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Hydrogen Behaviour Evaluation under SBO Induced Severe Core Damage Using 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) 4.03 version [1][2]. Specifically, hydrogen behavior [3] is analyzed at Wolsong Unit 2 that was equipped with PARs (Passive Autocatalytic Recombiners). These include in-/ex-vessel hydrogen generation from metal (such as Zr and Fe) steam oxidation and removal by PARS. This work is done for providing later code comparison basis with CAISER code. CAISER (CANDU Advanced Integrated SEveRe) code [4][5] is an up-to-date PHWR severe accident code being developed at KAERI (Korea Atomic Energy Research Institute) following a demand for an accurate and detailed code in a CANDU society.

Hydrogen mass and concentration in the reactor building (R/B, called containment in PWR) atmosphere is an important parameter to check the integrity of the plant. Hydrogen can be generated from the core (inside the calandria vessel (CV): in-vessel) and outside the core (inside the reactor vault: ex-vessel). In-core materials of zircaloy composing fuel cladding, pressure tubes and calandria tubes are the sources of the in-vessel hydrogen during the severe accidents, and also the suspended debris originating from the disassembled core can generate more in-vessel hydrogen. After CV failure, corium is delivered to the reactor vault (RV) and interact with the bottom (floor) concrete, causing a molten corium-concrete interaction (MCCI). In the process, remaining unoxidized zircaloy in the corium reacts with steam escaping from the concrete, resulting in ex-vessel hydrogen generation. As many steel bars (including some metal components) are embedded in the bottom concrete, these can generate more ex-vessel hydrogen through the metal-steam oxidation process. All these in-/ex-vessel hydrogen generation processes depend on severe accident conditions such as zircaloy oxidation in the suspended debris bed (SDB), corium spreading area and rebar density in the cavity concrete, etc. This paper will show the hydrogen behavior in PHWR SBO for typical conditions which may affect the hydrogen generation from inside and outside the calandria vessel.

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(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 Models

In this paper, SBO induced severe core damage is analyzed using ISAAC in a core nodalization scheme (Fig.1) of Wolsong unit 2/3/4 plants which have a typical CANDU6 PHTS configuration.

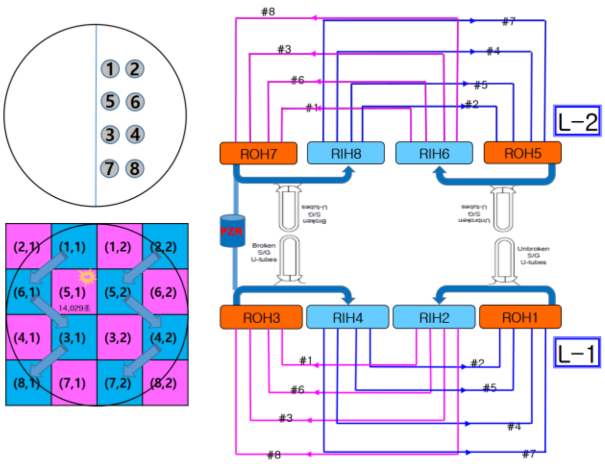

Fig. 1 CANDU6 core nodalization (4x4) scheme in ISAAC

The reference case (SBO-A) 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 (see Table 1). If 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 progresses to a severe core damage accident. The primary loops are not isolated from each other, and the operator intervening actions are assumed unavailable.

Table 1 Status of Major Safety System or Function in SBO-A

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

The assumption mainly related to hydrogen analysis is like the followings:

- Only the passive systems (which do not need power for operation) such as containment dousing spray and PARs are available
- The R/B is assumed intact throughout the calculation to analyze hydrogen accumulating behavior in R/B

- No hydrogen (jet local) auto burn is assumed in R/B (except in cavity (called RV in CANDU) MCCI process) for conservative hydrogen accumulation
- The total RV floor area is used for initial corium spreading after CV failure, and RV floor becomes penetrated when the downward ablation thickness exceeds 90% (= 2m) of the bottom floor thickness
- Once the fuel channel fails, starts to disassemble, and is displaced from the intact geometry, the damaged bundles form suspended debris supported by intact channels underneath them and relocate into the holding bins (called SDB) before relocating finally into the CV floor
- The Rebar (Fe) density (= mass of rebar per unit volume of concrete) in the RV basemat is 600[kg/m^3] which is about 7.7% by mass ratio of the basemat

The ISAAC models a broad spectrum of the following physical processes, in which hydrogen generation is related with the model No. 2/7/8.

1. Fuel/cladding temperature excursions, degradation and interaction with moderator system
2. Zirconium-steam exothermic reaction
3. Thermal mechanical failures of fuel channels
4. Disassembly of fuel channels
5. Formation of suspended debris beds
6. Motion of solid and molten debris
7. Interaction of the core debris with steam
8. Molten corium and concrete interaction (MCCI)

3. Hydrogen Behavior Analysis

During the SBO sequence, hydrogen is generated [7][8] as a result of the following two reactions: (1) Zr-steam reaction in the fuel channels and in the SDB during core debris oxidation, and (2) MCCI in the RV basemat.

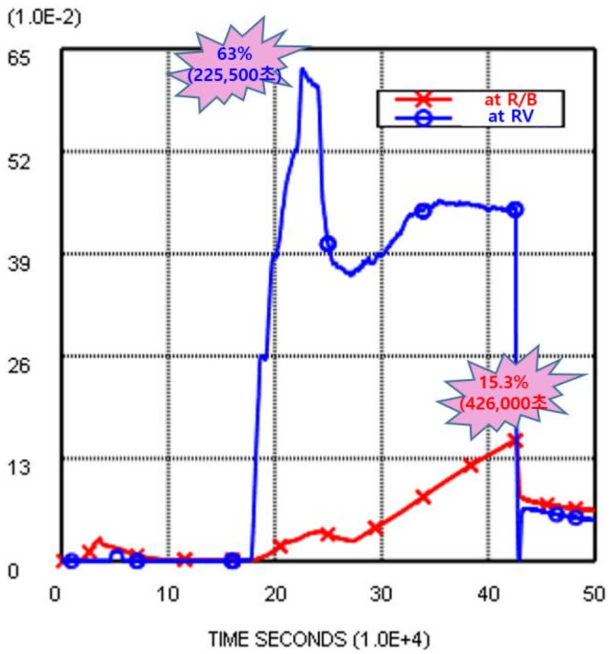

Fig. 2 H_2 Concentration in R/B and RV in Case of Successful PAR and Intact R/B [fraction]

Fig.2 shows that until about 6 days after SBO occurrence (with assuming no R/B failure and successful PAR operation including H_2 jet automatic combustion in MCCI), the maximum hydrogen concentration (as the average value in the R/B atmosphere) is approximately 15.3% (but 63% in ex-vessel H_2 generating space of RV room) just before RV failure.

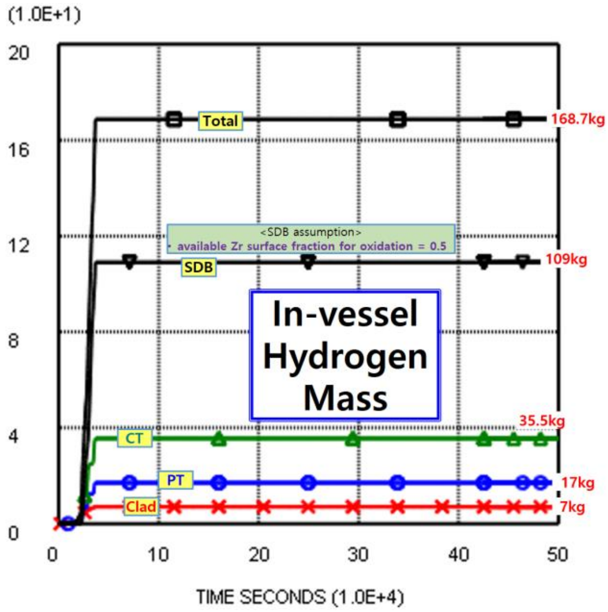

Fig. 3 In-Vessel H_2 Mass Separated by Generation Origin [kg]

Fig.3 shows that the maximum in-vessel hydrogen generation for one loop (Loop-1) is ~169kg at the time of 100% fuel channel relocation, of which about two-thirds (= 109 kg) occurs in the SDB. It is analyzed that the other loop (Loop-2) shows a similar trend resulting in the maximum in-vessel hydrogen generation was ~333kg (=168.7 (Loop1) + 164.3 (Loop2)).

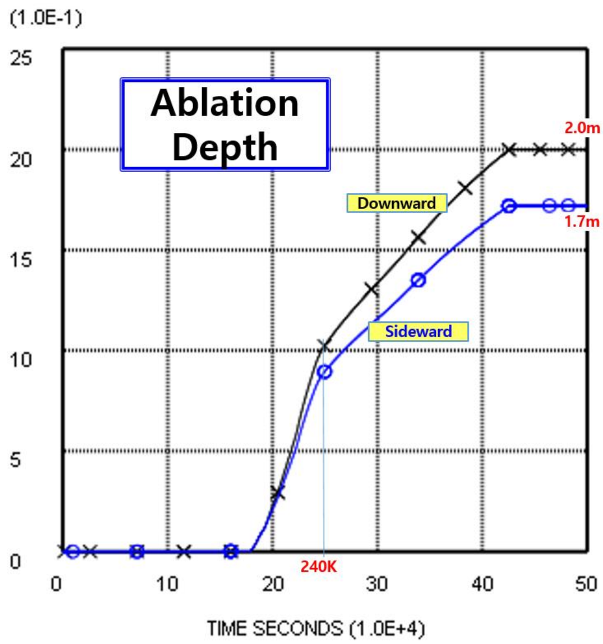

Fig. 4. Erosion Depth in RV Basemat [m]

Fig.4 shows that the maximum MCCI erosion depth of the RV floor is about 2.0m (downward) and 1.7m (sideward) just before RV failure (~RV bottom penetration). It is appeared that the highest MCCI erosion rate was about 2.3E-5[m/s] (downward) and 2.0E-5[m/s] (sideward) at 225K seconds. It was found that (1) Zr oxidation rate was about 70% at the time of CV failure, (2) when Fe oxidation starts (= after Zr oxidation is completed at ~240K seconds), the erosion rate sharply decreased.

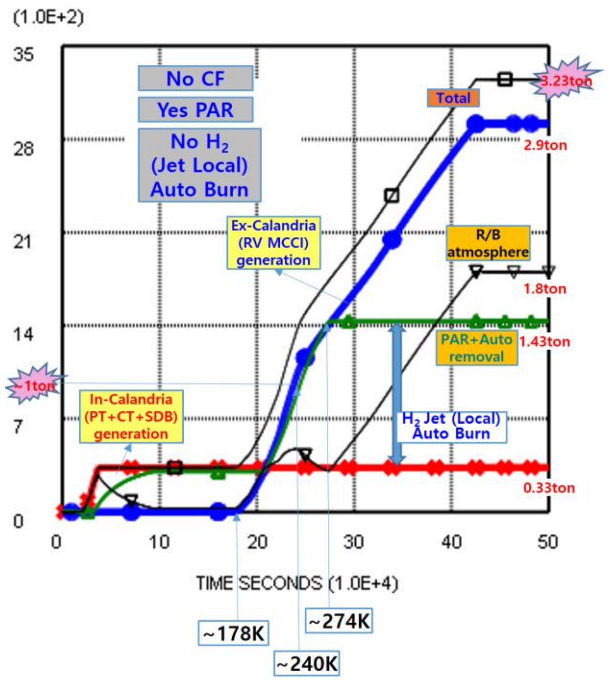

Fig. 5 H_2 Mass balance of Generation and Removal [kg]

Fig.5 shows the hydrogen mass balance between generation and removal. It shows that the maximum hydrogen generation (In/Ex-Vessel) is about 3.23 tons (cumulative) and 1.8 tons (under PAR operation, at R/B atmosphere) just before RV failure due to the maximum hydrogen removal which is about 1.43 tons (= 0.33 (PAR w/o Igniter) + 1.1 (MCCI automatic combustion)) at the time of oxygen depletion in the R/B atmosphere (~274K sec). The hydrogen mass generated inside the calandria was 330kg with about 2,900kg from outside the calandria, resulting in the total mass of about 3,230kg.

4. Sensitivity Analysis for PAR and R/B failure

If hydrogen burn (using PAR or automatic burn) is excluded with no containment failure assumed, the peak hydrogen concentration was 24% (in average for total R/B free volume) at the time of RV failure (refer to Fig.6). If PARs (with cavity jet automatic local burn) are available (which is true even in the SBO accident as PARs are passive), about 1,100kg of hydrogen can be removed, and the peak hydrogen concentration reduced to 15% (refer to Fig.2). It is noticed that even PARs are available, the hydrogen concentration does not reduce enough to flammability limit (<4%) as PARs are not working following the depletion of oxygen in the R/B at about 1 day after MCCI begins (refer to Fig.6).

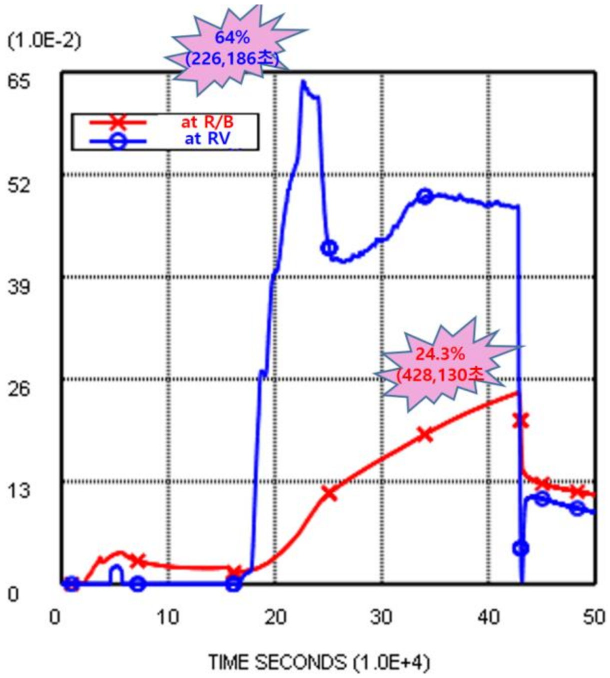

Fig. 6 H_2 Concentration in R/B and RV in Case of No PAR and Intact R/B [fraction]

When the R/B fails by steam over-pressurization at about 1 day after SBO starts (which is considered as the realistic case), oxygen depletion occurs earlier and PARs are not working properly soon after R/B fails (refer to Fig.7). This means that, for the R/B failure case, PAR's effect on reducing hydrogen from ex-vessel generation is limited where hydrogen concentration increases to as large as 56% (refer to Fig.8) due to the decrease of steam mass even for similar hydrogen mass left in the R/B. Fortunately, though the hydrogen concentration is high, there is no hydrogen explosion expected due to the depletion of oxygen in the R/B. However, more study is needed to develop the effective accident management strategy and to reduce the high hydrogen concentration during the long term SBO scenarios. Main event timing in SBO is shown in the Table 2 below for the reference.

Table 2: SBO Main Event Progress in ISAAC4.03

Event Timing [sec]	MAPP-ISAAC [s] (4x4 checker: local balloon)	
SBO start	0	
Fuel channel (PT/CT) failure	22,685(L1)/21,749(L2)	
100% fuel channel relocation	36,569	
Moderator dryout / Corium debris melt	40,054 / 48,313	
RV water saturation / RV water dryout	58,720 / 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	

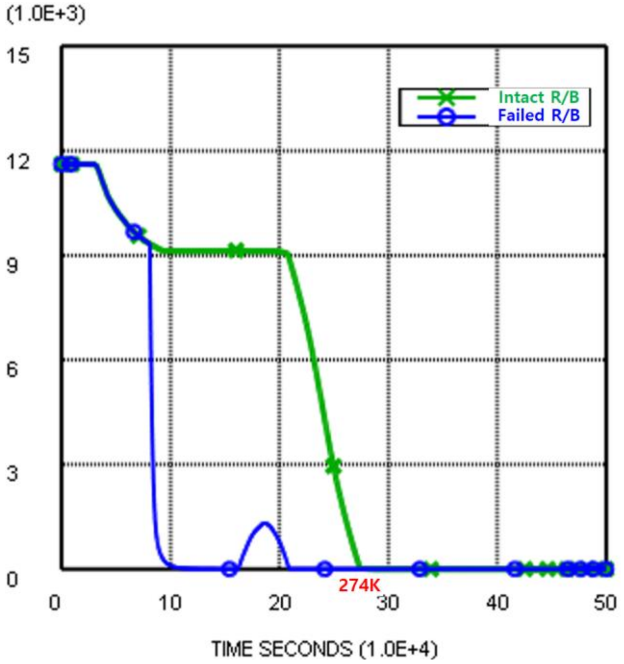

Fig. 7. Oxygen Mass in R/B Atmosphere [kg]

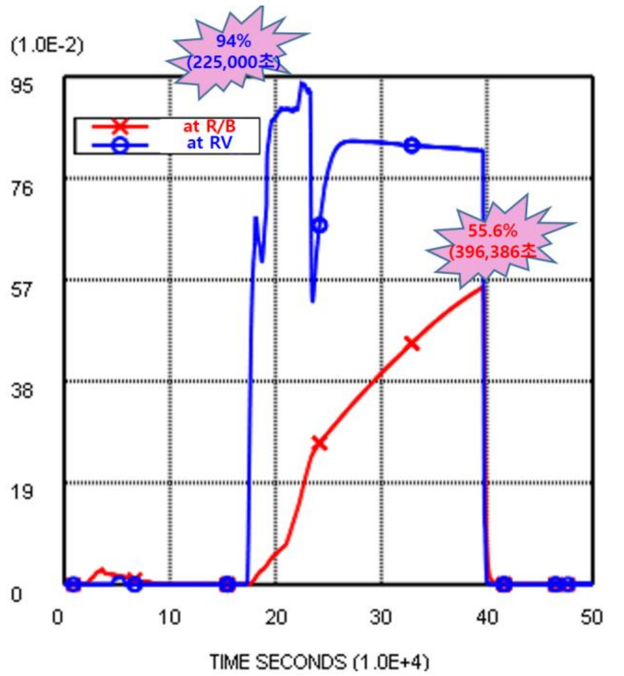

Fig. 8 H_2 Concentration in R/B and RV in Case of Successful PAR and Failed R/B [fraction]

5. Summary

Detailed R/B response evaluation for a representative sequence of SBO induced severe core damage using MAAP-ISAAC is made for WS 2/3/4 which are typical CANDU-6 plants. The main objective is to evaluate hydrogen behavior including mass, concentration and generation sources. The results show that the mass of hydrogen generated in the PHTS and CV is about 330 kg prior to CV failure, and is about 2,900 kg as a result of MCCI in the reactor vault, while a total mass of hydrogen removed by PARs reaches to about 1,100 kg.

ACKNOWLEDGMENTS

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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] D.H. Kim, Y.M. Song, J.H. Bae, Sensitivity Study for the Hydrogen Generation during SBO using ISAAC, Transactions of the CANSAS-2017 (6th International Workshop on "PHWR Challenging Issues for Safe Operation and Long-term Sustainability"), Haiyan, China, November 1-3 (2017).
[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] 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).
[8] 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).