# Preliminary safety analysis of CANDU irradiated fuel-bay using MARS-KS code: Part (I). Hypothetical Loss-of-Coolant-Accident

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## 1. Introduction

While CANDU reactor has advantages from operation efficiency with on-line refueling, the amount of spent fuels generated during operation is larger compared to pressurized water reactor. On-site storage capacity of CANDU spent fuel in Wolsong plant has reached to nearly saturation point [1] and safe management of spent fuels has been emphasized with additional dry storage facility being constructed, recently. Spent fuels of CANDU reactor are temporarily stored by water pool at least 6 years until the decay heat becomes small enough to handle in dry-storage facility.

Canadian Nuclear Safety Commission (CNSC) and Canadian Nuclear Laboratories (CNL) have been focusing on safety analysis of spent fuels stored in the water pool, so called irradiated fuel bay (IFB), and developing the computer code to simulate thermal-hydraulics, severe accident and source term during abnormal situation in IFB [2]. Published report for phenomenon identification ranking table (PIRT) by CNSC and CNL indicates that type and arrangement of CANDU fuel storage (i.e., horizontal fuel) result in different progress of accident situation and it is hard to use existing PWR codes (i.e., MELCOR, MAAP, and CINEMA) for safety analysis of CANDU IFB. KAERI has developed the computer code for safety analysis of CANDU IFB from 2022 and present study is related to thermal-hydraulics in IFB during accident using MARS-KS code based on project. Part I is loss-of-coolant accident.

## 2. Methods and Results

### *2.1 Irradiated fuel-bay of CANDU reactor*

IFB of CANDU reactor consists of auxiliary and main storage bay. Auxiliary bay indicates reception bay, failed (or canned) fuel bay and discharge bay, and decay heat power of them except the discharge bay is negligible (about 0.2 MW) in safety analysis [3]. Dimension of main storage bay is 11.89 m (width, x-direction), 19.84 m (depth, y-direction), 7.62 m (height, z-direction) and coolant inventory (light water) is about 1600 tons without 45,000 bundles. Pressure boundary of IFB in service building is in general atmosphere, which is smaller than that of the containment building and is vulnerable to leaks of radioactive aerosols or gaseous during accident.

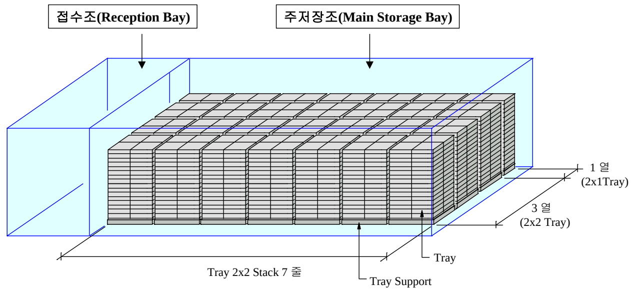


Figure 1. Irradiated Fuel Bay (IFB) in Wolsong IFB

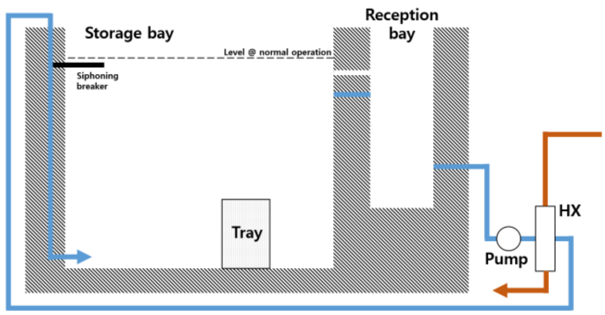


Figure 2. Cooling system in Wolsong IFB

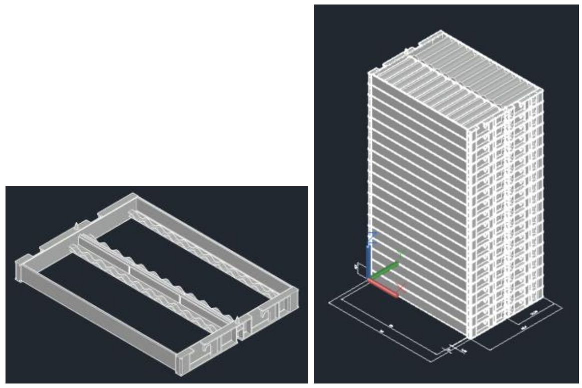

Figure 3. Tray 3D view in Wolsong IFB

Cooling system of the CANDU IFB consists of primary and secondary loop. Primary loop is semi-closed loop passing from the reception bay to the main storage bay and pipe diameter of primary loop is 8 inch. To prevent the siphoning during the pipe break of the primary loop, the siphon breaker is installed (3/4") in vicinity of the water level at normal operation. Spent fuels of CANDU are stored in IFB as horizontal direction with tray and 24 bundles are stacked with two rows per tray. Dimension of unit tray is 1.08 m (width), 1.52 m (depth) and 0.14 m (height). Height of 19 layered trays, so called stack, is about 3.0 m and distance between the free surface of the pool and top elevation of the stack is required at least 4.3 m for radiation shielding. Depending on the plant site, tray geometry is slightly different [4] and tray in Wolsong IFB is nearly closed geometry at x-y plane, which is hard to form crossflow between trays.

*2.2 Modeling of MARS-KS*

MARS-KS code is oriented as one-dimensional thermal-hydraulic system code for safety analysis of nuclear power plant and MultiD module in code facilitates the extension of application which does not cover the engineering problem by 1D module, for example, thermal stratification in tank [5]. Present study uses MultiD module for IFB modeling based on rectangular geometry. Each fluid volume has their own heat structures to simulate the trays and fuel bundles. Dimension of IFB, fuel bundles and tray are based on the design values of Wolsong Unit II [3].

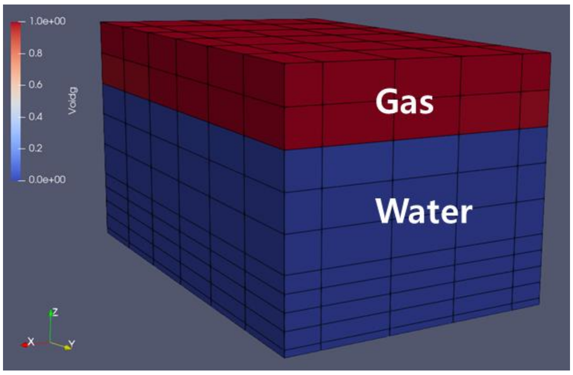


Figure 4. 3D nodalization of MARS-KS multiD

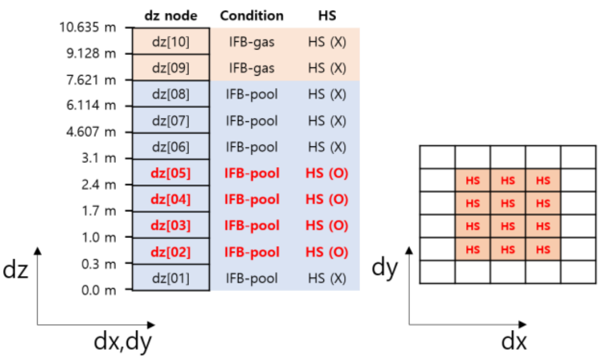


Figure 5. Node dimension and configuration of HS

Number of multiD node is 5 for [dx], 6 for [dy] and 10 for [dz], respectively and total dimension of the IFB geometry is identical to the design values of Wolsong Unit II. IFB is consisted of two part: liquid zone and gas zone. Initial liquid level is 7.621 m and height of the 19 trays (or, strack) simulated by heat structures for bundles (#1) and tray (#2) are 3.0 m. Heat structures are attached for dz node from [02] to [05] and are uniformly distributed at the x-y plane. Design value of mass for fuel (UO2), clad (Zry) and tray (Stainless steel) is 522.8, 52.9 and 68 kg per unit tray (or, 24 bundles), respectively. Present study considers 46,080 bundles, 1920 trays in MARS-KS model and two types of heat structure are attached at unit fluid node. Heat conduction between bundles and trays is neglected and heat source for simulating decay heat is only considered from the bundles.

Boundary condition of MARS-KS model is consisted of liquid (#400) and gas (#120) part. Valve (#405) connected to liquid boundary volume facilitates the simulation of different type of accident depending on valve state; loss-of-cooling (close) or loss-of-coolant (open) accident. In case of gas part, multiple junction components (#105) is used to consider well-distributed ventilation of steam or non-condensable gas from IFB. Leakage area of IFB is one of uncertain parameters because the IFB maintains nearly atmospheric pressure. Present study for loss-of-coolant accident uses 0.25 m2 leakage area enough to flow the gas between the IFB and boundary volume (#120). Boundary condition of gas is non-condensable gas (air) with room temperature (293 K) and atmospheric pressure. Initial condition of the gas and water in multiD is based on the design value of Wolsong Unit II; 311K and Patm.

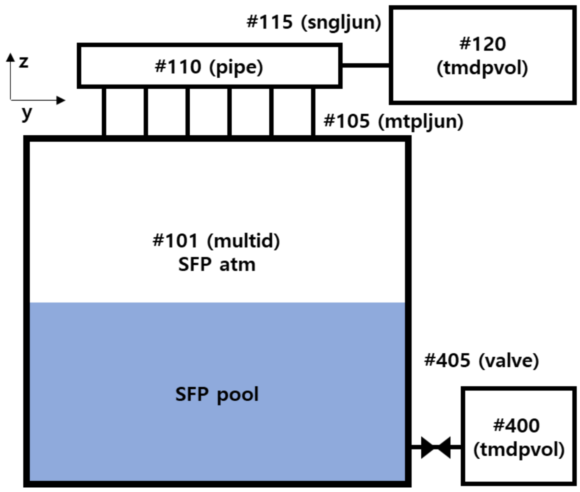


Figure 6. Boundary condition of MARS-KS model

*2.3 Sequence of event & test matrix*

Determination of representing break size (100%) is based on the pipe inner diameter (8") of the primary loop at IFB cooling system and present study evaluates the sensitivity of break size from 1 % to 50 % (Table I). Several assumptions are as below;

1. Containment gate of spent fuel transfer canal is closed between the reception bay and discharge

bay. Valves are closed and main storage bay is isolated from auxiliary bay.

2. Pumps (3441-P01, P02) and heat exchangers (3441-HX01, HX02) for cooling main storage bay are not available.
3. Coolant inventory for the feed of auxiliary water into main storage bay is not available: close for demineralized water feed valves (7165-V270, V271, V272, V273), fire protection water feed valves (7141-V232, V233), filtering water storage valves (3441-V2602, 71000-V7299-50).
4. Loss-of-coolant accident assumed to be initiated by the break of primary loop pipe (8") of main storage bay cooling at the bottom elevation (EL. 92.837m). There is siphoning breaker at the top side (EL. 99.695m, 3/4") of the 8" primary loop pipe and it is also assumed to be failed because of plugging by impurities.
5. Decay heat is constant during accident and its values is based on the abnormal condition: 3.108 MW [6].

*2.4 Results: Sensitivity analysis*

Thermal-hydraulics of IFB is evaluated depending on the break size. Power peaking factor (PPF) along the z-direction and decay heat level are identical in test cases. Increase of break size results in faster decrease of coolant level in IFB and this is closely related to the time for bundle uncovering. In case of large break area (50%), the IFB is dry-out before the coolant temperature reaches the saturation point. On the other hands, in small break area (1.0%), loss of coolant is caused by the evaporation of coolant as well as break flow.

Table I. Test matrix

| Break Size [%] | Break Area [m2] | Decay heat [MW] | PPF |
|---|---|---|---|
| 50 | 0.01621 | 3.108 | Uniform |
| 25 | 0.00811 | 3.108 | Uniform |
| 10 | 0.00324 | 3.108 | Uniform |
| 5.0 | 0.00162 | 3.108 | Uniform |
| 2.5 | 0.00081 | 3.108 | Uniform |
| 1.0 | 0.00032 | 3.108 | Uniform |

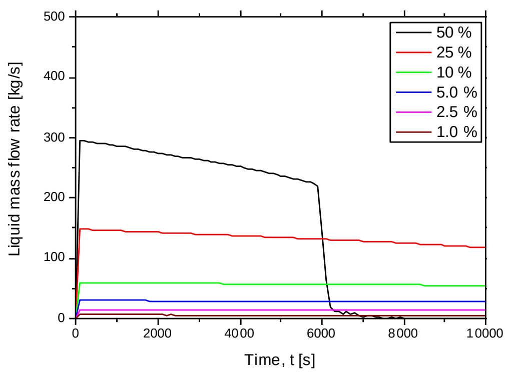


Figure 7. Discharge flow rate of CANDU IFB

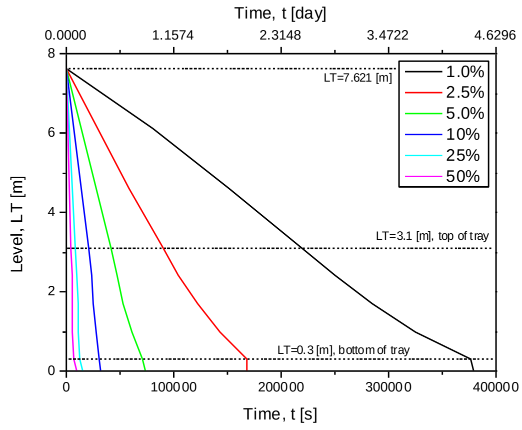


Figure 8. Water level of CANDU IFB

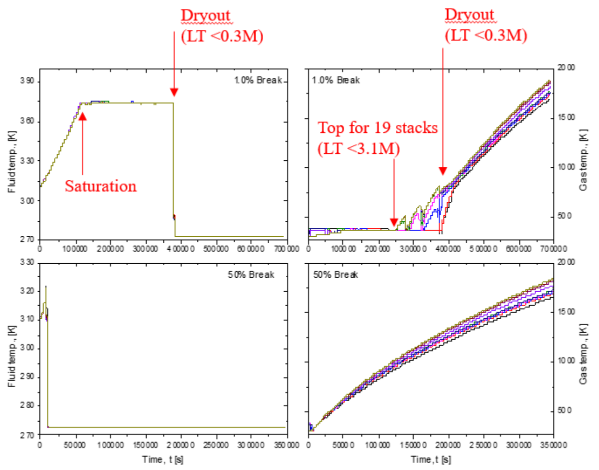


Figure 9. Fluid and gas temperature of CANDU IFB: 1.0% break versus 50% break case

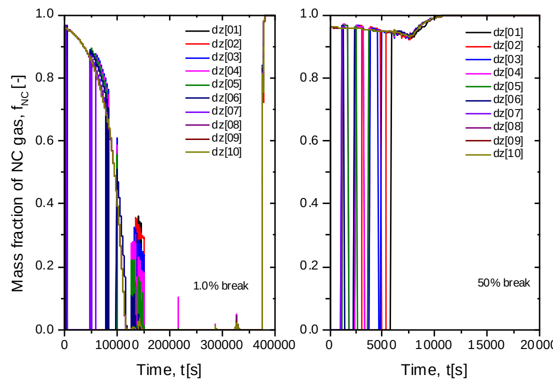


Figure 10. Mass fraction of non-condensable gas in CANDU IFB: 1.0% break versus 50% break case

Interesting point is that the gas environment of IFB is the air without steam when the bundles at the bottom of tray is uncovered. Steam generation by evaporation is not enough to fill the IFB with steam environment because (i) the coolant is lost mainly by break flow and

(ii) outflow of generated steam is formed by the leakage at the top of IFB.

*2.5 Estimation of Zr-air reaction*

Results of MARS-KS for loss-of-coolant accident show that bundle uncovery occurs in non-condensable gas (i.e., air) environment without steam in the present study. This is distinguishable to loss-of-cooling accident [7]. Different gas environment in IFB leads to different metal-gas reaction during accident. Product of Zr-Air reaction is only zirconium oxide and hydrogen issues to deteriorate the IFB safety is negligible. General reaction formula of zircaloy oxidation is described below according to the type of gas environment [8]. Zr-O2 reaction is dominant compared to Zr-N2 reaction in the air; air is usually mixture with nitrogen (80%) and oxygen (20%). It indicates that Zr-air reaction can be two times larger in exothermic heat than that of Zr-steam reaction.

$Zr + O_2 \rightarrow ZrO_2 + Q_{ox}$ (1101 kJ/mol)
$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + Q_{ox}$ (528 kJ/mol)
$Zr + 1/2N_2 \rightarrow ZrN + Q_{ox}$ (365 kJ/mol)

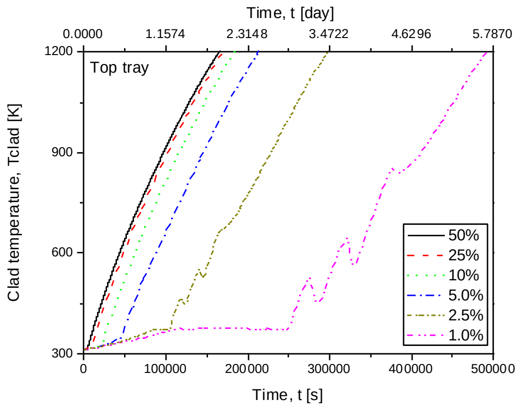


Figure 11. Clad temperature of IFB

Key phenomenon of Zr-Air reaction is a breakaway of oxide layer and temperature of zircaloy is increased sharply because of loss of passivation layer (ZrO2) and direct interaction between reactants [9,10]. NRC reported the test results of zircaloy oxidation in the air that ignition of zircaloy is occurred with fire at single or multiple fuel assembly of PWR and temperature criteria for stepwise increase is about 1200 K with zircaloy ignition causing fire [11,12]. Application of model for Zr-air reaction will be necessary to evaluate detailed progress and phenomena in CANDU IFB during loss-of-coolant accident, which will be available by coupling MARS-KS with CAISER-SFP for CANDU reactor.

## 3. Conclusions

Present study shows major results of loss-of-coolant accident at IFB using MARS-KS. Dry-out time of IFB during accident strongly depends on the break size. Air environment of IFB results in Zr-Air reaction and hydrogen issue becomes negligible. However, large heat generated by zirconium oxidation in the air will cause fast degradation of uncovered fuels as well as fire with zircaloy ignition.

## ACKNOWLEDGEMENT

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