Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, Oct. 19-21, 2022

Preliminary analysis of LB-LOCA-induced severe accident for CANDU reactor using CAISER code

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1. Introduction

Canadian Deuterium Uranium (CANDU) reactor has novel characteristics compared to the general light water reactor: for example, horizontal reactor core, confined geometry of reactor cavity (so called, reactor vault) and different primary coolant system. This leads to a need for development of CANDU severe accident code because of different behavior in core-degradation and relocation. CAISER (CANDU Advanced Integrated SEveRe accident analysis code) developed by KAERI has strengthened its strength (i.e., improved model and correlation, or generalization for core nodalization) and has made up for the weakness of existing CANDU severe accident codes such as MAAP-ISAAC or MAAP-CANDU [**1,2**]. Several studies using CAISER code have considered major type of accident (i.e., SBO, LB-LOCA and SB-LOCA) for CANDU reactor without *ex-calandria (or, ex-vessel) phenomena* [**3-7**]. Objective of the present study is to report the preliminary results of Large-break loss of coolant accident (LB-LOCA, RIH 35% break) with of full-scope analysis of CANDU severe accident by coupling between codes: MARS-KS/CAISER/CONTAIN code.

2. Methods and Results

2.1 MARS-CAISER-CONTAIN code coupling

Using dynamic link library (.dll), CAISER code can be coupled to MARS-KS code for reactor thermal-hydraulics and CONTAIN code for ex-calandria severe accident phenomena, respectively (Fig.1) [**8**]. CAISER code is in charge of *In-calandria* phenomena and communicates to MARS-KS with the coupling varaibles: for example, mass/energy (M/E) of core components such as fuel/clad/pressure tube/calandria tube, and fluid properties in primary system and heat flux from the core to the coolant. CONTAIN code is a role of analyzing the *ex-calandria* phenomena and coupling method between the MARS and CONTAIN code already exists[**9**]. Major coupling part is identical to the boundary condition (pressure/temperature, P/T) of MARS such as time-dependent volume. In case of CAISER/CONTAIN coupling, most of variables are related to an information of categorized fission products, molten-corium in calandria vessel and their decay heat, failure timing of calandria-vessel. Detailed method for code coupling is available in the reference [**8**].

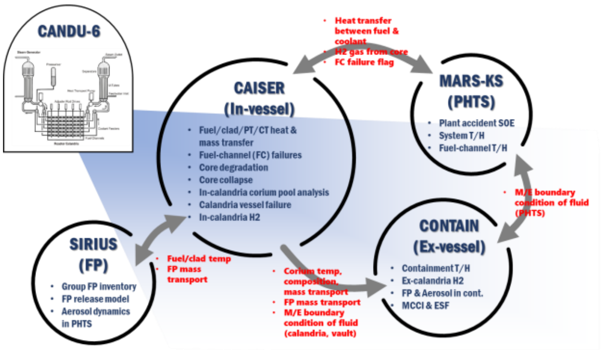

Figure 1. Coupling of MARS-CAISER-CONTAIN

2.2 CANDU reactor core and loop system

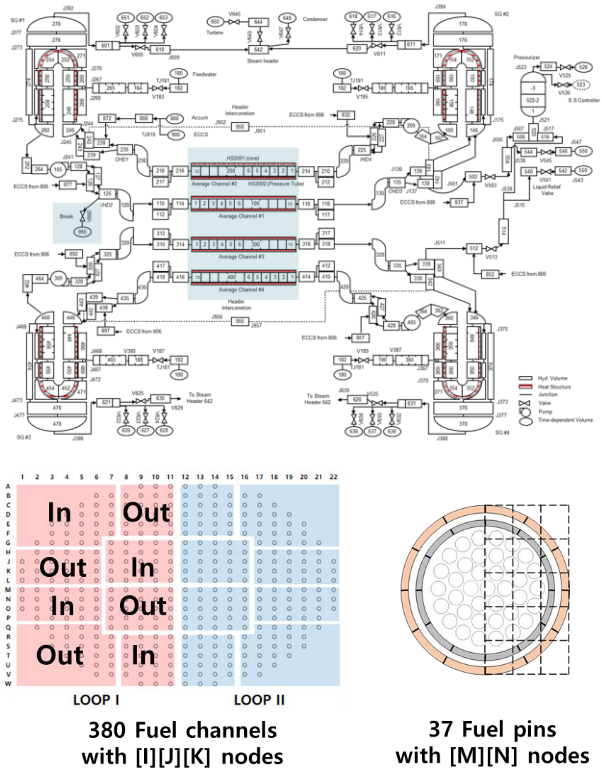

Figure 2. Core and PHTS nodalization

CAISER code designs 380 fuel channels of CANDU core system ([I][J][K]) and 37 fuel pins ([M][N]) per each fuel channel based on generalized Cartesian coordinate node system (Fig.2). Each node ([[I][J][K]) matches the heat structures attached for the fluid volume component (for the core) in MARS code. Node system for the present study is [I][J][M][N][K] =

[4][4][3][5][12]. Target reference of CANDU reactor system (such as primary heat transport system, PHTS) is Wolsong Unit-II reactor.

2.3 CANDU containment

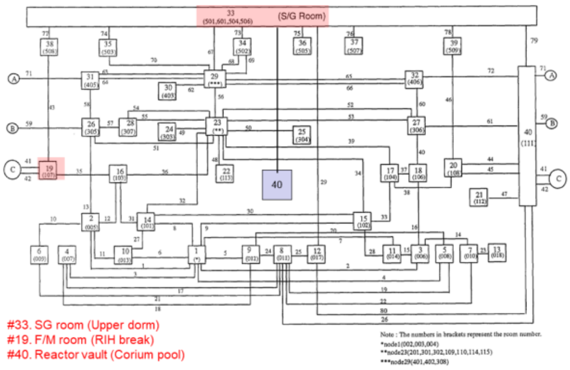

Figure 3. Containment nodalization

CONTAIN 2.0 code developed by Sandia National Laboratory is an integrated code for ex-vessel severe accident phenomena of containment building including the transportation of aerosol/fission product, hydrogen combustion, molten-corium concrete interaction (MCCI) and general containment thermal-hydraulics[10]. Present study developed the multi-cells model for CANDU containment building and based model for it is the PRESCON code used when AECL designed Wolsong Unit-II reactor (Fig.3) [11]. Major advantages of multi-cells model is able to evaluate local distribution in large containment volume (i.e., hydrogen gas fraction, fission product mass and aerosol).

Multi-cells model is consisted of 41 cells, 71 links and 222 heat structures, and includes reactor vault containing the calandria vessel. Reactor vault is semi-closed volume with over-pressure protection (OPP) system and leads to distinguishable MCCI phenomena compared to general PWR. CORCON-mod3 in CONTAIN code is used for wall ablation by MCCI and transportation/generation of aerosol by MCCI is incorporated with VANESA module. CAISER code contains the SIRIUS code to simulate the in-core fission products and categorized seven groups of FP is matched to that of CONTAIN code. Inventory of each group is transferred from the core to the containment by the host materials (gas or aerosol). Key nodes for MARS/CAISER/CONTAIN coupling in multi-cells CONTAIN model are steam generator(S/G) room connected to the degassing condenser relief valves (DCRV) and OPP from the reactor vault, fueling machine (F/M) room existing the reactor header, and reactor vault containing the molten corium discharged from the calandria vessel. Detailed information of reactor vault cell is available in the reference [12].

2.4 Sequence of event (35% ROH break) and assumption

Present study evaluate severe accident induced by large break loss of coolant accident (35% Reactor Inlet Header (RIH) break). Calculation time is confined as 150,000s and sequence of event (SOE) is summarized as Table I. Most of engineering safety features (ESF) and strategies are not available: emergency core cooling system (ECCS), crash cooldown for steam generator (SG), dousing spray in containment, local air-cooler (LAC), passive autocatalytic recombiner (PAR) and ignitor. Major components to simulate reactor thermal-hydraulics are available: degassing condenser relief valves (DCRV), loop isolation, OPPs for calandria vessel and reactor vault. Molten-corium pool analysis for *in-calandria* phenomena is simplified in the present study; calandria vessel (CV) failure time is manipulated for fast calculation by considering the simplified heat transfer coefficient (single-phase) boundary condition at the outer wall of vessel. For the containment analysis, decay heat by fission products (airborne or deposition) is negligible; all of decay heat is transferred to the corium in the reactor vault when the corium is discharged from the calandria vessel. UO2 mass in the core is about 50 tons nearly half of the design values (~100 tons) for the fast calculation.

Table I. Sequence of event criteria

SOE	***Criteria***
Reactor trip *Main feed water trip*	$P_{ROH} < 8.7$ *MPa*
Main Steam Safety valve open	*Open : 5.24 MPa* *Close : 5.11 MPa*
LOCA signal	$P_{ROH} < 5.516$ *MPa*
RCP trip (whole loop)	$P_{RIH} < 2.5$ *MPa*
Loop isolation	*LOCA signal + 20 s*
Liquid relief valve open	$P_{ROH} > 10.34$ *MPa*
Degassing condenser relief valve open	$P_{DCT} > 10.17$ *MPa*
Calandria vessel rupture disk	$P_{CV} > 138$ *kPa*
Reactor vault rupture disk	$P_{RV} > 69$ *kPa*

2.5 In-calandria phenomena

After the 35% RIH break (1000s), break flow of the coolant in the PHTS is tripped by the loop isolation (PRIH = 5.5 MPa) and two loops show independent thermal-hydraulic behaviors: the broken loop (low-pressure accident progress) and intact loop (high-pressure accident progress) (Fig.4). This indicates that the first failure of fuel channels for each loop shows clear difference (failure time and mechanisms): 2500s for the broken loop and 13500s for the intact loop. Failure of fuel channels leads to (i) the mass conversion from the fuel channel to the debris and (ii) loss of coolant mass in calandria vessel by pressure excursion. Debris in the calandria vessel is heated up by decrease of coolant level in the calandria vessel by evaporation and corium pool is formed with three layers: oxide layer, metal layer and debris layer. Even though dry-out of the calandria vessel is occurred (12,000s), the vessel is cooled-down: the *ex-calandria* vessel wall cooling by the coolant in the reactor vault of which coolant temperature reaches the saturation at 20,000s. Failure of the calandria vessel is assumed to the creep-failure in the present study (81,000s) and these timing is slightly faster than the dry-out time of the reactor vault because water level below the bottom of the calandria vessel nearly two meters at the bottom of the reactor vault (Fig. 5). Hydrogen mass generated by *In-calandria* phenomena is about 350 kg.

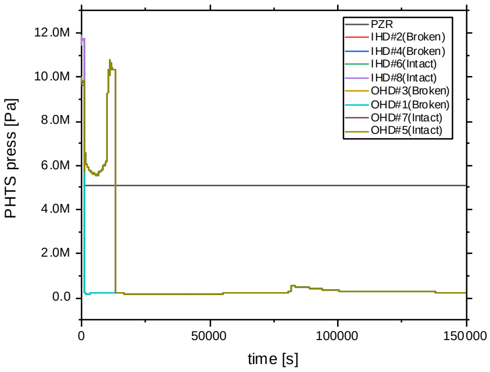

Figure. 4. Reactor thermal-hydraulics: PHTS pressure

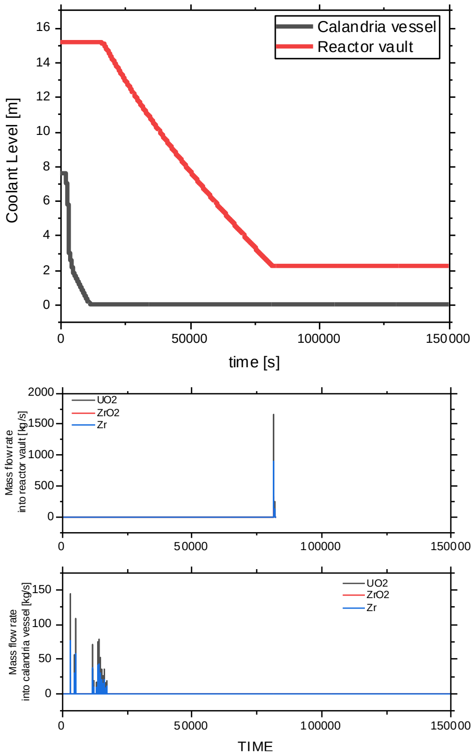

Figure. 5. *In-calandria* phenomena: coolant level of calandria vessel/reactor vault and corium mass flow rate into calandria vessel/ reactor vault

2.5 *Ex-calandria phenomena*

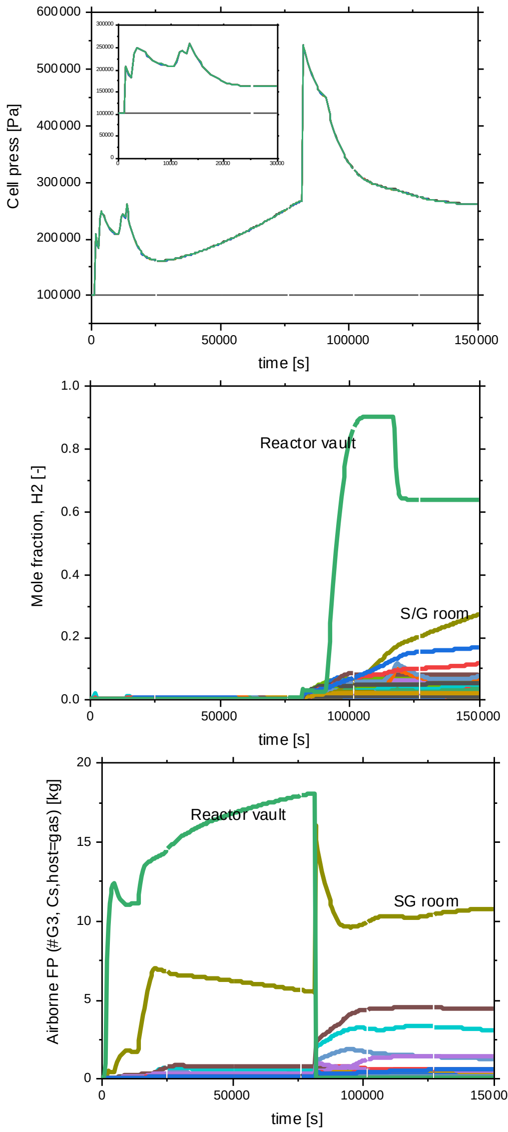

Figure. 6. *Ex-calandria* phenomena: containment thermal-hydraulics and hydrogen/FP distribution

In aspect of the containment, linearly increase of the pressure is started from the time when the coolant of the reactor vault reaches the saturation temperature causing evaporation (Fig.6). After the failure of the calandria vessel (81,000s), the mass of the molten corium is discharged to the reactor vault and the MCCI starts with peak pressure (545 kPa) of the containment building. Heat structures of the containment cells function large heat sink and containment pressure after the vessel failure is gradually decreased by wall condensation. Residual metal species (i.e., Fe and Zr) into the corium pool are oxidized during MCCI, which is from the clad material (Zr) and the rebar in the concrete (Fe). After the dry-out of the coolant in the reactor vault (91,000s), the ablation rate of the concrete is slightly increased and depletion of the zirconium in the corium pool is about 118,000s (Fig.7). Final ablation depth of the bottom of the reactor vault is about 1.1 m at 150,000s calculation smaller than the wall thickness, 2.44 m. Hydrogen mass generated by *Ex-calandria* phenomena is about 1,400 kg (Fig. 7) and rebar mass in the concrete plays a critical role of it [**12**]. Airborne fission product (i.e., Cs) and hydrogen gas are widely distributed in the containment and the reactor vault shows distinguishable; large concentration of the hydrogen and the fission products because of its semi-closed geometry with only confined flow path (rupture disk of the reactor vault connected to the steam generation room) (Fig.6).

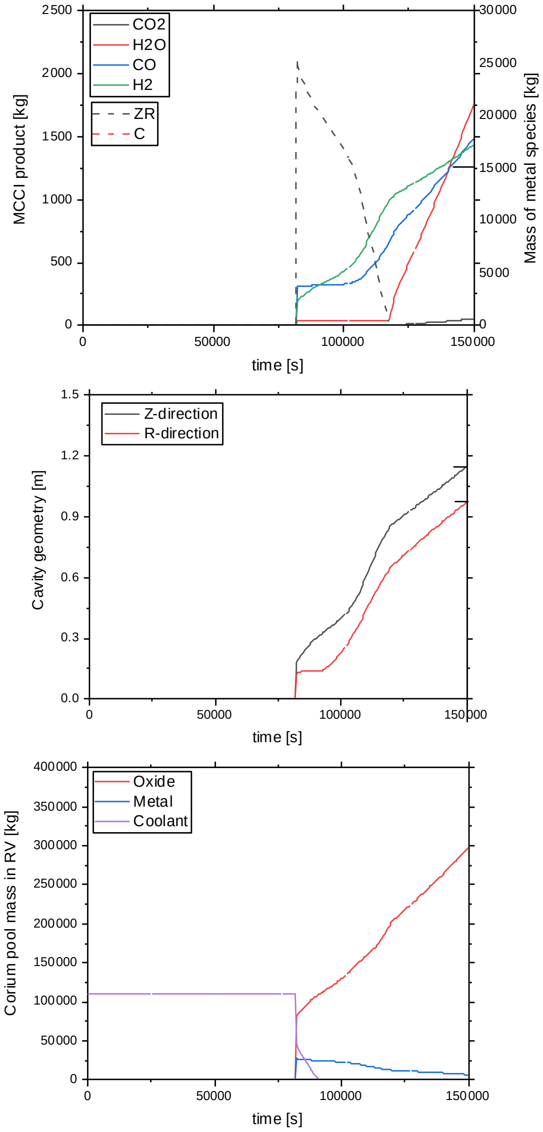

Figure. 7. *Ex-calandria* phenomena: MCCI

3. Conclusions

Present study indicates that CAISER code coupled with MARS-KS and CONTAIN well simulates 35% RIH break LOCA of CANDU reactor. Even though the sequence of event is simplified and approximated, we checked general progress of CANDU severe accident including *In-calandria* to *Ex-calandria* phenomena. Based on the series of preliminary analysis about CANDU reactor, code-to-code (i.e., MAAP-ISAAC) validation about several accident scenarios is in progress.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (Ministry of Science and ICT) (No. RS-2022-00155244)

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