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Consideration of Water Leak through Concrete Wall Cracks in CANDU Spent Fuel Pool

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1. Introduction

Spent fuel pool (SFP) is used to temporarily store irradiated nuclear fuels from the reactor. Because of its structural robustness, severe accidents involving SFP has not been expected to occur. However, after the Fukushima Daiichi nuclear accident, international interests have renewed regarding the safety of SFP under prolonged loss-of-cooling conditions although the SFP and the fuel stored in the pool remained safe during the accident [1].

SFP accidents can be partitioned into three temporal phases which are a pre-uncovery phase, an uncovery-phase and a fuel damage phase [2].

Pool water could be lost during the first phase of the accident so that the spent fuels start to get uncovered. Two critical events can be identified for the accident progression during the pre-uncovery phase with regard to the water level. Firstly, when the water level drops below the intake strainers at the top of the pool, suction to the SFP cooling system will be lost and it will be difficult to restart the pool cooling system. Secondly, if the water level drops to less than about half a meter above the top spent fuel lacks, analyses showed that the increased radiation field would prevent access to the spent fuel building [3].

Required time for evaporating the water down to a certain level for a loss-of-cooling accident depends mainly on the total heat load from the spent fuel, the pre-accident water volume and water temperature, possible loss of water through leaks, the atmospheric boundary conditions above the water free surface, and any corrective actions such as make-up water injection or forced cooling.

For the slow uncover accident scenario, the SFP is assumed to be intact when cooling is lost and the water starts to heat up. During the pre-uncovery phase, any deterioration and cracking of the pool concrete walls would be caused by the water temperature rise and the abnormal temperature gradients induced in these structures. It is expected that the temperature effects would not damage the pool to such an extent that substantial leakage would occur, however, there are few data which could support this judgement. If leakage is found to be possible due to temperature-induced deterioration, reference 1 suggests that experiments would be needed to support leak rate estimates.

Accordingly, in this paper we are focusing on the water leak phenomena through concrete wall cracks in PHWR SFP and how to model the process. We estimated a first order leakage through SFP walls in Wolsong PHWR using a crack model for Canadian SFP concrete at different temperatures.

2. SFP Structure in CANDU

In CANDU reactor, 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. 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 Pool (SFP).

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

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 as shown in Fig. 1. Concrete provides structures with strength, rigidity, and resilience from deformation. These characteristics, however, result in concrete structures lacking the flexibility to move in response to environmental or volume changes.

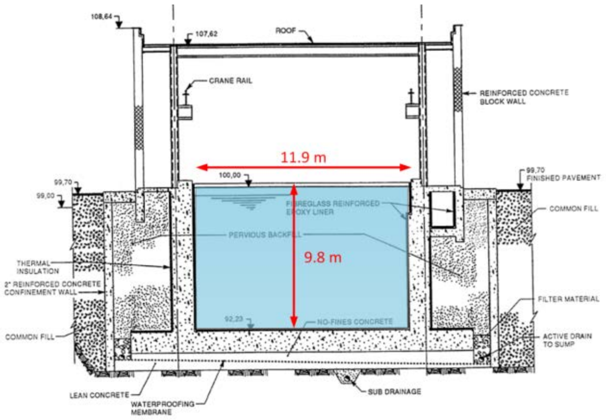


Fig. 1. Cross sections of the Spent Fuel Pool.

Concrete is a material with an inhomogeneous structure consisting of coarse aggregates and a continuous matrix composed of a mixture of cement paste and sand particles. The microscopic concrete behavior is governed by a combination of many physical and chemical material laws and depends upon many local material effects such as rebar and their appendages. Even under known mechanical loadings, concrete has a highly nonlinear behavior because of the nonlinear the internal structure of the composite. The deformation behavior as well as the strength depends on the type of loading and even under well-defined loading crack formation is still an inexact science. However, for most of the calculations the global crack behavior with macroscopic material models of the structure of interest are more suitable and the material behavior is homogenized.

With a normal water level of about 7.6m, the total surface area of the wetted concrete wall and floor is about 720m^2 (L: 19.84m, W: 11.89m, H: 7.6m). Should a rise in temperature cause the concrete to crack, leakage from all these surfaces can be substantial. Especially, at the joints with adjoining walls and floor, adequate resistance to corrosion, stress corrosion cracking and other age related degradation may have incipient cracks well before heat-up of water due to a loss of cooling.

3. Leakage Modeling through Concrete Cracks in CANDU SFP

3.1 Thermal Expansion and Tensile Stresses

Treated as a homogeneous mixture, concrete wall will freely expand with changes in temperature and as long as the wall expansion movement is free to take place. In this case there will be no tensile stresses developing. However, in reality, movement will be restrained due to internal (rebar) or external restraints (adjoining walls), which cause development of tensile stress, leading to cracking.

The concrete behaves differently under different types and combinations of stress conditions due to the progressive micro-cracking at the interface between the mortar and the aggregates [4]. It is an accepted fact that the safety limit for the pool water temperature is 50ºC at which unrecoverable cracking of the concrete structure occurs [5]. Cracks have been modelled to initiate at temperatures lower than 50 ºC and are calculated to be of higher intensity at lower elevations in the water pool.

The SFP Cooling maintains a nominal pool water temperature of (28ºC to 32ºC) and is designed to limit pool temperatures to less than 38ºC in abnormal conditions [6]. This has not always been the case as there have been instances where the bay water temperature has exceeded this design limit.

Concrete cracking in the pool wall is anticipated because of the low concrete strength in tension. There are small cracks in the walls at various locations to begin with and have led to installation of rubber membranes at Gentilly-2 spent fuel pool even after its shutdown.

3.2 Modeling of Flow through Concrete Cracks

Spent fuel concrete wall behaviour for CANDU reactors will be not much different than that for any other reactor type, barring substantive differences in material choices. Literature survey unearthed only one set of documents relating to Pickering spent fuel pool. That analysis did not report discharge through any cracks in the floor claiming that it was under the level of water in the soil (the water table). In fact that analysis also did not report any water loss from the pool once the level of water fell below the water table height in their calculations.

Reference 1 puts leakage through cracks as of minimal probability and that increase in water will not lead to concrete cracks and increased leakage. There is no basis for that ‘optimism’. The experts however states: “*If leakage is found to be possible due to temperature-induced deterioration, experiments would be needed to support leak rate estimates.*”

Cracks in concrete due to increase in surface temperature have been known to occur. Modelling for CANDU PHWR spent fuel pools is first comprehensively reported for Pickering NGS. Following are the results of their modelling on discharge through leaks for a full tank of water as a function of water temperature at which crack geometries were obtained by finite element modelling.

Table 1 shows the predicted leakage rate increases with pool water temperature. This is because with the increase of pool water temperature, more cracks are formed at lower elevations and the crack openings are increased. This means that in Wolsong where the driving force for discharge through the breaks is higher, there will be an even greater break discharge area.

Table 1. Concrete Crack Leak Rate used in Flow Modeling

Water Temp (°C)	Leakage rate (kg/s)	Leakage flux (kg/m^2 · s)
30	0	0.000E+00
40	0.1	3.004E-04
50	0.7	2.103E-03
60	1.8	5.408E-03
70	5.2	1.562E-02
80	20.8	6.249E-02
90	35.3	1.061E-01
100	51.3	1.541E-01

The modelling rigour for discharge characteristics varies from the one in the Pickering model where a rough pressure driven flow to a more sophisticated one as shown in Fig. 2.

We took the crack data for Pickering and applied it to Wolsong with corrections for surface areas (we disregard the water table and include discharge through the whole wetted concrete surfaces including the floor).

We have adopted the data for Pickering by computing the leakage discharge flux from their model and applying the calculated areas and a correction for the larger driving force (water height). Discharge flux through concrete crack leaks averaged over the whole available wall surface area is plotted as a function of peak water temperature is plotted in Fig. 3.

Sample predictions of leakage through cracks for Wolsong are given in Table 2. The reference discharge flux at 8 different peak temperatures is prorated for the deriving force (water height) and the decreasing wall surface area (adding a constant floor area).

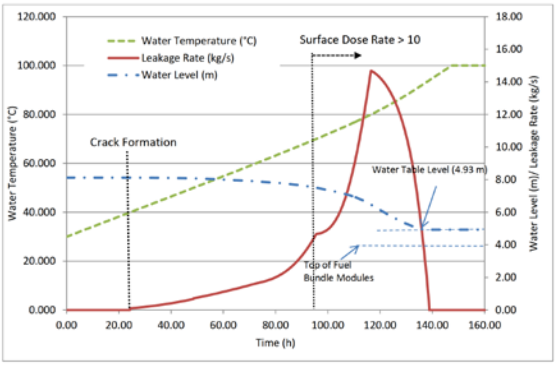


Fig. 2. Discharge flux based on model [6] and calculated first for Pickering

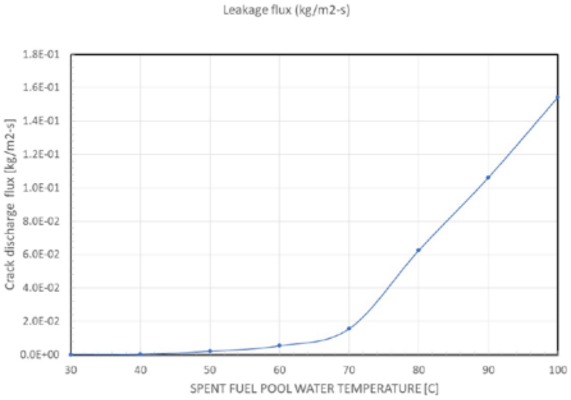
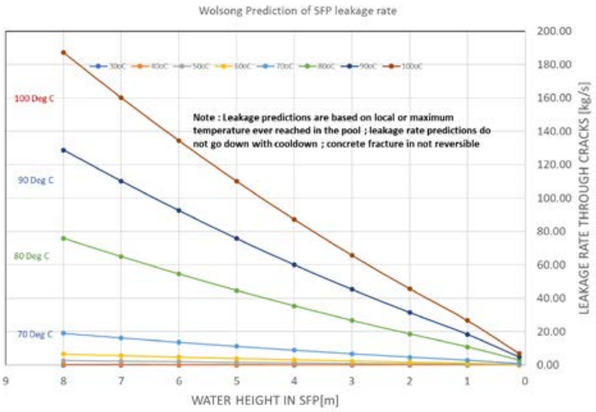


Fig. 3. Discharge flux based on model [6] and calculated first for Pickering NGS for a 3m water height over the water table.

Table 2. Prediction of leakage through Wolsong SFP walls for various peak water temperatures

			Leakage Rate (kg/s)								
Water Temp (°C)	Leakage flux at full water height of 3m [kg/m2-s]	Leakage flux at full water height of 8m [kg/m2-s]	water height [m]								
			8	7	6	5	4	3	2	1	0.1
30°C	0.00E+00	**0.00E+00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40°C	3.00E-04	**4.91E-04**	0.36	0.31	0.26	0.21	0.17	0.13	0.09	0.05	0.01
50°C	2.10E-03	**3.43E-03**	2.55	2.18	1.83	1.50	1.19	0.90	0.62	0.36	0.09
60°C	5.41E-03	**8.83E-03**	6.57	5.62	4.72	3.86	3.06	2.31	1.60	0.93	0.24
70°C	1.56E-02	**2.55E-02**	18.97	16.23	13.62	11.16	8.83	6.66	4.63	2.70	0.69
80°C	6.25E-02	**1.02E-01**	75.88	64.92	54.50	44.63	35.34	26.64	18.51	10.80	2.76
90°C	1.06E-01	**1.73E-01**	128.78	110.18	92.49	75.74	59.97	45.21	31.42	18.33	4.69
100°C	1.54E-01	**2.52E-01**	187.15	160.12	134.41	110.07	87.16	65.70	45.66	26.64	6.82

Fig. 4 and Table 2 were derived from data in for Pickering where the flow through cracks in concrete was computed for a 3m water layer above the water table (level of ground water outside the SFP walls). The SFP dimensions used were 110’ x 72’. These data were converted to discharge flux through cracks as a function of temperature at full 3m of water above the water table. Then the discharge flux data were applied to the Wolsong SFP geometry considering a water level and hence a driving force of 7.6m (multiplying the Pickering discharge flux data by $(7.6/3)^{0.5}$).



Note : Leakage predictions are based on local or maximum temperature ever reached in the pool ; leakage rate predictions do not go down with cooldown ; concrete fracture in not reversible

Fig. 4. Loss of water through leaks as a function of water height and maximum temperature of water.

4. Conclusions

Concrete walls of the SFP will crack upon heatup of water in the SFP. Their cracking is inevitable over the long time it would take the water to heatup. Using crack modelling for Pickering SFP concrete at different temperatures, we can get a first order estimate of leakage through SFP walls in Wolsong. In our calculations we do not use the questionable assumption made in Pickering of zero discharge from SFP through cracks into what is considered and level below water table or a continuum of water into which the SFP floats.

In order to provide a more realistic model, a finite element model of the SFP structure is required. The thermal hydraulic modelling in the reference analysis for Pickering is weak. We need to develop a more robust model for flow through concrete cracks.

ACKNOWLEDGEMENTS

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