Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

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

Y.M. Song*, J.Y. Kang, J.H. Bae, D.G. Son
Korea Atomic Energy Research Institute, Intelligent Accident Mitigation Research Division
989-111, Daedeok-daero, Daejeon, Korea
**Corresponding author: ymsong@kaeri.re.kr*

***Keywords:** In-Containment Source Term, MAAP-ISAAC, Wolsong Unit 2, SBO induced severe core damage

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][2]. 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 [3] with CAISER code. CAISER (CANDU Advanced Integrated SEveRe) code [4][5] 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, steam generator, 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 fission product behavior.

----

(1) MAAP[6] 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 a core nodalization scheme (as demonstrated in Fig.1) of Wolsong unit 2/3/4 plants which have a typical CANDU6 PHTS configuration. The 380 fuel channels in 2 closed loops are simply grouped by 16 (= 4x4) representative channels with checker board style coolant flow patterns [7].

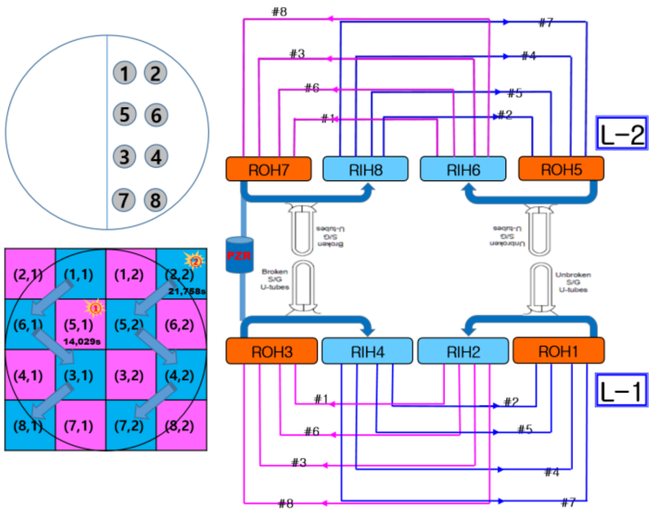

Fig. 1. CANDU6 Core Nodalization (4x4 checker board style) Scheme in ISAAC

The reference case is a representative high pressure accident 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 (as shown in Table I). If extreme event is assumed when any of the high/medium/low-pressure emergency core cooling system, SG main and 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 isolated from each other when the operator manual intervening actions are not assumed.

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

Cases	Rx Trip	PHTS loop Isolation	MFW or AFW	ECCS	MCS	ESC	Comments
SBO-A	O	X	X	X	X	X	no AC power

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.

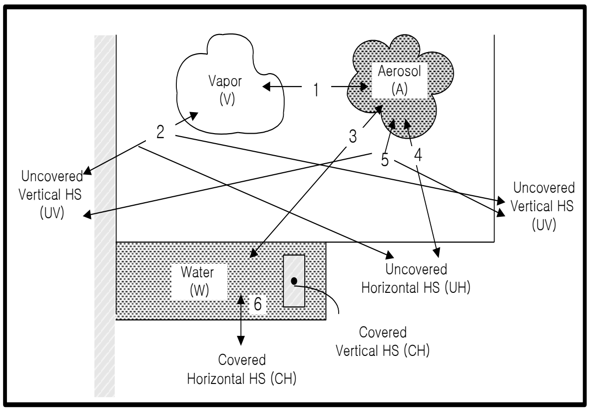

Fig. 2. ISAAC FP Transport Model for Distribution Analysis

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. R/B failure by any means such as steam overpressurization is not predicted in this study because no R/B failure is considered as the conservative case from a viewpoint of in-containment source term.

Table II: SBO Main Event Progress in ISAAC4.03

Event Timing	MAPP-ISAAC [sec] (4x4 checker board flow)
SBO start	0
Dousing spray operation	10,494~11,531 (Δt: ~1,000)
Fuel 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 / RV water dryout	58,720 / 166,690
R/B rupture failure	**N/A**
CV creep failure	157,163
RV floor MCCI start	175,730
RV floor peak ablation rate	224,736
Zr 100% oxidation	240,591
RV BMT failure	425,736
Calculation end	500,000

4. Decay Heat Distribution Analysis

In ISAAC, ANSI/ANS5.1-1979 decay curve using the following Wigner-Way formula is selected for decay heat prediction.

$$Q(t) = 0.0622 P_0 [t^{-0.2} - (t_0 + t)^{-0.2}]$$

Where, Q: decay heat [MW_{th}]
t: time after shutdown [sec]
P_0: reactor thermal power before shutdown (= 2157.5 MW_{th})

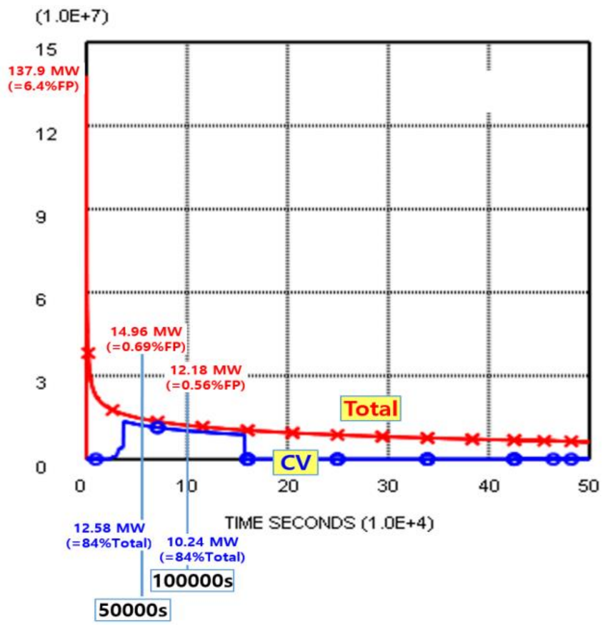

Fig. 3. Decay Heat Prediction in ISAAC

The decay heat calculated in SBO after successful shutdown at time zero is presented in Fig. 3, using the following method.

- Converse from exposure to burn up fraction based on 200 MeV/fission and 238 g/(mole of fuel)
- Calculate fission product activation correction
- Calculate sum of fissile isotope decay fractions

For R/B FP behavior analysis, the distribution analysis for decay heat is helpful to find out the FP locations inside R/B for the whole accident period. Fig. 4 shows the distribution of decay heat [fraction] in the event of a severe accident (SBO). According to this, it can be seen that up to 20% of the total decay heat is held by the released FP (= total radioactive nuclides excluding uranium (U) isotopes) existing outside the corium at atmosphere or as deposited (at pool or wall surface).

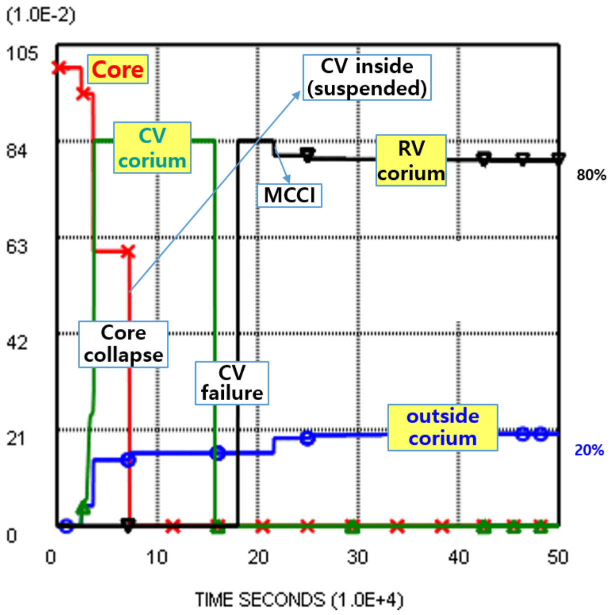

Fig. 4. FP locations inside R/B in SBO using ISAAC

5. In-Containment Source Term Evaluation

As in-containment source term evaluation, fission product behavior is assessed in detail under SBO induced severe core damage. Specifically, the proportions are estimated such as (1) FP distribution between inside and outside the corium, (2) FP amount [in kg mass] remaining in-core or ex-core, and (3) FP concentration outside the corium as deposited (at wall or pool) or at atmosphere (by form of aerosol or vapor). Fig. 5 shows the distributing locations for cesium(Cs) and iodine(I) species as representative FPs. According to these, the following three findings are highlighted:

1. Until the end of the calculation (~500,000 seconds), approximately 20% of the total decay heat is held by released FPs including Cs/I, as mentioned before. The release rate is different by species due to volatility difference. For example, total inventory of Cs is released while ~12% (=0.08kg) inventory of I remains in the ex-core corium after the 500,000 second period.
2. Before the onset of MCCI (Molten Corium-Concrete Interaction) (<~170,000 seconds), about 30% of Cs/I remains in molten pool within the core, while around 70% is released into the primary circuit or containment building. FP released into the R/B during in-core damage are almost of aerosol form, and they settle in mostly during 12 hours (20,000-63,000 seconds) based on a criterion of less than 1% Cs remaining in the atmosphere.
3. After the onset of MCCI (around 170,000 seconds), almost all Cs isotopes from the ex-core corium are released, while around 40% (=0.08kg) of I isotopes remain until the end of the calculation compared to before MCCI. During MCCI (ex-core), Cs isotopes are released by almost the same amount as those during in-core damage while I isotopes are released by 30% more. The released form during MCCI is a mixture of vapor/aerosol (by 1:1) while it is all aerosol during in-core damage. They settle in mostly during 8 hours (185,000-215,000 seconds).

6. Results

The main results of this study are as follows:

- Using the ISAAC code, which has the modeling characteristics based on empirical correlation and fast calculation time, the PHWR SBO induced severe accident progress for in-containment source term was simulated and analyzed.
- The ISAAC analysis results of this study (unlike previous studies) provide both very precise results for fission product behavior in the reactor building, and detailed and specific results at the required level from CAISER verification.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government (Ministry of Trade, Industry, & Energy, Republic of Korea) (No. KETEP- 20224B10300050).

REFERENCES

[1] KAERI (Korea Atomic Energy Research Institute), ISAAC Computer Code User's Manual, KAERI/TR-3645/2008 (2008).
[2] Y.M. Song et. al., Severe Accident Progression and Consequence Assessment Methodology Upgrades in ISAAC for Wolsong CANDU6, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 7-8 (2015).
[3] 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).
[4] 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).

[5] KAERI, CANDU severe accident LOCA scenario analysis using MARS-KS/CAISER coupled code system, KAERI/CM-2867/2020 (2020).

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

[7] 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).

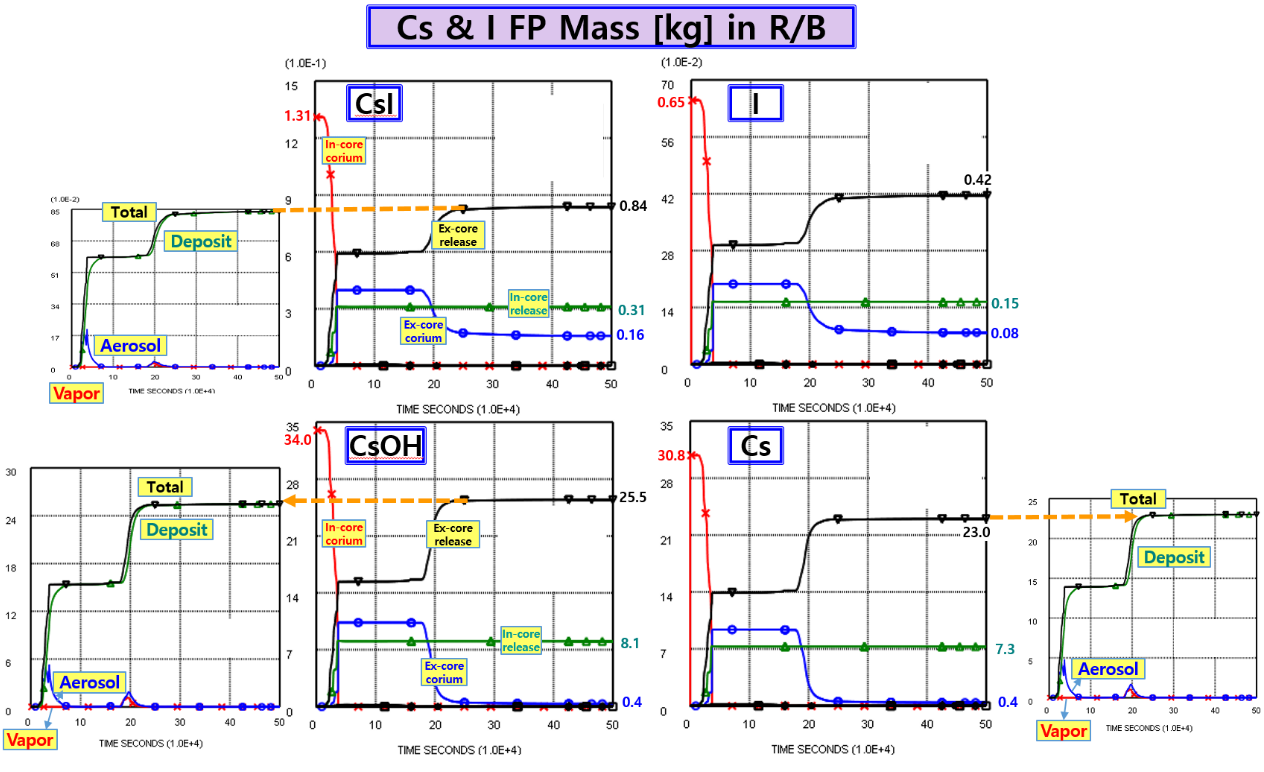

Fig. 5. In-Containment Source Term Evaluation for I/Cs