Detailed Core Response Evaluation of Small LOCA Induced Severe Core Damage Using ISAAC for M-CAISER Comparison Basis in Wolsong Plants

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1. Introduction

To benchmark the severe accident analysis codes for pressurized heavy water reactors (PHWR or CANDU), IAEA organized a coordinated research project (CRP)[1], titled "Benchmarking Severe Accident Computer Codes for Heavy Water Reactor Applications." Seven institutes joined the CRP using their own codes, among which dedicated codes for CANDU severe accident analysis were only two, MAAP-CANDU and MAAP(1)-ISAAC. The CRP results show pretty large difference in accident progression and behavior but validation work was identified to be hard mainly due to lack of PHWR experiment data. Another difficulty was lack of a detailed and mechanistic code, such as MELCOR for LWRs, as dedicated tools for CANDU severe accident analysis. According to this demand for an accurate and detailed code in a CANDU society, a new severe accident code called M-CAISER (**M**ARS plus **C**ANDU **A**dvanced **I**ntegrated **SE**ve**R**e code) [2][3] is being developed at KAERI (Korea Atomic Energy Research Institute). At present, the code development has finished the first stage of simulating the severe accident progression in a core. As a main feature, CAISER code has provided with a concrete core degradation modeling with a detailed nodalization scheme, which makes it possible to simulate channel failure process more accurately and realistically under severe accident conditions.

The main purpose of this paper is to evaluate a small break loss of coolant accident (SBLOCA) resulting in hypothetical severe core damage using MAAP-ISAAC and to analyze a core response for providing later M-CAISER comparison basis. The target plants are Wolsong (WS) NPPs which are a typical CANDU-6 type. Current study basically uses MAAP-ISAAC version 4.03 [4][5]. It is constructed in modules covering individual regions in the plant: primary heat transport system (PHTS), pressurizer, degasser condenser tank (DCT), steam generator (SG), calandria vessel (CV), and the reactor building (RB). The code provides an integrated tool for evaluating in-plant effects of a wide range of postulated accidents, for which a wide spectrum of phenomena including steam formation, core heat-up, cladding oxidation, hydrogen evolution and vessel failure can be evaluated.

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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. ISAAC Models and Nodalization

The ISAAC models a broad spectrum of physical processes in the core that might occur during accident, such as the:

- Fuel/cladding temperature excursions, degradation and interaction with moderator system
- Zirconium-steam exothermic reaction
- Thermal mechanical failures of fuel channels
- Disassembly of fuel channels
- Formation of suspended debris beds

In particular, the ISAAC models the CANDU feeders, end-fittings, fuel channels and fuel. The models in the ISAAC concentrate on the behavior of these core components within the CV as the fuel channels disassemble, form suspended debris supported by intact channels, and relocate to the debris bed within the CV. Each characteristic channel represents a larger number of channels (known as associated channels) with similar powers, elevations and feeder geometries. The ISAAC thermal hydraulic (T/H) models in PHTS are simplified by using assumptions such as coarse nodalization, equilibrium within a fluid phase, a uniform loop pressure and a single global void fraction at which phase separation occurs.

The Wolsong unit 2/3/4 plants which have a typical CANDU6 PHTS configuration are composed of two independent loops. Each loop, in turn, make two core passes (figure of eight loop) which is composed of 380 inter-connected U-tubes called channels. The ISAAC code allows the user to group 380 fuel channels into up to 74 core channels based on their elevations, power levels, core passes, and loops. In this simulation, 16 (4x4 with checker board pattern of blue and pink colors) core channels together with 4 individual SGs are used to represent 380 fuel channels shown in Fig.1.

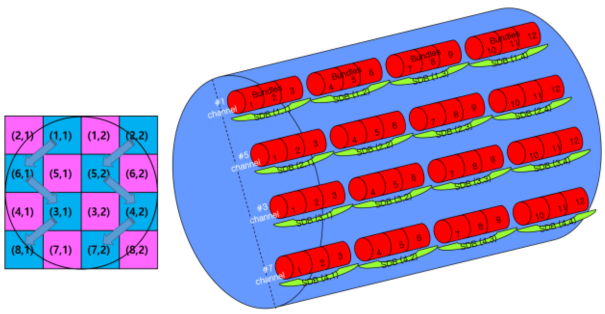

Figure 1 CANDU-6 core nodalization(4x4) scheme in ISAAC

3. SBLOCA Analysis in ISAAC

The reference case (SLO-A) is a representative de-pressurization (= low pressure) accident defined as a transient (see Table 1) initiated by a 2.5% (= initial break flow of 193 kg/s as shown in Fig.2) reactor inlet header (RIH) break of PHTS Loop-1 and break elevation of 10.696 m referenced to the bottom of calandria vessel. If the SG main (MFW) and auxiliary feed water (AFW) systems, high/medium/low-pressure emergency core cooling system (ECCS), moderator cooling system (MCS) and end-shield cooling system (ECS) are not available, the accident sequence progresses to a severe core damage accident. The PHTS loops are successfully isolated from each other with no SG crash cool-down (CC) operation in this scenario, and the operator intervening action are assumed unavailable.

Cases	Rx Trip	PHTS loop Isolation	MFW or AFW	ECCS	MCS	ESC	Comments
SLO-A	O	O	X	X	X	X	no SG CC

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

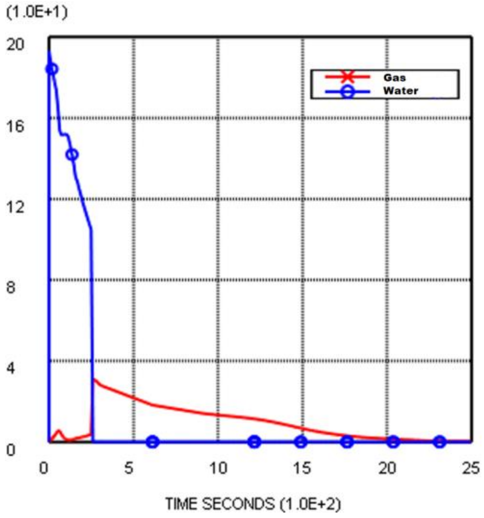

Figure 2 Break Flowrate of Coolant [kg/s]

The postulated initiating events for the SBLOCA scenario with no feed water supply into steam generators are imposed at the start of the calculation. Following the initiation of accident, in the broken loop (L1), the reactor coolant decreases due to the continuous loss of the primary coolant through the break and SG dry out does not happen. On the contrary, in the intact loop (L2), the reactor coolant maintains after a loop isolation and SG secondary side becomes to dry as a result of heat transfer from natural circulation [7]. This means that L1 shows a low pressure scenario while L2 shows a high pressure scenario before PT failure occurs.

After SG dryout, the PHTS pressure shown in Fig.3 continuously increases in L2 due to no heat removal through the secondary side and as a result the LRVs start to vent primary coolant into the DCT when reaching their set points. Because all possible cooling sources to the primary system are not available in this scenario (including moderator cooling system), the core becomes to dry out and the moderator temperature increases due to the heat transfer from the fuel channels. After all, the CV rupture disk fails when reaching its pressure set point for opening, and the concurrent loss of the calandria moderator reduces thermal margin for core cooling by the moderator. Because the recovery action to mitigate the core damage is not available in this scenario, the calandria moderator dries out, and the calandria vessel finally fails.

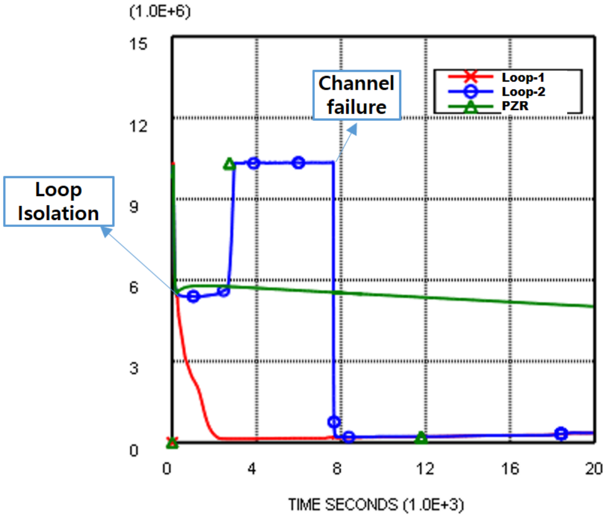

Figure 3 Pressure Behavior in the PHTS

4. ISAAC Core Response Analysis

In this paper, a concrete core response for SBLOCA induced severe core damage is analyzed using ISAAC in Wolsong unit 2/3/4 plants. Especially, the response for the first channel failure occurred in L2 top channel is analyzed as follows:

① PHTS inventory in L1 decreases rapidly while it decreases after the relief valves of DCT (DCRV) opens at 3,000s just before SG dryout (Fig.4).

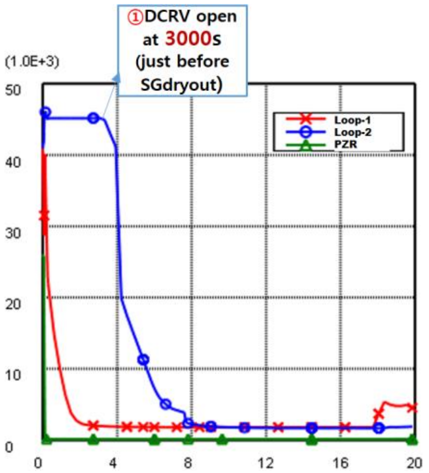

Figure 4 PHTS Water Inventory [kg]

② As PHTS inventory in L2 decreases after DCRVs open, all channels including top (1,2)/bottom (7,2) are separated from the headers at 4,000s (Fig.5).

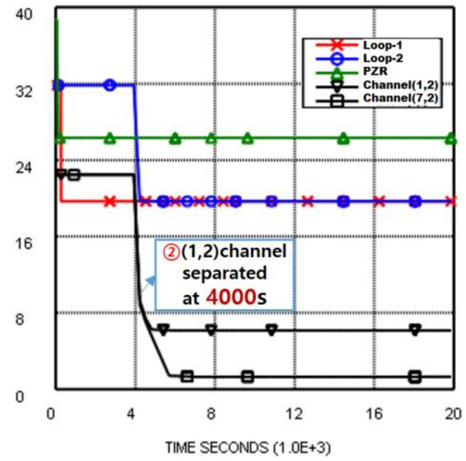

Figure 5 PHTS Water Level from CV Bottom [m]

③ As the MCS has failed, the moderator temperature gradually increases and finally reaches at the saturation one of 386 K at 5,494s (Fig.6).

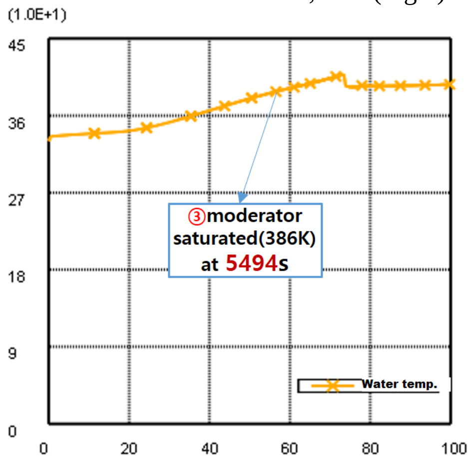

Figure 6 Moderator Temperature in CV [K]

④ CV overpressure rupture disk fails open at 7,298s and rapid water expulsion happens (Fig.7).

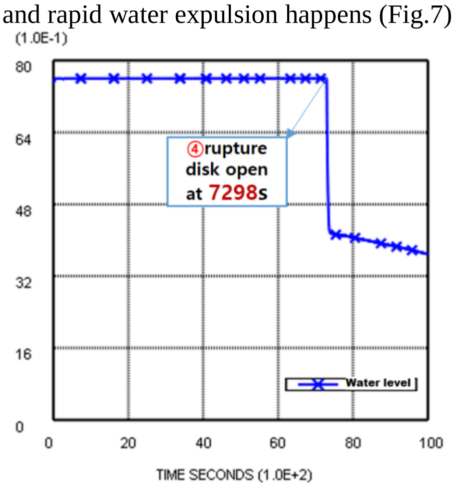

Figure 7 Moderator Water Level from CV Bottom [m]

⑤ After the rupture disk opens and water expulses, CT temperature starts to increase at 7,400s in the top channel which has already uncovered from instantaneous drop of the moderator level (Fig.8).

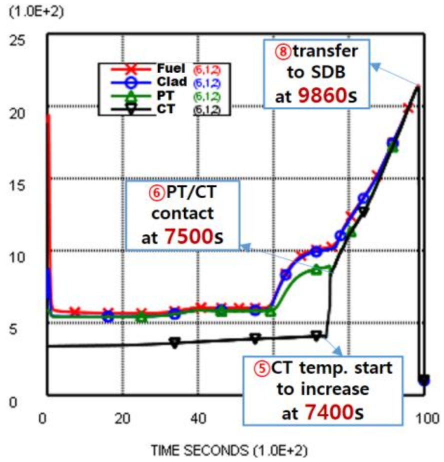

Figure 8 Top Channel (= bundle (6,1,2)) Temp. Behavior

⑥ As PHTS inventory inside the channel dries out (Fig.5) and the moderator outside the channel is saturated (Fig.6), the temperature of fuel/clad/PT begin to rise fast which results in PT ballooning in L2 until PT/CT contact occurs at 7,500s (Fig.8). However PT ballooning does not occur in L1 in which the pressure is very low.

⑦ Just after the PT/CT contact, PT at the central bundle (6,1,2) of the top channel (1,2) in L2 fails at 7,633s from excessive PT stress (Fig.9). Differently from L2 failure, the PT failure in L1 results from a bundle melt which should occur after channel uncover from moderator. This means L2 failure occurs earlier than L1 failure.

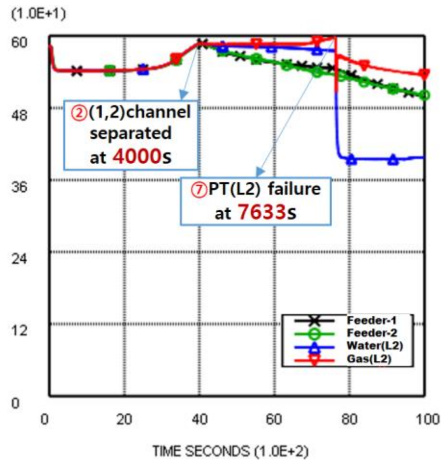

Figure 9 Temperatures of Feeder surface and PHTS (L2)

⑧ Though PT has failed, the fuel stays inside the channel until fuel is melted, and then relocates (to lower places such as SDB (suspended debris bed), for example, in ISAAC modeling) (Fig.8).

5. Results

The main results of this study are as follows:

- A concrete core response for SBLOCA induced severe core damage is analyzed using ISAAC in Wolsong unit 2/3/4 plants. Especially, the response for the first channel failure in representative 16 (4x4 with checker board pattern) core channels together with 4 individual SGs is analyzed.
- According an ISAAC core response analysis, the PT failure under a low pressure circumstance in broken loop results from a bundle melt, while the PT failure under a high pressure circumstance in intact loop results from a ballooning. In the SBLOCA induced severe core damage scenario, the ballooning occurs earlier than the core melt. This is because the core melt requires the precondition of channel uncover from moderator which rapidly occurs after any channel failure.
- The results on a location of the first channel failure is against the normal expectation that broken loop failure would occur earlier than intact loop failure. So, further analysis is needed later, especially via a comparison with the results of the new detailed code of M-CAISER for the same scenario [8].

ACKNOWLEDGMENTS

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