MCCI analysis using CONTAIN code for CANDU application

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1. Introduction

Containment of the CANDU (CANadian Deuterium Uranium) reactor has relatively small design pressure and different characteristics compared to the general light water reactor (LWR), including the reactor cavity (called reactor vault, RV). The molten corium-concrete interaction (MCCI) phenomenon of the CANDU shows different behavior. RV is filled with the light water under normal operation and calandria vessel is submerged into it, which indicates the wet-cavity condition for the MCCI phenomenon when the calandria vessel failed under severe accident. RV is closed-volume with the over-pressure protection system (RV relief valve, RD-1 and RD-2) and is easy to be pressurized by non-condensable gas (i.e., hydrogen) evolved by the MCCI. AECL designed the Wolsong Unit-II analyzed the containment thermal-hydraulics using PRESCON [1]. Detailed multi-cell model of the containment volume facilitates an analysis of the local distribution of the hydrogen gas and evaluates the effects of the engineering safety features (i.e., local air cooler, spray). CANDU containment model by PRESCON became a reference and several researches were reported on the containment thermal-hydraulic by using MELCOR [2,3] and CONTAIN [4] code. Objective of the present study is to evaluate the MCCI phenomena for CANDU reactor by using the the CONTAIN code with three-cell containment model simplified for the preliminary test. Multi-cell model based on the PRESCON for the CANDU containment will be analyzed in the future.

2. Methods and Results

2.1 CONTAIN code

CONTAIN 2.0 code developed by the SNL is an integrated severe accident code simulating the containment phenomena [5]. MCCI is evaluated by the CORCON-MOD3 module and it incorporates the VANESA code for calculating the aerosol dynamics and fission products by MCCI. In this study, CONTAIN code has been coupled with the MARS-KS (reactor thermal-hydraulics) [6] and CAISER code (In-vessel severe accident [7]. Final objective of the present study is to develop the integrated code-package for the CANDU severe accident.

2.2 CANDU containment and reactor vault

Failure pressure of the CANDU containment is generally known as 500 kPa(a), which is slightly larger than design pressure (18 psig) with the volume of the containment building, 48480 m^3 [8]. Pressure and temperature are 101 kPa(a) and 31.85 C under normal operation. RV-floor of the Wolsong Unit-II is basaltic-type concrete and RV-side wall has asymmetric geometry [9]. RV has two rupture disks for depressurization (I.D. = 4.026" with 10 psig) and is directly connected to the steam-generator room (R501) [10]. General criteria of the MCCI failure is to ablate the floor wall of the RV (2.44 m, above R012) and is different with that of LWR considering the basemat melt-through, because the CANDU containment designed inner liner as an epoxy paint, not steel liner for the pressure boundary of the containment building.

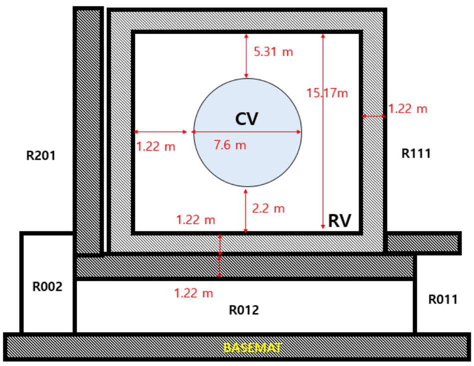

Figure 1. Geometry of CANDU RV

Present study is preliminary analysis for application of the CANDU containment and uses simplified three-cell model: reactor vault (RV, 500 m^3), lumped containment volume (LCV, 50000 m^3) and environment (Env, 0 m^3). Heat structures such as concrete and steel as a heat sink are only considered in RV.

2.3 MCCI sensitivity: parameters

Present study considers a sensitivity analysis about the MCCI phenomena including the corium temperature, rebar mass fraction and layer configuration of the corium pool. Expected results from the sensitivity study are (i) total accumulated mass of hydrogen gas and (ii) ablated cavity shape. Major assumption of the CONTAIN model of the present study are as below.

(i) Initial water mass containing the RV is assumed to be 110,000 kg and the corresponding water level is 2.2m from the RV-floor identical to the level of the calandria vessel bottom. This indicates that MCCI starts after a calandria vessel fails.

(ii) Decay power by the fission products in the airborne aerosol or gas is neglected.

(iii) Composition of the corium is assumed to be UO_2, and Zr of which mass is 100,000 kg and 40,000 kg, respectively. Mass of Zr considered the cladding, the pressure tube and the calandria tube, which is design values for Wolsong Unit-II [11]. As the boundary condition, corium is discharged into the RV for 10 seconds. Corium starts to discharge after 2,000s indicating the calandria vessel failure.

(iv) Engineering safety features for the containment including the containment spray and local air cooler are not available.

(v) Flow junction between RV and LCV is single pipe of which area is large enough to guarantee the interaction of pressure and gas mass flow between cells.

(vi) RV failure by MCCI is assumed when a corium penetrates through a RV-floor; wall thickness is 2.44 m. Failure of the RV-side (vicinity of R111) is evaluated by using a conservative wall thickness, 1.22 m.

Table II: Test matrix

TEST Matrix	T*	T_{UO2} [K]	T_{ZrO2} [K]	T_{Zr} [K]	M_{rebar}/M_{con}	Layers
#1.1	1.00	3200	3000	2100	0.07	Mixture
#1.2	0.75	2780	2630	1960	0.07	Mixture
#1.3	0.50	2380	2280	1820	0.07	Mixture
#2.1	1.00	3200	3000	2100	0.00	Mixture
#2.2	1.00	3200	3000	2100	0.03	Mixture
#2.3	1.00	3200	3000	2100	0.13	Mixture
#2.4	1.00	3200	3000	2100	0.20	Mixture
#3.1	1.00	3200	3000	2100	0.07	Stratified

Among three main factors for MCCI, the first is a corium temperature. Corium is flowed into RV after a calandria vessel failure and its temperature strongly depends on an accident scenario. Dimensionless temperature (T^*_{CCI}) of corium pool for MCCI phenomena is suggested to evaluate the effect of the corium temperature at the MCCI phenomena;

$$T^*_{CCI} = \frac{T_{i,cor} - T_{abl}}{T_{i,cor,m} - T_{abl}}$$

where $T_{i,cor}$, T_{abl} and $T_{i,cor,m}$ is the temperature of the i material in the corium, ablation temperature of the concrete, and melting temperature for the i material, respectively. Material i of the present study is the UO_2, ZRO_2, Zr. (Test matrix #1.1, #1.2, #1.3).

Second, mass fraction of the reinforcing steel bar (called, rebar) in the concrete plays a critical role on the behavior of a metal layer in the corium pool during MCCI. Rebar is the ferrite (Fe), and it functions the source of the hydrogen generation by the metal-gas reaction (Fe-H2O oxidation). Large mass of rebar in the concrete results in an increased mass of hydrogen gas by MCCI and general order of the rebar mass fraction is 7-20 % [12] (Test matrix #1.1, #2.1, #2.2, #2.3, #2.4).

Last, layer configuration in the corium pool is an important factor of concrete ablation. CONTAIN code provides several options to set layers (i.e, heavy oxide, metal, and light oxide) whether they are considered as the mixture- or the stratified-layer. Depending on the layer configuration, the heat transfer between layers is significantly varied (#1.1, #3.1).

2.4 MCCI sensitivity: results

Effect of corium temperature on the RV floor failure time and the hydrogen mass in MCCI is negligible (243,000 s ± 6,000 and 3400 kg ± 60) because of the wet-cavity condition of the RV. An increase of corium temperature results in just earlier time of water dry-out in the RV.

Table III: Test results

TEST Matrix	RV side failure time [s]	RV floor failure time [s]	H2 mass [kg], 100,000s	H2 mass [kg], 150,000s	H2 mass [kg], 200,000s
#1.1	66000	237000	2404	3104	3465
#1.2	78200	251000	2292	3029	3393
#1.3	84400	242000	2233	2964	3355
#2.1	66400	209000	1630	1630	1630
#2.2	62200	219000	2041	2182	2317
#2.3	71600	249000	2347	3073	3762
#2.4	75400	261000	2282	2983	3647
#3.1	N/A	105000	2241	2974	3694

Effect of the rebar mass fraction on the RV floor failure time and the hydrogen mass in the MCCI is significant (235,000 s ± 25,000 and 2900 kg ± 1300). In case #2.1 (0.00 for rebar mass fraction), the hydrogen mass is restricted to 1630 kg fully reacted by Zr-H_2O reaction. Increase of the rebar mass fraction leads to an increase of the hydrogen mass up to 3700 kg due to an additional Fe-H_2O reaction during the MCCI.

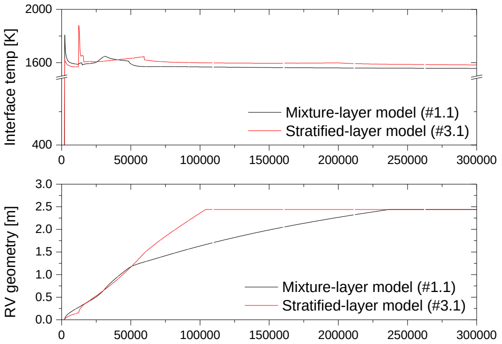

Figure. 2: Effect of layer configuration at MCCI: (top) corium pool temperature contacting to the concrete, (bottom) RV geometry for the z-direction (floor)

Effect of the layer configuration of the corium pool is significant on the RV-floor failure time (170,000 s ± 70,000), while the hydrogen mass is nearly identical between two cases (3,500 kg ± 50) (#1.1, #3.1). Mixture-layer model (#1.1) have only single layer as the heavy mixture (HMX) including the UO_2, ZRO_2, and Zr together. During MCCI, the mass of oxide is gradually increase in the pool and conduction heat from the corium pool to the concrete decreased because of the decrease of mass fraction of the metal in the pool. On the other hands, stratified-layer model (#3.1) considers the heavy oxide (HOX), metal (MET) and light oxide (LOX), independently. Early stage of MCCI have the HOX-MET-LOX layer configuration based the balance of density. When the density of HOX is smaller than that of the MET, the HOX is converted to the LOX. Late stage of MCCI have MET-LOX layer configuration. Highly conductive metal layer directly contacts to the RV-floor and it accelerates the concrete ablation in z-direction. Corium temperature contacting to the concrete for the stratified-layer model (MET layer) is higher than that of the mixture-layer model (HMX layer) (Fig. 2). This results to the difference on the concrete ablation rate between models. It is noted that the stratified-layer model (#3.1) shows a clear deterioration of the concrete ablation in r-direction compared to the mixture-layer model (#1.1) and these correspond to the role of the metal-layer during the MCCI and similar hydrogen mass between tests.

3. Conclusions

Present study evaluated the PHWR MCCI phenomena using CONTAIN code with sensitivity parameters, which indicated that CONTAIN code can afford to apply in the analysis of the CANDU containment. In the future, in addition to the MCCI phenomena, general ex-vessel phenomena will be evaluated for the next step, including containment thermal-hydraulics, fission products and aerosol dynamics for the CANDU reactor. Based on the present study, KAERI are developing an integrated code package (called M-CAISER) for the CANDU severe accident analysis by coupling the reactor thermal-hydraulics (MARS), in-vessel severe accident (CAISER), and source term analysis (SIRIUS) with ex-vessel severe accident (CONTAIN) [7].

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REFERENCES

[1] AECL, Containment models, Wolsong Unit-II design manual (86-03500-AR-006_02_001)
[2] H.C. Kim et al., Validation of the MELCOR input model for a CANDU PHWR containment analysis by benchmarking against integrated leakage rate tests, Nuclear Engineering and Design, 340, 2018, 201-218
[3] W.Choi et al., Efficacy analysis of hydrogen mitigation measures of CANDU containment under LOCA scenario, Annals of nuclear energy, 118, 2018, 122-130
[4] K.H Bang, Development of safety assessment technology for safety issues of CANDU reactors, KINS_HR_CONTAIN(2005)
[5] K.K.Murata et al., Code manual for CONTAIN 2.0: A computer code for nuclear reactor containment analysis, NUREG/CR-653, SAND97-1735
[6] B.D. Jeong et al., RELAP5/MOD3.2.2. system code coupling with CONTAIN 2.0 containment analysis code using dynamic link library, 2002, NTHAS-3
[7] J.H. Bae et al., Establishment of coupling structure in CAISER code for an integrated severe accident simulation of CANDU reactor, Transaction of KNS autumn, 2021.
[8] IAEA-TECDOC, Benchmarking severe accident computer codes for heavy water reactor applications, IAEA-TECDOC-1727, 2013
[9] AECL, shielding design manual, part 1- reactor building, Wolsong Unit-II design manual (86-03320-DM-001)
[10] AECL, TUBRUPT mode, Wolsong Unit-II design manual (86-03500-AR-004)
[11] AECL, CANDU 6 generating station physics design manual, Wolsong Unit-II design manual (86-0310-DM-000)
[12] OECD-NEA, state-of-the-art report on molten corium concrete interaction and ex-vessel molten core coolability, NEA/CSNI/R(2016)15, 2017