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

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1. Introduction

Present study is preliminary analysis results for irradiated fuel bay (IFB) accident using MARS-KS code. Part II is loss-of-cooling-accident and detailed information about modeling and design for IFB is available in Part I [1].

2. Methods and Results

2.1 Performance requirement

Initial temperature of coolant in IFB is limited by 311 K (38 C) under normal condition and entry point for operator action is when the coolant temperature reaches 322 K (49 C) leading to damage of epoxy liner at bay wall [2]. Normal or abnormal condition of IFB is determined by the decay heat level [3]. First, normal condition considers the decay heat generated by ten years accumulation of spent fuel at an 80% capacity factor refueling rate. On the other hands, abnormal condition considers the decay heat of the normal condition plus one-half charge of core discharged from the reactor. Performance requirement of loss-of-cooling scenario in Table I becomes a guideline of operator action based on the coping time for accident mitigation.

Table I. Performance requirement for Wolsong IFB

Type	Time [h] for Tf =366.5 K	Time [h] for Tf =367.6 K	*Time [h] for level ≤ 3.1m
Normal	58.4	65.4	468.9
Abnormal	27.4	31.5	268.0

2.2 Sequence of event & test matrix

Loss of cooling accident in IFB indicates the loss of class IV electrical power and is similar to the station black-out accident of reactor case. Detailed assumption about the MARS-KS analysis is available in the Part.I [1].

Present study considers two types of non-uniform power peaking factor (PPF) along z-direction (height); F and B is forward and backward, respectively. Forward (F) case indicates that the bundles discharged from half core (2280) in which the highest level of decay heat is located at the top tray (19^{th}) and backward (B) is ate the bottom tray (1^{st}). In case of abnormal condition, bundles are categorized by two groups: type(a) low decay heat by about 4 x 10^4 bundles with daily on-line fuel discharge during 10 years and type (b) high decay heat by 2280 bundles within 20 days. Normal condition has only fuel bundles of type (a). Table II is the PPF of each case and bundle distribution at the forward case is described as an example.

Table II. Power peaking factor

	PPF			**Bundle distribution**	
	Uniform	Non-uniform (F)	Non-Uniform (B)	Type (a)	Type (b)
dz[05]	0.25	0.5595	0.1147	9240	2280
dz[04]	0.25	0.1790	0.1468	11520	-
dz[03]	0.25	0.1468	0.1790	11520	-
dz[02]	0.25	0.1147	0.5595	11520	-
Sum.	1.0	1.0	1.0	43800	2280
Heat [MW]	-	-	-	1.735	1.373

Table III. Test matrix

Test ID	**Decay heat [MW]**	**PPF**	**Area frac.**
Abnormal (Uniform, 0.5)	3.108	Uniform	0.5
Abnormal (Nonuniform, B)	3.108	Bot. high	0.5
Abnormal (Nonuniform, F)	3.108	Top. high	0.5
Normal (Uniform, 0.5)	1.735	Uniform	0.5

2.3 Results: Sensitivity analysis

Table IV. MARS-KS result for Wolsong IFB

Type	Time [h] for Tf =366.5 K	Time [h] for Tf =367.6 K	Time [h] for level ≤ 3.1m
Abnormal (Uniform, 0.5)	34.3	35.7	218.8
Abnormal (Nonuniform, B)	34.9	35.6	212.9
Abnormal (Nonuniform, F)	34.9	35.6	217.4
Normal (Uniform, 0.5)	62.1	63.4	366.9

Results of MARS-KS are slightly overestimated compared to the performance requirement for Wolsong IFB until coolant level reaches 3.1 m, which is the top position of the stack (Fig. 1-3, Table IV). Decay heat is dominant to determine the evaporation rate of coolant in IFB compared to the power peaking factor. Result of forward PPF case shows that bundles at the top tray have relatively high-level decay heat and they do not play a role in evaporating coolant anymore after uncovering. This results in time delay of IFB dry-out compared to the backward PPF case. Mass fraction of non-condensable gas is 0.0 and uncovered bundles at the bottom tray is under the steam environment during loss-of-cooling accident.

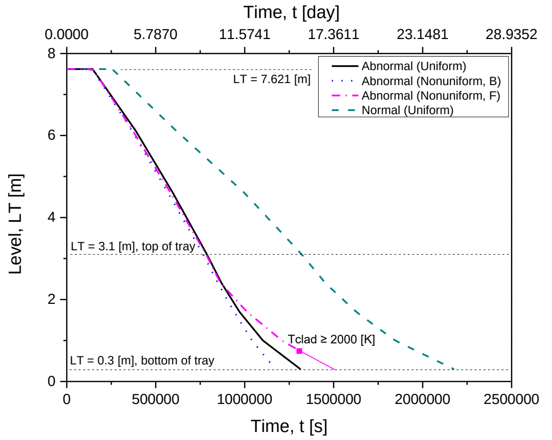

Figure 1. Coolant level of IFB

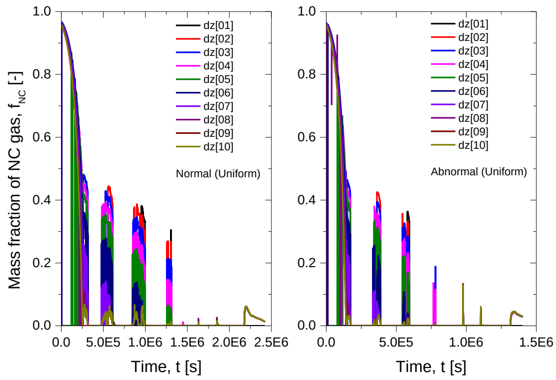

Figure 2. Mass fraction of non-condensable gas in IFB

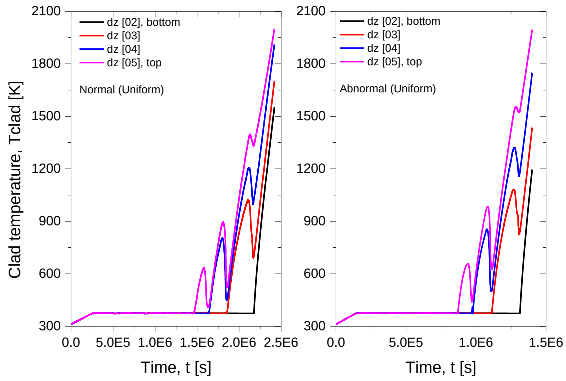

Figure 3. Clad temperature at IFB

2.4 Comparison evaluation: existing research

In Romania, evaporation rate and time for bundle uncovering at IFB were evaluated for application of the stress test at Cernavoda plant (CANDU-6 reactor) in 2011, by using the CATHENA code [4]. Recalculated results using MARS-KS adjusted input for the reference [4] (i.e., water level, decay heat, number of bundles) show that key events are well matched between cases in Table VI. Even though the range is limited for full-scope thermal-hydraulic analysis (i.e., IFB dry-out) during accident, it implies that the model in the present study using multiD module of MARS-KS is appropriate.

Table V. Comparison evaluation between codes

	CATHENA [4]	MARS-KS (adjusted)
Time for saturation [day]	2.5	2.5
Time for top-tray uncover [day]	13.3	13.4
Initial water level [m]	7.1	7.1
Top tray height [m]	2.6	2.6
Bay water surface area [m2]	235.9	235.9
Water volume above stack [m3]	1061.5	1072.0
Number of trays for stack [ea]	19	19
Decay heat [MW]	2.0	2.0
Initial water temp. [K]	38.0	38.0

2.5 Estimation of Zr-steam reaction

Loss of cooling accident in the present study shows that bundles expose to steam environment, which is distinguishable to loss of coolant accident: air environment [1]. Compared to the reactor core (4560), number of the bundles (more than 45,000) in IFB is significantly large and it results in massive generation of hydrogen by Zr-steam reaction, even though small decay heat of spent fuels leads to slow progress for heat-up and oxidation. Mass of zircaloy per fuel bundle is 2.206 kg and total mass of hydrogen generated by 100% metal-water reaction (MWR) is about 4500 kg under ideal condition, which corresponds to the oxidation of about 100 tons of zirconium by 46,080 bundles. Present study using MARS-KS does not consider the exothermic heat by Zr-steam reaction and realistic the heat-up rate of cladding can be further increased compared to the results in Fig. 3.

2.6 Comparison evaluation between accidents

Table VI. Comparison evaluation between scenarios

	Loss-of-cooling	Loss-of-coolant
Epoxy liner failure time (TF > 322K) [h]	7.1	6.7
Saturation time (TF > 372K) [h]	38.6	31.2
Bundle uncover time (LT < 3.1 m) [h]	218.8	60.8
IFB dry-out time (LT < 0.3 m) [h]	365.0	104.4
Environment	Steam	Air
Reaction formula	Zr-steam	Zr-O2 or Zr-N2

Loss-of-cooling : Abnormal (uniform, 0.5)
Loss-of-coolant : Abnormal (uniform, 0.5), 1.0% break

Table VI is the major sequence of event between accidents: loss-of-cooling and loss-of-coolant scenario. Compared to the spent fuel pool of Fukushima Dai-Ichi accident (Unit. IV, BWR), Westinghouse-type PWR or OPR1000 (PWR), CANDU IFB has relatively large mass of coolant per mass of fuel/clad with relatively small decay heat level [5-7]. Even though the loss-of-coolant accident shows faster progress than the loss-of-cooling accident in CANDU IFB, the coping time against bundle uncovering at the top-tray seems to be enough to mitigate the accident compared to other type of reactor. Another difference between them is environment of bundle oxidation (steam or air) and this can afford to cause different type of phenomena. Present study includes assumption and limitation: neglection of radiation heat transfer and exothermic heat by oxidation. Detailed analysis about uncovered bundles is also under plan by coupling the MARS-KS to CAISER-SFP code for fuel degradation and its relocation in IFB.

3. Conclusions

Evaporation of IFB based on the performance requirement of Wolsong plant is evaluated by using MARS-KS code for loss-of-cooling accident. Coolant evaporation of IFB is strongly influenced by the decay heat power while power peaking factor has small impact for the evaporation rate until the coolant level is above 3.1 m. Gas environment of IFB depends on the accident scenario and comprehensive evaluation about bundle degradation and its failure is necessary as future works.

ACKNOWLEDGEMENT

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