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Necessity of Accident Analysis Tool for CANDU Spent Fuel Pool

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1. Introduction

In a CANDU reactor, the production, transport and storage of spent fuel is a continuous process that starts within a year after the initial startup and continues until decommissioning. Spent fuel bundles are removed from the reactor core by refueling machine everyday (typically 16 fuel bundles from two channels are refueled with eight bundles each) and transferred from the fueling machines into the Discharge Room through the spent fuel port, then they are transferred to the Reception Bay and Spent Fuel Storage Bay where is a wet storage of spent fuels. Reference [1] describes the overall process about the spent fuel treatment in CANDU reactor and what we have to consider from a safety perspective, as follows.

Spent fuel continues to produce power and emit radiation after it is discharged from the reactor. Therefore, we have to manage heat from the spent fuel and to monitor its activity to remain the safety of the spent fuel. Fortunately, since the power and radiation from the spent fuel decay with time, we can deal with the spent fuel through two phases of storage before final disposal like followings:

- Immediately after its discharge from the reactor, the spent fuel is stored for several years in deep cooling pools adjacent to the reactor.
- After several years of forced-circulation cooling in water, the spent fuel is transferred to concrete containers which are air-cooled by natural convection. The spent fuel can reside in these storage cylinders for up to 100 years before its final disposal.

During the spent fuel is stored in the water pool, we have to focus on some considerations to protect workers and public from radiological exposure from the spent fuels as follows:

- <u>Avoid overheating of irradiated fuel</u>: Even after discharge from the reactor, since spent fuel continues to produce power, the potential temperature increase caused by decay power should be controlled effectively to prevent overheating of both spent fuel and the materials used in the structures which have their respective temperature limits for safe operation.
- <u>Avoid mechanical damage to irradiated fuel bundles</u>: Irradiated fuel bundles are handled remotely by fueling machines during their removal from the reactor into the irradiated fuel pool, and by operators using remotely operated tools for subsequent transfers. During these transfer of spent fuel, all procedure should be done safely so that the spent fuel bundles are not damaged.
- <u>Limit chemical and metallurgical damage to irradiated fuel bundles</u>: Damaged fuel can release highly radioactive substances into the irradiated fuel bay and also potentially into the air above. Such radiological contamination must be controlled to acceptably low levels to protect the workers and the general public. Therefore, degradation and damage to bundles must be limited to acceptably low levels.

In this paper, a general aspects of the CANDU spent fuel pool (hereafter, called SFP) are described and the reason why we should focus on the development of an accident analysis tool for CANDU SFP and what models we have to consider during the development are explained.

2. Description of SFP in CANDU

2.1 CANDU Fuel Transfer Path

Spent fuel bundles are removed from the reactor core by the fueling machines every day (typically 2 channels are refueled with 8 bundles each) and transferred from the fueling machines through the spent fuel port into a fuel transfer mechanism which transports the fuel into the Discharge Bay in Room R-001. From there, it is transferred to the Reception Bay through the interconnecting transfer tunnel on a conveyor underwater, and from there also underwater to the Spent Fuel Storage Bay as shown in Fig. 1.

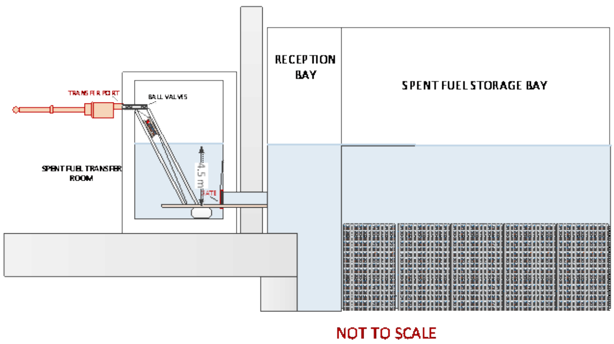

Fig. 1. Schematic diagram of three connected SF water pools.

2.2 CANDU SFP structures

The fuel bay is designed to contain spent fuel for 10 years and is designed to accommodate an additional full core discharge of fuel (4560 fuel bundles). It is filled with demineralized light water and has a dedicated purification and cooling system.

SFP is in a building that is outside the containment but adjacent to it. The bottom of the spent fuel bay is below grade in Service building which is a conventional reinforced concrete structure and a structural steel superstructure with metallic cladding and thermal insulation. A dedicated spent fuel bay cooling and purification system serves to keep the fuel covered with demineralized water and cools and maintains water chemistry and activity at acceptable levels. A ventilation system aides in maintaining air quality above the water level. The storage bay and the receiving bay are both provided with a glass fiber reinforced epoxy liner to prevent leakage. A sub drainage system intercepts any leakage and is drained to the sea. This drainage system is isolated from the surrounding water table and is not nuclear grade, not seismic qualified system.

The base slab and side walls are 1.22m thick reinforced concrete to satisfy the shielding requirements and the stringent control on crack development because of possible temperature differentials across the wall thicknesses.

2.3 Pool Geometry

The long term spent fuel bay at Wolsong is 19.84 m long, 11.89 m wide and 9.77 m deep [2] as shown in Fig. 2. The 26.7m x 20.4m building is 9m below grade for a total height of 16.5m. The spent fuel rack towers are placed 9 wide and up to 12 deep at the end of 10 years.

The CANDU irradiated fuel bay contains spent fuel in storage trays or modules, each typically containing 24 fuel bundles in 2 rows of 12 bundles. Trays are placed into a racking or framing system (towers) and a specified minimum water level is maintained above the top tray.

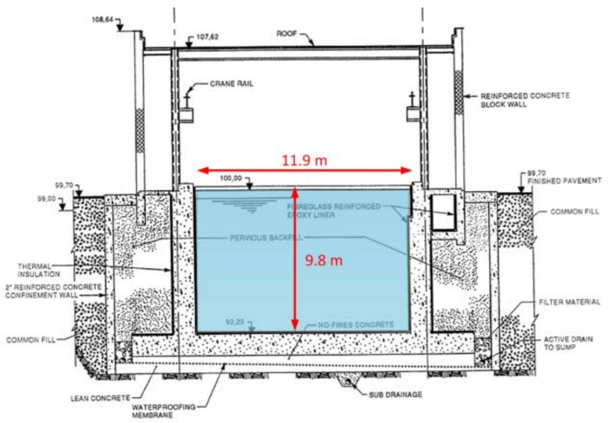

Fig. 2. Cross sections of the Spent Fuel Pool.

3. What We Have to Consider for SFP Phenomena

The fuel bundles are examined for failures in the fuel transfer room (discharge bay) where any damaged bundles are identified and separately canned but stored along with intact spent fuel. Scoping studies on fuel bundles stored in the long term storage in the SFP draining and subsequent heatup have helped us make the following observations:

- While submerged in liquid water with sufficient subcooling, spent CANDU fuel cannot heat-up as the heat flux is significantly lower than the dryout heat flux (CHF) in water.
- CANDU fuel is packed in geometries (fish basket-like trays stacked 16 high) that do not promote natural circulation heat removal by air. In absence of a liquid water envelope, there are almost no heat sinks for vast majority of fuel and adiabatic heatup gives a good representation of the timing of onset of oxidation by air.
- While some fuel bundles in the spent fuel pool can be as old as 7 years old, a number of fuel bundles can be as fresh as a week or less old.
- Fuel heat-up rates in dry stagnant air can be significant for bundles that have been out of the reactor for up to a few months. Fuel bundles may heat-up to temperatures that cause air oxidation within a day after loss of water as a heat sink. Fig. 3 shows the heat-up rate of the spent fuels.

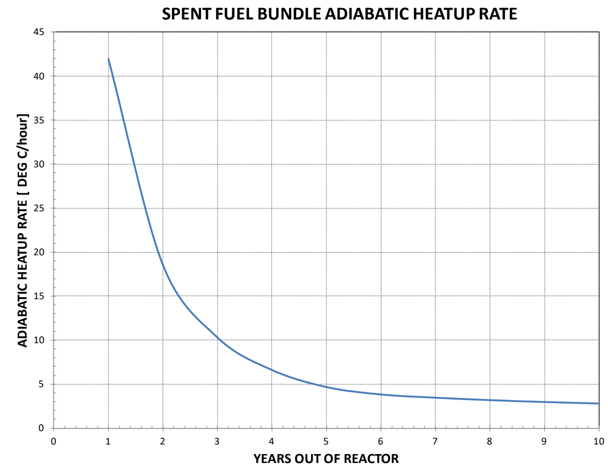

Fig. 3. Schematic Average fuel bundle adiabatic heatup rate

- Zircaloy oxidation reaction rates in an oxygen rich environment (air) are an order of magnitude higher than rates of oxidation of Zircaloy in a steam environment. As an example, and only for this scoping analysis, we use the correlations used in MELCOR.
- Heat generation during oxidation per unit mass of Zircaloy is 2 times higher in air than in steam (12.05 MJ/kg for air oxidation vs. 5.7 MJ/kg for steam oxidation). Nitrogen reactions are also exothermic and a nitride acts as a catalyst, accelerating oxidation by air.
- As a result, heat generation rates are more than an order of magnitude higher in steam (85.2 kW/m^2 in for

oxygen vs. 5.6 kW/m^2 at 1500 ^{o}K, 50 micron oxide thickness – as an example). Same heat generation rate occurs at a temperature about 300 ^{o}K lower in air than in steam as shown in Fig. 4.

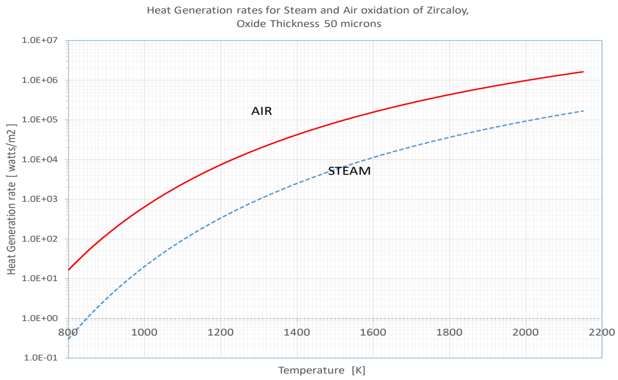

Fig. 4. Heat generation rates at a moderate oxide thickness of 50 microns.

• A 100 kW/m^2 heat generation rate due to air oxidation is a good average value for discussion purposes. Surface area of sheaths in a fuel bundle is about 0.75 m^2. Rate of growth of oxide layer is a function of temperature and oxide thickness. Fig. 5 illustrates the exothermic heat generation rate at one temperature and a range of oxide thicknesses.

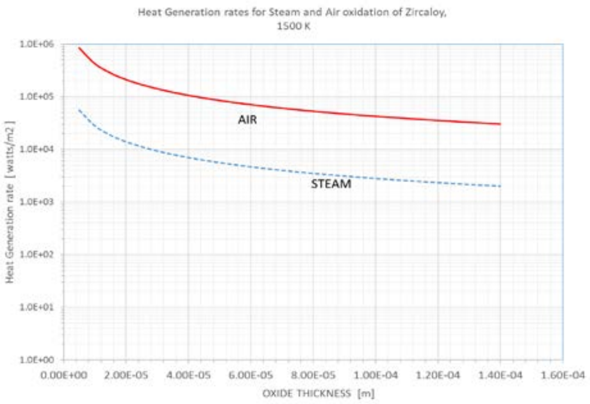

Fig. 5. Heat generation rates at one temperature and a range of oxide thicknesses.

• For a total sheath surface area of about 0.75 m^2, it translates into about 75 kw of heat generation compared to a few watts of decay power after a year (decay power is always less than 700 W).

• Amount of heat generated during rapid oxidation can promote Zirconium fires starting at bundles that have been added more recently.

• Total heat generated due to air oxidation of 2.218 kg of Zircaloy in a fuel bundle is about 27 MJ. It can theoretically raise the temperature of that bundle sufficiently to melt the eutectic. (Enthalpy of UO_2 at melting point is about 1.1 MJ/kg; therefore oxidation energy is enough to bring UO_2 to melt). It is also sufficient to raise the temperatures of adjacent bundles sufficiently to initiate oxidation and to promote air circulation that brings in additional oxygen.

• Disassembly of a fuel bundle due to air oxidation can physically move broken fuel elements onto lower lying fuel bundles and initiate local oxidation in previously cold fuel elements. The effect can be akin to throwing a lighted match onto an unlit one.

• Once a Zirconium fire induced heat-up of the adjacent, older bundles starts, the age and inherent decay power of the bundle becomes irrelevant and the fire can spread in all directions.

In view of the above observations, an integrated spent fuel bundle heat-up model needs to be developed to predict the effect of a sustained loss of water envelope on thermal and thermal-chemical behavior of the over 50,000 fuel bundles stored in the spent fuel pool. The analytical tool is also expected to be useful to look into the effectiveness of any mitigating measures that may be available.

4. Conclusions

Given that a series of interdependent phenomena occur during heat-up of fuel bundles located over vast geometries, a dedicated approach to modelling of thousands of fuel bundles within hundreds of closely stacked fuel trays is required to predict accident consequences and mitigating action effectiveness. This is incorporated in a new computer code for CANDU spent fuel pools called CA-SFP. CANDU spent fuel pools contain fuel bundles in geometries not replicated in any other reactor. Therefore, the phenomenological issues are somewhat different and require a dedicated approach.

For scenarios where operators' actions cannot be credited, the computer program provides an estimate of progression of spent fuel bundle heat-up and provides release estimates for direct dose calculation using an external fission product dispersion and dose conversion code. Major components of the CA-SFP computer code are:

- Pool Drain
- Pool Water Evaporation
- Fuel Bundle Heat-up
- Air Oxidation
- Fuel failure
- Debris Melt Relocation
- Melt quench and hydrogen generation
- Fission Product Release

- Fission Product concentration in the building
- SFP building behavior
- Mitigating Actions and SFP Building
- Fission product release into the environment

ACKNOWLEDGEMENTS

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[1] M. Tayal and M. Gacesa, “Essential CANDU, Chapter 19 Storage and Disposal of Irradiated Fuel”, UNENE, 2015.
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