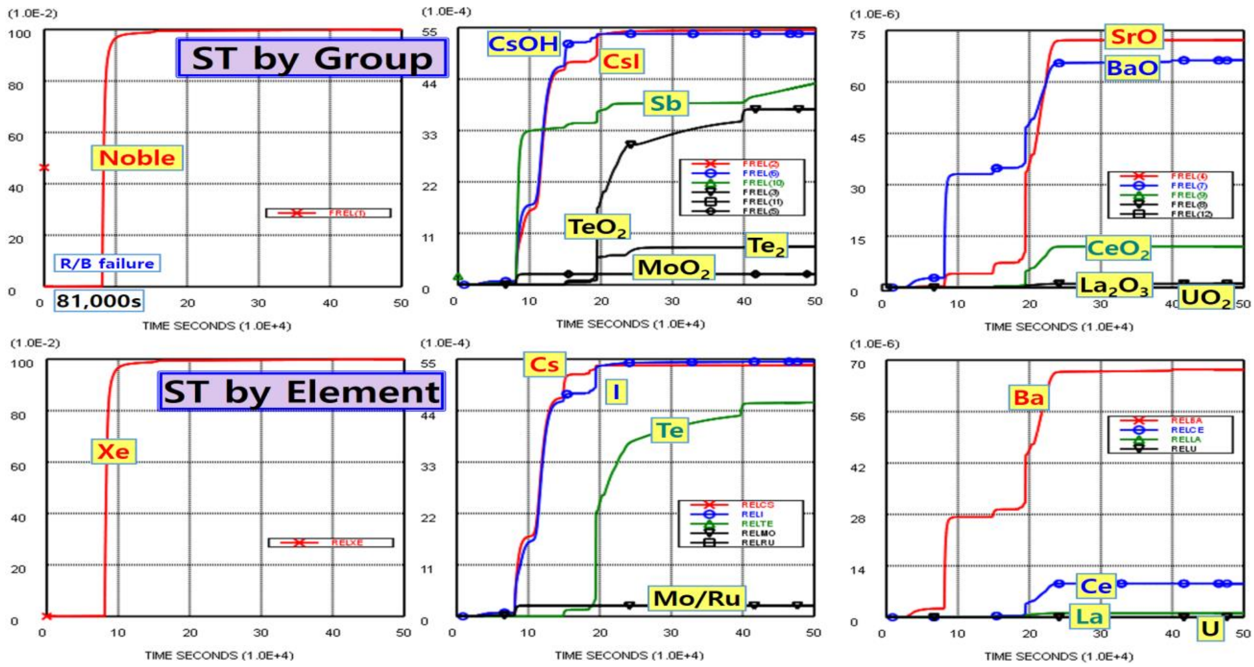

Fig. 6. Source Term Evaluation for Major Fission Products Using ISAAC